REMOTE MOISTURE MONITORING OF TIMBER BRIDGES: A CASE STUDY

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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 their durability; 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.

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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 their durability; 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.

Timber as a natural and reusable resource has gained importance; the little energy required for production, the modification and dismantling possibilities act in favor of

timber as a building material. 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. But timber is biodegradable; therefore timber structures must be inspected at regular intervals to determine their condition (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 environment (including UV exposure, temperature, mechanical erosion and weathering). 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 or don't pay sufficient attention (Kleppe 2010). As a result of growing environmental awareness, chemicals are used less, 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 also 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; this exchange depends on the relative humidity and air temperature 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; wood also changes dimension as it gains or loses moisture: it shrinks when losing moisture and swells when gaining moisture (Simpson and TenWolde 1999).. 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.

To determine the MC of wood, electrical and oven-drying methods are used. The principal advantages of the electrical method are speed and convenience, and that the tested piece is only minimally damaged. Electrode needles, either insulated or un-insulated, are driven into the wood: un-insulated electrodes sense the highest MC along their length; therefore the results are influenced by MC gradients. To guard against this problem, electrodes with insulated shanks measure MC only at their tips. 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 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

The need for monitoring of bridges can arise from multiple motivations such as regular assessments, 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 on-site visits that only give qualitative answers to whether a structure conforms to regulations or not. 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 2007; Ko and Ni 2005).

Monitoring of bridges in other material domains has developed from a time-consuming, labor-intensive manual exercise to highly automatic independent and versatile systems, benefitting from the technologies of the information age that can be tailored to provide almost any type of information required on the condition of a bridge and its environment and loadings (Spuler et al. 2011). Automated monitoring systems can be utilized to provide real-time information on any structure's condition, identifying gradual changes and offering immediate notification by SMS or e-mail of any sudden changes or when predefined alarm values are exceeded. Having such a system in place allows any changes to be recognized immediately and appropriate strengthening work to be planned or, if necessary, the structure to be closed. Structural health monitoring systems are also often applied to assess the overall structure's performance and thereby lengthen the structure's service life time. It is for example today's state of the art to equip new built major bridges with sophisticated monitoring systems. But this is also of interest to ensure the ongoing safety of older bridges.

Various research, e.g. in 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 timber bridges demonstrated that MC can reach low levels (10-15%) and was still decreasing after 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.

1.4 Objectives

Research is needed to provide information related to the remote structural health monitoring of timber bridges in regard to placement of sensors, cost and 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)

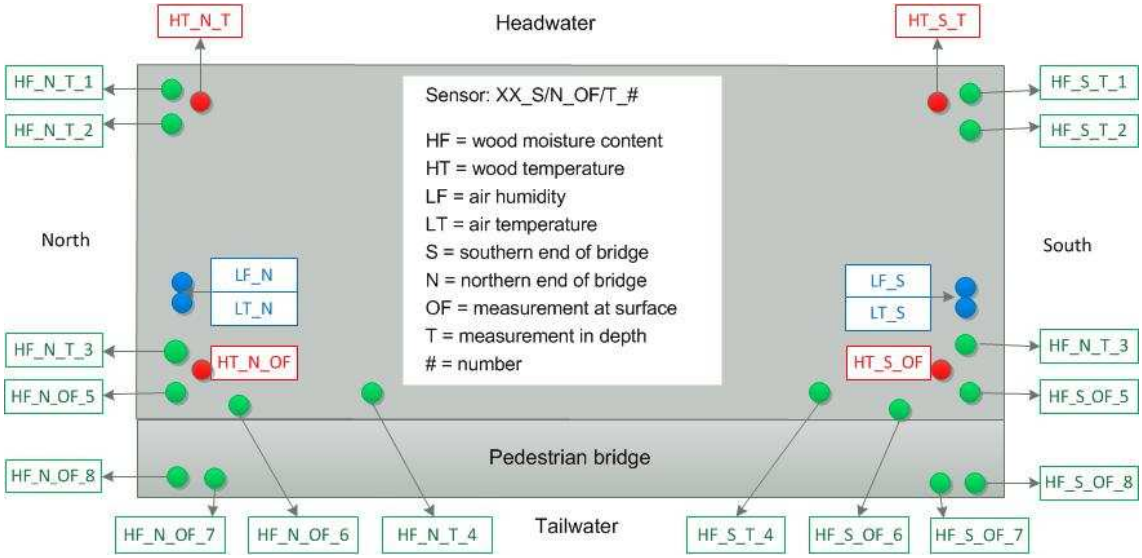

Figure 3. Layout of measuring points including sensor names

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.

