Long-term behaviour of moisture content in timber constructions – Relation to service classes

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1 Introduction

Due to the hygroscopic behaviour of wood, moisture content influences the physical and mechanical properties, when the wood is dried under the fibre saturation point (FSP). 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. According to EN 1995-1-1:2004, Eurocode 5 (2004): Service class 1 is characterized by an ambient climate of 20 °C temperature and 65% relative humidity and a moisture content in wood is in average less than 12 M%; in SC 2 the moisture content in wood is in average less than 20 M%; and SC 3 comprises cases with moisture content higher than 20 M%. In SC 1, the relative humidity can be higher than 65% for few weeks per year. National annexes specify the ranges for the service classes differently, e.g. Germany and France. These three classes are a simplification for the planning engineers, because different wood species and wood products react different on climate changes.

The assignment of timber elements to one service class according to the ambient climate condition is one important step for the design of the load carrying capacity and ultimate limit states. However, the development of moisture gradients over the cross section due to daily, weekly or seasonal changes of the climate situation and thus moisture content are not directly considered. For example, an increase of the moisture content leads to moisture induced tension stresses inside the cross section. Thus, when exceeding 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 tension perpendicular to the grain or shear, as shown in Figure 1.

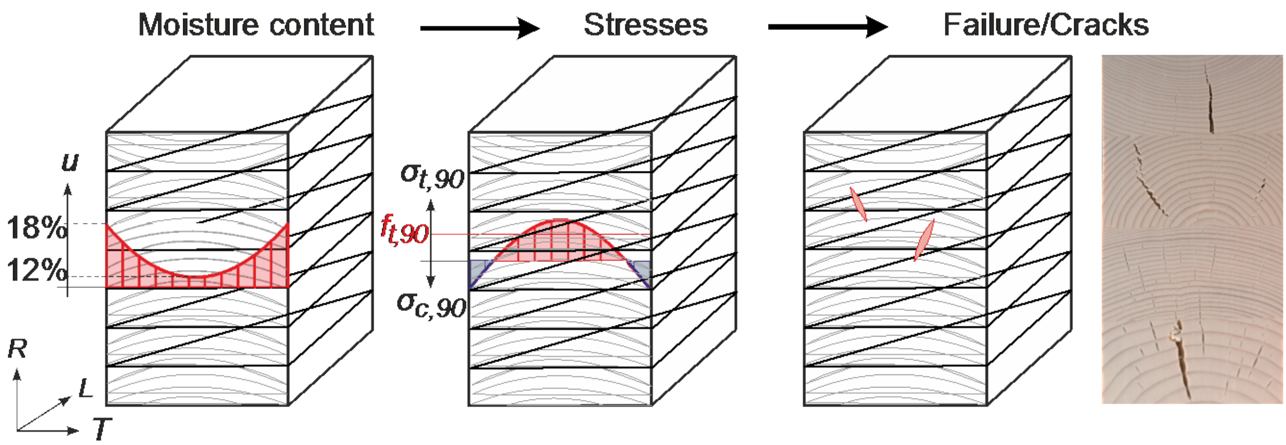

Figure 1: Moisture and stress distribution as well as failure of the cross section for an adsorption process

2 Investigation of the moisture content in wood

2.1 Experimental test series under laboratory conditions

2.1.1 Material and Conditioning

For the observation of the developing moisture content over the cross section, the test series were prepared specifically 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 considered, see Figure 2. The side faces of the test specimens were sealed, so that the moisture diffusion only takes place in one material direction. On each specimen, gauges 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 before and during the preparation and afterwards loaded with 95% relative humidity for a period of about 12 months.

The electrical resistance method was used for the determination of the moisture content using a pair of insulated stainless steel screws as sensor. A Thermofox and Gigamodul from Scanntronik Murgauer GmbH were used to log measurements every 6 hours.

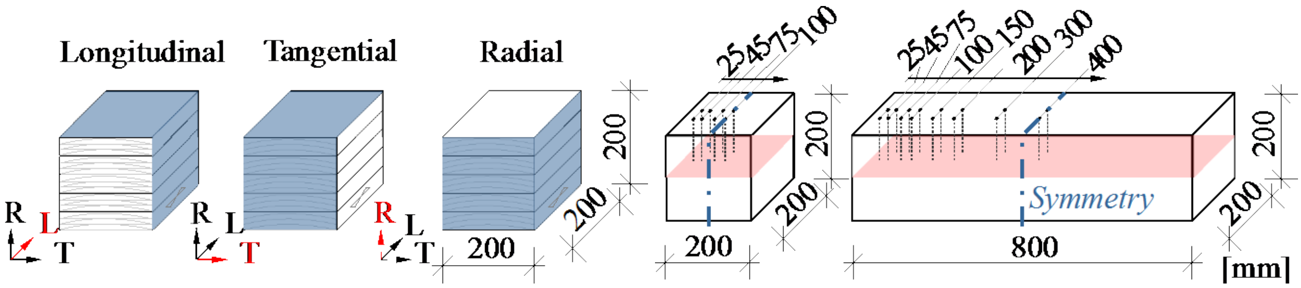

Figure 2: Test specimens with sealed surfaces in blue (top) and position of measuring points for the 200 mm and 800 mm long specimens (bottom)

2.1.2 *Results*

The moisture distribution in the cross section for the measuring period for the 200/200/200 mm test series are summarized in Figure 3. The diagrams include one curve for each measuring point per material axes. 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 moisture content according to the climate of 20°C/95% is 24 M%. The oven dry method carried out after the tests confirmed a moisture content of 24 M%. It was observed, that the screws showed, even using galvanised steel, some kind of corrosion which may influence the resistance and led to the lower measurement. This could be taken into account by determining an additional time dependent calibration factor. However, the corrosion should not occur and other materials should be used.

