Conference Proceedings 4th ICTB (2022)
https://doi.org/10.24451/3jpy-3q31

ICTB 2021 PLUS
4th International Conference on Timber Bridges
Biel/Bienne, Switzerland, 9 -12 May 2022

Advanced data logging system for moisture monitoring of timber bridges – background and large-scale application

Kai Simon[1], Jürgen Hezel, Simon Aicher

1 Introduction

Wooden bridges are amongst the oldest structures of man-made infrastructure. While strength and stiffness, processing properties and sizes are assets of wooden members for bridge constructions, the limited natural durability of wood, unless considered adequately, is detrimental. Unfortunately, in the past many wooden bridges were designed without considering the rules for structural wood protection properly [1]. Therefore, the Stuttgart Timber Model Bridge (STMB) incorporating an integral timber-concrete abutment connection was developed on the basis of a wide database of bridge damages. Here, a seamless construction method with a completely gapless waterproofing layer is used. In the course of the construction of the model bridge on the campus of the University of Stuttgart, a system for the long-term monitoring of climate data, wood moisture content, stresses in connection parts and leakage detection was configurated and field-tested. Especially the system for the detection of punctual wood moisture is of high interest in areas of abutments, connections and fasteners to detect and prevent a possible damage development at an early stage.

Although the monitoring system used at the Stuttgart Timber Model Bridge provides very good measurement results there are some drawbacks. To overcome these disadvantages, an optimized system for recording the wood moisture content and climate, among other data, was developed in the context of orders to MPA University of Stuttgart from building owners and engineers for recently built and new timber bridges. Especially for large structures with several supporting areas and an increased number of potential measurement areas, the newly developed data recording system is advantageous.

2 Stuttgart Timber Model Bridge

2.1 Monitoring systems

The detailing of the Stuttgart Timber Model Bridge (STMB) results from an existing research project [1] on damages and related preceding mistakes in the construction of existing timber bridges. The STMB was built in the year 2016 at the Campus of the University of Stuttgart. To ensure and prove the function of the realized construction preservation measures, basically given in EN 1995-2 [5], a monitoring concept with the following components was installed:

- 16 sensors for the punctual moisture content in different depths (electrical resistance method)
- 3 sensors for the climate beside and under the GLT superstructure beam and between the GLT structure and the sealing layer
- 3 sensors for the temperature of the wood
- 11 sensors for a leakage detection at the second sealing layer
- 1 displacement transducer for the temperature and moisture dependent length variation of the GLT
- 5 displacement transducers for the relative displacements at the integral GLT-concrete abutment connection
- 8 strain gauges on the surface of the GLT beam to obtain the stresses at the integral support
- strain gauges on 8 of the glued-in rods at the integral GLT-concrete connection

After six years of monitoring there exists a valuable database which enables to adapt some of the systems for other constructions and buildings. All systems are working and are sending their data in a regular interval wireless to a server. A big challenge of the combination of five different data logging systems is the consolidation and evaluation of the data. For the installed sensors over all five data loggers of different manufacturers are necessary. Every system has its own method to record, transcript and send the data to the web. Some are sending the files via email protocol, others are using the File Transfer Protocol (FTP) to a server hosted by the customer and the last ones are sending the data via FTP to a server of the manufacturer where the customer gets access to read the data. To create a continuously updated health status of the bridge

[1] Kai Simon, Materials Testing Institute, University of Stuttgart, Germany, kai.simon@mpa.uni-stuttgart.de

it represents an enormous effort to gather and host all these different files, formats and accessibilities of data. Due to space limitations of the paper a special attention is given here to the moisture monitoring system only, what is explained below.

2.2 Advantages and Disadvantages of the moisture monitoring system used at STMB

The system used for the moisture content reading of representative points in the GLT beam structure of the STMB is a commercial system for every kind of consumer (Scanntronik Mugrauer GmbH, Germany). The system is well proven at small to medium sized timber bridges and other constructions; valuable results are presented in several publications, e.g. by Dietsch et al. [4], Müller and Franke [9] or Koch et al. [8]. It is possible to install and use the system with almost no knowledge of data processing which makes it appealing to a wide spectrum of users. Most components are just installed by plug and play. The system comes with a more or less intuitive software to ensure data reading and evaluation of smaller monitoring projects. The manufacturer provides a wide range of sensors for e.g. climate, material moisture content or displacements.

