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Monitoring systems for quality assurance of timber bridges

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1 Introduction

Wood properly protected and controlled is very powerful and durable.

Continuous monitoring of wood moisture content is a suitable early warning system. The importance of wood moisture in relation to possible damage in timber construction is shown in a study of Frese [1], where 50 % of all investigated objects show damage or failure due to wood moisture changes or low and high wood moisture contents. Another study by Dietsch [2] shows that 30% of these objects are damaged due to seasonal or climate-induced wood moisture changes. Since the distribution of wood moisture is often not constant across the cross-section, internal stresses perpendicular to the grain (moisture-induced stresses, MIS) arise due to the anisotropic moisture-strain behaviour. These stresses can easily exceed the characteristic tensile strength perpendicular to the grain and lead to crack development, [3]. In curved glulam beams, these stresses can also lead directly to the total loss of load-bearing capacity, as shown in [4] or [5].

For structures exposed to the outdoor climate (service class 2), such as wooden bridges, monitoring systems have already been used for many years together with other measures to ensure safety and durability, [6]. Two important aspects are crucial to ensure the safety and functionality of the bridge during the desired lifetime, ASTRA guideline 12002 [7]. First, the design must focus on this goal and second, the condition of the structure must be ensured during the whole operational phase. This is usually done by regular visual checks and inspections combined with control measurements. If the control measurements are carried out continuously by means of a monitoring system, trends in the behaviour, damaging events or even damages can be derived from the data and controls and inspections can be planned more efficiently in time and cost.

Components that are difficult to monitor and concealed are often unavoidable in "protected" wooden bridges. Today, it is possible to monitor a bridge structure by means of point or laminar measurements. The determination of the wood moisture concentrates on the critical points/hazard zones/hot spots, such as connections, roadway transitions, penetrations, and support areas. With a certain amount of experience, it is usually possible to detect significant deviations in the wood moisture content at an early stage by monitoring over a long period of time, [8]. The waterproofing systems can usually not be checked or only with expensive effort. In most cases, this is only done if damage to the deck is already visible, [6]. A laminar leakage detection integrated in a monitoring system can detect irregularities earlier and damage can be avoided.

2 Planning, data management, transmission, and data analysis

For the planning, implementation and evaluation of a monitoring system, an exchange with appropriate experts should take place. At the beginning, the choice of the measured quantity is a first important step next to the definition of the control points and their number. The density of measurement data must be defined individually from object to object or from control point to control point. Specialists in this field can assist and advice in deciding on a suitable system.

The installation of measurement sensors enables the acquisition of measurement data at defined intervals. Data can be transmitted from individual measuring points, e.g., by WLAN, LoRaWan or LPWan to a central module (gateway) and further to a WebPortal, as shown in Figure 1. If the measurement data are stored on a WebPortal, they can be viewed in quasi real time, e.g., from the workplace, and are available worldwide. The server can evaluate the measurement data and trigger warnings or an alarm. Storage and evaluation of the measurement data can also take place directly on the gateway or other measurement/storage units and release warnings or alarms (e.g., via SMS). After commissioning, these systems operate autonomously.

The various components (measuring points, measuring device, gateway and user interface) form the monitoring system. Battery-powered systems can operate maintenance-free for up to several years, depending on the system and the number of measuring points.

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3 Measurement of wood moisture content

3.1 General to the measuring methods

For the measurement of wood moisture content, single point and laminar measuring systems can be used, see overview in Figure 2. For the monitoring of small critical areas, the resistance measuring method, the sorption isotherm method and the passive RFID tag method are available. The principal description of the measurement techniques for wood moisture content is given in the paper "Assessment of wood moisture and its effects", [10]. Specifics for monitoring purposes are added below.

