Moisture Content Monitoring of a Timber Footbridge

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Construction of modern timber bridges has greatly increased during the last 20 years in Sweden. Wood as a construction material has several advantageous properties, *e.g.*, it is renewable, sustainable, and aesthetically pleasing, but it is also susceptible to deterioration. To protect wood from deterioration and ensure the service life, the wood is either treated or somehow covered. This work evaluates a technology to monitor the moisture content in wood constructions. Monitoring the moisture content is important both to verify the constructive protection and for finding areas with elevated levels of moisture which might lead to a microbiological attack of the wood. In this work, a timber bridge was studied. The structure was equipped with six wireless sensors that measured the moisture content of the wood and the relative humidity every hour. Data for 744 days of the bridge are presented in this paper. Results show that the technology used to monitor the bridge generally works; however, there were issues due to communication problems and malfunction of sensors. This technology is promising for monitoring the state of wood constructions, but a more reliable sensor technology is warranted continuous remote monitoring of wood bridges over long periods of time.

Keywords: Wireless sensors; Timber bridge; Monitoring; Moisture content

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INTRODUCTION

During the last 20 years, approximately 1600 modern timber bridges for traffic and pedestrians have been built in Sweden. Advantageous properties such as abundance, easy shaping, good strength to weight ratio, renewability, sustainability, and aesthetically pleasing appearance, together with modern adhesives and engineered wood such as glue-laminated timber, make timber a good material for constructing bridges.

However, timber is prone to deterioration by fungi and insects. To protect the wood from deterioration and to ensure the service life, the wood is protected with some surface treatment and/or constructive layer. Timber is also subjected to both seasonal and daily changes in temperature and relative humidity (RH), which affect the moisture content (MC) of the timber. Wood can contain up to 140% of water based on dry weight. Depending on species, the fiber saturation point (FSP) of wood is at the range of 28% to 30%, where water is chemically bonded to the wood fiber. Moisture contents over the FSP are due to free water in the wood cell lumen. Dimensional changes of the wood take place only up to the FSP, where the highest amount of bonded moisture in the cell wall corresponds to the most swollen state of the wood. The shrinking and swelling leads to the generation of stresses in the wood and leads to propagation of the cracks in the material. The shrinking and swelling also introduce stresses in the glue line of glulam and cross laminated timber. A crack can be an entranceway for water and cause water pockets that might introduce even more water into the wood. A suitable surface treatment has the potential to prevent cracks and prolong the service life of outdoor wood (Pousette and Sandberg 2013). High moisture content (MC) in a timber construction can affect the structural integrity of the construction. If the MC of wood exceeds 20% for long periods, there is a risk of rot, which will start decaying the timber and reduce the structural integrity. If MC exceeds 30%, the risk is considerably increased (Viitanen 1994). Studies of the development of brown rot fungi show that the humidity must be above 95% to 98% for a long time and the wood moisture content around the FSP, 25% to 30% (Viitanen 1994). Viitanen (1994) also stated that the most suitable moisture content for the growth of brown rot fungi is 30% to 70% MC in wood (Fig. 1). Biodeterioration (*i.e.* mould, decay, and insect damage) may be a critical factor for durability and usages of different building materials. Table 1 shows different organisms growing and living in the building materials and their living conditions (Viitanen and Salonvaara 2001).

