Advantages of moisture content monitoring in timber bridges

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Summary

Timber road bridges are high performing structures and built worldwide since centuries. Modern timber bridges are designed for operational life cycle of 80 to 100 years. Reliable design and proper planning fundamentals, as well as the right choice of assessment method and monitoring systems, support the planning process and maintenance. The electrical resistance measurement method has proven to be suitable for the moisture content monitoring of timber bridges. The long-term monitoring of moisture content of structural components enables to react to discrepancies at an early stage of possible damage. The monitoring results of six timber bridges showed that the wood moisture content in the load bearing cross sections under regular ambient climates was between 12 M% - 22 M%, i.e. continuously below the range for fungi decay. Numerical methods were used to estimate the dependency of moisture content over the cross section on the yearly climate loads.

Keywords: Structural assessment methods, moisture content monitoring, large cross sections, service class, timber bridges.

1. Introduction

The timber members for bridges can be supported, connected and protected at a high-quality level. The acceptance of wood increases through safe and reliable design and planning fundamentals. This quality must be maintained to further promote acceptance of timber bridges. Timber road bridges have been built worldwide since centuries. In Switzerland, historical pedestrian and road bridges made of timber are still being used. For example, the Kapellbrücke in Lucerne, was built in 1333 and is still used by pedestrians every day. The high efficiency of wood as a load bearing material is proved today through presence of many long spanned constructions. Glued laminated timber members, hybrid cross-sections, and large block glued laminated timber members replace the historic solid cross sections. Still, the durability and safety of timber bridges must be ensured for the life cycle of around 80 to 100 years. Whereas most bridges we used for either pedestrian to light traffic, a significant increase has been observed in the amount of bridges (>20 tons) for heavy traffic after 2000 (swisstimberbridges.ch). This has led to an increase in used widths of the main load

bearing members from 200 mm to 800 mm or more. The main members of timber bridges are generally protected by construction details, e.g. closed roadway passage or hybrid bridges cross sections (timber concrete composite), against water and wind driven rain.

The daily and seasonal climate changes lead to a variation of air temperature and air humidity. Swiss winter and spring tends to be dryer whereas summer and autumn can be more humid. The timber members of the bridge adapt to the surrounding climate through the hygroscopic nature of wood. As the moisture content changes at the surface an inhomogeneous distribution of moisture content over the cross section follows. The deformations lead to development of internal stresses perpendicular to the grain. Apart from this, the moisture content also affects the physical and mechanical properties. Hence, the correct estimation of the moisture content is important for the design and life cycle of timber structures. Currently, the planning engineer respects this complex hygroscopic behaviour of wood in the design by the application of service classes. The design standards consider this behaviour by three different service classes (SC) corresponding to the annual average moisture content, EN 1995-1-1:2004, [1].

Modern timber bridges require a different approach to guarantee structural lifetime. As cross sections increase, visual inspection becomes more difficult. Apart from that, with frequent passage of heavy traffic, special attention must be paid to protective measures such as asphalt. Experience shows that imminent damage can be detected in an early stage of its development through moisture content measurements. The paper also discusses as to what the structures will experience to during their lifetime, what appropriate assessment methods could be, and which inspection periods are recommended.

2. Assessment methods

2.1 Key points in timber bridges and inspection/monitoring methods

The key points at timber bridges are e.g. the structure, cross section, bearing/support, road deck, pedestrian passage, or kerb/handrail. Focus to most detail design is to minimise the risk for development of moisture content just under the fibre saturation point or higher. To ensure the safe operation regular examination of the structure is required. Through visual inspections, minor damage at the structure’s surface can be detected and repaired to prevent need for larger repair measures later. Here, the time intervals and scopes of inspection are essential. A general annual inspection as e.g. required in the new German guideline RI-EBW-PRÜF (2013) [2], requires that wooden bridges over or close to rivers be inspected yearly due to the expected wood moisture content, but this is not necessary or essential for the wooden material. Standardized testing methods as well as guaranteeing the comparability of results of studies that are conducted at different times can considerably reduce the associated amount of effort.

