5th International Conference on
Structural Health Monitoring of Intelligent Infrastructure (SHMII-5) 2011
11-15 December 2011, Cancún, México

Remote moisture monitoring of timber bridges: a case study

Thomas Tannert
University of British Columbia, Canada

Roman Berger
mageba SA, Switzerland

Mareike Vogel
Bern U. of Applied Sciences, Switzerland

Andreas Müller
Bern U. of Applied Sciences, Switzerland

This paper reports on the remote moisture monitoring of a timber traffic bridge in Switzerland. Timber has been a structural material for bridges for centuries, exploiting its high ratio of bending strength to weight. Numerous examples throughout the world demonstrate the durability of timber; if designed and monitored adequately. But timber is biodegradable, and it is recommended for timber bridges that inspections are carried out at regular intervals; until recently, such inspections were carried out exclusively through on-site visits. An automated remote monitoring system provides a more efficient way to enable a sound structural assessment with continuous records of almost any required parameter. This is of special interest to owners of bridges, who must ensure the on-going safety of their structures. In the case study, a concept to experimentally gather relevant moisture data was developed, at different locations of the structure as well as different depths inside individual members; additionally, climate variables are recorded and related to the moisture content measurements. A data recording system was installed and all data is automatically and remotely transferred to a server. A web interface provides continuous information on the structure's condition, and allows identifying gradual changes over a period of time. The presented case-study provides valuable information on applications and limitations of remote moisture measurement systems for timber bridges.

Corresponding author's email: thomas.tannert@ubc.ca

Remote moisture monitoring of timber bridges: a case study

Thomas Tannert[1], Roman Berger[2], Mareike Vogel[3], and Andreas Müller[3]

[1] The University of British Columbia, Vancouver, Canada
[2] mageba SA, Bülach, Switzerland
[3] Bern University of Applied Sciences, Biel, Switzerland

ABSTRACT: This paper reports on the remote moisture monitoring of a timber traffic bridge in Switzerland. Timber has been a structural material for bridges for centuries, exploiting its high ratio of bending strength to weight. Numerous examples throughout the world demonstrate the durability of timber; if designed and monitored adequately. But timber is biodegradable, and it is recommended for timber bridges that inspections are carried out at regular intervals; until recently, such inspections were carried out exclusively through on-site visits. An automated remote monitoring system provides a more efficient way to enable a sound structural assessment with continuous records of almost any required parameter. This is of special interest to owners of bridges, who must ensure the ongoing safety of their structures. In the case study, a concept to experimentally gather relevant moisture data was developed, at different locations of the structure as well as different depths inside individual members; additionally, climate variables are recorded and related to the moisture content measurements. A data recording system was installed and all data is automatically and remotely transferred to a server. A web interface provides continuous information on the structure's condition, and allows identifying gradual changes over a period of time. The presented case-study provides valuable information on applications and limitations of remote moisture measurement systems for timber bridges.

1 INTRODUCTION

1.1 Timber as construction material for bridges

Timber has been a structural material for centuries; exploiting its high ratio of bending strength to weight. Bridges in Mesopotamia dating back as far as 3000 BC illustrate that timber was used already at that time in the construction of big structures using simple tools and assembly methods (Gerold 2002). Numerous examples throughout the world demonstrate the durability of timber; if treated adequately, timber has a long service life, as can be seen in bridges and multi-story framework buildings that are over 400 years old.

The development of new adhesives and connecting techniques, the ability to better analyze the resistance of members and joints, and intelligent monitoring methods created new possibilities for timber structures. Timber as a natural and reusable resource has gained importance; the little energy required for production, the modification and dismantling possibilities and the low maintenance costs especially of roofed bridges act in favor of timber as a building material. But timber is biodegradable, therefore timber bridges must be inspected at regular intervals to determine their conditions (Wilkinson et al. 2005) using non-destructive, semi-destructive and destructive methods (Kasal and Anthony 2004). The ability of a structure to resist degradation depends on its material, design, maintenance and the surrounding environment (including UV exposure, temperature, mechanical erosion and weathering). More specifically, the durability of wood depends on the natural resistance of the species, its moisture content, and surface treatments. Wood as an organic material subject to decay and insect attack; damage attributed to bio-deterioration decreases the service life and capacity of structural members.