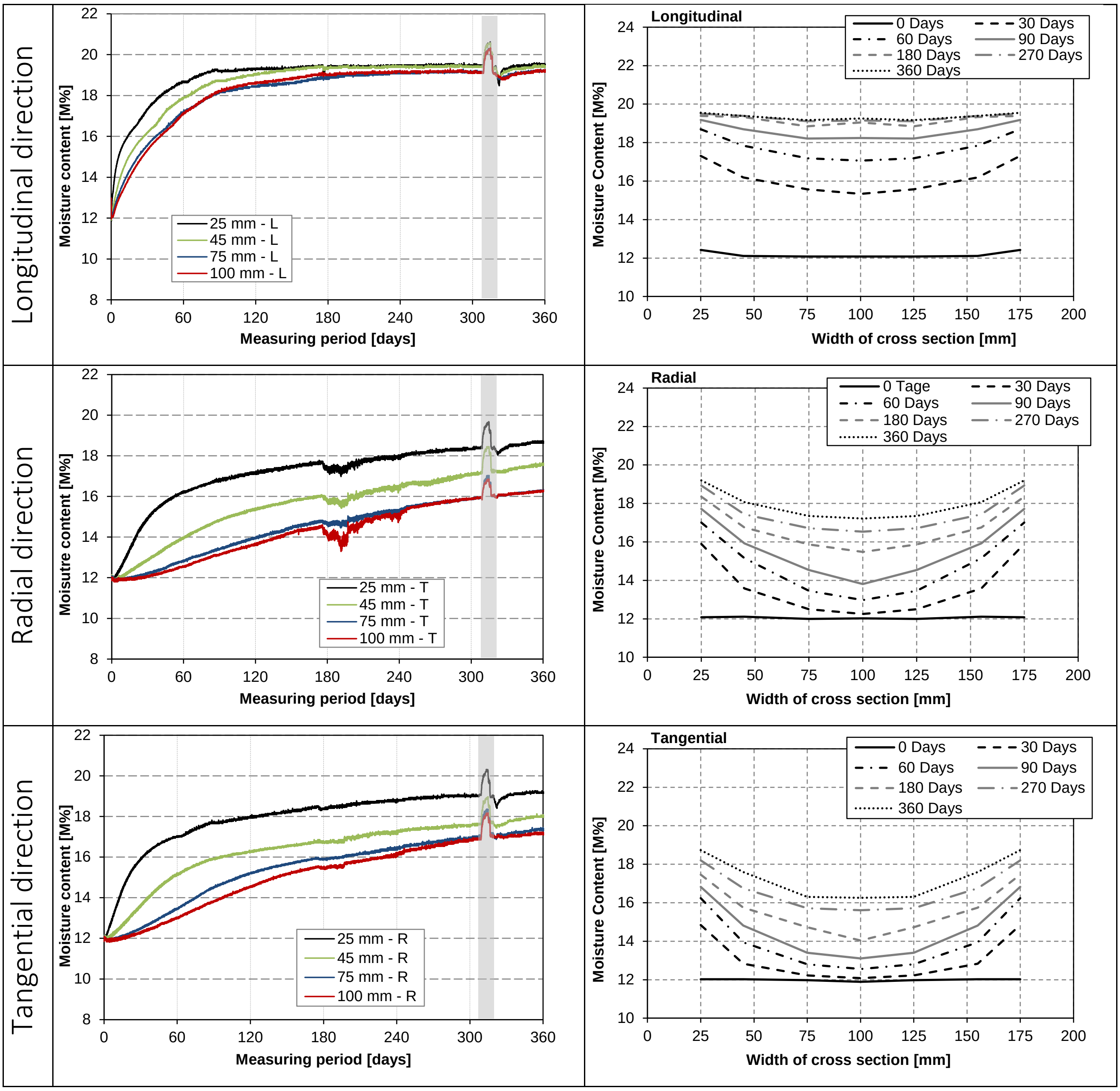

Figure 3: Moisture content development over time and cross section for the three material directions

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 gradient depends on the diffusion direction. For the experimental test series 200/200/800 mm similar results could be observed, as summarized in Franke et al. (2016). The grey shaded time period in the diagrams presents a short break down of the climate chamber within the measuring period.

2.2 Monitoring of timber bridges

2.2.1 General

Timber road bridges where monitored for the assessment of timber members directly exposed to the climate. The Bern University of Applied Sciences, the Institute for Timber construction, Structures and Architecture monitored and assessed six timber bridges in different climate regions of Switzerland, see Figure 4. Table 1 summarizes the main construction details as well as measuring periods and measuring values for each timber bridge. In addition to the direct local measurements at the timber bridges, the climate (air temperature and relative humidity) of close by meteorological stations (Meteo) was observed using data from www.meteoswiss.admin.ch.

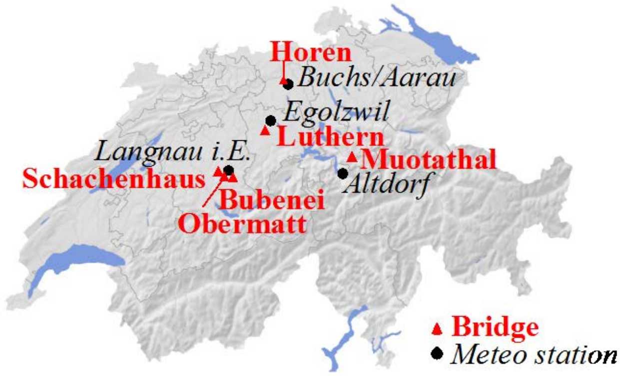

Figure 4: Location of timber bridges monitored and close by meteorological stations

Figure 5: Timber road bridge Horen

2.2.2 Results

For the timber bridge Obermatt, the measuring results for the direct ambient climate (air temperature and relative humidity) as well as the moisture content are shown as example in Figure 6 for a period of 41 months. The single data of each parameter are summarized in averaged curves over 14 days. The seasons of the year can be clearly distinguished; the winter season with low temperatures from -5 to 5 °C and higher relative humidity, than the summer season with temperatures of 15 to 20 °C and about 80% relative humidity as well as the two transition seasons spring and fall with the increase respectively decrease of the temperature and the relative humidity reversely.

