Advanced Materials Research Vol. 778 (2013) pp 749-756
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.778.749

Long term monitoring of timber bridges - Assessment and results

Bettina Franke[1,a], Steffen Franke[1,b], Andreas Müller[1,c], Mareike Vogel[1,d], Florian Scharmacher[1,e] and Thomas Tannert[2,f]

[1]Bern University of Applied Sciences, Architecture, Wood and Civil Engineering, Solothurnstrasse 102, CH-2504 Biel/Bienne, Switzerland

[2]University of British Columbia, Forest Science Centre, #2933 2424 Main Mall, Vancouver, BC, Canada V6T 1Z4

[a]bettina.franke@bfh.ch, [b]steffen.franke@bfh.ch, [c]andreas.mueller@bfh.ch, [d]mareike.vogel@bfh.ch, [e]florian.scharmacher@bfh.ch, [f]thomas.tannert@ubc.ca

Keywords: Timber, Bridges, Monitoring, Moisture content

Abstract. Timber bridges have been built for decades all around the world. The hygroscopic material behavior of wood leads to the change of the moisture content of the wood and the dimensions depending on the climate. The objectives were to investigate the material behavior due to climate changes regarding the natural material axes or within the cross section and secondly the influence of the climate on the moisture content. Therefore traffic timber bridges with big cross sections were long term monitored within a research project. The results of the moisture contents measured and a comparison between the different measuring groups and positions are presented. The analyses confirm that the moisture content in the wood follows the climate changes delayed and with smaller amplitude against the calculated equilibrium moisture content. In first steps, a different behavior of the change of the moisture content could be determined over the cross section and along the span of the member.

Introduction

Timber bridges have been built for decades all around the world. Thus there are many historical bridge constructions but also recently erected timber bridges in Europe and especially in Switzerland. Because of the hygroscopic material behavior of wood, climate changes result in the change of the moisture content of the wood and thus change of dimensions as well (swelling and shrinking). For a reliable assessment, the material behavior of wood due to the climate changes within a year or over the lifetime of the bridge has to be known. The changes of the moisture content have to be classified as well as the difference between the natural material axes or over the cross section of the structural members. The stress strain behavior of wood under varying moisture content was mostly investigated in laboratory conditions, [1] - [4]. The investigations show that there are differences in the moisture content over the cross section which leads to internal stress gradients. The research done by Häglund [5] - [8] shows that parallel to the absolute also the relative moisture changes influence the load capacity as well as the serviceability of timber structures. First investigations are also done for glulam and cross laminated timber, [9] - [15]. But the discussion for reliable approaches for the assessment or design is ongoing and internationally no recommendations have been published.

Within a research project at the Bern University of Applied Sciences, four traffic timber bridges were long term monitored for two years or longer. The timber bridges are placed in Switzerland in different regions with different climate conditions. In all cases, the moisture content in the wooden member is measured in relation to the prevalent climate. The paper presents the measuring equipment used and the results of the moisture contents measured. For a comparison between the different measuring groups and positions, sensors were positioned close to the surface and further inside of the cross section. Furthermore sensor groups are located close to the end grain of the timber members as well as in a certain distance to the end grain or at the mid span in order to evaluate the moisture content in parallel to grain direction.

Material and Method

Solid wood, glulam and block-glued glulam members. Wood is natural grown material which was used in the first constructions known and also in recently impressive large span constructions like halls or bridges and even in multi-story buildings. The evolution of using wood as construction material starts from logs to sawn cross sections of solid wood to improved engineered wood products like glulam and block-glued glulam. Solid wood describes sawn cross sections out of logs with a width from 80 to 300 mm and a depth of 160 up to 300 mm. Glulam is a member of single lamellas of around 40 mm thickness laminated together. The lamellas are finger jointed so that theoretically infinity spans possible. The cross sections of glulam members rise from 200 mm to 300 mm in width and up to 3 meters in depth. The width is limited due to the lamella widths. To produce larger cross sections, single glulam members can be glued together side by side to create a block-glued glulam member.