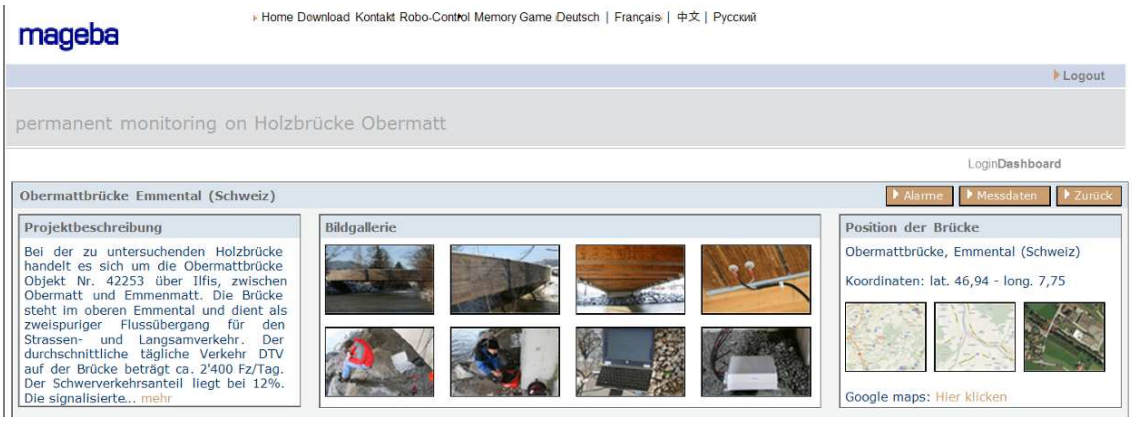

Figure 4. Screenshot web interface: home page

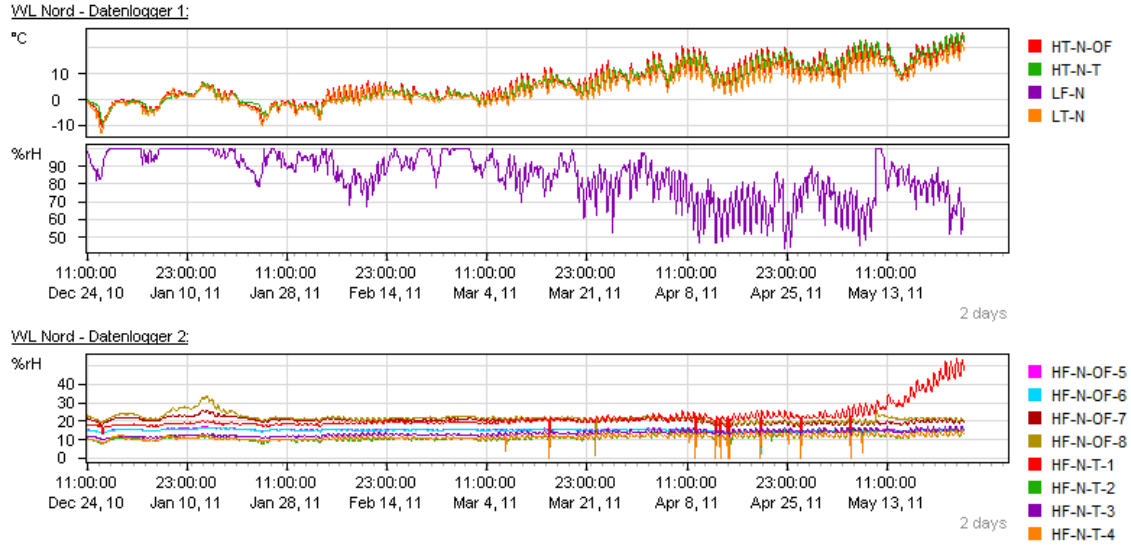

Figure 5. Screenshot web interface: results of data logger North

2.4 Results and Discussion

After installation, only one visit to the bridge was necessary due to a damaged cable. Since then, the remote data transmission allows for weekly updates on the MC of the timber elements. Figure 5 illustrates the results for the loggers on the north side of the bridge. The graphs show that MC at all measuring points remains well below 25% with the MC nearby the surface being slightly lower than in deeper regions. This rather unexpected finding still needs to be analyzed, however since the differences are within few %, it might also be caused by measurement variations. One outlier 'HF-N-T-1' shows an increasing MC which will be evaluated during the next on-site visit. Given that all other MC measurements remain relatively constant, the authors believe this to be a measurement equipment problem and not a sign of some structural problem.

The environmental variables (air temperature and relative humidity) show the expected large long term variations with some short term fluctuations; neither of which having a significant impact on the MC of the timber in service. The wood temperature follows very closely the air temperature; changes in air temperature are translated into the wood with very little delay. This finding allows future temperature corrections of the MC in bridges where the wood temperature is not being measured to be based on measurements of surrounding air temperature.

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 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.

The progress in sensing and data processing technologies has resulted in a significant interest to monitor the integrity of infrastructure. To improve the assessment of timber bridges, research is required to accurately quantify MC changes, moisture induced stresses, as well as their impact. The development of reliable wireless networks can provide valuable information to detect moisture leaks soon after first occurrence, to initiate in-depths inspections at time, to stop the progress of deterioration, and to prevent unnecessary decommissioning. Ongoing research contributes 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.

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