Moisture content at the cross sections’ surface will increase during fall and decrease during spring. Where the moisture content shows variations at the surface, it will vary close to the yearly average at the middle of the cross sections [3], [4]. The following hygro-expansion will cause the wood at the surface either to swell or shrink while the center of the cross section will not follow in this process. The different swelling and shrinking cause tension stresses to develop in the cross sections during wetting, and on the surface during drying [5], [6], [7]. Stresses can be high enough to exceed tension stress perpendicular to the grain and initiate cracks. The cracks at the surface will best be visible after dry climate. The cracks at the surface of the cross section will then tend to close during wetter periods, making them harder to detect during visual inspections. Furthermore, the prescribed measurement of moisture content at the surface, as done with handheld tools, will not be representative for the situation in the center of the cross section. Measured real wood moisture content through installation of monitoring systems is more effective, [5], [16], [17].

2.2 Monitoring campaign of timber bridges

The developments of moisture content variations in cross sections have mainly been investigated under laboratory conditions. However, the Institute for Timber Construction, Structures, and Architecture of the Bern University of Applied Sciences monitored and assessed six timber bridges directly exposed to the climate in several research projects. All monitored timber bridges were in different climate regions of Switzerland, see Figure 1. The main girders comprised: glulam members, block glued glulam members, and timber-concrete composite members. The local climate (temperature and relative humidity) measured at the timber bridges was logged alongside climate (air temperature and relative humidity) of meteorological stations located in the vicinity (MeteoSwiss, www.meteoswiss.admin.ch). Moisture content sensors were placed at two different

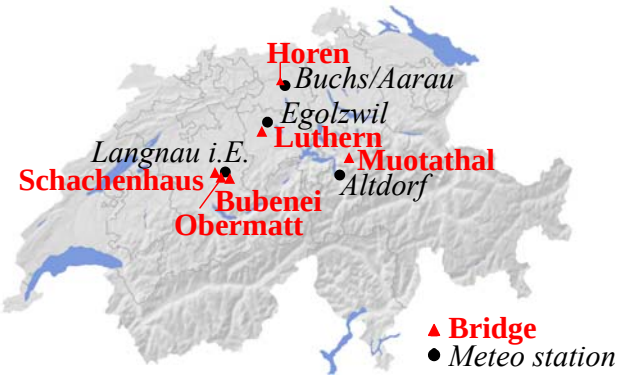

Fig. 1: Location of timber bridges monitored and close by meteorological stations

Fig. 2: Timber road bridge Horen

depths from the surface and at two different cross sections measured from the end grain. Table 1 summarizes the main construction details, monitoring periods, and measured MC values at each timber bridge. Further information and results are given in [5], [8].

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

2.3 Laboratory tests

To observe of the development of moisture content over the cross section, test series were prepared specifically in the three material axes: radial (R), tangential (T) and longitudinal (L), [5]. Two different sizes (200/200/200 mm and 200/ 200/800 mm) per material axes were considered, see Fig. 3. The side faces of the test specimens were sealed, so that the moisture diffusion only could take place in one of the principal material directions. 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 %RH before and during the preparation and loaded afterwards with 95 %RH 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 Mugrauer GmbH were used to log measurements every 6 hours.