The purpose of each step of development was to increase the stiffness and load carrying capacity for greater span and to get a more homogenous material. As result, the cross section increased with each step from sawn solid wood to glulam and block-glued glulam, as shown in Fig. 1. However, large cross sections can lead to higher moisture induced internal stresses because of the hygroscopic behavior.

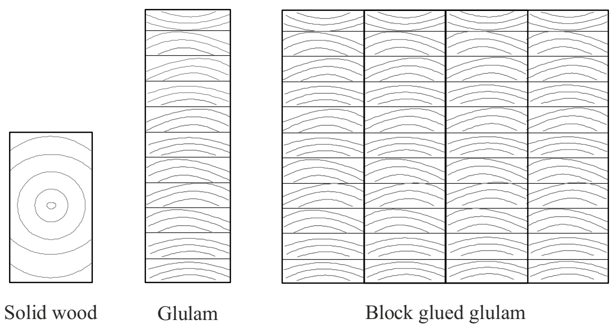

Fig. 1 Cross sections of solid wood, glulam, block-glued member

Hygroscopic behavior of the material. The hygroscopic behavior of wood describes the adsorption and desorption of moisture to maintain equilibrium depending on the surrounding climate including the temperature and relative humidity. The adsorption of moisture occurs in two steps in the range from 0 % to 30 % where the moisture is transferred into the cell walls of the wood. Above 30 % moisture content, the cell walls are completely saturated and the moisture is transferred into the cavities of the cells. The moisture content of 28- 30 % is called fiber saturation point. Changes in the moisture content below the fiber saturation point affect the physical, mechanical and rheological properties of wood, like as the shrinking and swelling, the strength values or the modulus of elasticity or rigidity, [16], [17].

To avoid the change of moisture content in wooden members during the life cycle, normally timber should be conditioned installed to the average moisture content which is expected in service. However, glulam and also block-glued glulam is been produced with a moisture content of 8 to 10 % and will then mostly be installed with this moisture content, but the moisture content in service can be much higher depending on the application. Members in bridges in normal European climate conditions are expected to have a moisture content of around 15 % to 20 %, [18]. Therefore a gradual increase of the moisture content happens within the constructions and results in dimension changes of the cross section and also in internal stresses, as shown in Fig. 2 and Fig. 3.

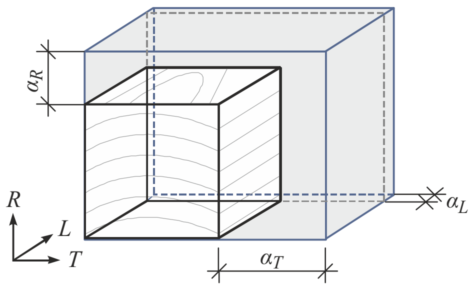

Fig. 2 Shrinking or swelling depending on the material direction

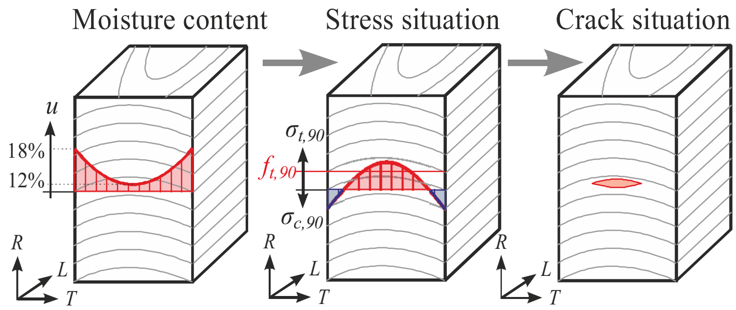

Fig. 3 Gradual increase of the moisture content and the corresponding internal stresses and crack growth

Bridges. Four traffic timber bridges have been long term monitored in Switzerland. The timber bridges are placed in different local regions with different climate conditions. The bridge “Horen” was erected in June 2008. Its total span is 31 meters. The structural system consists of two main members of block-glued glulam four times supported and with secondary members spanning across for the deck construction, as shown in Fig. 4. The second bridge “Muotathal” is an arch bridge of glulam spanning a length of 32 meters, as shown in Fig. 5. The beam bridge “Obermatt” spans also over 32 meters. It is built with two main members with crossing secondary members, as shown in Fig. 6. The fourth bridge “Schachenhaus” is a timber concrete composite bridge and spans over 20.4 meters, as shown in Fig. 7.