Table 1: Monitoring details of the timber road bridges

Bridge/Erection Meteo station	Characteristics	Measuring period/ -rate/ -system	Measuring values
Horen 2008 Buchs/Aarau	Beam bridge Spruce Glulam Block glued	since Oct 2009 every 6 hours local system	20 moisture content sensors 1 air temperature sensor 1 relative air humidity sensor
Muotathal 2009 Altdorf	Arch bridge Spruce Glulam Block glued	Oct 2009 - Dec 2011 every 6 hours local system	16 moisture content sensors 4 wood temperature sensors 2 air temperature sensors 2 relative air humidity sensors
Obermatt 2007-2008 Langnau i. E.	Beam bridge Spruce Glulam	Dec 2010-2014 every 6 hours remote system	16 moisture content sensors 4 wood temperature sensors 2 air temperature sensors 2 relative air humidity sensors
Schachenhaus 2000 Langnau i. E.	Timber-concrete composite bridge	Mar 2011-2013 every 6 hours local system	8 moisture content sensors 2 wood temperature sensors 1 air temperature sensor 1 relative air humidity sensor
Luthern 2010 Egolzwil	Spruce glulam Block glued Deck of Kerto-Q	Nov 2009-Sept. 2011 Every 6 hours local system	18 moisture content sensors 1 air temperature sensor 1 relative air humidity sensor
Bubenei 1988 Langnau i. E.	Arch bridge Spruce Glulam, Deck of cross pre stressed glulam	since July 2012 every 12 hours local system	24 moisture content sensors 1 air temperature sensor 1 relative air humidity sensor

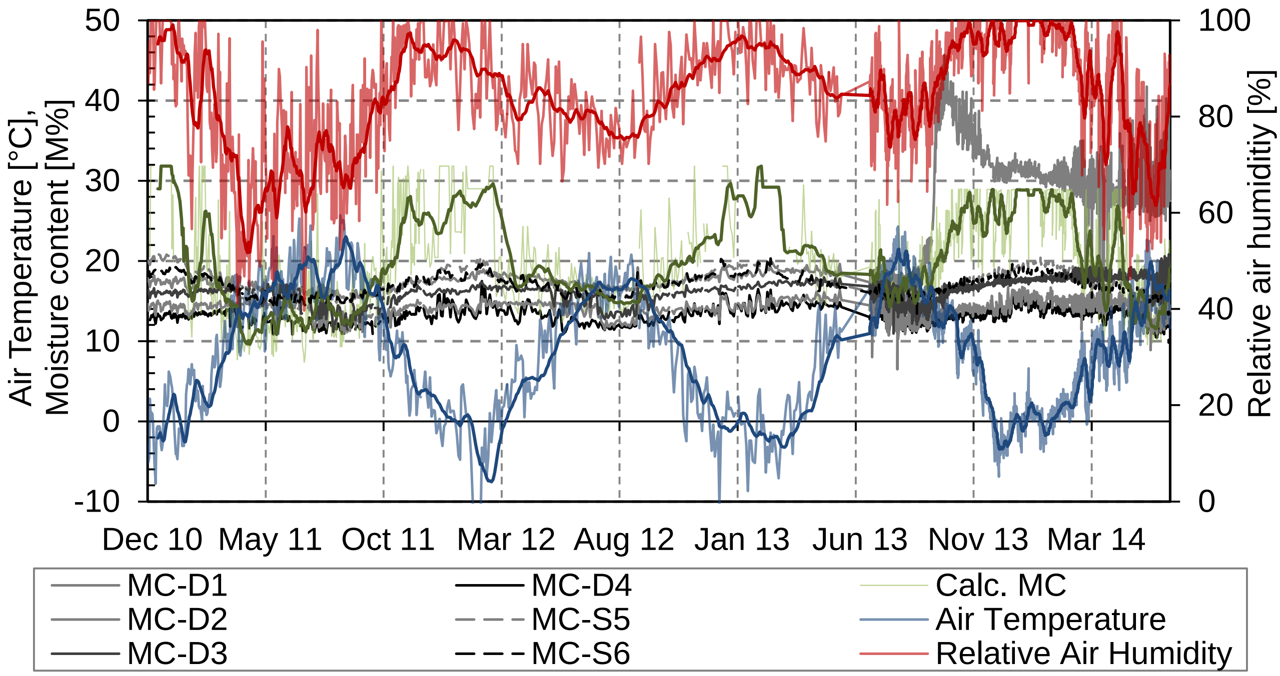

Figure 6: Timber bridge Obermatt, Measured climate and moisture content and calculated equilibirum moisture content

The moisture content is shown for sensors close to the surface (MC-S) and sensors in a depth of 200 mm (MC-D). The equilibrium moisture content calculated according to the measured ambient climate was added as comparison. A time offset according to the moisture diffusion transport and climate duration is not considered. Theoretically, the equilibrium moisture content is valid for the complete cross section by a constant climate. The moisture content measured in the timber cross section follows the seasonal effective climate changes. The response is delayed and with lower variations for both sensor locations at the surfaces and inside compared to the calculated equilibrium moisture content. The moisture content varies between about 14 and 20 M%. The variation of the moisture content at the surface is practically of about 5.5 M% between the summer and winter period. The curves of the moisture content at the inner structure are more evenly distributed and compact to each other, with variations of 2.5 M%. The difference between the inner and outer moisture content of 3 M% results in internal moisture induced stresses. The phase shift between the theoretical calculated equilibrium and measured moisture content is about 2 to 3 months depending on the gradient of climate change and the phase of adsorption or desorption. In general, the measured moisture content did not exceed 20 M%. The behaviour determined and shown for the bridge Obermatt could, in a similar range, also be observed for the other five timber bridges, Franke et al. (2016).

For the planning phase of timber bridges, the analyses of the ambient climate on the bridge and the regional climate by a close by meteorological station are compared. For example Table 2 summarizes the mean, maximum and minimum values for the air temperature, relative humidity and the calculated equilibrium moisture content for the timber bridge Obermatt. The differences in the measured values results in differences in the equilibrium moisture content as well. The mean equilibrium moisture content will be achieved in the inner cross section during the life cycle. After the erection, the ambient climate may induces a moisture gradient in the cross section considering a moisture content of 8 - 12M % from the production line/condition without pre conditioning.

For each timber bridge monitored, the comparison with a nearby meteorological station shows differences which reach up to 6 M%, as summarized in Table 3. For each case, the same measuring period was used wherefore the mean values can differ for the same meteorological station. As conclusion, the local effects regarding the location and the kind of bridge (e.g. water or street crossing) should not be neglected.