Timber bridges need either structural or chemical protection, or a combination thereof; they may have limited service life if designers are not fully aware of this problematic or don’t pay sufficient attention to it (Kleppe 2010). As a result of growing environmental awareness, protective chemicals are almost banned, and protection relies heavily on designs that (i) prevent water or moisture to reach the structural elements and (ii) allow the structure to dry out quickly. Wood destroying fungi need free water to grow, consequently the wood MC should be kept well below the fiber saturation point. The load-bearing capacity of timber elements and systems is affected by MC changes. As an example, the tension perpendicular to grain strength sections can be reduced by up to 50% by moisture induced stresses (Jönsson and Thelandersson 2003).

1.2 Hygroscopic behavior of wood

Wood exchanges moisture with the surrounding air; the rate of this exchange depends on the relative humidity and temperature of the air and the current wood moisture content (MC). Conceptually, the MC at which only the cell walls are completely saturated is called the fiber saturation point, which averages approximately 30% across species. Below that MC, the physical and mechanical properties of wood change as a function of MC. The equilibrium moisture content (EMC) is defined as the MC at which the wood is neither gaining nor losing moisture. Timber in service is exposed to both long-term (seasonal) and short-term (daily) climatic changes, thus, timber is constantly undergoing at least slight changes in MC. These changes are usually gradual, and short-term fluctuations tend to influence only the surface. MC changes can be retarded, but not prevented, by protective coatings of various kinds. Below the fiber saturation point, wood also changes dimension as it gains or loses moisture: it shrinks when losing moisture and swells when gaining moisture (Simpson and TenWolde 1999).

To determine the MC of wood, electrical and oven-drying methods are used. The principal advantages of the electrical method are speed and convenience: only little time is required and the tested piece is only minimally damaged by an electrode needle, thus, this method can be applied in structures. Either insulated or un-insulated, are driven into the wood: un-insulated electrodes will sense the highest MC along their length; therefore moisture gradients between the surface and the interior impact the results. To guard against this problem, electrodes with insulated shanks can be used that measure MC only at the tips of the electrodes. When properly used, the average MC from the readings should be within 1% of the true average for values below 30% (Simpson 1999). Said (2007) reviewed the methods and performances of MC measurement in building envelopes with a focus on continuous monitoring applications and concluded that resistance-based methods are most suitable for continuous monitoring applications as they can be readily connected to a data logging system.

1.3 Long-term monitoring of timber bridges

Various research in several countries, e.g. the US and Sweden, on the inspection of timber bridges resulted in instructions for inspections and repairs (Gustavsson et al. 2010). A Norwegian project dedicated to monitoring a series of timber bridges demonstrated that MC can reach very low levels (10-15%) and was still decreasing or remained at these values more than 10 years (Dyken and Kepp 2010). The long-term-moisture behavior of block-glued laminated timber elements was studied by Tannert et al. (2010). Different MC's were observed depending on the cross sectional depth and height as well as position along the beam. If not restricted by the large cross section, the observed MC changes would lead to significant dimensional changes and differences in such dimensional changes within the cross section.

The need for monitoring of bridges can arise from multiple motivations such as suspicions of impairment of the structural safety, the expiration of the planned lifetime, and exceptional incidents. Although recent developments focus on simple, robust and redundant monitoring systems, at present, the monitoring of timber mostly consists of regular on-site visits that only give qualitative answers to whether a structure conforms to regulations or not. The knowledge of the integrity of in-service structures on a continuous time basis is an important aspect that can be implemented using modern monitoring techniques to assess the condition over time. In recent years, wireless sensor networks are emerging in the structural engineering field; they became inexpensive and can play a role in the processing of structural response data to screen for signs of structural damage (Lynch and Loh 2006; Ko and Ni 2005).

There exists more experience with remote monitoring of concrete and steel structures. They can serve a wide range of purposes, providing continuous records of almost any variable in a structure's condition.

This may be of special interest to owners of older bridges, who must ensure the ongoing safety of their structures – not only because of the unavoidable deterioration that comes with age, but also due to the greatly increased traffic loading of recent decades, and the fact that many bridges which were built in the past to different design and construction standards may not necessarily satisfy today's increasingly rigid safety demands. An automated monitoring system can be utilised to provide real-time information on any structure's condition, allowing gradual changes over a period of time to be identified and offering immediate notification by SMS or e-mail of any sudden changes in a chosen variable, or exceeding of predefined alarm values. Having such a system in place can allow the structure's owner to be sure that any changes in its condition will be recognised immediately, allowing appropriate strengthening work to be planned or, if necessary, the structure to be closed.

On the other hand, structural health monitoring systems are also often applied to assess the overall structure's performance. The benefit of SHM-Systems is to lengthen the structure's service life time and / or consequently reduce the integral life cycle cost of a structure. It is for example today's state of the art to equip all new built major bridges with sophisticated monitoring systems. Besides the performance assessment, the measured results allow the engineers to update their FEM models and to understand the structural behaviour in detail, e.g. during a seismic event or when a thunder storm hits the construction.