Measuring the moisture content. The measuring of the moisture content can be done directly by the oven drying process in the laboratory of wood samples taken from the structure (destructive), or indirectly using moisture meters (non-destructive). Moisture meters work with the relation of the moisture content to certain physical properties like e.g. the electrical resistance, capacity or temperature. Moisture meters are commonly used in praxis and also for long term measuring. For the investigation of the bridges, the electrical resistance measurement method is used in combination with local data loggers or remote systems. Chrome steel screws with insulated shanks

Fig. 4 Bridge Horen

Fig. 5 Arch bridge Muotathal

Fig. 6 Bridge Obermatt

Fig. 7 Bridge Schachenhaus (www.hirsbrunner-holzbau.ch)

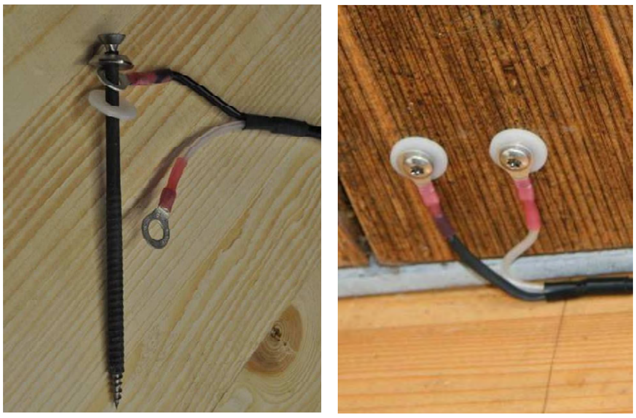

Fig. 8 Electrodes used with moister meter, uninstalled (left), and installed (right)

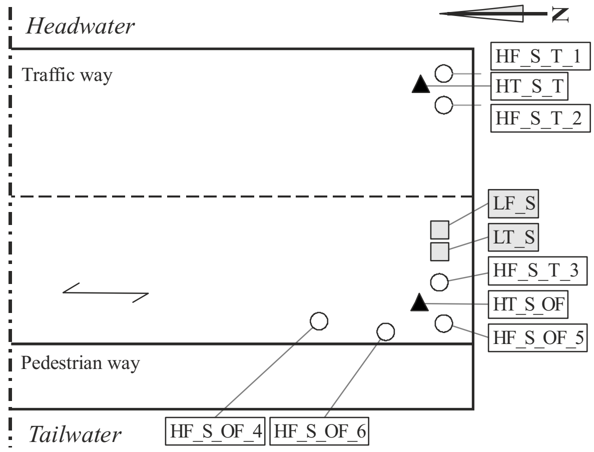

Fig. 9 Layout of measuring points including sensor names, south side of the Obermatt bridge

are used as electrodes, as shown in Fig. 8. The screws are applied with certain lengths in predrilled holes with a distance of 32 mm between to measure the moisture content in different member depths.

As example, the measuring plan for the Obermatt bridge is shown in Fig. 9. The measuring points are positioned at both ends symmetrically to the span of the bridge. They are grouped to measure the air temperature (LT_S) and air relative humidity (LF_S) as well as the moisture content at the surface (HF_S_OF) or inside the structure with a depth of 200 mm (HF_S_T). Furthermore two temperature sensors (HF_S_T) for the temperature correction are installed next to the moisture sensor groups. For long term monitoring, a remote data transmission system was installed in cooperation with the company mageba SA, [18], [20]. The data will be collected every 6 hours and remotely transmitted every week. This provides a sufficient period to react when extensive changes in the moisture contents happen, e.g. because of any damages or defects in the construction.

