Timber bridges – Load carrying behaviour according to climate changes

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Abstract

Timber road bridges have been built worldwide since centuries. The high performance of wood as structural material is approved. However the influence of moisture induced stresses in cross sections according to the varied ambient climate are still questioned. Results observed in the long term monitoring of six timber bridges provide first guidelines for practitioners. Further on, first numerical simulations are carried out for the assessment of the long term behaviour of timber bridges over the life cycle. The numerical simulations include the moisture diffusion transport in wood as well as the resulting stress strain behaviour of the timber member. The research results provide new guidelines for the planning engineers, the definition of an active or passive zone of the cross sections, and provide a differentiation of the service class over the cross section.

Keywords: Road bridges, moisture content, stresses, service classes.

1 Introduction

Timber road bridges have been built worldwide since centuries. The high performance of wood is approved through many constructions. However, there are still doubts using wood by the planning engineer, which reduce the number of realized project. One main point for timber bridges is the influences of the varied moisture content according to 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.

Further on for timber bridges the moisture distribution 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, [1]. For example, an increase of the moisture content at the outer part 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. The design standards consider this behaviour by three different service classes (SC) according to the annual average moisture content, [2].

But questions rise: What happens over the lifetime of a construction or within exposed timber bridges or bigger cross sections? The discussion about methods for the assessment of the moisture induced stresses in timber bridge cross sections is continuing.

2 Monitoring of timber bridges

2.1 Timber bridges and their monitoring system applied

The moisture induced stresses in cross sections according to the varied ambient climate are mainly investigated under laboratory conditions. 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 1. Table 1 summarizes the main construction details as well as measuring periods and measuring values for each timber bridge. Further information and results are given in [8].

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. 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.

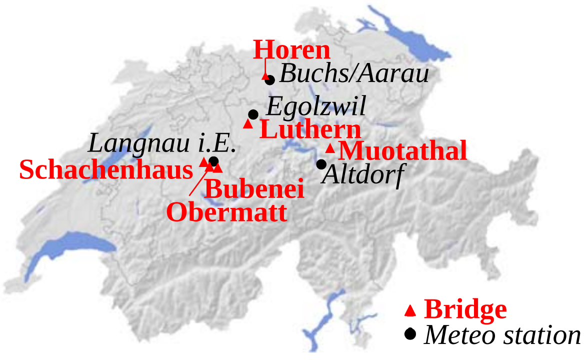

Figure 1. Location of timber bridges monitored and close by meteorological stations

2.2 Monitoring 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 2 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.

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

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

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, [5], [8].

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, [10]. 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 induce a moisture gradient in the cross section considering a moisture content of 8 - 12 M% from the production line/condition without pre conditioning.

Table 2: Comparison of the moisture content at the timber bridges and meteorological stations

Bridge / Meteo station	Moisture content - mean value [M%]	
	Bridge meas.*	Meteo calculated
Mouthatal	16.6	15.9
Horen	16.4	17.5
Luthern	13.5	20.5
Bubenei	22.5	24.7
Obermatt	18.1	20.3
Schachenhausen	17.0	20.5

* Mean value of every measuring point close to the surface

For each timber bridge monitored, the comparison with a nearby meteorological station shows differences which reach up to 6 M%, as summarized in Table 2. 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.