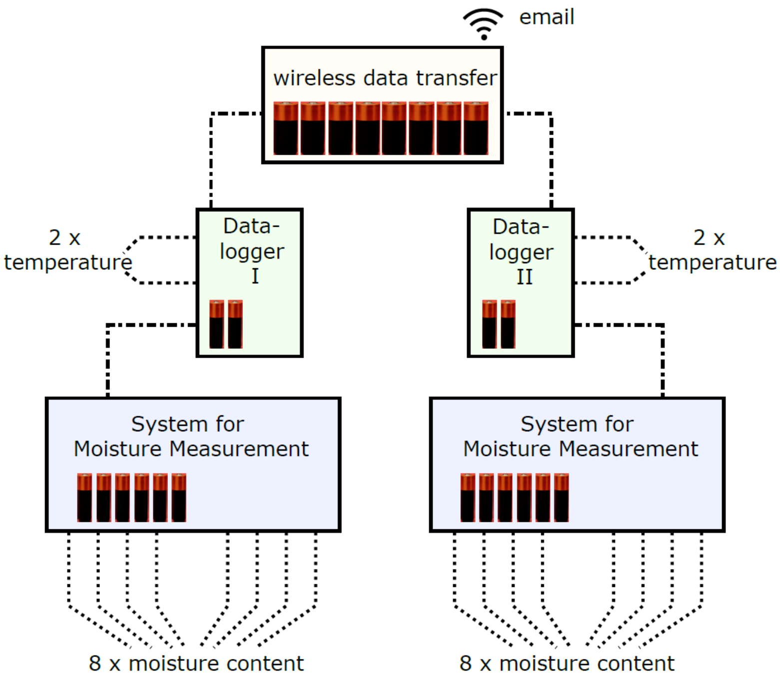

Figure 1: components and battery requirements of the monitoring system at the STMB

The setup principle consists of a modular way. The sensors are connected to each specific measurement unit, which is connected to a data logger. The data logger (optionally) is connected to a wireless data transfer system which can send the measured data via email to the user. The system always sends the complete data set what affords much energy and data traffic. Without this remote system the user is induced to get the data manually with a notebook from the data loggers. For big monitoring systems with a high number of sensors and a small interval of measuring, the data storage reaches the limit after less than one year. An example for a possible setting of then described moisture content reading system is shown in Fig. 1. It is important to mention that this is the maximum number of sensors which can be used with one remote system. In case of a requirement of the double number of sensors, all components of the shown system are needed twice.

A profound disadvantage consists in the limitation of connectable sensors to the different measuring units or data loggers. For any sensor type a separate measurement unit is required. So, for example it is not possible to replace one of the eight moisture content sensors in the configuration shown in Fig. 1 by one displacement sensor. Therefore, a separate data logger together with a displacement measuring unit would be needed. The number of connectable data loggers to one remote system is also limited to two. The greatest handicap noted while using the system was the very large amount of batteries required for the system to run. Every component of the system needs its own quantity of batteries. In the given example configuration 24 batteries are required to supply the monitoring of 16 punctual moisture content sensors. The maximum interval for changing the batteries is about one year. Also, the cable distance between the moisture measuring unit and the sensor, consisting of two electrodes, is limited. In case of long cable distances between the measuring unit and the pair of electrodes this makes the system vulnerable for external radio or electricity signals.

3 Development of a new Moisture Monitoring system

3.1 Setup and functionality

Because of the limitation of the number of sensors, the great energy demand and some other disadvantages some research work was undertaken at MPA University of Stuttgart, Dept. of Timber Constructions, to develop an improved system especially for large timber bridges / buildings. Together with a manufacturer for measurement and sensor technologies a new system for the measurement of the moisture content of timber with the method of the electrical resistance [1] was built up.

The system consists of one central processing and data logging unit, which (optionally) sends the data via FTP to a server of the customer. Sensors are connected to Hubs each gathering up to 11 inputs. From each Hub one data cable connects to the logging unit. The sensors are addressed by a BUS-system (RS-485) which allows to have long cable distances between the logging unit and the HUBs as well as between the HUBs and each sensor. In case of measuring the moisture content or the electrical resistance a small interface near the sensor (2 electrodes) is required to convert the BUS-signal to an electrical measurement signal. From one interface two pairs of electrodes (2 sensors) can be fed.