Results and Discussion

Climate data and moisture content observed. For the Obermatt bridge, the measuring results of the climate and moisture contents are shown in Fig. 10 to Fig. 12 for a period of 25 months. The climate data observed includes temperature and relative humidity of the air. The seasons of the year can be clearly distinguished, for the winter with low temperatures from -5 to 5 °C and high relative humidity, for the summer with temperatures of 15 to 20 °C and the two passage seasons spring and fall with the increase respectively decrease of the temperature and the relative humidity reversely. Corresponding on these measuring results, the equilibrium moisture content of the wood is calculated using the Keylwerth-Diagram for spruce [19] and added in Fig. 10. The moisture content results theoretically between 10 % in summer and 32 % in winter.

In general, the moisture content measured in the timber follows the seasonal affective climate changes. The response is delayed and with much less amplitude for both cases of the sensors, at the surfaces and inside. The amplitude of the moisture content at the surface between the summer and winter period is practically of about 5.5 % where theoretically the calculated equilibrium changes of 22 %, as shown in Fig. 11. The moisture content varies between about 14 and 20 %. The reaction shift is about 2 to 3 months depending on the gradient of climate change and the phase of adsorption or desorption.

The moisture sensors at a depth of 200 mm show even a smaller seasonal variation than the results of the surface sensors, Fig. 11 and Fig. 12. The curves of the moisture content at the inner structure are more evenly distributed and compact to each other, with a range of the amplitudes of

2.5 %. The difference between the sensors at the surface and inside is around 3 % of moisture content in average independent of the season. The difference between the inner and outer moisture content of 3 % can results in internal moisture induced stresses. Generally the moisture content keeps under 20 %. This material behavior determined and shown for the bridge Obermatt could be observed in the other three bridges in a similar range, [20].

Moisture transfer/distribution in the different material directions. With the measuring set up at the bridge Horen, the moisture transfer in radial and tangential direction was also observed. Fig. 13 shows the cross section of one block-glued glulam member with the positions of the sensors grouped in two measuring lines 205 and 925 mm from the outside and 400 mm from the end grain. Each measuring group includes 5 sensors for the moisture content. The distance between each other is around 100 mm. The moisture content in the wood was analyzed for a period of 5 months beginning in May 2010, which represents a theoretical increase of the moisture content according to the climate data and the equilibrium from 12 to 27 %, as shown in Fig. 14.

The moisture content within both measuring groups, outside and inside, shows almost no differences in the amplitude of change, see Fig. 15 and Fig. 16. These small changes are within the range of the measuring accuracy of around 1.5 %, [15]. Because of the position of the sensors, it seems that they are well protected against rain and wet situations. The hazard of decay is minimized or can even be excluded.