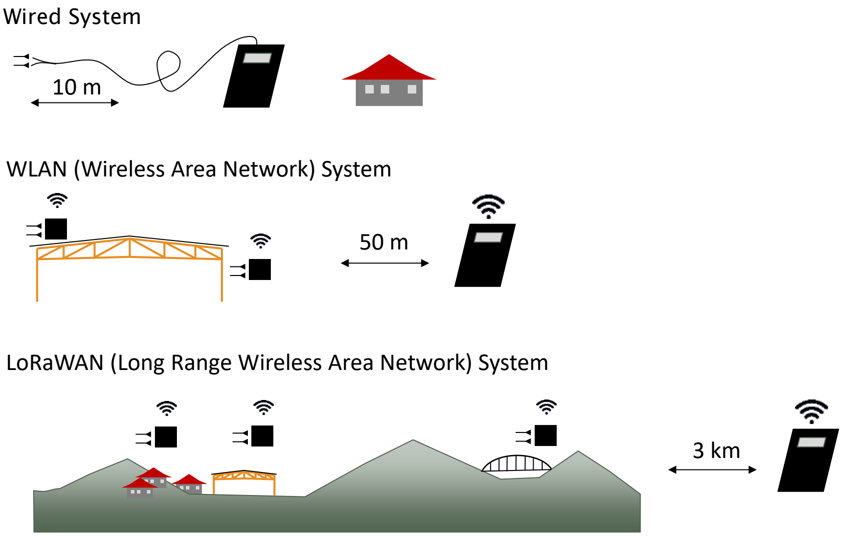

Figure 1: Overview of monitoring system's data management

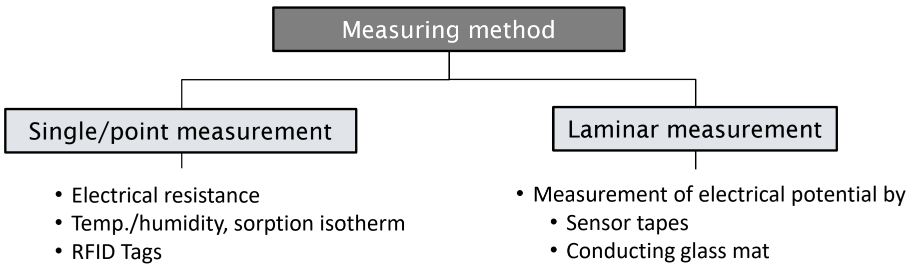

Figure 2: Overview of selected measurement methods for wood moisture content in the monitoring application

The electrical resistance measurement method is technically very simple to implement, easy to install and can be replaced from the outside. The sorption isotherm method provides high accuracy by measuring relative humidity and temperature in an insulated cavity, [9]. An RFID tag measures the humidity in the immediate vicinity of the tag averaged over a certain component depth using the principle of capacitive sensing. The use of RFID tags is inexpensive and wireless. Passive RFID tags do not require an external power supply or battery and can be used in many applications, [11].

Two-dimensional components can be reliably monitored with conductive glass fleece or with tape sensors. Both solutions rely on potential measurements and are mainly used in building construction for monitoring flat roofs, [12]. When the humidity changes or when water is present, the electrical potential of the conductive fabric changes and one can perform a real time moisture monitoring, [11].

In monitoring systems, a distinction is made between two main groups in the sensors, the active and passive sensors. This designation is used to distinguish whether the sensor requires electrical auxiliary power for the measurement or not. Active sensors require a supply voltage and then generate an output signal. This group includes, among others, the sorption isotherm and electrical resistance measurement methods as a point-by-point measurement of wood moisture. Passive sensors, on the other hand, operate without a supply voltage and use the energy in the environment, e.g., of the reader. Passive sensors include some radio frequency identification (RFID) tags.

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3.2 Single measurements

3.2.1 Electrical resistance measurement method

The electrical resistance method is the most common non-destructive method to monitor moisture content developments. The method allows measurement of moisture content in different depths from the surface and measured resistances can logged over extended periods of time. The accuracy of the method is about 1 M% [13]. Factors affecting the accuracy concern amongst others the grain orientation, type of electrodes, wood density, and temperature. Resistance between two electrodes roughly ranges between 100 kΩ to 100 GΩ from the fiber saturation point to about 5 M%, respectively. Once resistances are large, electrical currents are extremely small and electrical fields around the monitored structure are considered a possible source of error.

The choice and installation of electrodes should be done carefully, especially for objects subjected to outdoor climate, strong climatic variations, or direct weathering. Due to the shrinkage and swelling of the wood, normal wood screws or nails may have no or poor contact with the wood or the cable. Both lead to falsification of the resistance measurement and mostly indicate lower wood moisture contents than in reality. The use of hanger bolts and a protective box has proved to be successful, cf. Figure 3. The hanger bolts must be insulated with suitable material except for the tip. The cables are fixed directly to the hanger bolt with nut and locknut. The shrinkage and swelling of wood have almost no influence on the required good electrical contact between wood and electrode. All metallic parts of the electrodes should be made of stainless steel, if possible, [11].

Figure 3: Principle sketch and photos of the installation of the hanger bolt electrodes and protective box, [11]

3.2.2 Sorption isotherm method

The sorption isotherm method is most suitable in the presence of glue joints, the influence of salts, the use of protective and impregnating agents, or even in the presence of prolonged temperatures below 5 °C. All these factors do not influence the measurement by means of sorption isotherms. The application and implementation of the measuring probe requires a cavity size of 8 to 10 mm in diameter, whereby the depth of the measuring probe can be controlled as desired, see Figure 4.