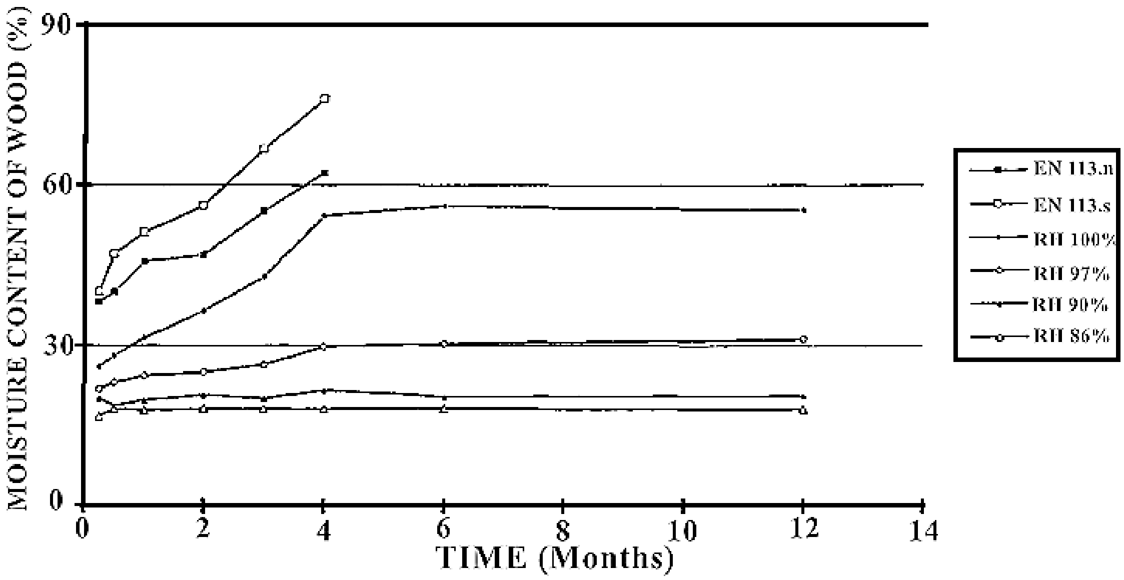

Fig. 1. Moisture content of pine sapwood exposed to *Coniophora puteana* in different humidity conditions and in a decay test performed according to EN 113 (Printed with permission from Viitanen 1994)

Modern timber bridges in Sweden have an expected technical lifetime of 40 or 80 years, depending on the construction type (Anon. 2009). To ensure the technical lifetime, bridges are regularly inspected. Bridges in Sweden are inspected and cleaned at least once every year, and bridges with heavy traffic load are inspected even more often. A thorough major inspection is conducted every six years. The major inspection should predict the performance of the bridge for the coming 10-year period and decide if any repairs must be made (Pousette 2008). The inspections look for damages to the construction, cracks in the super structure, places where debris or vegetation is lying against wood, *etc*. Fasteners, constructive cladding, end grain, abutments, *etc*. are of special interest during inspections (Pousette and Fjellström 2004). The inspections are performed mostly by visual assessment, but moisture content meters, both resistance and dielectric, are also used. If rot is suspected, resistance drilling can be performed to determine whether rot is present. For bridges with pre-stressed decks, the rod forces are also controlled.

Table 1. Organisms Involved in the Damage and Defects of Building Components (Printed with permission from Viitanen and Salonvaara 2001)

Type of organism	Damage/problem type	Humidity or moisture range (RH or MC %)	Temperature range (ºC)
Bacteria	Biocorrosion of many different materials, smell, health problems	Wet materials RH > 97%	*ca.* -5 to +60
Mould fungi	Surface growth on different materials, smell and health problems	Ambient RH > 75%, depends on duration, temperature and mould species	*ca*. 0 to +50
Blue-stain fungi	Blue-stain of wood permeability change of wood	Wood moisture content > 25 - 120%, RH > 95%	*ca*. -5 to +45
Decay fungi	Different types of decay in wood (soft rot, brown rot or white rot), also many other materials can be deteriorated, strength loss of materials.	Ambient RH > 95%, MC > 25 - 120%, depends on duration, temperature, fungus species and materials	*ca*. 0 to +45
Algae and lichen	Surface growth of different materials on outside or weathered material.	Wet materials also nitrogen and low pH are needed	*ca.* 0 to +45
Insects	Different type of damages in organic materials, surface failures or strength loss.	Ambient RH > 65% depends on duration, temperature, species and environment	*ca.* 5 to +50