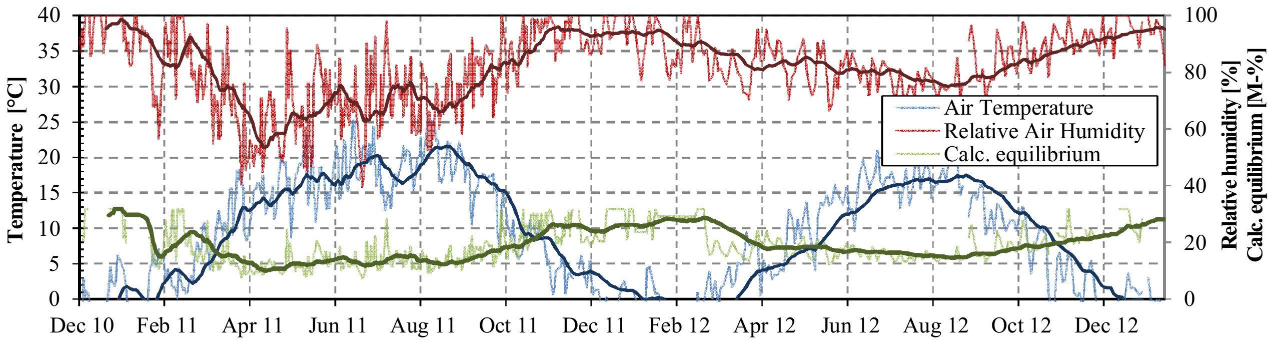

Fig. 10 Climate results and calculated equilibrium for the bridge Obermatt

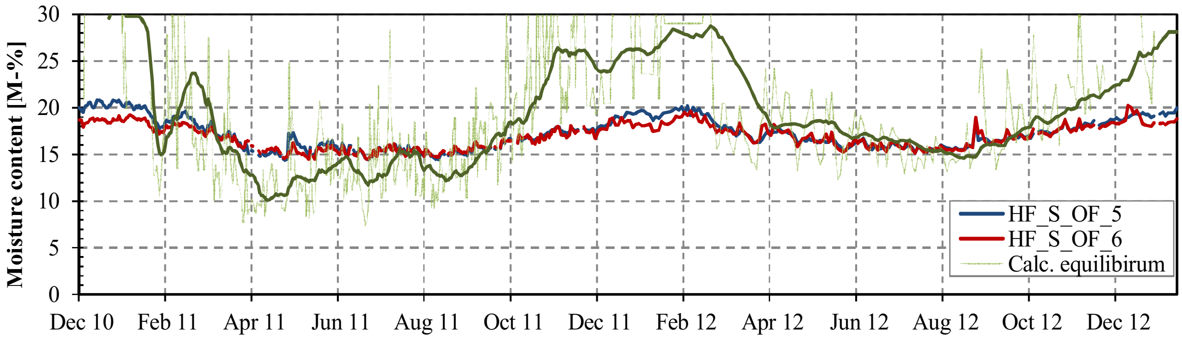

Fig. 11 Moisture content of the sensors at the surface

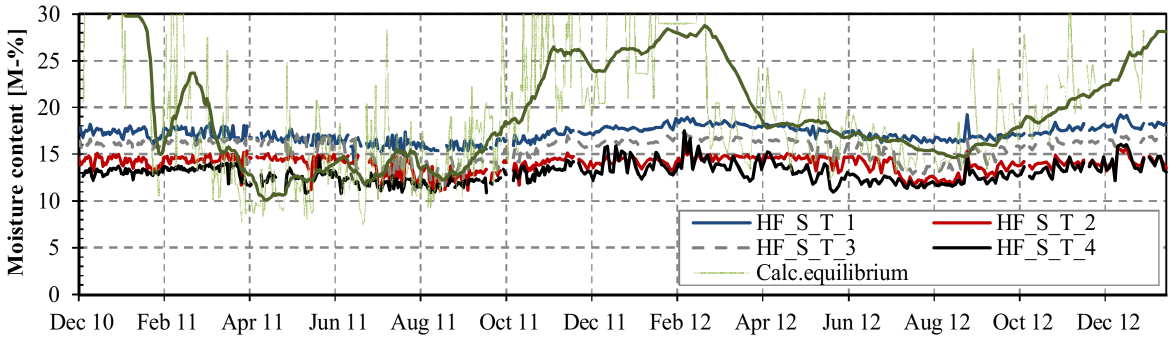

Fig. 12 Moisture content of the sensors in the inner structure, with a depth of 200 mm

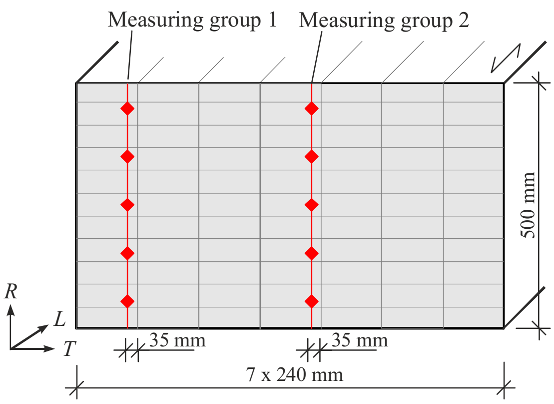

Fig. 13 Measuring plan of bridge Horen, cross section at the support

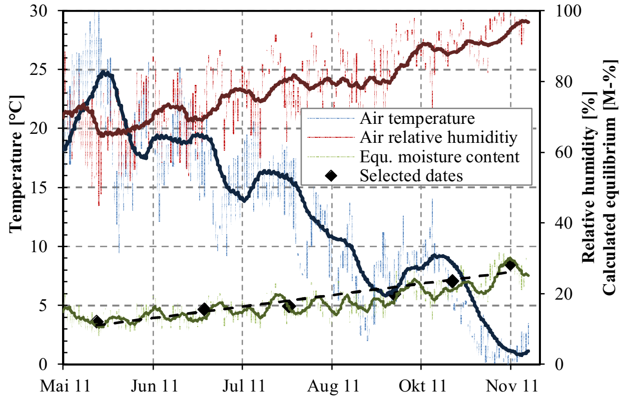

Fig. 14 Climate data and equilibrium moistore content of bridge Horen for a adsorption period