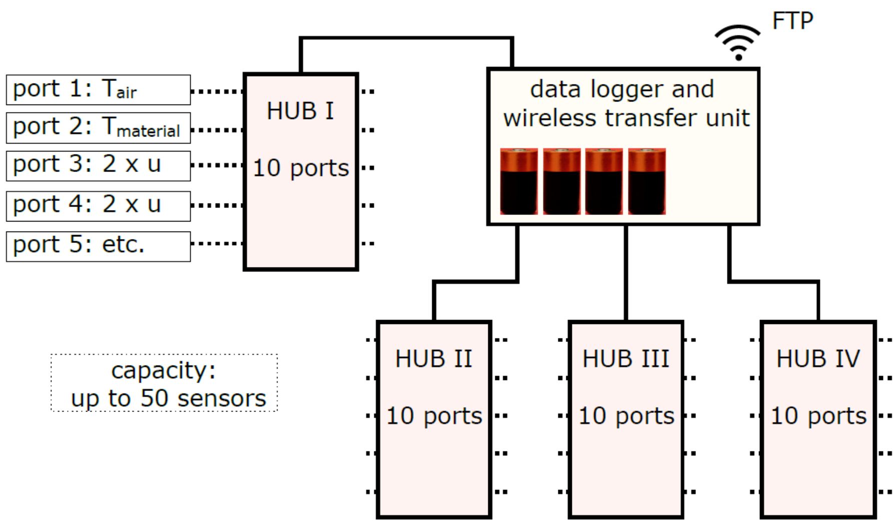

Figure 2: components and battery requirements of the developed monitoring system

Because the data logging system uses an universal BUS-system to address sensor interfaces, it is possible to connect any further sensor types, such as sensors for temperature, relative humidity, leakage/free water detecting, strain gauges, etc.

A schematic system configuration of the system is shown in Fig. 2. The logging unit is able to manage up to 50 sensors or 100 in case of moisture content sensors. Despite the large number of ports, the system gets by with only four mono-type batteries.

3.2 Data processing

The implementation of the data evaluation software was made by MPA University of Stuttgart. The system delivers values for the temperature and the relative humidity in °C and %, respectively, so they can be used as they are. The values from the moisture content sensors are delivered as raw data resistance in MOhm and have to be converted into a moisture content value in %. Several tests in the laboratory with electrodes from stainless steel and timber parts, which were oven dried after the tests to get the moisture content, together with the calculation model from Samuelsson [10] and Forsén and Tarvainen [7] served as a basis for the calibration of the sensor interfaces for spruce. The compilation and verification of different calculation models by Forsén and Tarvainen [7] also deliver a calculation model for the influence of the wood temperature on the electrical resistance which is implemented in the data evaluation.

The script written with the programming language Python© can automatically retrieve the data from the FTP server and save them in a local database. This addresses all further calculations like converting electrical resistance into timber moisture content, summarizing of data sets, exclusion of error measurements from the evaluation or determination of the equilibrium moisture content of the wood surface induced by the surrounding climate according to Avramidis [3]. From the calculated data several diagrams of the monitoring results can be plotted directly, as shown in Fig. 7, or optionally can be embedded on a website. The data form the logging unit is uploaded once a day so then the evaluation software runs once a day and updates the database automatically.

Form every data upload by the data logger the protocol gives the health status of the system. With the script the battery voltage or the signal quality of the remote unit can be read out and documented in form of a health report or an error message to a mail account or a smartphone if for example the battery voltage falls below a critical value.

3.3 Advantages of the system

Although the system still needs to be improved and has some susceptibilities, such like error measurements while there are other electrical signals around or sending problems induced by low GSM quality, there are some advantages compared to the system used at the STMB. First of all, it would be possible to process almost all sensors installed at the STMB by a simple logging unit of the new system. This becomes evident in Table 1, showing a comparison of the two bridges monitored by the established and new systems.

One of the most important advantages consists in the fact that only four batteries are required for the central processing unit. Also, the option to connect several different sensors via the BUS-system to that one unit gives a clear arrangement and a low space requirement.

The logging unit is sending only the new data gathered since the last sending protocol to the FTP-server hereby saving a great amount of data and energy usage. The data is also copied to the local storage which provides 32 Megabytes. The intervals for measurements and data uploading can be chosen separately by the user. The providing of the battery voltage and the sending signal quality at each protocol makes it easy to prevent a data loss or a breakdown of a system. The possibility to connect up to 50 sensors to one unit and to upscale the system as well as the wide range of applicable sensors makes the system attractive for more than just a moisture content monitoring at timber constructions.