The functioning and results of the sorption isotherm method over different component depths are shown as an example in Figure 5 for a solid wood wall. The diagram shows the measured wood moisture content and the calculated equilibrium moisture content (green line) from the room climate over a period of two years. It can be seen very clearly that the sensor near the surface in the wall at a depth of 5 - 10 mm (orange line) reacts very quickly to the room climate with a similar rate of change and amplitude as the calculated compensation moisture. Only in the summer months, when the indoor climate becomes more humid very quickly, there are differences between the orange and green lines. However, these differences quickly equalize. In this construction, for example, plasterboard and abrasion are very diffusion-open materials.

Furthermore, the diagram contains the measured wood moisture contents at depths of 20 - 30 mm, 70 - 80 mm and 95 - 105 mm. Already from a depth of 20 mm (purple line), a "damped" behavior of the wood moisture with respect to calculated equilibrium moisture can be observed. Here, the wood moisture values are lower in summer and higher in winter than the calculated equilibrium moisture. In this case, the sorption isotherm method allows very precise evaluations of the wood moisture content and the interaction between the room climate and the water content in the solid wood wall.

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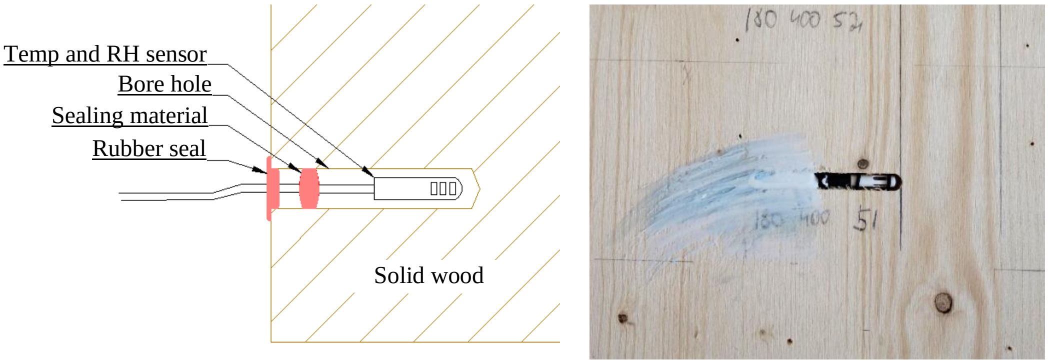

Figure 4: Installation of air temperature and relative humidity sensors in solid wood

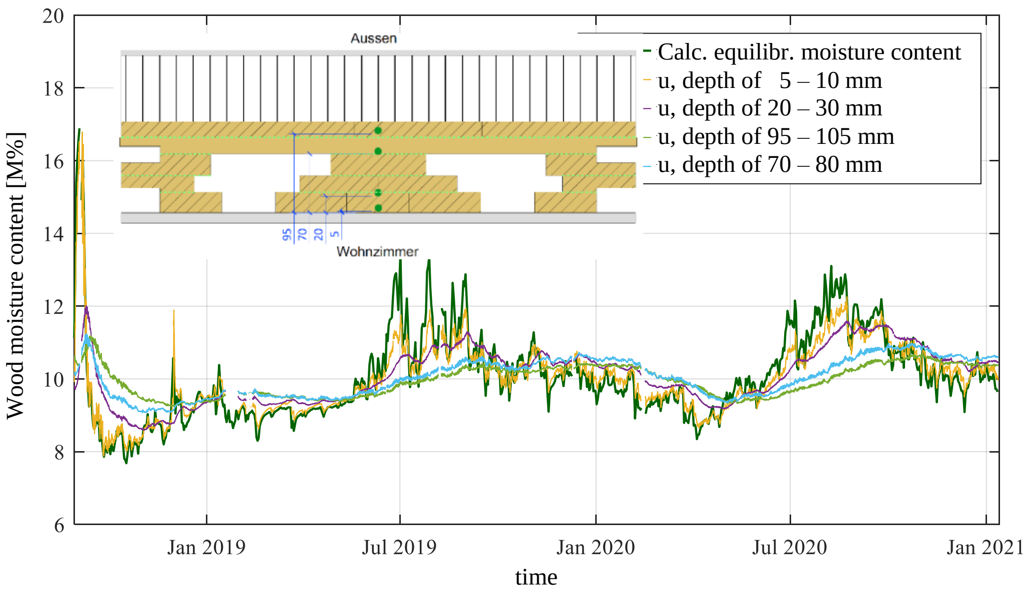

Figure 5: Evaluation of the wood moisture content measured with the sorption isotherm method at different depths in a solid wood wall

3.3 Moisture Sensor developed at BFH

An extra small battery-operated sensor for wood moisture measurement with radio data transmission was developed at the Bern University of Applied Sciences. It is inexpensive and easy to apply, see Figure 6. It measures, among others, the air humidity, and the temperature in a cavity in the material, and transmits it by radio (LoRa) directly to the cloud or to a gateway (Figure 7). The measurement results can then be processed and visualized. The sensor is located at the tip of the pin shaped extension below the electronic facing outwards. The extension which will be screwed into a drill hole. Different extension lengths could be realized to measure in different depths. Measurements up to two years can be made with one battery.