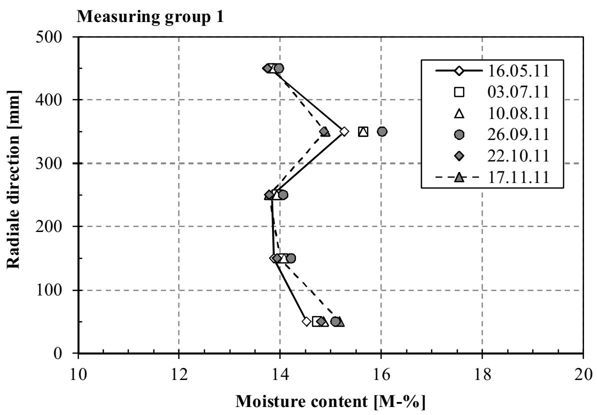

Fig. 15 Moisture content in radial direction at 205 mm in tangential direction

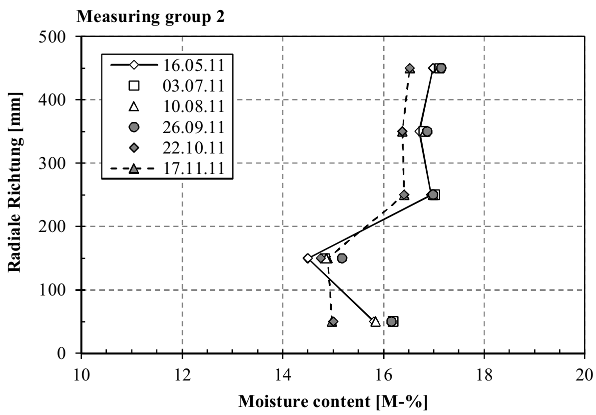

Fig. 16 Moisture content in radial direction at 925 mm in tangential direction

For the investigation of the moisture transfer in longitudinal direction, the measuring results observed at the bridge Muotathal are used. The measuring setup is shown in Fig. 17, where the first measuring line is installed in longitudinal distance of 800 mm from the end grain and the second line with a distance of 2000 mm. The cross section is 1000 mm by 800 mm. Each measuring group includes 5 sensors for the moisture content. The distance between each sensor is around 175 mm. The moisture content was again analyzed for a period of almost 5 months beginning in December 2010 representing an theoretically decrease of the moisture content according to the climate data and the equilibrium from 25 % to 9 %, as shown in Fig. 18. The theoretical change of the moisture content is higher than in the case before.

The results show at both positions a decrease of the moisture content in the wood of about 2 %, as shown in Fig. 19 and Fig. 20. No major differences in longitudinal direction could be observed. The measuring position of the first group is already quite far away from the end grain in order to see a dependency of the moisture content in longitudinal direction. The less influence of moisture adsorption from the end grain is in this case also reduced due to the steel plate of the connection covering the end grain area.