Visual inspections are always dependent on the skill of the inspector, and the results can vary considerably (Moore *et al.* 2001). Modern sensor technology enables hidden defects to be detected, which could be a valuable complement to visual inspections. Long-time monitoring can provide tools and data for better planning of the inspections and to detect damage at an early stage. Early detection of damage can reduce costs and downtime for reparations. A reliable monitoring system should decrease the frequency of inspections needed to assure the structural integrity of the bridge. While monitoring of concrete bridges and steel bridges is common and quite mature (Glisic *et al.* 2009), timber bridges demand efficient monitoring methods to remain competitive with bridges built of other materials. New sensor technology provides continuous measurements suitable for reliable monitoring of timber bridges (Tannert *et al.* 2011). These sensors provide more information than visual inspections and could reduce the maintenance cost and set the foundation for better planning maintenance activities and evaluating the remaining service life. Monitoring of timber bridges can also help the design and development of the next generation of timber bridges (Saracoglu and Bergstrand 2015). MC monitoring of various timber constructions has been reported by several researchers: Sandberg *et al.* (2011a) reported more than 600 wireless sensors being used for monitoring beams, posts, and buildings. Brischke *et al.* (2008) constructed an MC sensor that was long-term tested at 29 locations in Europe and the USA. Dyken and Kepp (2010) monitored the MC indirectly by measuring RH and temperature in small cavities at five timber bridges and concluded that the MC eventually dries out from massive glulam elements over time.

The overall aim of this study was to evaluate tools and data for better planning of the inspections and to detect damage at an early stage for timber structure. The specific objective of this paper was to present the long-term MC monitoring of Älvsbacka Bridge and to evaluate the suitability of HygroTracs® as a MC monitoring system for timber constructions.

MATERIAL AND METHODS

Älvsbacka Bridge

In August 2011 the Älvsbacka Bridge was erected in Skellefteå (64°45'N 20°57'E). The Älvsbacka Bridge connects the Älvsbacka district on the north side with the Anderstorp district on the south side of the Skellefteå River. The bridge is for pedestrian and bicycle traffic and designed to carry a snow removal vehicle (a distributed load of approximately 4 kN/m^2). The cable-stayed bridge spans 130 m and is in total 182 m long, with the bridge deck measuring four meters wide and the 24-m-high pylons. The pylons secure the 20 cables suspending the bridge deck. The cable diameter varies between 45 and 80 mm. The superstructure consists of two glulam beams with a cross section of 0.65 by 1.10 m. The pylons have a cross section of 0.9 by 0.9 m. The glulam is made of untreated Norway spruce (*Picea abies*) with defunct Swedish grade L40 (comparable to European grade GL30C). The superstructure is covered with painted spruce matched tongue and groove board cladding of panels (22 x 145 mm). Such panels are used for UV protection as well as prevention moisture ingress in the wood. Between the cladding and glulam beam, there is a 25 mm air gap for good ventilation. Cross bracing and other metal details are made of steel that has been hot dipped in zinc. The bridge has an open decking with 45-mm-thick pine boards. The bridge has a technical lifetime of 80 years. Skellefteå municipality is the owner of the bridge.

Moisture Content Sensors

The MC sensors used for this project are a commercially available system, Protimeter HygroTrac® wireless sensors by General Electric (USA). The sensors were mounted at the factory during the manufacturing of the primary glulam beams in summer 2011. When Internet access and electrical installations had been completed at the bridge in early 2012, the gateway for the sensors was activated. The sensors are calibrated for spruce and are battery-powered with an expected battery life of 15 years when measuring once per hour. Technical specifications are found in Table 2.

Each sensor was mounted with two stainless steel screws. The screws are 25 mm long and are not isolated. The conductivity between the screws was measured along the whole length of the screw, and the MC reported was the highest value found, measured 25 mm in from the surface.