4 Large-scale application Bad-Mergentheim

The pedestrian bridge in the spa park in Bad Mergentheim, built in 2020, connects the spa park area with the city over the river Tauber, see also Fig 3. The load-bearing structure of the bridge consists of two parallel block-glued glulam (GLT) superstructure beams with variable height. The bridge girders are supported on a total of 8 RC-abutments; the total length of the bridge is around 90 metres. The largest partial span then crossing the river is 30 m. The deck of the bridge is made of pre-cast concrete slabs resting on cross girders. Fig. 3 shows a view of the bridge structure. Figures 4 and 5 show a side view and the cross-section build-up, respectively, of the GLT superstructure.

A total of 52 pairs of electrodes are installed as sensors for moisture content monitoring. The measuring locations are arranged i) at the end grain faces of the GLT beams at both end abutments (A and B) and ii) at inner supporting pile locations C, D and at the mid-river apex point (C&D). The measuring electrodes at locations C,D and C&D are arranged laterally on the girders to capture the moisture influence area of the river as shown schematically in Fig. 4.

Figure 3: View of the Kurpark Bridge in Bad Mergentheim

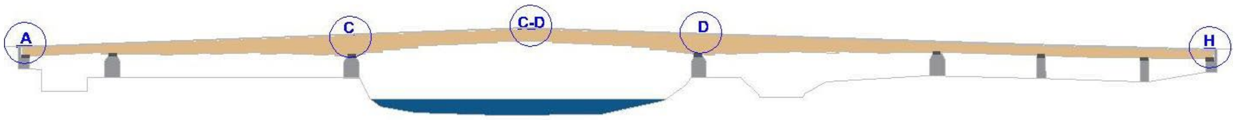

Figure 4: Arrangement of measuring points at the locations A-H

At the two end abutments (locations A and H), each of the superstructure GLT beams has 4 measuring points installed at the end grain face whereby each point includes 2 moisture content sensors measuring at depths of 40 mm and 65 mm. At the abutments on both sides of the river (locations C and D), three measuring points exist, two on the side surfaces of the glulam beams and one on the upper side of the beams, directly below the sealing coat. At the apex of the bridge (area C&D), a further 4 measuring points are placed laterally on the glulam beams on the north side of the structure which is excepted to be the area with the highest moisture input.

Details of the arrangement of the sensors at the cross-sectional end grain face of the beams are shown in Figures 5 and 6. The installation of the sensors was carried out during the production of the bridge elements in the manufacturing plant. This had the advantage that the measuring points could be arranged over the entire width of the cross-section. In the case of subsequent installation of monitoring systems on existing structures, access to the neuralgic component cross-sections is usually no longer possible.

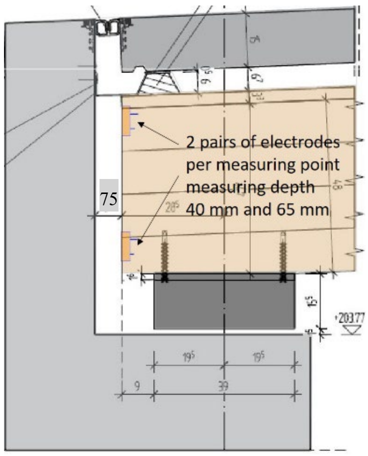

Figure 5: Side view of end abutment (A, H) construction detail, with position of moisture sensors (see Fig 6 also)

A total of 52 electrode pairs for wood moisture measurement, 4 temperature sensors (wood temperature) and one climate sensor are installed. The sensors of each measuring locations A - H are connected to four HUBs. A data cable runs from each HUB to the processing unit, which is installed above the abutment D. The lengths of the 4-wired data cables from the HUBs to the referenced sensors and from the four HUBs to the processing unit add up to a total cable length of 224 m.

Figure 6: Cross-sectional end grain face view of the superstructure GLT block girders with 2x4 measuring points, each with 2 pairs of electrodes for moisture measurement

https://doi.org/10.24451/3jpy-3q31

4.1 Results after two years of logging

The graph in Fig. 7a shows the time dependent evolution of the wood moisture profiles at the end grain face at different cross-sectional depths of 40 and 65 mm in the glulam beams for the measurement period from April 2020 to May 2022. The wood temperature curve is given, too. Fig. 7b reveals the recorded climate data (rel. humidity and air temperature) and the hereon calculated equilibrium moisture content of the wood acc. to [10]. The sensor for the climate monitoring is located in the area next to abutment D at the bottom side of the superstructure GLT beams.