Table 2: Timber bridge Obermatt; Comparison of direct measuring at the bridge and meteorological station (meteo)

	Mean Value		Minimum		Maximum		Variation	
Bridge Obermatt	Bridge	Meteo	Bridge	Meteo	Bridge	Meteo	Bridge	Meteo
Temperature [°C]	8.0	8.3	-18.1	-19.1	25.3	31.7	43.4	50.8
Relative humidity [%]	86.8	84.1	34.5	21.8	99.9	100.0	65.4	78.2
Equilibrium moisture content [M%]	20.6	20.3	6.9	4.7	29.0	29.1	22.1	24.3

Table 3: Comparison of the equilibrium moisture content according to the ambient climate measured at the timber bridges or meteorological stations (Meteo) and the moisture content measured

Bridge / Meteo station	Measuring period	Moisture content - mean value			Moisture content - variation		
		Bridge		Meteo	Bridge		Meteo
		Meas.*	Calc.	Calc.	Meas.*	Calc.	Calc.
Mouthatal / Altdorf	15 month	16.6	15.6	15.9	7.5	24.3	25.6
Horen / Buchs	12 month	16.4	15.6	17.5	6.9	23.3	23.6
Luthern / Egolzwil	14 month	13.5	15.7	20.5	8.1	20.2	22.9
Bubenei / Langnau	25 month	22.5	17.2	24.7	5.7	26.6	18.1
Obermatt / Langnau	45 month	18.1	20.6	20.3	8.9	22.1	24.3
Schachenhausen / Langnau	23 month	17.0	15.9	20.5	6.7	21.3	24.3

* Mean value of every measuring point close to the surface

Further, the influences on the ambient climate due to constant shadows, flora, and wind are not insignificant. A positive result is that the moisture content measured is less than the equilibrium moisture content according to the climate of meteorological station.

2.3 Numerical simulations

2.3.1 Numerical model and parameter settings

A 2D numerical model in FE was set up to simulate the moisture diffusion. Linear 4-node plate elements with a regular mesh size of 5 mm were used. The time step size in the calculations was set to a constant interval of 0.1 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, Schiere (2016). The inaccuracies occur right after loading, close to the surface of the beam. These inaccuracies do not affect the moisture content developments in the center of the cross section more than the aforementioned inaccuracy of 0.1%.

The modelled beam was loaded as a parallel shaped body, like set up for the experiments and seen in Figure 2. In that way, the material was loaded in its principal material axes.

Moisture diffusion was modelled to be Fickian. In case of wetting processes, Fickian moisture diffusion is expected to give a good approximation of the actual process. In case of drying, non-Fickian moisture diffusion is often preferred over normal Fickian diffusion. This means that extra input parameters have to be given to properly simulate the evaporation of moisture from the wood surface. However, the drying process in the simulation was modelled through a Fickian process as well.

2.3.2 Validation of numerical model

The simulations made with the model were compared to experimental values. This was done for both wetting and drying in the case of a 90 mm wide beam in Jönsson (2004), and for wetting in radial and tangential direction in case of the 200 mm wide beam for the own experiments in Franke et al. (2016).

In this first validation case, the difference between radial and tangential moisture diffusion is difficult to make, because the pith location of each board in the tested glulam beam was close to the board edge. Radial and tangential moisture diffusion is often averaged to one single value, although small differences do exist according to Siau (1971). The wetting and drying was performed from 9 to 16 M% vice versa, see Figure 7. The simulations overlap the moisture content values obtained from experiments. The used diffusion values for wetting and drying were already proposed for the 90 mm wide beam in Angst and Malo (2010).

Diffusion values for validation of the wetting experiments of the 200 mm wide beams were derived in Schiere (2016). The diffusion values for radial moisture diffusion were higher than for tangential diffusion, 2.89e-10 m^2/s and 1.61e-10 m^2/s, respectively. Both were modelled as constant values. The wetting process was simulated from 12 M% to 20 M%, see Figure 8.

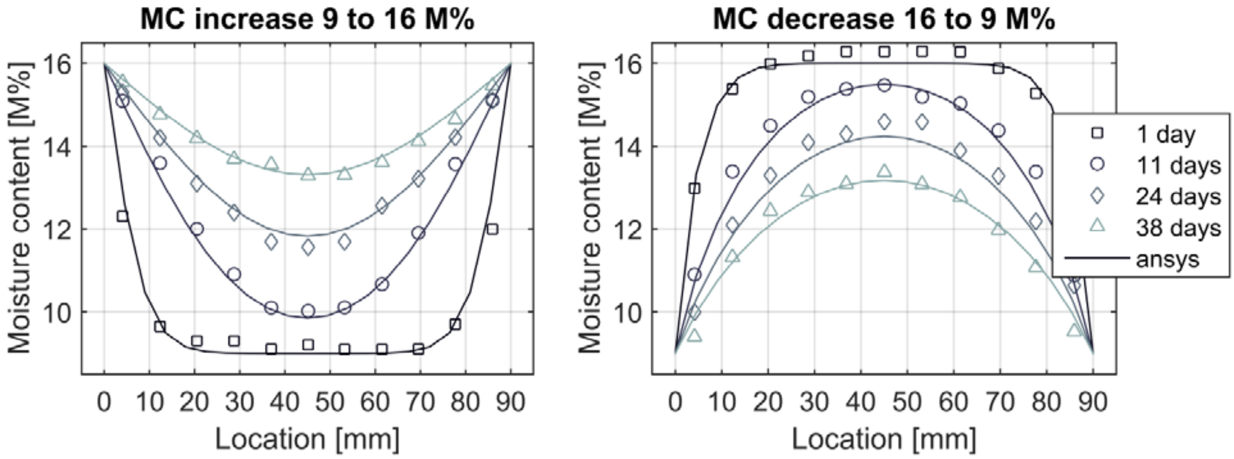

Figure 7: Comparison of experiments and simulations of wetting and drying process of a 90 mm wide beam

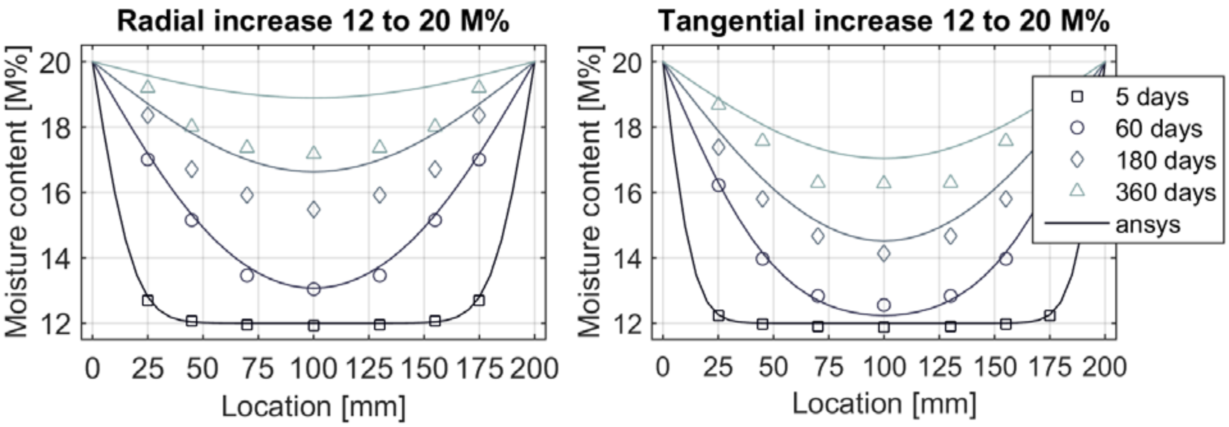

Figure 8: Comparison of experiments and simulations of wetting process in radial and tangential direction of a 200 mm wide beam

Comparisons between simulations and experiments overlap over at least the first 60 days of the experiments very well. Afterwards, differences are observed and they become larger over time, although the differences barely exceed 1 M%. The measurement might also be influenced by corrosion affecting the measured resistance between the gauges, but this is currently under investigation. The differences could also be due to some non-Fickian effects explained by Droin-Josserand et al. (1989) for instance, where moisture diffusion slows down approximately halfway the moisture content increase.