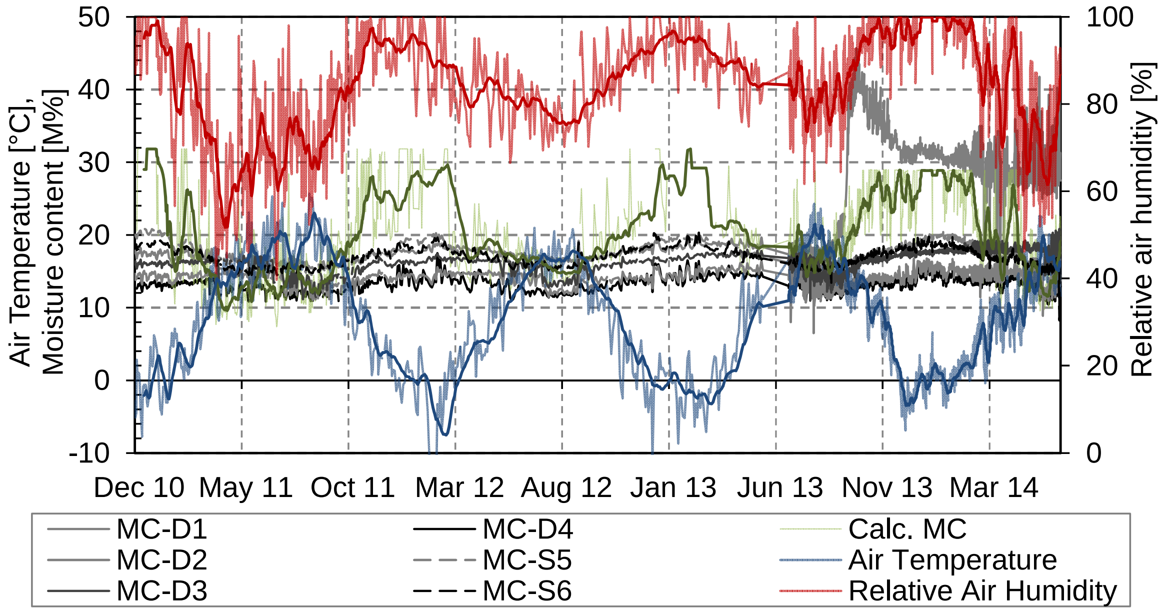

Figure 2. Bridge Obermatt, Measured climate, moisture content, and calculated equilibrium moisture content

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.

3 Numerical model for moisture diffusion transport

3.1 Definition of numerical model and parameters used

Further on, first numerical simulations are carried out for the assessment of the long term behaviour of timber bridges over the life cycle. The numerical simulations include the moisture diffusion transport in wood as well as the resulting stress strain behaviour of the timber member.

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, 1/10th 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 [4]. The inaccuracies occur right after loading, close to the surface of the beam.

The modelled beam was loaded as a parallel shaped body. 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.

3.2 Numerical simulation results

Simulations were performed to validate the numerical program using experiments [11] and diffusion parameters ($D = 3e\text{-}10\ [m^2/s]$) 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 3. 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.

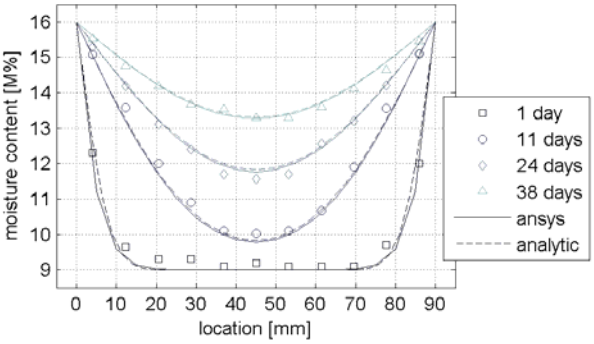

Figure 3. Comparison of experiments with numerical simulations and analytical equations on 90 mm wide specimens

Secondly a simulation for the timber bridge Horen was performed. In this calculation only the numerical model was used. 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 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 $D = 3.0e-10$ [m^2/s], [9]. The model was loaded as a parallel shaped body again.

First the moisture content development over the year 2014 was calculated, illustrated in Figure 4. The moisture content development was calculated at different 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.

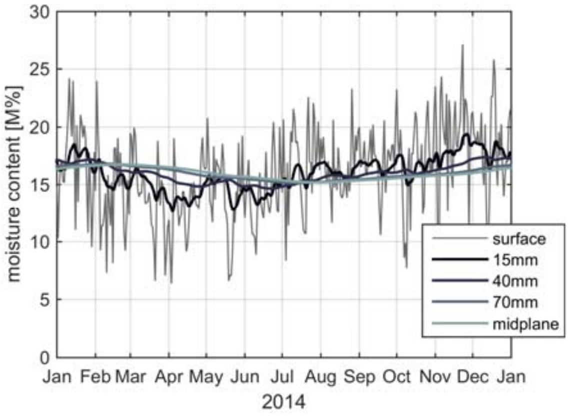

Figure 4. Moisture content time traces at different depths of the beams surface throughout 2014

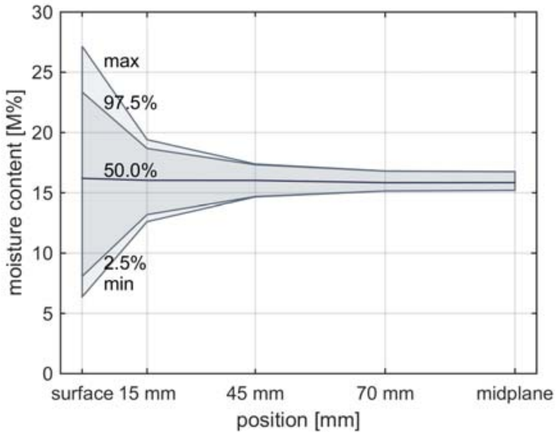

Figure 5. Minimum, maximum and percentiles of moisture content calculated for a 200 mm wide beam

Similar calculations were made over a 10 year period. The minimum, 2.5%, 50%, 97.5%, and maximum moisture contents over this period are plot in Figure 5. Over the 10 years, 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.