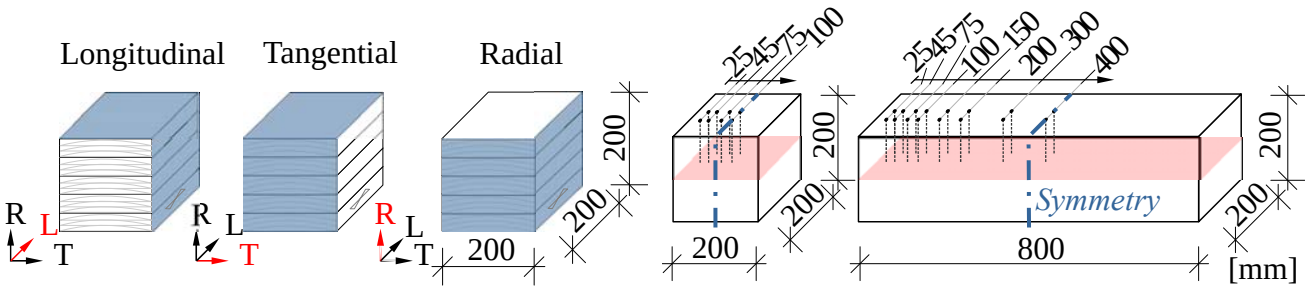

Fig. 3: Test specimens with sealed surfaces in blue (top) and position of measuring points for the 200 mm and 800 mm long specimens (bottom)

2.4 Numerical model for the moisture diffusion transport

The numerical simulations include the moisture diffusion transport in wood as well as the resulting stress strain behaviour of the timber member. These numerical methods can be used to estimate and calculate the cross-sectional dependency on the outer climatic loads. This helps to understand annual moisture content developments in timber cross sections as well as investigate differences between measurements and expectations. The moisture diffusion was modelled by a single phase Fickian law, which is one of the simpler models available. 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 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.

In the finite element program ANSYS®, a 2D numerical model 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, [9].

The numerical simulations made with the model were compared to experimental values. This was done e.g. for both wetting and drying process by Jönsson (2004), [9] or Angst (2012) [11], [12] as shown in [10]. For the own experiments, the diffusion values for validation of the wetting experiments of the 200 mm wide beams were derived in [10]. The values for longitudinal diffusion was 10.42e-10 m^2/s. 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 Fig. 6.

3. Research results

3.1 Timber bridges

The moisture content developments of six timber bridges were monitored continuously for several years. The moisture content adapted to the daily and seasonal surrounding climatic conditions. Whereas the outer parts responded more direct to the ambient climate loads, the inner parts responded slowly and with significant time lag, as shown in e.g. in Fig. 4. The moisture content is shown for sensors close to the surface (MC-S) and sensors at a depth of 200 mm (MC-D). The equilibrium moisture content at the surface was calculated [14] according to the measured ambient climate and temperature and added to the figure as comparison. Theoretically, the equilibrium moisture content is valid for the complete cross section at a constant climate. The moisture content measured in the timber cross section follows the seasonal effective climate changes. The response in the centre of the cross section is delayed along with lower variations for both sensor locations compared to the calculated equilibrium moisture content. The moisture content at the surface gauges varies between about 14 %M and 20 M%. The variation of the moisture content at the surface varies about 5.5 M% around the mean between the summer and winter period.