As anticipated for timber structures exposed to service class 2 condition the moisture curves show a seasonal variation of the moisture content. The differences of the moisture measurement at 40 and 65 mm are rather small (about to 1%). A difference between these two sensors would indeed indicate a possible moisture input.

The measurement curves available up to now, show material moisture levels of around 12 - 13 % in the summer months, rising to around 15 % in winter.

In no case a sudden increase of humidity at one measuring point, which would indicate local water penetration into the construction, has been encountered since implementing the monitoring system.

In addition to the continuously evaluated measurement results, which only monitor selected local areas of the structure, an extensive visual inspection of the timber components is carried out once a year as part of the maintenance of the monitoring system.

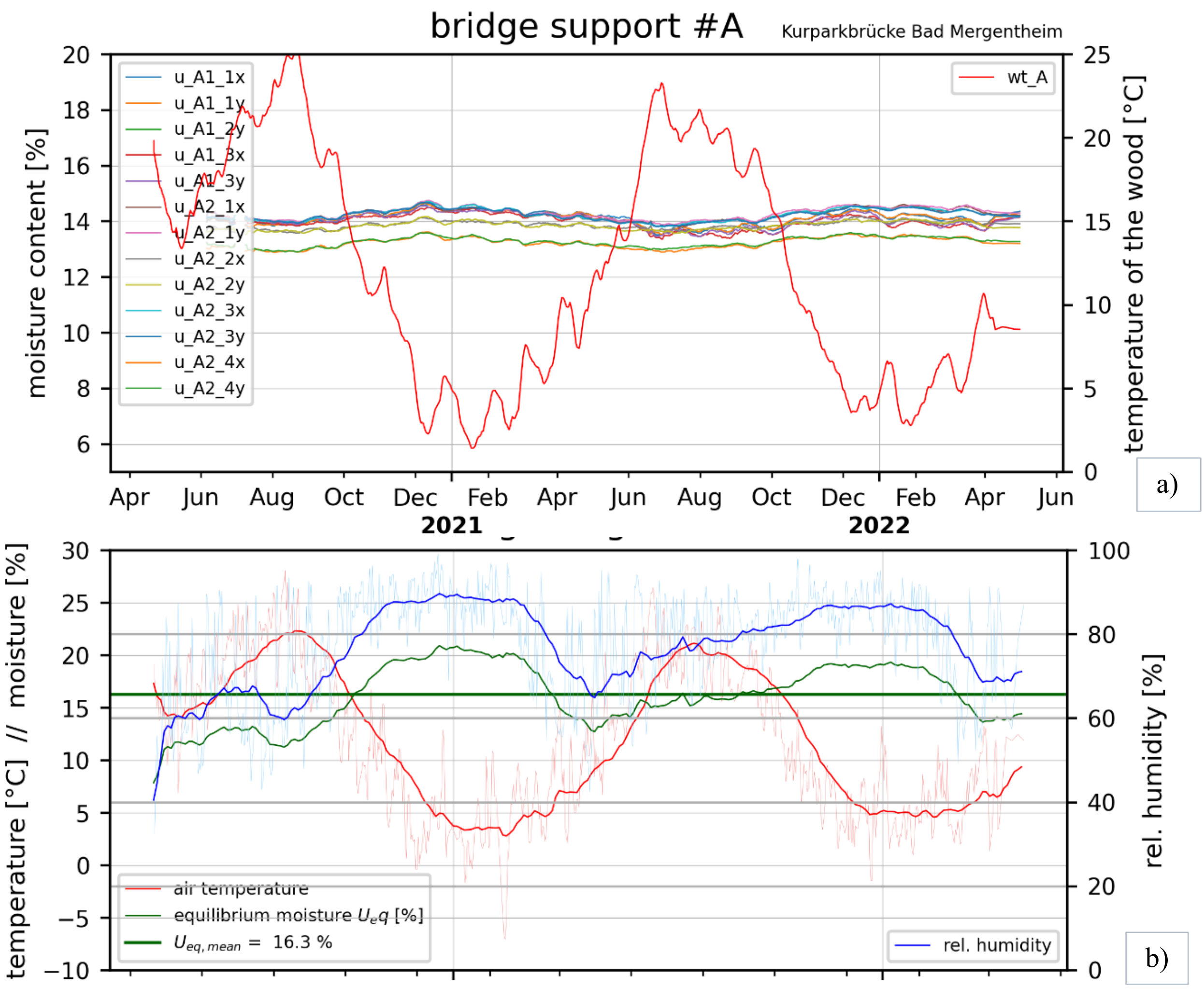

Figure 7: Results of the wood moisture content and climate monitoring over two years measurement time
a) wood moisture content at 2x8 sensors in 45 mm and 60 mm distance to the end grain face at location A
b) climate recording and calculated equilibrium wood moisture content near location D