4 Discussion of research results and recommendations

4.1 Service classes for timber bridges

The analysis of the monitoring results observed for bridges show typical characterizations. Timber bridges show a wide variation of the moisture content, but can still be assigned to service class 2, as shown in Figure 6. The timber bridge Bubenei is the only bridge with higher moisture content 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 6 includes the measured moisture content on timber bridges as mean 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 simple 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.

4.2 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 [5] or in e.g. in Figure 7. 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.

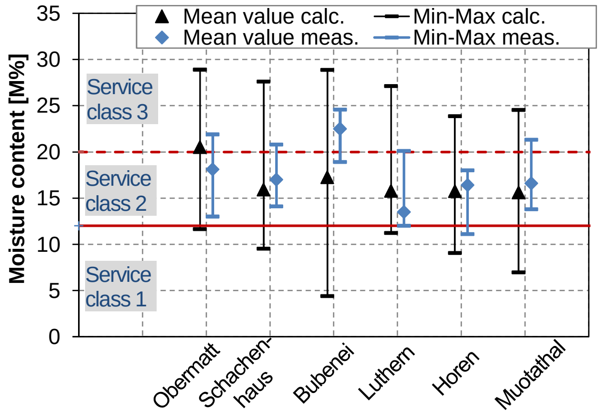

Figure 6: Average moisture content in typical timber building constructions and relation to service classes according EN1995-1-1:2004

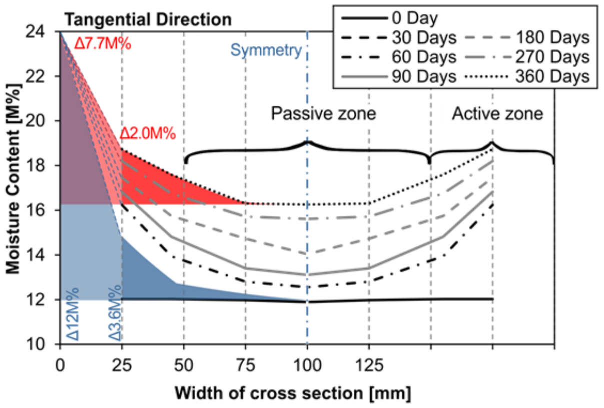

Figure 7: Experimental results of moisture distribution in radial direction for the adsorption process, 200/200/200 mm

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, as shown in Figure 5.

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 8 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

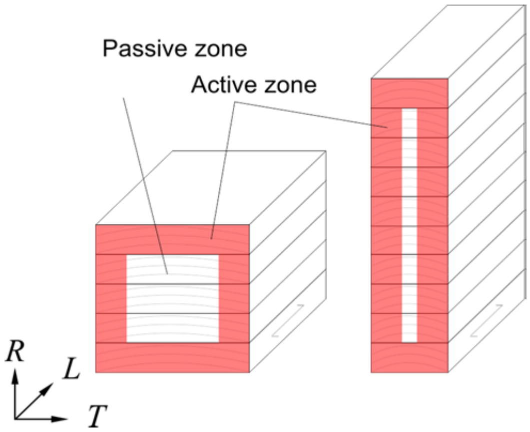

Figure 8. Differentiation of cross section in active and passive zone

that the stress in the wood exceeds the tension strength perpendicular to the grain.

5 Conclusions and view

Results observed in the long term monitoring of six timber bridges provide first guidelines for practitioners. 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 allow a characterization according to the service classes. These first results support the practical planning engineer.

It was shown that the simple estimation of the moisture content over the cross section could be performed using analytical equations and more complex using numerical programs. The numerical model was validated on experimental test series, research results published. Furthermore the numerical simulation could successfully applied to a case study of a timber road bridge. 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. 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.

Being able to calculate stress levels in large glulam beams due to moisture loads is relevant for increased application of wood in future structures. Of particular interest here are the acceptable stress levels perpendicular to the grain. It was shown earlier that load amplitude, beam geometry, and board layup affect these levels, and that the larger beam cross sections potentially suffer larger moisture induced stresses. The factors affecting these moisture induced stresses are to be researched further in order to develop recommendations for planning engineers.

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