1.4 Objectives

There is presently not much information available on the remote structural health monitoring of timber bridges. Research is needed to provide information related to the optimal placement of sensors to decrease the cost while increasing the reliability of the measurements. The purpose of the case study presented herein was to provide a solution for the cost effective remote long-term moisture monitoring of timber bridges.

2 CASE STUDY

2.1 Traffic bridge Obermatt

The construction of the bridge in Obermatt was one project within the renovation of four timber bridges in the famous Swiss Emmental valley. Floods in the summer of 2005 partly damaged the bridge and showed that the original free board height of 0.9m did not provide sufficient protection against a possible blockage. The responsible engineers (Paul Grunder and Raymond Weinmann) therefore incorporated a hydraulic lifting system at the abutments, this way, at flood risk the bridge can be hydraulically raised by 0.7m. The bridge, illustrated in Figure 1, was designed according to Swiss Standard SIA 261:2003 for a traffic load of 40tons, it contains two longitudinal main beams of glued-laminated timber (GL24 according to EC5); the load from the deck is transferred by a series of secondary glue-lam beams. The average daily traffic on the bridge is 2400 vehicles with a 12% proportion of heavy traffic. At present, the allowable traffic velocity is 40km/h, which is planned to be increased to 50km/h.

Figure 1. Timber traffic bridge in Obermatt

After two years of operation, some discoloration at various structural elements was detected. While this in itself was no reason for concern, the district authorities nevertheless wanted the cause of this discoloration to be clarified. In 2010, the Bern University of Applied Science (BFH) was approached with the request by the local traffic administration department to assist in monitoring the structural health of the bridge. The results are expected to provide insights into possible improvements to existing design solutions for timber bridges. Given previous experience on the long-term moisture monitoring, it was decided to use this project to install a remote data sensing device in collaboration with mageba SA.

2.2 Measurement equipment and plan

It was decided to use the commercially available MC measurement system “Gigamodul”© by Scanntronik© (Figure 2 left) together with self-made electrodes consisting of chrome-steel screws with insulated shanks (Figure 2 middle) which were then driven into the wood with a 32mm distance between them (Figure 2 right). The MC in the support structure and the deck, in particular at the interface between slab and base, are being measured and recorded. A total of 16 measuring points was selected; to investigate the influences of the position in the structure and the depth inside the beam (surface and 200mm depths). The approximate positions and the corresponding labeling are illustrated in Figure 3.

Figure 2. Measurement equipment: Gigamodul© (left), electrode (middle) and installed (right)

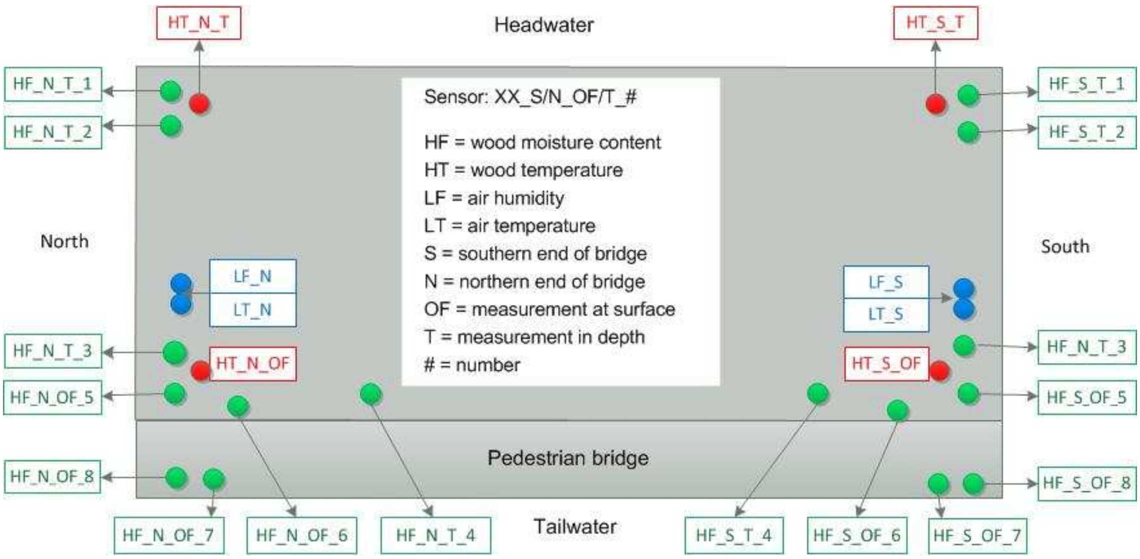

Figure 3. Layout of measuring points including sensor names

To allow for later temperature corrections of the measurements, an additional two temperature sensors next to two of the moisture sensors were installed. Additionally, the air temperature and the relative humidity are recorded (sensor location illustrated in Figure 3).