Table 2. Technical Specifications of the HygroTrac® Sensor

Measured property	Range	Accuracy
MC	8% to 40%	+/- 1%
RH	0% to 100%	+/- 2.5% in the 0-90% range
Temp.	-40 to 85 °C	+/- 0.5 °C at 25 °C

* Technical specifications from GE Measurement and control (2014)

Every hour, the six sensors measured MC, RH, and temperature. Each sensor has a unique ID, and the data were transmitted wirelessly from the sensors to a gateway located in the south abutment of the bridge. The seven-character sensor ID is presented as sensor 1 through 6 for convenience in this paper. The sensor placement on the bridge is shown in Fig. 2. From the gateway, the data were sent to a server and displayed on a password-protected site.

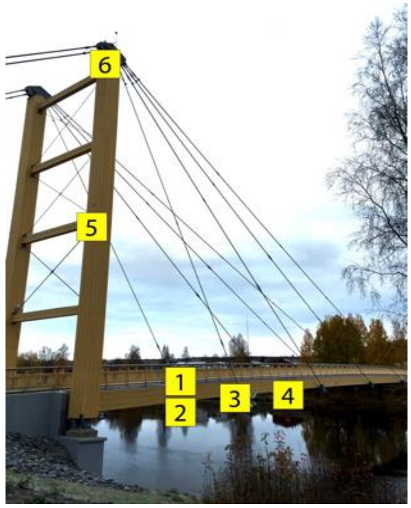

Fig. 2. Placement of HygroTrac® sensors on the bridge

Sensors 1 to 4 were placed beneath the bridge deck on the east-facing main glulam beam (Fig. 2). The first two (sensors 1 and 2) were mounted 7.2 m from the south abutment at both the top and bottom of the primary beam. Sensor 1 was mounted at the top of the beam just beneath a ledge and was used to compare with sensor 2, which is mounted beneath at the bottom of the beam (Fig. 3). Just above sensor 2 was a metal fastener for the transverse beams where water would pour down along the edge of the metal fittings; high levels of MC were expected to be found there. Sensor 3 was mounted 12.2 m from the south abutment, and sensor 4 was located 26.5 m from the south abutment.

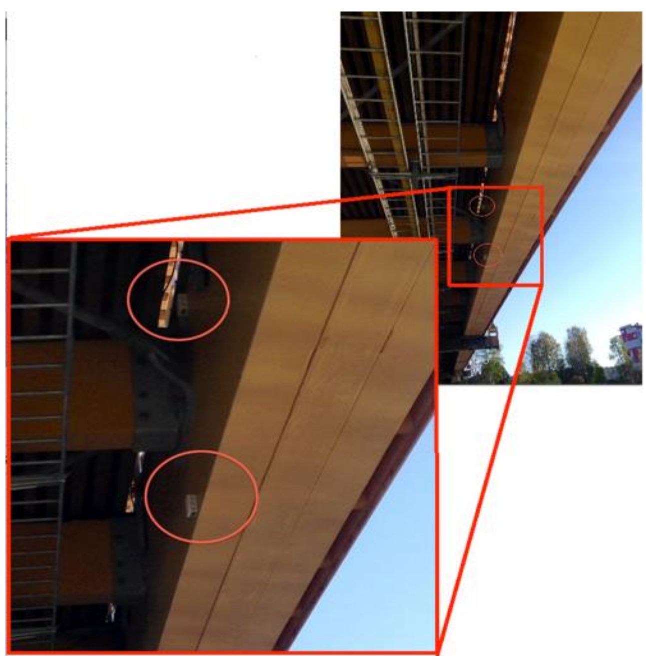

Fig. 3. Photographs showing sensor 1 at the top and sensor 2 at the bottom of the glulam beam

Sensors 5 and 6 were mounted on the southeast pylon (Fig. 2). Sensor 5 was placed at the middle, 11.5 m from the bridge deck, and sensor 6 was at the top, 23 m from the bridge deck. The sensors on the pylon were shielded by the cladding protecting the glulam.

Approximately 200 m from the northeast side of the bridge, there are three multistory timber buildings. These buildings are also monitored for moisture content. For comparison with the bridge MC sensors data, one of the sensors placed on the south façade of the timber building was studied. The façade is made of spruce, as is the glulam used for the Älvsbacka Bridge.