3 Results and relation to standards

3.1 Building types vis a vis service classes

The analysis of the monitoring results observed or published by Gamper et al. (2014), Cruz (2006), Jorge (2014) for different building types and bridges show typical characterizations. In general, the moisture content measured was used where available. In all other cases, the equilibrium moisture content was calculated according to the monitored temperature and relative humidity using the method by Simpson (1973).

In most cases, one service class according to EN 1995-1-1:2004 can clearly be assigned, as shown in Figure 9. However, the building types ice halls, sports halls and swimming pools show a wider variation compared to the other ones. This is related to the specific user profile, e.g. ice halls are not always used over the complete year. Timber bridges show also a wide variation compared to the other ones, but can still be assigned to service class 2, as shown in Figure 10. The timber bridge Bubenei is the only bridge with higher moisture contents which is related to a leaky deck which was reconditioned. In this process, the monitoring system was installed to observe the drying process of the timber structures. These values are not used for further discussions. Figure 10 includes the measured moisture content on timber bridges as mean

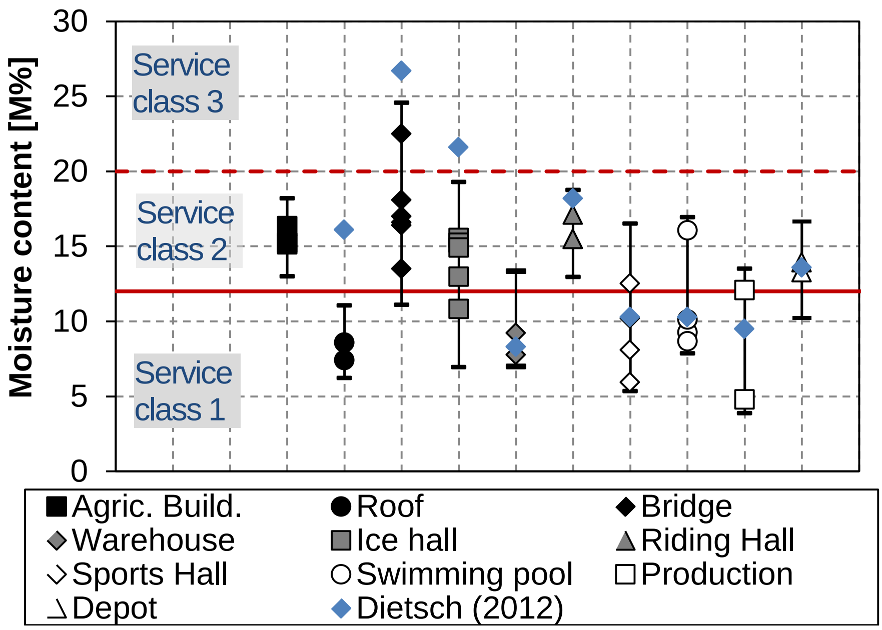

Figure 9: Average moisture content in typical timber building constructions and relation to service classesaccording EN 1995-1-1:2004

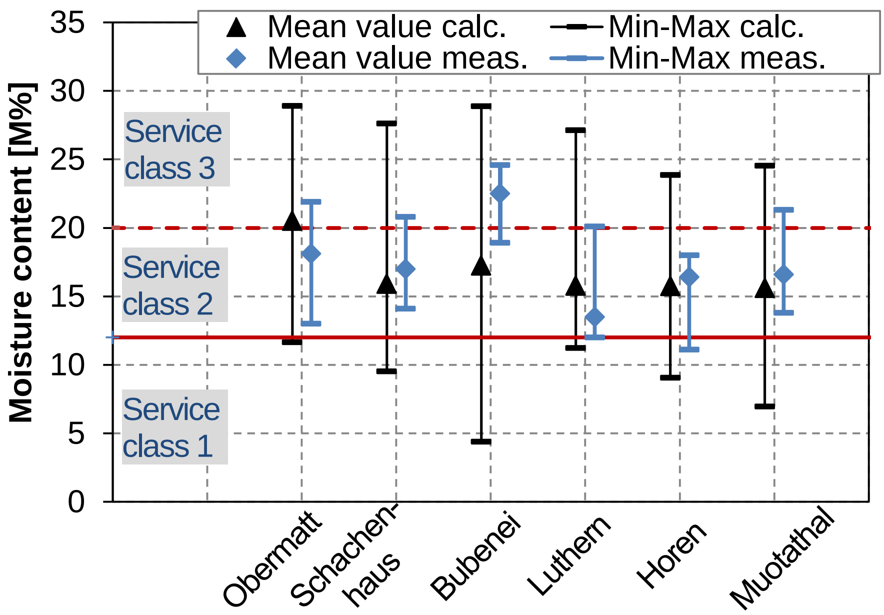

Figure 10: Average moisture content in typical timber building constructions and relation to service classes according EN1995-1-1:2004

values against the measuring points close to the surface and the equilibrium moisture content according to the ambient climate measured. The comparison confirms again that the ambient climate at a bridge has to be considered carefully and that the simply use of information from nearby meteo stations can lead to overestimations of the moisture content.

The results presented are important guidelines for planning engineers, since recommendation of assignment of timber structures to service classes are not available in the standards. The research results presented by Dietsch (2012) confirms the characterizations by building types as shown in Figure 9 where the mean values are included for comparison.