While every node could work and transmit its data individually, the results of several nodes can be synchronized and collected by using a Gateway. It receives the data by LoRaWAN, saves it and transmits them at once via 4G data net. The gateway also provides a remote access for checking the system conditions.

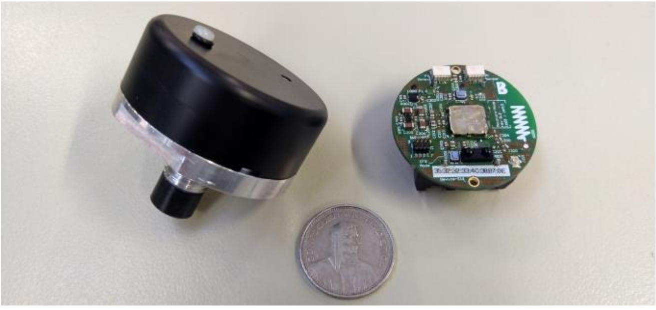

Figure 6: Moisture-Sensor, system with waterproof housing (left), electronic (right).

Figure 7: Gateway to use and control several sensor nodes

3.4 RFID tags for local leakage detection

Radio Frequency Identification (RFID) tags are small devices that use low-power radio waves to receive, store, and transmit data to nearby readers (Figure 9). The basic types of RFID tags are passive, active, and semi-passive or battery-assisted passive (BAP), [14].

- Passive RFID tags do not have an internal power source but are powered by electromagnetic energy transmitted from an RFID reader.
- Active RFID tags have their own transmitter and power source on board the tag.
- Semi-passive or battery-assisted passive (BAP) tags consist of a power source integrated into a passive tag configuration.

In addition, RFID tags operate in three frequency ranges:

- Ultra-High Frequency (UHF),
- High Frequency (HF) and
- Low Frequency (LF).

RFID tags can be attached to a variety of surfaces and are available in different sizes and designs. Dimensions vary from a few millimeters to several centimeters. RFID tags are also available in a variety of shapes (dogbone or patch, Figure 8). The Smartrac company or RFMicron are already using passive RFID tags for capacitive measurement of moisture or humidity. These tags have been successfully applied in the fields of construction, energy, but also healthcare.

First applications with RFID tags have also been carried out (Figure 9). The tests have shown that the installation of these RFID tags in the wood allows a punctual measurement of the wood moisture, but with a greater measurement uncertainty than the electrical resistance or sorption isotherm method, which can be seen at the wide band of results in Figure 10 . The RFID tags should be located inside the component and are readable until the overlying material layers do not shield the signal. A comparison of the placement the

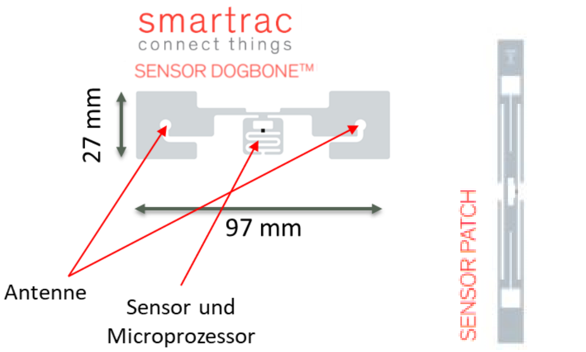

Figure 8: Components of a passive RFID tag from Smartrac without supply voltage

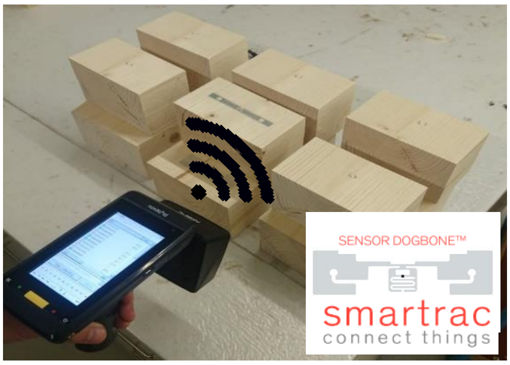

Figure 9: Simultaneous measurement of several RFID tags installed in the wood specimen