2.3 Remote data monitoring

In cooperation between BFH and mageba SA, a remote data transmission system was installed. Battery life has been identified as the primary limiting factor for wireless sensor technology (Chen and Lin 2007). To address this issue, several approaches were proposed: e.g. cycling through different states (dormant, sleeping and active) or using multi-scale networks, which only activates sub-networks in areas of suspected damage. In the presented case study, it was decided that one measurement every six hours provides sufficient data density and that a remote transmission once per week allows for a short enough response time. The MCs were manually recorded at the time of installation and from then on automatic measurements were taken. The data is collected by a logging device, sent per e-mail to a server, and then uploaded to a website: http://www.mageba.ch/robo_control.html (screenshot shown in Figure 4). The website allows the district authorities as well as the researches from BFH to continuously monitor the bridge.

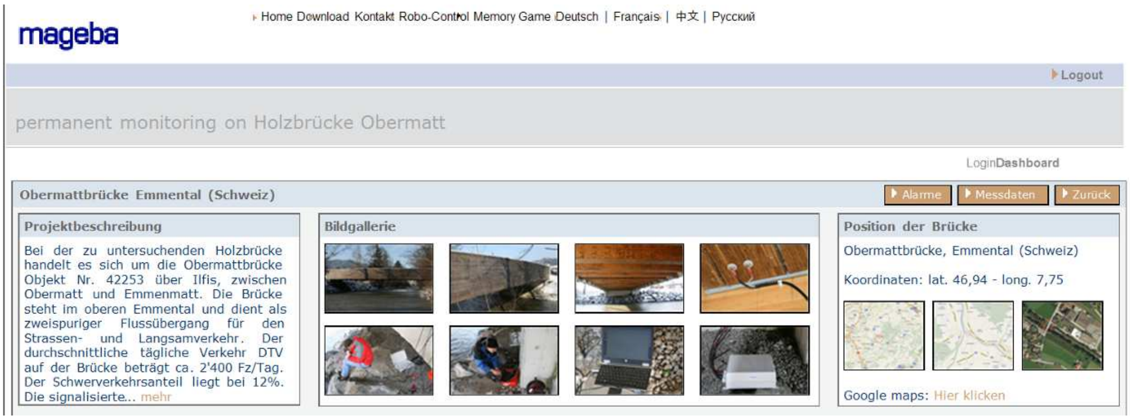

Figure 4. Screenshot web interface: home page

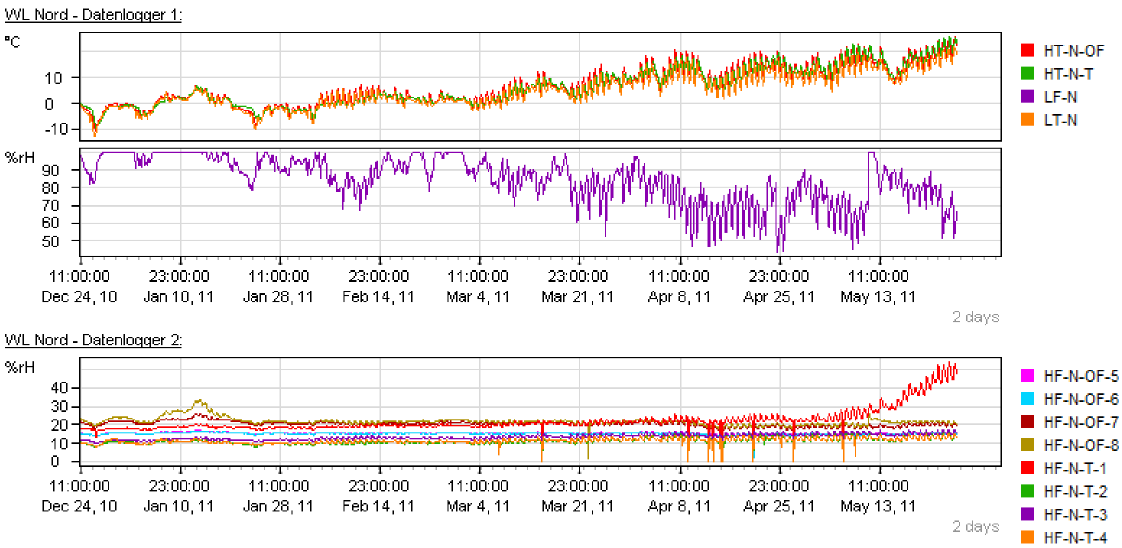

Figure 5. Screenshot web interface: results of data logger North

3 CONCLUSIONS

Following conclusions can be drawn from the presented case study:

- The remote data transmission system proved to be simple in its application, robust in terms of environmental influences and battery life is no concern after six month monitoring.
- The website provides an easily accessible platform to monitor the moisture developments.
- The recorded MC measurements are consistent with values from previous experience; MC in the timber fluctuates only slightly and stays well below the fiber saturation point.
- Wood temperature follows very closely without any apparent delay the surrounding air temperature (within the chosen six hour measurement intervals).

The progress in sensing and data processing technologies has resulted in a significant interest in them to monitor structural integrity of infrastructure. To improve the assessment of timber bridges, more research is required to accurately quantify MC changes, moisture induced stresses, as well as their impact on the strength. The development of reliable wireless networks can provide valuable information to detect moisture leaks may soon after first occurrence, to initiate in-depths inspections at time, to stop the progress of deterioration, and to prevent unnecessary decommissioning of infrastructure. Ongoing research strives to contribute to a broader and safer use of timber, e.g. the new Cost Action FP1101 “Assessment, Retrofitting and Monitoring of Timber Structures” aims to increase the acceptance of timber in the design of new structures by developing and disseminating methods to assess, reinforce and monitor them (Cost 2011). An increased and more innovative use of timber as structural material based on stronger confidence will bring environmental and economic benefits since more and more durable timber structures will result in a more diverse and appealing built environment and benefit society as a whole in the development of a low-carbon economy.

4 REFERENCES

Cost (2011) http://www.cost.esf.org/domains_actions/fps/Actions/FP1101.

Chen YM and Lin CY. 2007. Dynamic Simulation of Wireless Structural Monitoring System Using Petri Nets. *Proc 3rd Int Conf on Struct Health Monit of Intell Infrastruct*, Vancouver, Canada.

Dyken T and Kepp H. 2010. Monitoring the moisture content of timber bridges. *Proc Int Conf on Timber Bridges*, September 12-15, Lillehammer, Norway.

Gerold M. 2002. Bloc-Glued Laminated decks for timber bridges. *Structural engineering international*, 12(3): 214–217.

Gustavsson A, Pousette A and Björngrim N. 2010. Health Monitoring of timber bridges. Proc Int Conf on Timber Bridges, September 12-15, Lillehammer, Norway.

Jönsson J and Thelandersson S. 2003. The effect of moisture gradients on tensile strength perpendicular to grain in glulam. *Holz als Roh- und Werkstoff*. 61(5): 342–348.

Kasal B and Anthony RW. 2004. Advances in in-situ evaluation of timber structures, *Progress in Structural Engineering and Materials*. 6: 94–103.

Kleppe O. 2010. Durability of Norwegian timber bridges. *Proc Int Conf on Timber Bridges*, September 12-15, Lillehammer, Norway.

Ko JM and Ni YQ. 2005. Technology developments in structural health monitoring of large-scale bridges, *Engineering Structures*, 27(12): 1715-1725.

Lynch JP and Loh KJ. 2006. A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring. *The Shock and Vibration Digest*. 38(2): 91–128.

Said MN. 2007. Measurement methods of moisture in building envelopes - a literature review, *International Journal of Architectural Heritage*, 1(3): 293-310.

Simpson W and TenWolde A. 1999. Physical Properties and Moisture Relations of Wood. Chapter 3, *Wood handbook - wood as an engineering material*. General Technical Report FPL–GTR–113. Forest Products Laboratory, Madison, USA.

Simpson W. 1999. Drying and Control of Moisture Content and Dimensional Changes. Chapter 12, *Wood handbook - wood as an engineering material*. General Technical Report FPL–GTR–113. Forest Products Laboratory, Madison, USA.

Tannert T, Mueller A and Vogel M. 2010. Structural health monitoring of timber bridges. *Proc Int Conf on Timber Bridges*, September 12-15, Lillehammer, Norway.

Wilkinson, K, Thambiratnam, D and Ferreira, L. 2005. Non Destructive Testing of Timber Bridge Girders. *Int. Conf. on Structural Condition Assessment, Monitoring & Improvement*, Perth, Australia.