The MC, RH, and temperature were measured at six locations on the bridge from February 22, 2012 to February 3, 2014, leading to 744 days in total.

RESULTS AND DISCUSSION

The measured RH *vs*. MC and temperature *vs*. MC for all sensors are displayed in Fig. 4 and 5, respectively. All six sensors showed similar readings for RH and temperature. Therefore, only one curve from sensor 1 was chose to represent the RH or temperature in the figure. Of the six sensors, two malfunctioned. Sensor 6, located at the top of the pylon, only sent data for a few days, which is not presented here. Sensor 4 stopped working after 10 months. This could be battery-related or due to condensation, snow, or faulty hardware. Sandberg *et al.* (2011b) reported similar experiences. The RH varied between 35% and 100% over the year (Fig. 4); the RH was higher during winters and lower during summers. It was the same trend for the MC readings, which showed the highest values during the winters and the lowest during the summers. The temperature *vs.* MC is demonstrated in Fig. 5, and ranged from -20 to 25 °C. The temperature was higher in summers and lower in winters, just opposite to MC readings.

Sensor 1 (red line in Fig. 4 and 5), located at the top of the main beam, at a location protected from water flowing down through the bridge deck, showed expected behavior, with a MC under 20% except for a few peaks. Sensor 2 (brown line in Fig. 4 and 5), placed at the lower end of the glulam beam, was more exposed to water pouring through from the open bridge deck. Thus, it showed the highest MC, reaching well over 40% for short periods and over 25% for long periods during the winter. MC over 40% is not within the calibrated interval of the sensor and is probably due to water pouring/melting down and pouring into the borehole. It is reasonable to expect that if the borehole for the sensor had not been mounted, the free water would not be able to penetrate the painted surface of the beam and the MC would be approximately 15% to 20% (below the FSP), similar to the close-by and protected sensors. From Fig. 3, it can be seen that there were no visible cracks nearby the sensor 2. Therefore, even though the MC was varying over and under the FSP, it does not seem to have affected the timber, which is a good indication that it was just water in the borehole that was responsible for the elevated MC values.

Sensor 3 (dark blue line in Fig. 4 and 5) showed behavior similar to that of sensor 1, with a MC below 20%. Sensor 4 (light blue line in Fig. 4 and 5) reported the lowest MC levels until the failure. Sensor 5 (yellow line in Fig. 4 and 5), located inside of the protective cladding on the pylon, showed higher MC than the sensors in the main beam, reaching over 30%. It reported a MC above 20% in September to October 2012 and January 2014, which must be further investigated. Sensor 5 suffered from some sort of malfunction and had problems sending data, with limited data acquisition between December 2012 and April 2013. Viitanen (1994) states that the critical humidity level for fungi growth was RH at

80% and over, with temperatures above 20 °C. Although RH values were high during December to February, the low temperature was not favorable for fungal growth.