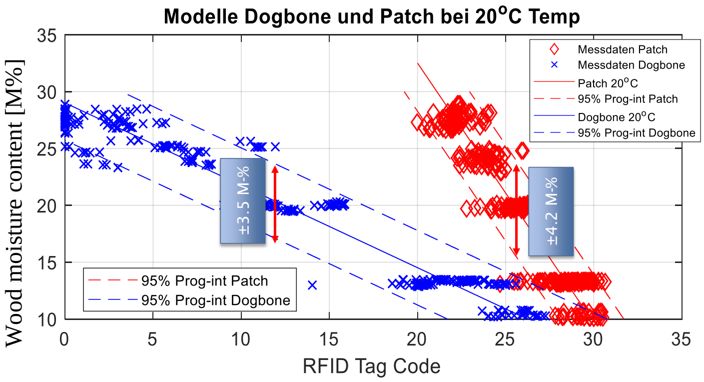

Figure 10: Correlation between RFID tag code vs. wood moisture at 20 °C for the dogbone and patch tag

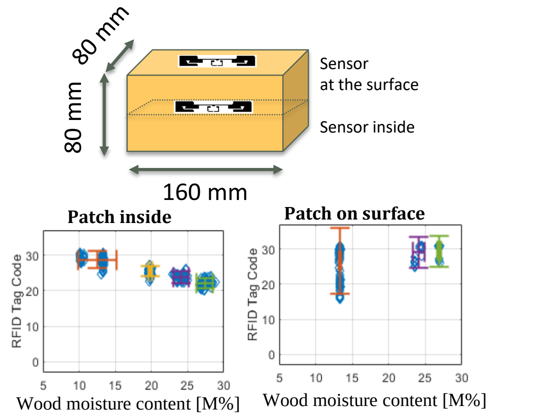

Figure 11: RFID sensor tests at surface and inside, setup (top), correlations (bottom)

RFID tag at the surface or inside was carried out, which showed greater variations of the results for the surface use, cp. Figure 11. This makes it possible to monitor hard-to-reach and invisible components even without a power supply. The RFID sensors are said to have a service life of 50 years.

The correlation between the read-out sensor code and the wood moisture must currently still be determined on the basis of reference checks and is RFID tag-specific. Figure 10 shows an example correlation between sensor code and wood moisture together with the prediction interval. The width of the prediction interval results from the scatter of the measurement data used to derive the correlation. Depending on the application, temperature compensation of the measurement must also be considered. The application range of the model is between 10 M-% and 28 M-% for the wood moisture. The measurement error of the dogbone and patch tag is ± 3.5 M% and ± 4.2 M% respectively, derived from the width of the prediction interval.

Due to the very low price of RFID tags and their small size, several sensors can be installed at each measuring point and an average of the sensor codes can then be calculated. In this way, a higher measurement accuracy can be achieved, and the system is less susceptible to the failure of individual RFID sensors.

3.5 Areal measuring methods

3.5.1 Area leakage detection with sensor tapes

With sensor tapes, it is possible to detect high moisture or wetness in a linear manner, e.g., under a waterproofing layer of flat roofs or road pavements. Band sensors consist of a plastic fabric and stainless-steel wires, see e.g., Figure 12. During monitoring, a potential measurement is made between two wires in the sensor band. The presence of water causes the electrical resistance to drop and can be detected.

This measuring method is mainly used in places where water or moisture can spread under the waterproofing. Depending on the spacing and arrangement of the individual tapes, quasi-area monitoring can be achieved with the sensor tapes. For the application in bridge structures, it must be ensured that for a two-dimensional leakage detection with linear sensor tapes, a roadway structure with a waterproofing without bond is used. This is because, depending on the planned transverse and longitudinal slope of the bridge, any water that has penetrated the separating layer between the waterproofing and the deck slab would flow

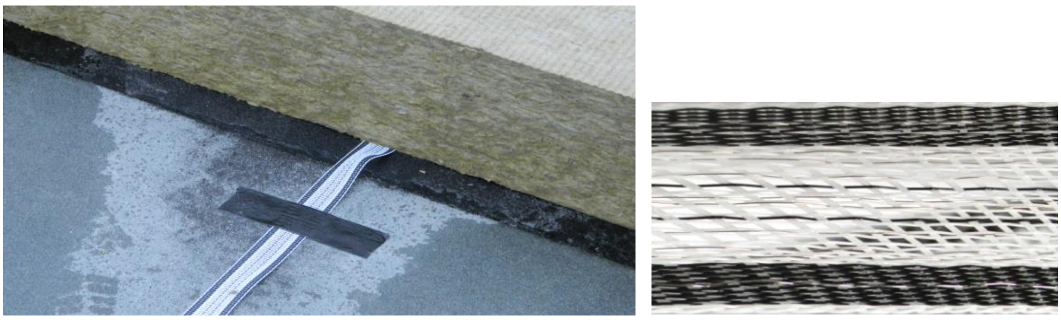

Figure 12: Tape sensor "dm" from ProGeo in a warm roof structure (left) and detail of the tape (right)

in the direction of the slope and could be detected here, e.g., at a bridge edge or deck transition. Point or linear sensors can be used at the slope edges.