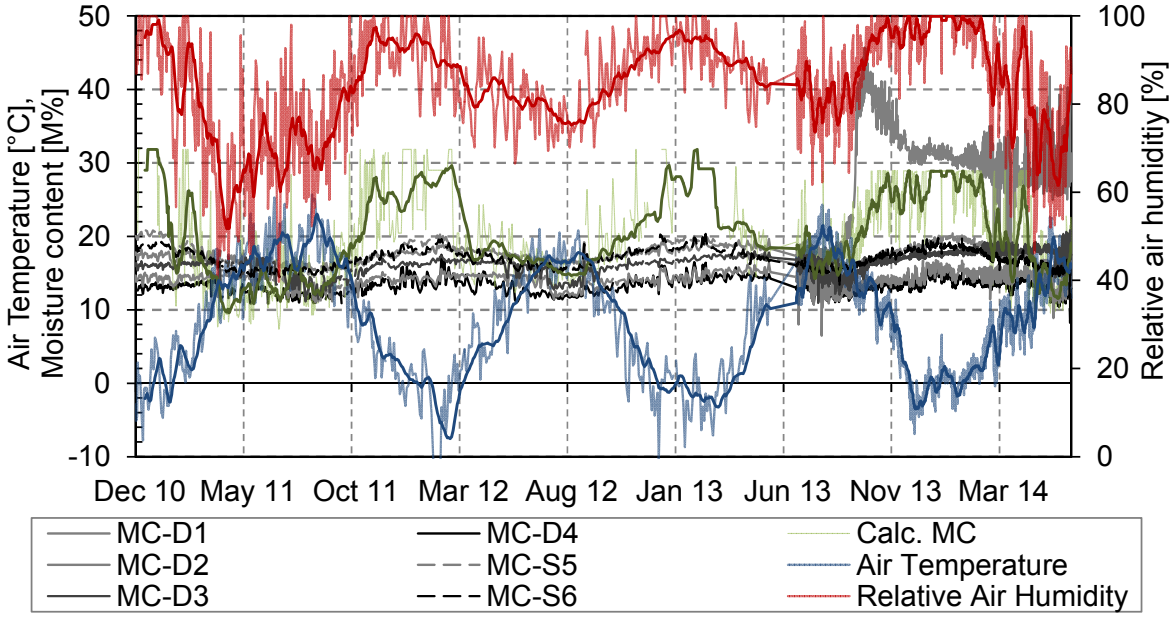

Fig. 4: Timber bridge Obermatt, Measured climate and moisture content and calculated equilibirum moisture content

Table 2: Comparison of the equilibrium moisture content according to meteorological stations and the moisture content measured

Bridge / Meteo station	Measuring period	Moisture content - mean value [M%]	
		Bridge meas.*	Meteo calculated
Mouthatal / Altdorf	15 month	16.6	15.9
Horen / Buchs	12 month	16.4	17.5
Luthern / Egolzwil	14 month	13.5	20.5
Bubenei / Langnau	25 month	22.5	24.7
Obermatt / Langnau	45 month	18.1	20.3
Schachenhausen / Langnau	23 month	17.0	20.5

* Mean value of every measuring point close to the surface

The curves of the moisture content at the inner structure are stabler, with variations of 2.5 M% around their mean. The extra difference of 3 M% observed between the inner and outer moisture content sensors results in internal moisture induced stresses. The phase shift between the theoretical calculated equilibrium and measured moisture content is about 2 to 3 months. Overall, the measurements showed that the wood moisture content in the beam cross-sections under ambient climates was between 12 - 22 M%, which is continuously below the range for fungi decay, [5], [8]. It could, furthermore, be shown that well-planned structures show similar results and are required to guarantee a long service life.

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 were compared. Differences were observed between the two. The comparison with a nearby meteorological station shows differences which reach up to 6 M%, see Table 2. For each case, the same measuring period was used for which the mean values can differ for the same meteorological station. It is concluded that the local effects regarding the location and type of obstacle (e.g. water or road crossing) should not be neglected. Further influences on the ambient climate due to constant shadows, flora, and wind also play a role. A positive result is that the moisture content calculated from climate at the bridges is lower than the one calculated from the meteorological stations in 5 out of 6 cases.

After the erection, the ambient climate will induce a moisture gradient in the cross section starting at a moisture content of 8 M% – 12 M % while coming from the production line and entering ambient climate conditions.