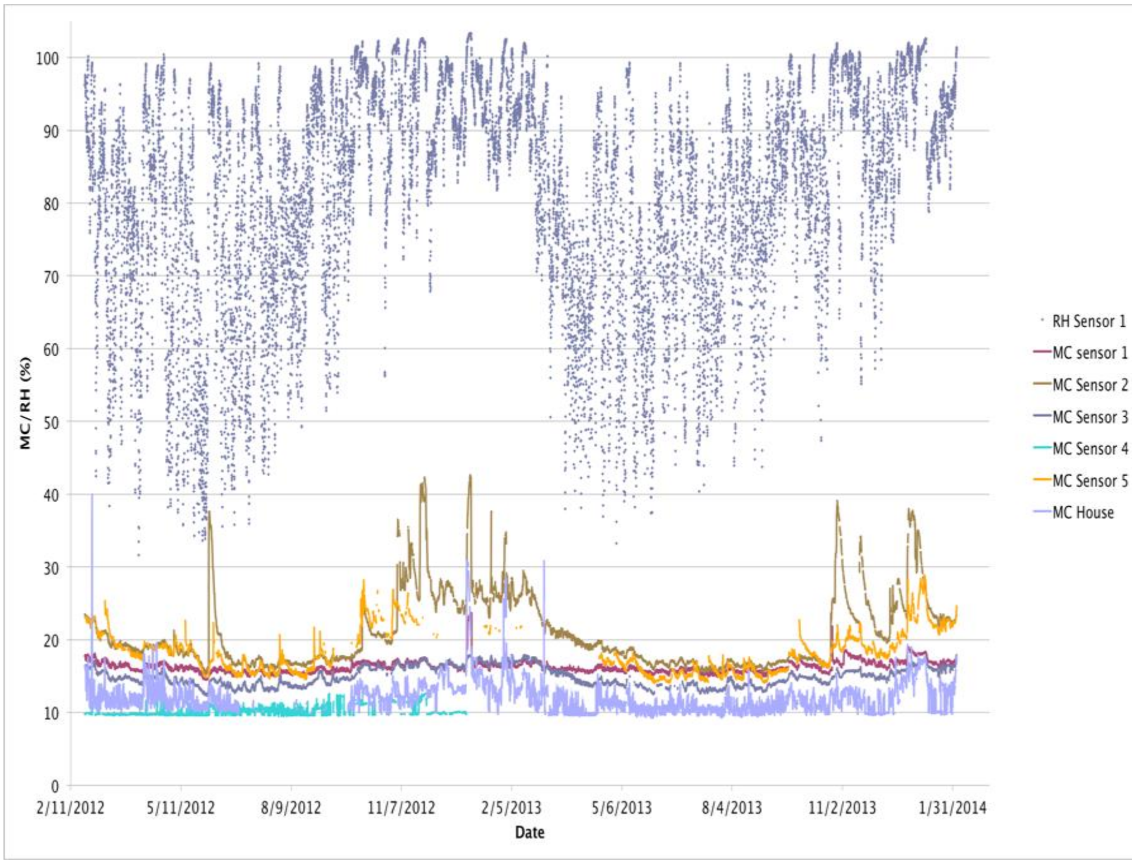

Fig. 4. RH *vs*. MC for all sensors

The correlations between RH and MC for five working sensors on the bridge and one sensor on the nearby timber building are presented in Table 3. Sensor 4 exhibited the lowest correlation (0.36); however the collected data seemed to hover around 10% MC, which differs from the other sensors placed on the bridge. The reliability of sensor 4 could be questioned. The rest of the sensors showed quite reasonable correlations (between 0.49 and 0.66). Since there is a time-lag between RH changes and resulting MC changes, the correlation was not high.