The foot and cycle path bridge between Rupperswil and Auenstein was equipped with sensor tapes cf. Figure 13 and Figure 14. The monitoring system monitors the possible leakage of the waterproofing and additionally records climate data, material temperature and wood moisture, Figure 13. The on-site measuring unit evaluates the measurement data and sends it to a cloud so that it can be retrieved worldwide at any time using a browser. Warnings and alarms are triggered when critical values are reached.

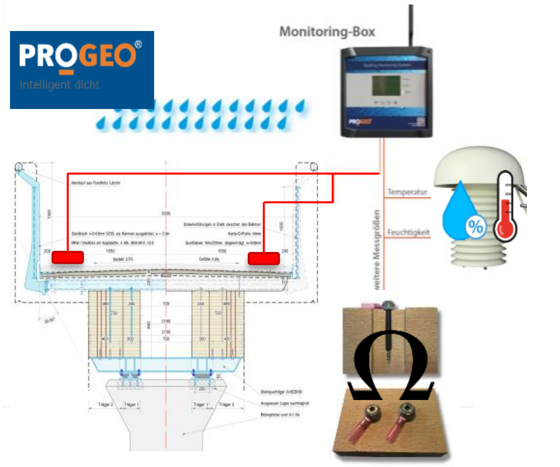

Figure 13: Monitoring system for the foot and cycle path bridge between Rupperswil and Auenstein

Figure 14: Sensors on the wooden panel and laying of the glass fleece and PBD seal

3.5.2 Area leakage detection with conductive fleece

In an intact waterproofing, there is no water flow and therefore no electrical current flow. In case of a leakage in the waterproofing, water penetrates the waterproofing and allows the conduction of electric current in the conductive fleece underneath the waterproofing. Based on this physical principle, areal monitoring of flat roofs or landfills is possible nowadays, [12]. The presence of water in the case of a leakage changes the electrical properties, respectively the measured value, thus leakages can be detected. After drying out, the original values are restored.

Early detection and the detection of hidden water damage are possible. The same functional principle can be used to detect the presence of water in the area of riser zones, installation spaces or interstitial spaces. Various monitoring systems for flat roofs are currently available on the market, e.g., smartex mx from ProGeo (D), Optidry from Ortungstechnik Nachbaur GmbH (A) or RoofProtector from RPM Gebäudemonitoring GmbH (A). These systems measure electrical parameters via conductive mats (laminar) or tapes (linear).

For leakage detection in flat roofs, for example, a conductive glass fleece is installed under the waterproofing and above the insulation. In addition, a grid of flat cables is installed. These form the inner pole of the measuring system. Above the waterproofing, a contact plate is used to set the second pole (Figure 15). During a rain event, the current is conducted from the contact plate over the entire wet surface to the waterproofing. The measuring unit performs a potential measurement between the two points. Using the cable grid, it is possible to display the potential curve in the surface and to determine the position of the leaks.

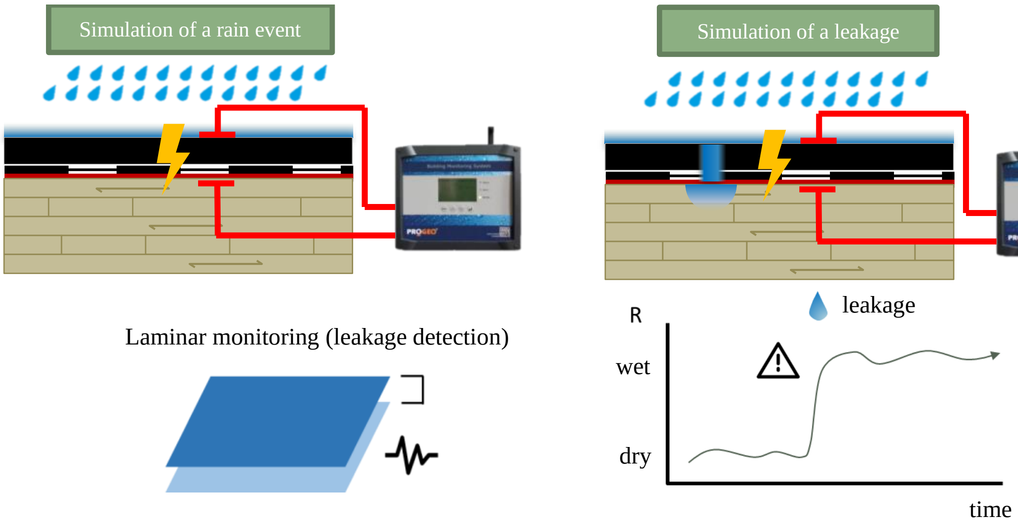

Figure 15: Schematic representation of the measurements on wood panels with conductive glass fleece, PBD waterproofing and mastic asphalt for a full composite structure