3.2 Distribution over the cross section

The distribution of the moisture content over the cross section could be experimentally and numerically determined during an intensive adsorption process by 20 °C and 95% relative humidity. For two different sizes and three material directions, the distribution over the cross section was determined, as shown in Franke et al. (2016) or in e.g. in Figure 11 and Figure 12. The measured distribution over the cross section was theoretically extended to the surface according to the resulting equilibrium moisture content according to the climate. The distribution of the moisture content along the radial or tangential direction is not converged for a cross section of 200/200/200 mm even after one year of an intensive adsorption process. 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.

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. Figure 13 and Figure 14 show the moisture content at different material depths for an ice rink and a timber bridge according to the ambient climate measured at the timber structures.

Currently, only a constant service class is used for the design. As proposal, a differentiation of the service class over the cross section, as shown in Figure 15, could be used for the activation 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. The question is how to define the size of the active zone. A theoretical analysis using the shrinkage swelling mass show that a difference greater than 1.5 M% is enough that the stress in the wood exceeds the tension strength perpendicular to the grain, as shown Table 4.

Table 4: Theoretical limits of the moisture content for the risk of fracture of the cross section

Material direction	Shrinkage/Swelling mass for Spruce	Modulus of Elasticity E [MPa]	Tension strength f_t [MPa]	Limit of moisture content
Longitudinal	α_L = 0.01 %/M%	10'000	80	> 80 M%
Radial	α_R = 0.19 %/M%	800	2.7	> 1.8 M%
Tangential	α_T = 0.39 %/M%	450	2.7	> 1.5 M%

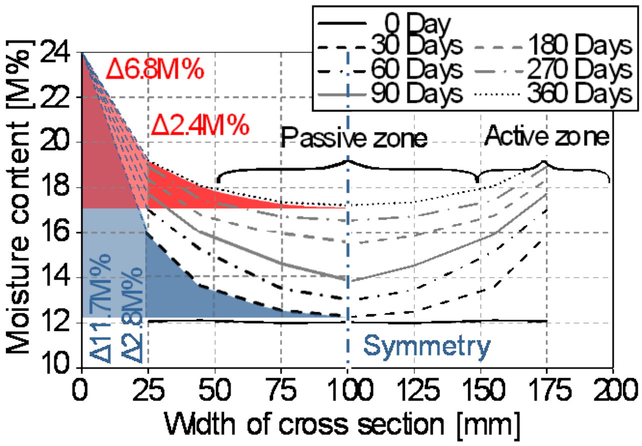

Figure 11: Experimental results of moisture distribution in radial direction for the adsorption process, 200/200/200 mm

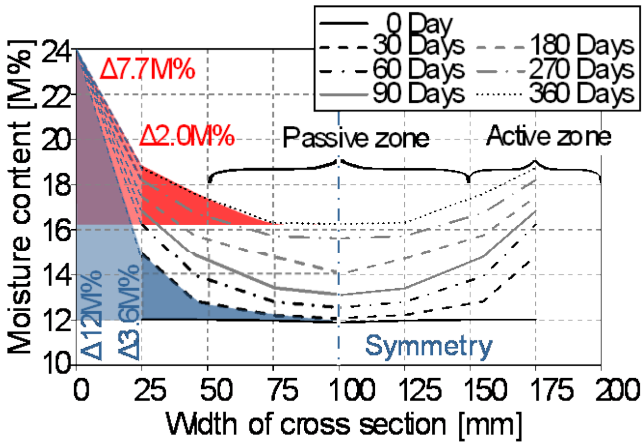

Figure 12: Experimental results of moisture distribution in tangential direction for the adsorption process, 200/200/200 mm

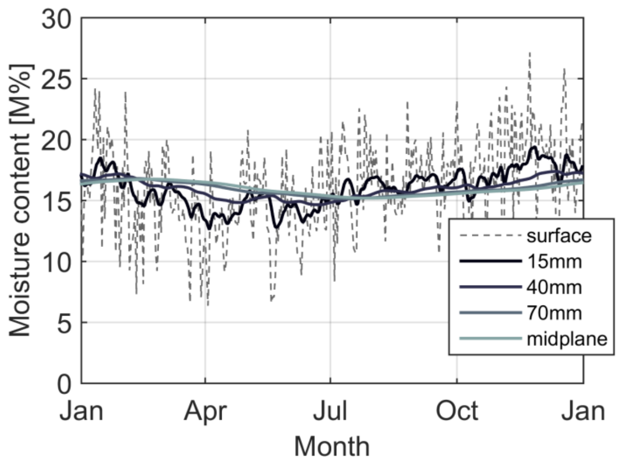

Figure 13: Seasonal moisture content developments on a bridge on a 200 mm wide beam

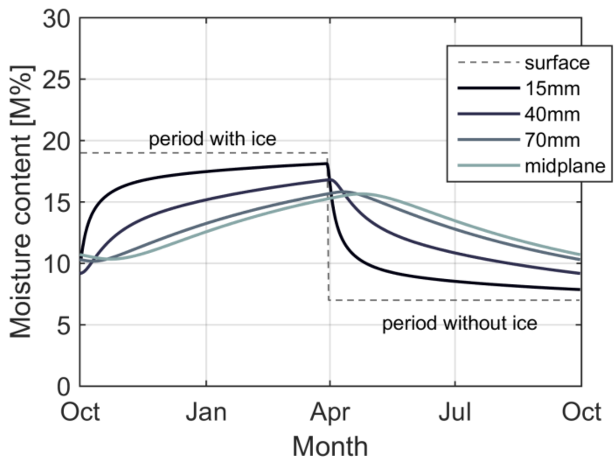

Figure 14: Seasonal moisture content developments in an ice rink in a 200 mm wide beam