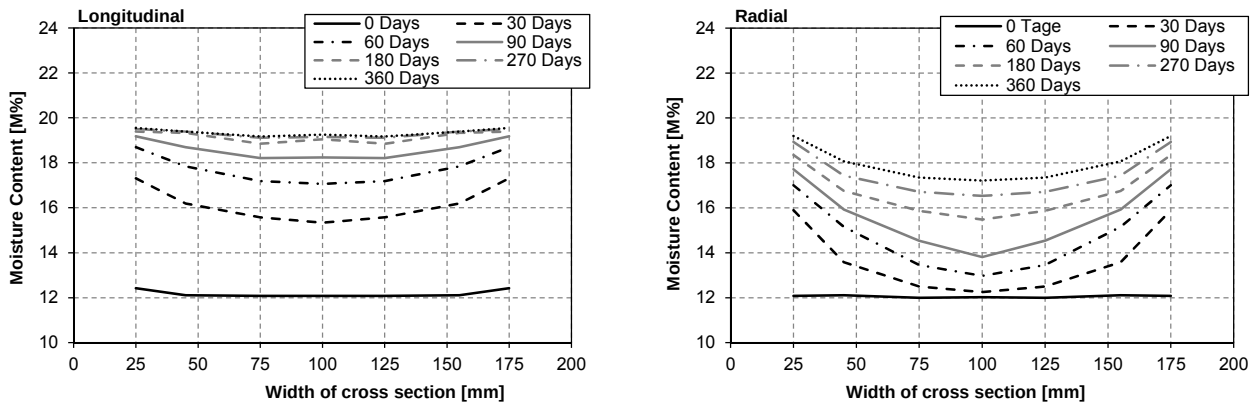

Fig. 5: Results of wetting process of 200/200/200 mm test series in longitudinal and radial direction

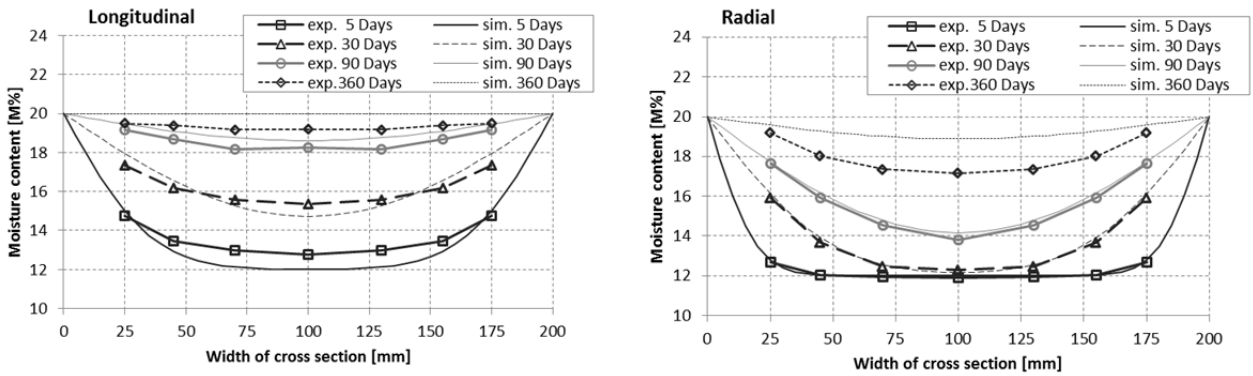

Fig. 6: Comparison of experiments and simulations of wetting process in radial and tangential direction of a 200 mm wide beam

3.2 Laboratory test results and numerical simulations

The moisture distribution in the cross section for the measuring period for the 200/200/200 mm test soon reached a plateau in longitudinal direction, roughly after 90 days. However, in radial and tangential direction, an increase of the moisture content was still present after 360 days, illustrating the slower process of wetting, as shown in Fig. 5, [5]. 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%. After measurements were finished it was observed that, although galvanised, the screws showed corrosion. This may affect the measurement of moisture content. This could be considered by determining an additional time dependent calibration factor. However, the comparison of the measurement with the two numerical simulations should not occur and other materials should be used.

Comparisons between simulations and experiments overlap over at least the first 90 days of the experiments. Afterwards, differences are observed and they become larger over time, although the differences barely exceed 1 M%, as shown in Fig. 6.

This is most likely due to non-Fickian effects taking place as moisture content in the cross-section approaches equilibrium moisture content [13]. This is not accounted for in the numerical model. The measurement might also be affected by corrosion affecting the measured resistance between the gauges.