4 Measurement of eigenfrequencies for damage detection

Every structure vibrates due to natural excitation or use in its natural frequency, which depends on the mass and stiffness. If damage occurs, the stiffness may change and so does the natural frequency. The constant recording can be used for a systematic gain of knowledge. The constantly occurring measurement data (accelerations, vibrations) must be digitally recorded, filtered, and analysed so that differences in the vibration behaviour, in the natural frequency, can be recognised. In this way, e.g., as a traffic lights principle, authorities can obtain results about the condition and at the same time engineers or researchers can obtain general data sets to improve vibration measurement or design. In timber construction, knowledge is available for the pure vibration assessment of timber ceilings. The application to timber bridge structures for condition assessment is not yet known.

The departments AHB and TI jointly developed a stand-alone vibration measurement system consists of several sensor nodes and a powered HUB, Figure 16. Each sensor node includes the 3-axial acquisition of the accelerations and the wireless data transmission (via BLE - Bluetooth Low Energy - up to 100 m) of the measurands directly to a PC or the HUB. They are battery-operated (runtime 0.5 year) and easy to install and handle. Several nodes can be integrated into one measuring system by the HUB at the same time. The raw data is stored locally and sent to a time series database. The hub controls and monitors the sensor nodes. Problems such as short interruptions in the connection to the sensors are handled correctly, so that long-term use is ensured. A specially developed software is used to control the sensor nodes and visualize the acceleration data. The sensor data can be displayed in the time domain as well as in the frequency domain, Figure 16 right. This makes it possible to determine the natural frequencies.

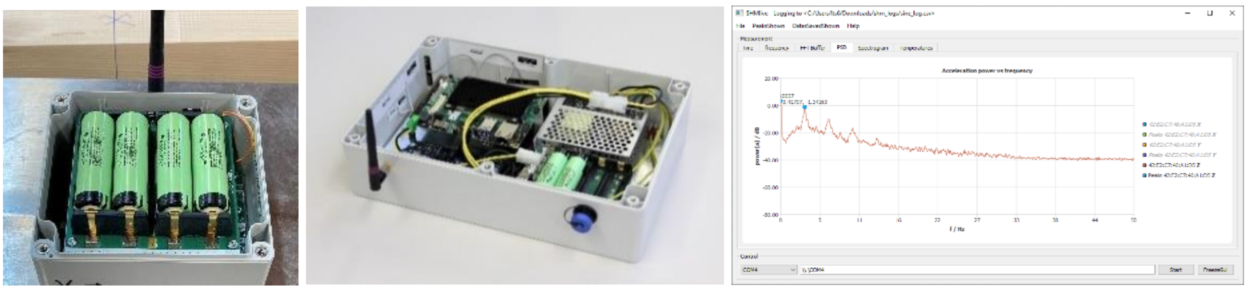

Figure 16: Sensor node with 3-axis acceleration sensor below the battery pack (left), HUB (center) and FFT analyses of the frequencies (right)

5 Case study – Monitoring of a timber bridge

Within the framework of research projects, various road bridges in wood within Switzerland have already been monitored by the Institute for Timber Construction, Structures and Architecture at the Bern University of Applied Sciences. The structures range from beams, arches, trough bridges to log bridges and timber-concrete composite bridges. The locations vary regionally as do the bridge crossings over rivers, valleys or roads. Spans range from 13 to 50 m. More detailed information is summarized in [6] and [15].

Figure 17 shows the course of the air temperatures and relative humidity measured on site together with the calculated equilibrium moisture content on the surface of the wood for the Obermatt bridge in the Emmental valley as an example. Figure 17 contains the measurement locations shown on the bridge cross-section. The other diagrams in Figure 18 show the wood moisture content measured in the supporting cross-section. The wood moisture content was measured near the surface, approx. 20 mm deep, and in the cross-section with a depth of 200 mm. In addition, the calculated equilibrium moisture content was determined for each measuring point; a time delay due to the moisture transport in the wood and the duration of exposure to the climate was not considered. The course of the measured wood moisture content shows a delayed and damped course compared to the calculated compensation moisture content.