Table 3. Correlation between RH and MC for All Sensors

Sensor	1	2	3	4	5	House
Correlation	0.53	0.49	0.66	0.36	0.50	0.57

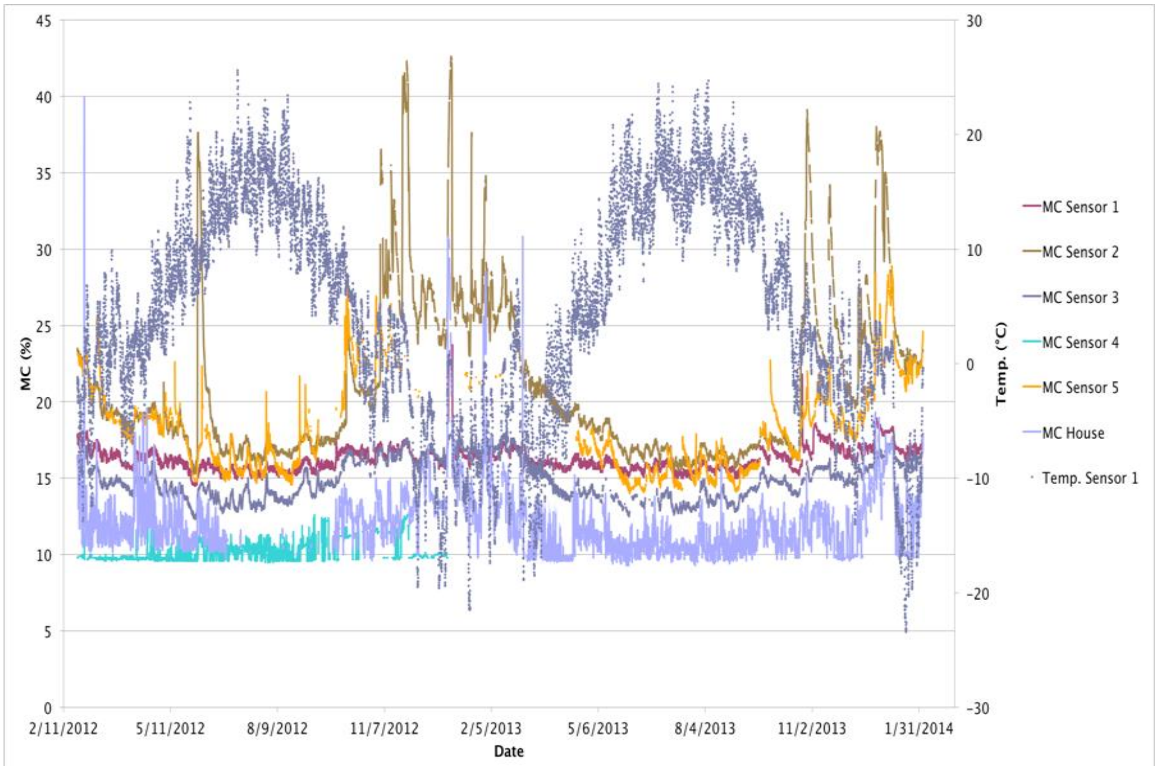

Fig. 5. Temperature *vs.* MC for all sensors

One of the sensors from the nearby timber building was used for comparison with the bridge data. Purple lines in Fig. 4 and 5 show the measurements of this sensor. Although the RH values were generally lower, the trend was similar to the RH measured at the bridge. The higher RH values for the sensors on the bridge could be due to the moisture from the nearby river. The MC of the sensor on the timber building was quite steady at approximately 10% to 15%, with a few peaks over 20%. The same problem as with sensor 5 was also present here: for a period of a few months, only very sporadic measurements were reported.

Timber constructions such as bridges need to be inspected and monitored in search of elevated MC levels. The MC monitoring system on Älvsbacka Bridge consisted of six sensors, where only four were still sending data. Limited sensors cannot monitor a whole bridge, but they can verify if the construction is in good shape or not, by selecting a few key measurement points.

All sensors were expected to work well when they were installed. The initial plan for monitoring was that there were possibilities for regular checking or reparation of the sensors under the bridge deck. However, the budget was cut and the inspection deck that was planned to be under the bridge was not realized, and then it was difficult to reach these places.

CONCLUSIONS

This paper presents the long-term monitoring of moisture content (MC) of Älvsbacka Bridge, and evaluates the suitability of HygroTrac®-sensors as a MC monitoring system for timber constructions.

1. It is possible to monitor the MC on the timber bridge with low-cost sensors.
2. The HygroTrac® sensor used for monitoring the MC on Älvsbacka Bridge is an established product. The wireless sensors were convenient to set up, but sometimes the sensors needed a restart to function.
3. The points monitored on the bridge were critical and important. They should not be too difficult to reach for inspection or for the restarting or exchanging of faulty sensors.
4. More sensors could have been installed to cope with the eventual sensor loss and to give valuable data for bridge condition.
5. This kind of sensor might not be enough to monitor the bridge throughout its technical lifetime. The lifetime of the sensors is much shorter than that of the bridge, therefore, a more thorough sensor system might be installed.
6. For future work a more robust sensor is suggested. A sensor that can last longer than current sensors and preferably during the whole lifespan of the timber construction. It is also considered important to eliminate the large gaps of missing data.

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