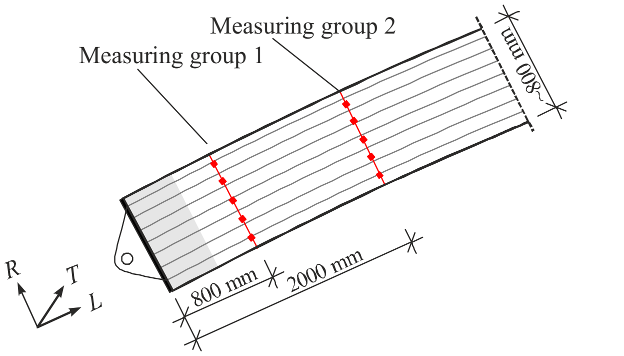

Fig. 17 Measuring plan of arch bridge Muotathal

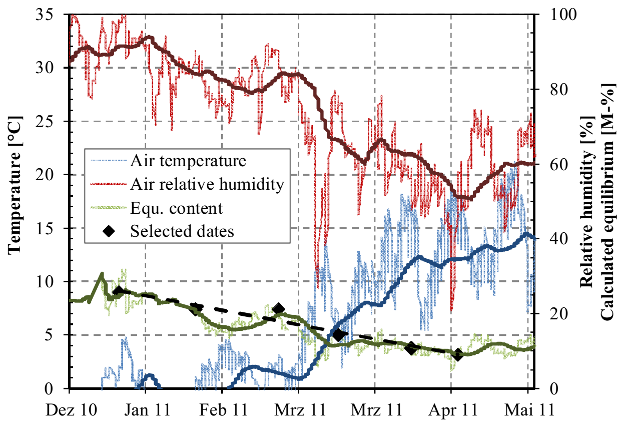

Fig. 18 Climate data and equilibrium moisture content of bridge Muotathal for desorption period

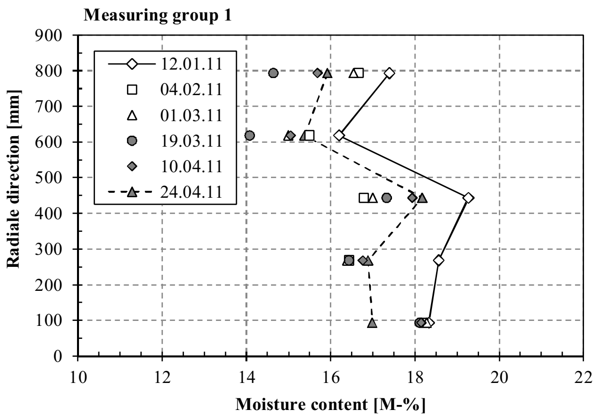

Fig. 19 Moisture content in radial direction in a distance of 800 mm in longitudinal direction

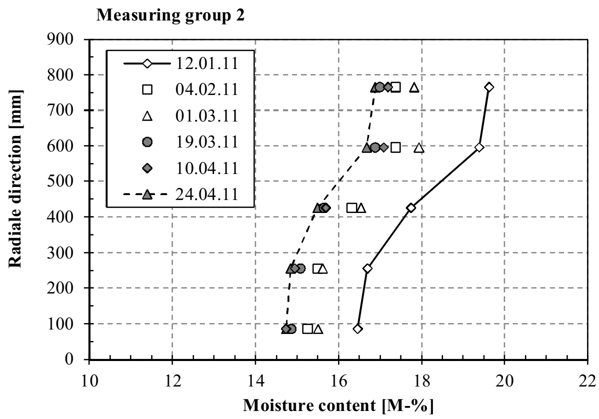

Fig. 20 Moisture content in radial direction at 2000 mm in longitudinal direction

Conclusions and view

The electrical resistance measurement method used in the case studies is capable for long term monitoring of timber structures. The used remote system is simple in its application, robust in terms of environmental influence and long-lasting. In case of mistakes or later damages, the long term monitoring gives the possibility to observe extensive and unusual moisture accumulations at an early stage to avoid decay/fungal development. However, the monitoring can realistically not be done at every position of the construction, but could be done at important locations.

The monitoring of four traffic timber bridges and the analyzes of their moisture contents confirm generally that the wood moisture contents follow the climate changes. The reaction against the calculated equilibrium moisture content due to the climate changes is delayed and with smaller amplitude depending on the distance to the surface. It could be shown that the moisture content in timber members subjected to outer climate condition varies between about 12 and 22 %, which is well below the critical moisture content of about 25 % for decay hazards. But it requires a well planned and conducted structural protection of the wood against rain or snow, so that a general moisture load is prevented.