On the south side, an increase in wood moisture content for one measurement sensor can be observed from August 2013. This is associated with partial structural leakage, which has since been corrected and the wood is allowed to dry out again. In this case, the installed monitoring system has acted as an early warning system and later serious structural damage could be avoided at an early stage.

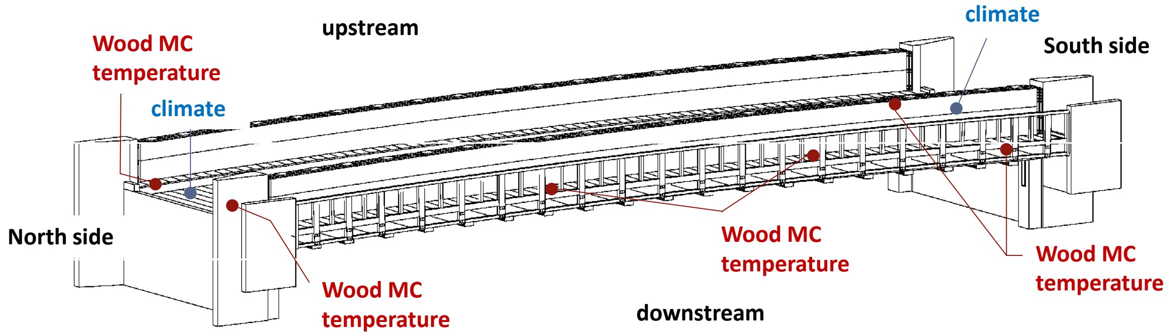

Figure 17: Positioning of the measuring sensors at the Obermatt bridge

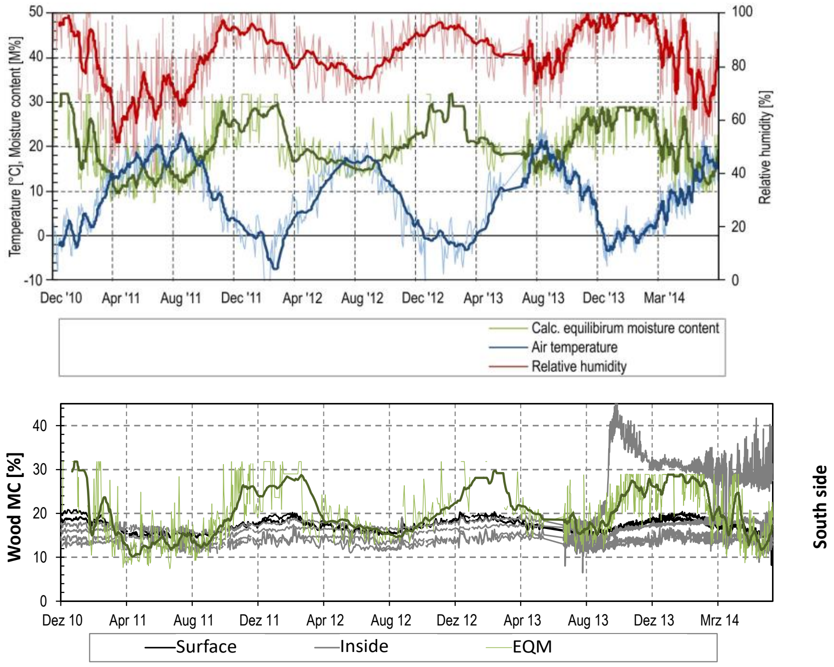

Figure 18: Climate, wood moisture content and calculated equilibrium moisture content for the Obermatt Bridge, after August 2013 Leakage visible in cross-section.

6 SUMMARY

Wood is a living and recognized construction material for the realization of diverse load-bearing structures such as houses, ice, riding and sports halls as well as swimming pools, warehouses, production buildings and bridges. However, wood is also a hygroscopic material and can absorb or release moisture from the surrounding climate. The so-called wood moisture content (MC) influences the material strengths and stiffnesses as well as the long-term load-bearing behavior. As the studies of [1] and 10 show, half of the cause of damage to wood structures is due to a change in wood moisture content or seasonal and climate-related changes in wood moisture content. For this reason, continuous monitoring of wood moisture content is a suitable early warning system to increase the quality of wood structures in the future in a pioneering way and to detect changes in time. The control points in the monitoring should be placed in possible danger zones/hot spots. These can include roadway crossings, support areas, transition areas and penetrations. The various point and area methods presented are suitable for measuring wood moisture content. For the planning, implementation and evaluation of a monitoring system, the number of measuring points, the accuracy and the data storage/transmission should always be defined with a view to the objective. At this stage, an exchange with appropriate subject matter experts can provide positive support.

ACKNOWLEDGMENT

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