Discussion

The measured moisture content on timber bridges show a wide variation compared to other structures e.g. agriculture building, ware houses, or halls, but can still be assigned to Service Class 2, as shown in Fig. 7. The timber bridge of Bubenei is the only bridge with higher moisture content. This is related to the monitoring system being was installed after repair of a leaking deck to monitor the drying process. These values are not used for further discussions. Fig. 7 includes the measured moisture content on timber bridges as mean values, minimum and maximum from a gauge close to the surface and the equilibrium moisture content calculated from the local ambient climate. The comparison confirms again that the ambient climate at a bridge needs to be considered carefully and that the simply use of information from nearby meteorological stations can lead to overestimations of the moisture content. The presented results are important guidelines for planning engineers, since recommendation of assignment of timber structures to service classes are not available in the standards.

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 %RH. For two different sizes and three material directions, the distribution over the cross section was determined, as shown in Fig. 8 or [5]. The measured distribution over the cross section was extrapolated to the surface according to the resulting equilibrium moisture content calculated from the climate. The distribution of the moisture content along the radial or tangential direction is not converged after one year of an intensive adsorption process, [5], [6], [7]. Daily or weekly climate changes like experienced by timber bridges result in a change of moisture content in the outer zone of the cross section, which is relatively small for more modern type of cross sections of large timber bridges. Fig. 9 shows a numerical result the moisture content at different material depths on a 200 mm wide cross section subjected to ambient climate.

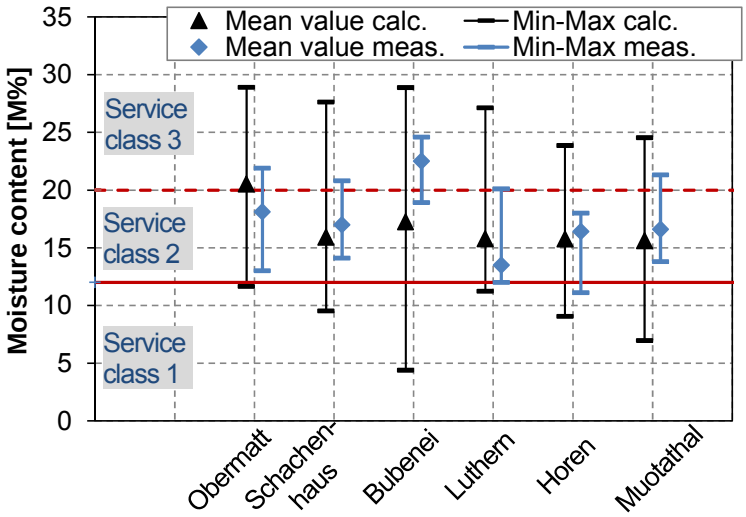

Fig. 7: Average moisture content in typical timber building constructions and relation to service classes according EN1995-1-1:2004

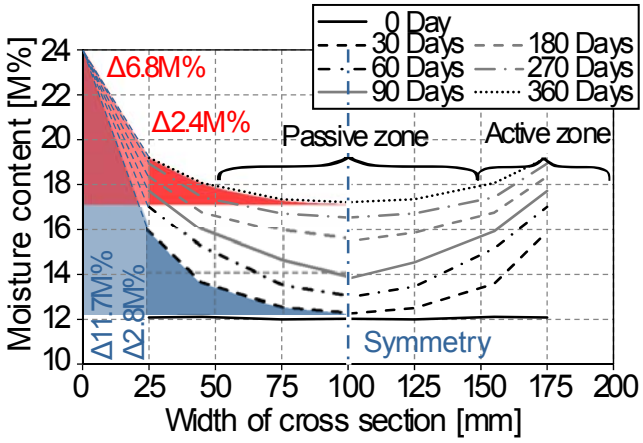

Fig. 8: Experimental results of moisture distribution in radial direction for the adsorption process, 200/200/200 mm