In first steps, the behavior of the moisture content could be determined over the cross section of block glued glulam members in radial and tangential direction and along the span of the member in longitudinal direction. In the cases observed no major differences could be detected between the positions measuring sensors because of too large distances from the surface or the end grain. For a prediction model, the sensors should be positioned in a closer range for specification of differences in material axes and also investigated in specified and controlled climate changes.

The measuring results observed show that it is important to respect the moisture of the wood according to the climate change. Especially close to the end grain, cross section and in the outer glulam members of block-glued members the moisture gradients observed can lead to moisture induced stresses and furthermore to internal or external cracks.

References

[1] J. M. McMillen, Drying stresses in red oak. Forest Products Journal Vol. 5 (1955) 71-76.

[2] T. Toratti, Moisture induced stresses, Presentation at Cost E55 meeting Trondheim (2009)

[3] S. Svensson, T. Toratti, Mechanical response of wood perpendicular to grain when subjected to changes of humidity, Wood Science & Technology, Vol.36 (2002) 145-156.

[4] S. Svensson, A. Martensson, Simulation of drying stresses in wood - I: Comparison between one and two dimensional models, Holz als Roh- und Werkstoff, Vol.57 (1999) 129-136.

[5] M. Häglund, Moisture content penetration in wood elements under varying boundary conditions Wood SciTechnol Vol.41 (2005) 477–490.

[6] M. Häglund, S. Thelandersson, Consideration of moisture exposure of timber structures as an action, In Proceedings CIB-W18/38-11-2, (2005)

[7] M. Häglund, Varying moisture content penetration in wood elements under varying boundary conditions, Wood Science & Technology, Vol.41 (2007), 477-490.

[8] M. Häglund, Varying moisture content penetration in wood elements under varying boundary conditions, Wood material science and engineering, Vol.3 (2008), 38-45.

[9] T. Gereke, P. Niemz, Moisture-induced stresses in spruce cross-laminates. Engineering Structures, 32 (2010), 600-606.

[10] T. Gereke, Moisture-Induced Stresses In Cross-Laminated Wood Panels, doctoral thesis, ETH Zurich, Switzerland, (2009).

[11] V. Angst, K.A., Malo, The effect of climate variations on glulam-an experimental study, European Journal of Wood and Wood Products,70/ 5(2012), 603-613.

[12] V. Angst-Nicollier, Moisture Induced Stresses in Glulam. PhD Thesis, Norwegian University of Science and Technology, Trondheim, (2012).

[13] T. Tannert, A. Müller, M. Vogel, Structural health monitoring of timber bridges, International Conference on Timber Bridges (ITCB, 2010).

[14] M. Frese, Wechselwirkung zwischen der Anisotropie der Schwind- und Quellmasse sowie der Holzfeuchte-Änderung in der Ebene von gekrümmtem Brettschichtholz, European Journal Wood and Product (2011) 69, 259-367.

[15] S. Winter, M. Sieder, A. Gamper, P. Dietsch, M. Merk, Gebäudeklima - Langzeitmessung zur Bestimmung der Auswirkungen auf Feuchtegradienten in Holzbauteilen, Research report, Technical University Munich, Germany, (2012).

[16] F.H. Neuhaus, Elastizitätszahlen von Fichtenholz in Abhängigkeit von der Holzfeuchtigkeit, Technical Reports, Ruhr-University of Bochum, Germany, (1981)

[17] P. Niemz, Physik des Holzes und der Holzwerkstoffe, DRW-Verlag, Leinfelden-Echterdingen, Germany, (1993)

[18] F. Scharmacher, A. Müller, Erfahrungen und Konsequenzen aus der Langzeitüberwachung von Holzbrücken, Bridge Symposium – Grünbrücken aus Holz, Stuttgart, Germany (2012)

[19] R. Keylwerth, D. Noack, Die Kammertrocknung von Schnittholz, Holz als Roh- und Werkstoff, 22 (1964), 29-36.

[20] B. Franke, A. Müller, M. Vogel, T. Tannert, Langzeitmessung der Holzfeuchte und Dimensionsänderung an Brücken aus blockverleimten Brettschichtholz, Research report, Bern University of Applied Sciences, Switzerland, (2012).