Table 1: Comparison of the capacity and energy consumption of the established and the new developed system

monitored dimension	**systems at STMB**	**“new” system at Kurpark-bridge**
data logging and communication	4 GSM units 7 data loggers 4 SIM cards required	1 processing unit (1 logger and 1 GSM unit integrated) 1 SIM card required
energy requirements	20 AA-type batteries 16 C-type batteries 2 Lithium battery packs	4 D-type batteries
moisture content and climate	16 pairs of electrodes 2 climate sensors 2 wood-temperature sensors	52 pairs of electrodes 1 climate sensor 4 wood-temperature sensors
mechanical (strain gauges / LVDTs)	16 strain gauges 6 LVDTs	possible to connect with no more energy or logger requirements (no long-term experience yet)
leakage detection	11 stripe sensors	

5 Conclusions

The new developed monitoring system incorporates an enhanced capability to evolve smart buildings and check their health status in different dimensions. The system is installed and tested at four timber bridges and could easily be used for other buildings. With the possibility to connect up to 50 different sensors to one processing unit it is possible to install a very flexible system with hardly any limitations. Even for large structures with long distances between observation points the system is able to handle this by distributions of the sensors via HUBs. After gaining some experience it can be summarized that the logging functions as well as the data uploading operates well. Together with a Python written script the data handling and warning systems can transfer results very fast and automatically. The energy usage at the bridge outlined in chapter 4 gets along with 4 D-type batteries for one year while measuring five times a day and uploading the data once a day. Table 1 gives a comparison of the monitoring used at the Stuttgart Timber Model Bridge and the new developed system installed at Kurpark-bridge, where the possibilities and advantages become visible. In summary it can be stated that the developed and field-tested advanced health monitoring system is very well apt, especially for timber buildings in service class 2. The system can be easily combined with other measurement devices (e.g. strain gauges) to monitor interesting mechanical variables, e.g. strains, to assess the long-term mechanical response and the utilization of the structure.

References

[1] Aicher, S. (2016): Dauerhaft Holzbrücken – Schäden, Lösungsansätze, integrale Bauweisen (in German), 4. Internationale Holzbrückentage IHB 2016, Stuttgart, Germany.

[2] Aicher, S; Leitschuh, N (2015): Geh- und Radwegbrücken aus Holz - Ergebnisse und Konsequenzen aus 100 Brückenbegutachtungen (in German), Tagungsband 3. Stuttgarter Holzbausymposium, Stuttgart, Germany.

[3] Avramidis, S. (1989): Evaluation of "three-variable" models for the prediction of equilibrium moisture content in wood, in Wood Science and Technology 23, pp. 251-258, Vancouver, Canada

[4] Dietsch, P., Gamper, A., Merk, M., Winter, S. (2015): Monitoring building climate and timber moisture gradient in large-span timber structures. J Civil Struct Health Monit 5, pp. 153–165, https://doi.org/10.1007/s13349-014-0083-6

[5] EN 1995-2 (2004): Eurocode 5: Design of timber structures - Part 2: Bridges, European Committee for Standardization (CEN), Brussels, Belgium.

[6] EN 13183-2 (2002): Moisture content of a piece of sawn wood – Part 2: Estimation by electrical resistance method. European Committee for Standardization (CEN), Brussels, Belgium.

[7] Forsén, H. and Tarvainen, V. (2000) Accuracy and Functionality of Hand Held Wood Moisture Content Meters. Technical Research Centre of Finland.

[8] Koch, J., Arndt, R., Simon, A., Jahreis, M. (2018): ProTimB - Monitoring von konstruktiv geschützten Holzbrücken (in German), Fachtagung Bauwerksdiagnis 2018, Berlin, Germany

[9] Müller, A. and Franke, B. (2016): Langzeit-Monitoring von Holzbrücken – Erkenntnisse zum Feuchteverhalten im Tragquerschnitt (in German); 4. Internationale Holzbrückentage IHB 2016, Stuttgart, Germany

[10] Samuelsson, A. (1992): Calibration Curves for Resistance-type Moisture Meters, 3rd IUFOR International Wood Drying Conference, Vienna, Austria.