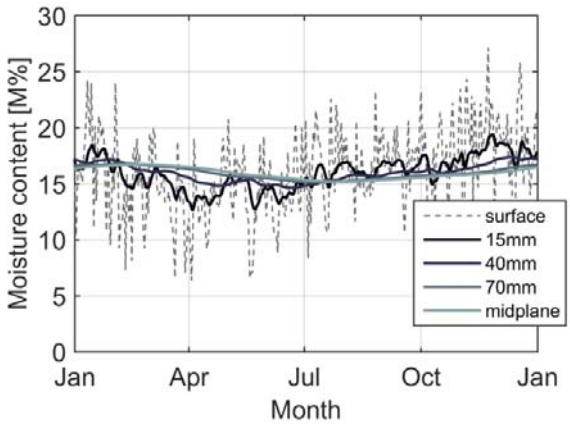

Fig. 9: Seasonal moisture content developments on a bridge on a 200 mm wide beam

The analyses of the experimental and numerical results show that the moisture content distribution over the cross section allows a division in an active and passive zone. Currently, only a constant service class is used for the design. It is suggested to differentiate the service class over the cross section, as shown in Fig. 10. The existing load capacities (active zone = SC 3, passive zone = SC 2) could increase the capacity of the structure, depending on its location and operational conditions. Another suggestion could be to calculate the bridge cross section according to a Service Class 2, and use a margin of active zone as a buffer zone to take the climatic variations. The definition of the active zone can be delicate though. A theoretical analysis using the shrinkage swelling mass show that a difference greater than 1.5 M% is enough to increase allowable stress levels over the tension strength perpendicular to the grain, as shown Table 3.

4. Conclusions and recommendations

Results observed from the long term monitoring of six timber bridges provide first guidelines for designers. High frequent changes in the surrounding ambient climate show little influence on the global distribution of moisture content. Only long wetting phases like in the fall lead to a measurable increase of the moisture content in the timber bridge cross sections. Parameters like the

Table 3: Theoretical limits of the moisture content for the risk of fracture of the cross section, material characteristics according [6].

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%

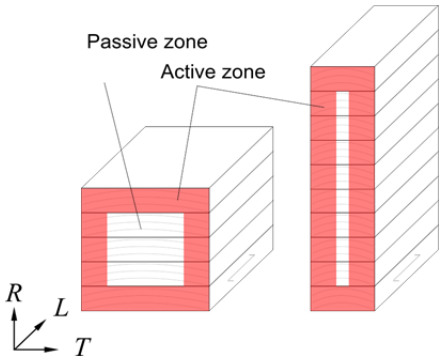

Fig. 10: Differentiation of cross section in active and passive zone

air flow around the bridge, the orientation and location with respect to microclimatic effects influence the developed moisture content distributions.

Through the electrical resistance method, moisture content in structural cross sections can be found in a range of 12 M% - 22 M% under the present climate situations. In all six cases the moisture content was below the critical level for fungi decay. Experience has shown that if adequate measures are taken against leakage of bridge decks, attention is paid to detail design, timber bridges can be appointed a long service life.

The research results provide new guidelines for the planning engineers for the assignment of service classes. The analysis of ambient climate data of timber bridges allows a first characterization according to the service classes. An annual assessment of timber bridges, as e.g. required in the German guideline RI-EBW-PRÜF [2] for timber road bridges over/close to water, can be questioned. The experiences show that the application of monitoring systems is more efficient and insight into structural health of large timber cross sections can be obtained. The monitoring system can track changes in the ambient climate and detect possible leaks in the construction.

Through simulations, insight was gained on moisture content developments on large cross sections. The numerical model was validated on experimental test series and published experimental results. The numerical simulation could successfully be applied to a case study of a timber road bridge. The experimental and numerical results support scientific as well as the planning 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. Service Class 2 could be applied. Daily or weekly climate changes result in a change of moisture content only in the surface of the cross section, which is relatively small for example for the cross section of large timber bridges.

5. Acknowledgements

The research work was proudly supported by the Federal Office for the Environment (FOEN) and the industry partners Roth AG, Makiol and Wiederkehr, and Tiefbauamt des Kanton Bern.

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