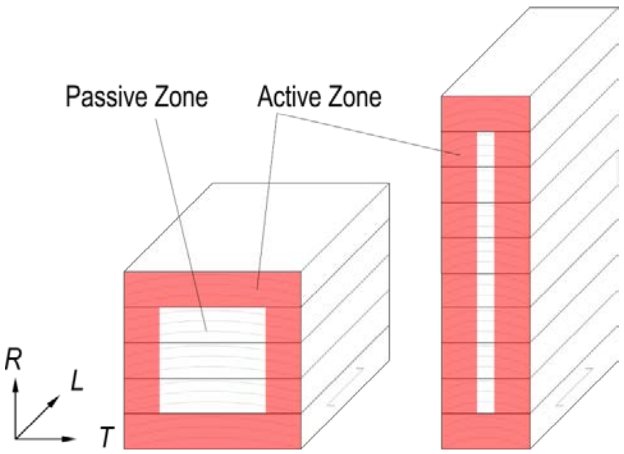

Figure 15: Differentiation of cross section in active and passive zone

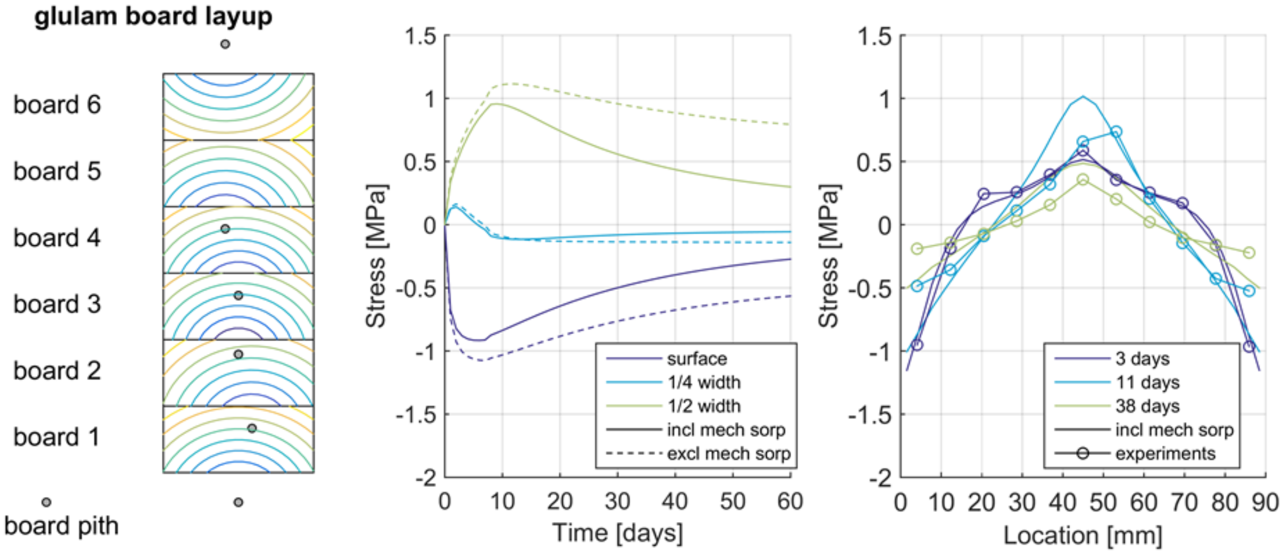

Figure 16: Development of moisture induced stresses in- or excluding time dependent effects in a six layered glulam beam tested in Jönsson (2004).

The real stress distribution is a complex process requiring time dependent parameters. Stress distribution depends on beam width, loading time, pith location of the individual boards, material anisotropy, etc. An example of this stress distribution, calculated as a linear (elastic) distribution and as a non-linear (time dependent) distribution is given in Figure 16. The figure shows the calculated and measured stress distribution in a 90 mm wide and 270 mm high beam, where the pith location is in the order of 1 cm to 2 cm from the individual board edge. The 1D-model explained by Häglund (2008) allows calculation of stress distribution as function of time and allows the comparison between in- and excluding mechano-sorptive stress developments. The time dependent calculations are compared to experimental values given in Jönsson (2004).

4 Recommendation and conclusions

4.1 Erection time period or maintenance/service times

Earlier simulations and validations have shown that the moisture diffusion can be approximated using numerical simulations. The physics behind these complex processes are roughly understood and numerical models should include more than only Fickian moisture diffusion. Although past laboratory experiments focused on a single transient increase and decrease or a cyclic moisture load on wooden beams, real structures operate in more complicated environmental conditions.

As the boards are generally stored, sawn, planed, and glued into glulam beams under moisture contents of approximately 12 M%, it is recommended to investigate the effects this has on the construction and operational events. Relevant questions could be if risk of internal damage due to moisture induced stresses is larger during building construction in winter or in summer periods. Another question could be if better ambient climate control around highly loaded timber elements is required.

This is partly worked out in an example in which various single transient moisture loads are applied to 5 beam sizes with a fixed aspect ratio and board pith location of 50 mm under the board edge, see Figure 17. The stress distribution per time step is calculated over an extended period of time, including time dependent effects. Alongside, an extra variation is made alternating the pith locations by 15 mm from the centreline, see Figure 18.

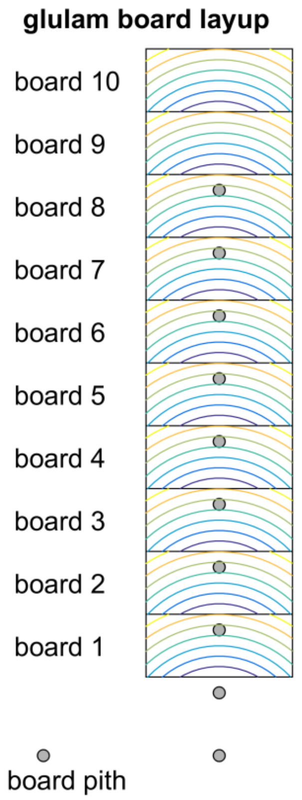

Figure 17: Glulam beam 100/400 mm with pith location on centerline and 50 mm under board edge

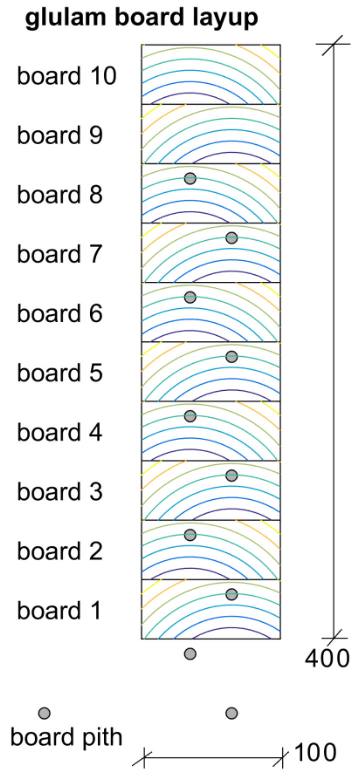

Figure 18: Glulam beam 100/400 mm with alternating pith location on +/- 15 mm from the centerline and 50 mm under board edge

To calculate the stress distribution, the 2D-FE model used earlier was extended and time dependent effects mentioned in Häglund (2008) were included as well. In this case, smaller elements would clearly result in higher accuracies, but calculation times would become longer too. Uncertainties here were expected to be acceptable, in the order maximum 5%, depending on the location, as explained by Schiere (2016).

Examples like Angst-Nicollier (2012) have already shown that the location of the pith with respect to the board edge is important in the development of the stresses during wetting and drying. This is mainly due to the material anisotropy that is high around the pith locations. Different beam widths were considered to see what the relation was between size and maximum stress level was, see Figure 19 (top left). The figure shows the tension stress levels as a function of single load amplitude change and beam width/height. It is observed that under constant loading, tension stress levels of well above 3 MPa can be achieved under extreme wetting conditions. The limit of 1.8 MPa as suggested by Blass and Schmidt (2001) was also drawn in this figure to see where measures are possibly needed to prevent crack generation in the centre of the glulam beam. This line shows that tension stress levels are exceeded at load variations above 9 M% on a 150/600 mm wide/high beam.

Figure 19 on the top right shows that stresses can be reduced more than 10 % by taking care of pith arrangement. Larger pith distances from the board edges will reduce

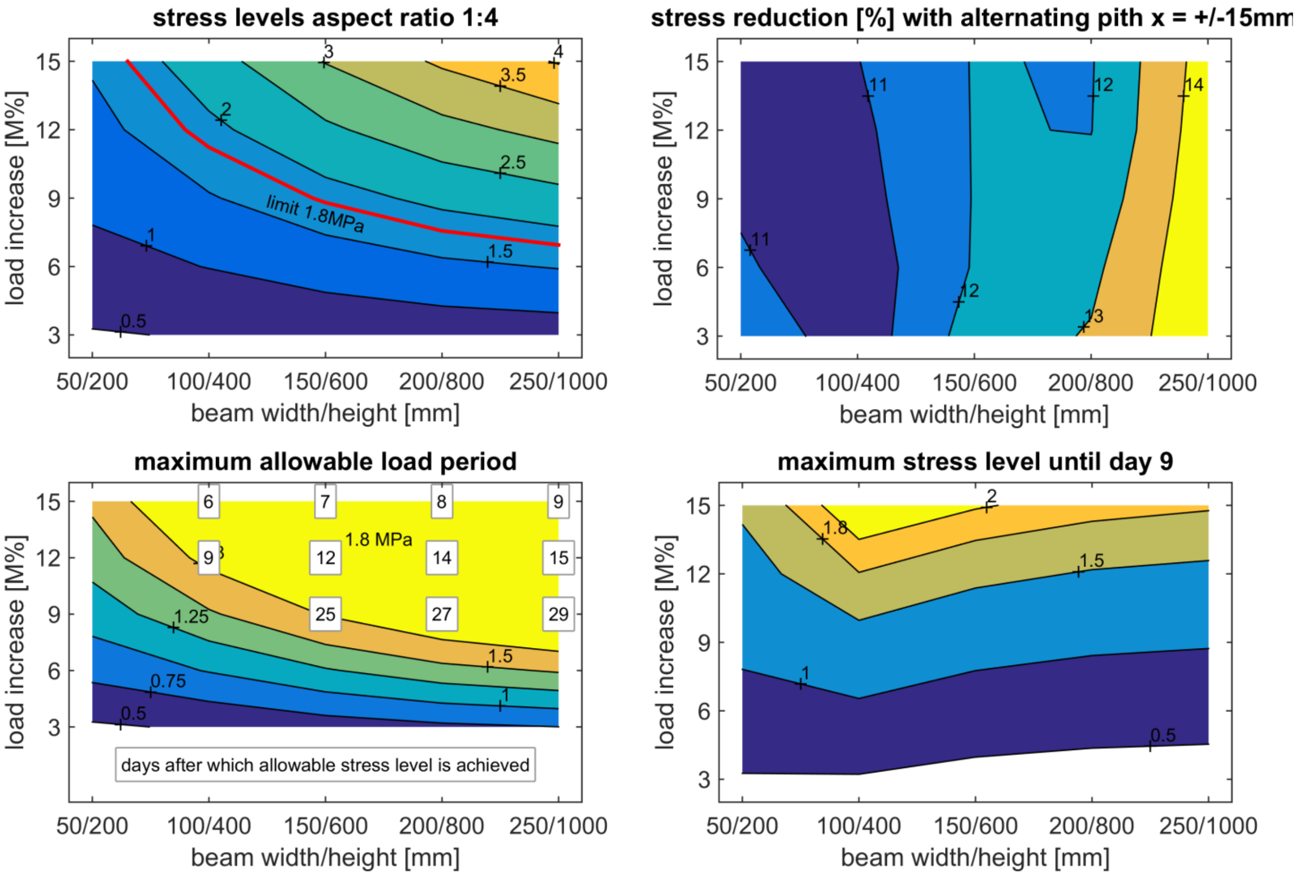

Figure 19: Stress levels, differences of alternating pith locations, maximum allowable loading time, and tension stress levels after 9 days

stress levels as well. Furthermore, larger distances from the beam centreline will also help to reduce the maximum tension stress levels.

Figure 19 (bottom left) further shows the maximum allowable loading time to maintain stress levels under the maximum allowable value of 1.8 MPa. If the maximum stress levels are not achieved at all, no time limit is shown. This figure is useful to have when a building needs to be erected and large changes in ambient climate are expected, or in defining allowable maintenance periods e. g. for ice rinks.

Finally, Figure 19 (bottom right) also shows the maximum stress values in the different beams under different loading up to day nine. This figure explains the maximum stress levels under different loads in case a maintenance event for the structure would last nine days. This could be useful for structures where climate can be controlled, such as a swimming pool perhaps or an indoor ice rink.

The possibility to perform simulations to calculate moisture induced stress developments is a useful tool. Design limits can be simulated and beam dimensions could be chosen upon accordingly, or extra measures could be taken. The possibility to include mechano-sorptive effects, which serves as a stress relaxation, increases the accuracy of the obtained stress levels.

4.2 Conclusion

The analysis of ambient climate data of different building types and timber structures allow a characterization according the building type to service classes. These results support the practical planning engineer and confirm the recommendations in the explanations to DIN1052:2004 by Blaß et al. (2004).

It was shown that the estimation of the moisture content over the cross section can be performed using 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.

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 20 M% and, therefore, belongs to service class 2 where higher modification factors could be applied.

Being able to calculate stress levels in glulam beams due to moisture loads is a useful tool to estimate the risk involving the generation of moisture induced stresses. It is shown that there is an influence of load amplitude and beam dimension, and that higher risks are found in larger beams. It was also confirmed that taking care of pith location in board choice and layup can help to reduce stress levels.

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