WCTE 2016
World Conference on
Timber Engineering
August 22-25, 2016 | Vienna, Austria

MONITORING OF MOISTURE CONTENT OF PROTECTED TIMBER BRIDGES

Johannes Koch, Antje Simon[2], Ralf W. Arndt[3]

ABSTRACT: The efficiency of measures of structural timber protection on protected timber bridges and the influence of special local climates on the moisture content of the timber should be evaluated and analysed by long-term measurements of the moisture content. Therefore, a monitoring system for the moisture content of the timber and the ambient climate was set up and implemented on a protected timber bridge. The first measurement results of several measuring points are evaluated and discussed. In an ongoing research project, more protected timber bridges will be equipped with a monitoring system to create an extensive database. The following paper explains setup and application of the measurement system. Furthermore, first measurement results of moisture content and ambient climate will be described and discussed. First insights will be derived, concerning the correlation between local climate and moisture content of protected timber bridges.

KEYWORDS: monitoring, timber moisture content, protected timber bridges, structural timber protection

1 INTRODUCTION

In the last decades only a few timber bridges have been built in Germany. It is the opinion of the authors that only protected timber bridges might be able to compete with bridges of other building materials, in relation to high durability, long service life as well as economical aspects. Furthermore, protected timber bridges are more ecological and sustainable, compared to bridges of other building materials. In the German-speaking countries structural timber protection has been established as a modern and ecological method for constructing protected timber bridges without chemical wood protection measures. For creating durable timber bridges, it is desirable to plan constructive measures that prevent precipitation from the load-bearing structure. Examples for structural timber protection measures are roof projection, side cladding and sheet covering. According to DIN EN 1995-1-1 [1] all timber members have to be classified into service classes. The classes are defined by the environmental climate as well as the equilibrium moisture content of timber. It is recommended to classify structural protected timber members into service class 2. This class characterises timber members with an average moisture content below 20 percent by mass (M%), which is the essential limit regarding the durability of structural timber [2]. If the moisture content is permanently higher than 20 M%, fungal growth and organic destruction cannot be ruled out.

The development of timber moisture content over a long time period can be recorded by monitoring systems. Such systems allow a reliable and permanent qualitative and quantitative observation of the timber moisture contents. Therefore it is possible to detect and repair defects in time before serious damage develops. Furthermore, monitoring systems allow to control the effectiveness of protective measures and to recognise areas of vulnerability. Therefore, monitoring systems can provide a major contribution to plan even better constructions of protected timber bridges in the future.

2 LONG-TERM MEASUREMENTS OF MOISTURE CONTENT OF PROTECTED TIMBER BRIDGES

2.1 PROTECTED TIMBER BRIDGES

In timber bridge construction, it is of high priority to differ between protected timber bridges and non-protected timber bridges. There is a significant difference regarding the durability and economic efficiency. Non-protected timber bridges are more likely to be affected by fungal growth and organic destruction and with a higher damage growth rate. Protected timber bridges are more durable if inspections and maintenance are frequently and reliably done. A remarkable and famous example is the "Kapellbrücke" in Lucerne in Switzerland. This covered wooden pedestrian bridge was built in 1333 and is still in service up till now.

[1] Johannes Koch, Fachhochschule Erfurt, University of Applied Sciences, Germany, johannes.koch@fh-erfurt.de
[2] Antje Simon, Fachhochschule Erfurt, University of Applied Sciences, Germany, antje.simon@fh-erfurt.de
[3] Ralf W. Arndt, Fachhochschule Erfurt, University of Applied Sciences, Germany, ralf.arndt@fh-erfurt.de

According to DIN EN 1995-2/NA [3] protected members of timber bridges are accurately defined as members that are protected from precipitation and moisture ingress for example through driving rain. Figure 1 shows different possibilities to realise this intention. It can be seen that a roof projection under an angel of 30° can be equally efficient as a waterproofing while both are less prone to moisture induced damage.

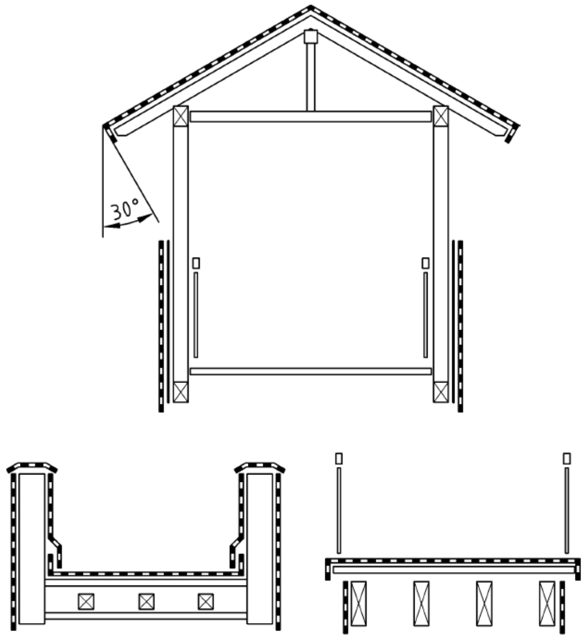

Figure 1: Definition of protected members of timber bridges according to DIN EN 1995-2/NA [3]

In consequence of the protective measures, the timber moisture content will remain at a low level. Hence the risk of fungal growth and organic destruction will be minimised, while the durability of the construction and the service life as well as the cost effectiveness will be raised. Against this background it seems obvious why only protected timber bridges should be built in the future. Furthermore, this construction method relieves the national economies because it helps to save expensive repair measures as well as replacement costs compared to non-protected timber bridges.
As an additional effect, timber bridges are sustainable. They use natural renewable building materials that help to counteract the anthropogenic climate change. Trees remove carbon from the global carbon cycle and have low energy consumption in contrast i.e. to the cement, concrete and steel production of other bridge-material types.

2.2 OVERVIEW OF THE STATE OF THE ART

In the last few years some research projects have been carried out in German-speaking and Scandinavian countries that deal with results of timber moisture monitoring at different timber structures. The projects differ regarding to the measuring methods as well as the analysed objects.
At the University of Hamburg, a research project was carried out dealing with results of monitoring of the stressed ribbon pedestrian bridge near Essing over the Main Danube Canal [4, 5]. The system logged the electrical resistance of various timber members using self-made electrodes. Furthermore, some reference test sets were implemented at the bridge. Other devices logged the temperature and relative humidity of the ambient air. After three years of monitoring, it was observed that the timber moisture content was significantly lower at protected members. Unprotected members showed high moisture content far beyond the 20 M%-limit over long time periods as well as fungal decay.
In a research project at the Technical University of Munich, more than twenty buildings were equipped with monitoring systems based on the electrical resistance method [6 – 8]. The Teflon-insulated electrodes were implemented at glued laminated timber members in various depths between 1.5 and 7.0 cm. In addition to the electrical resistance, the temperature of the members was measured as well as the climatic parameters temperature and relative humidity of the ambient air. It was discovered that the type of use at different buildings ensures really different effects on moisture content and its distribution over the cross section. Additionally, it was shown that the used monitoring system works relative reliably over a long time period, however with the exception of chlorinated air (indoor swimming pools).
Another research project dealing with timber bridges has been performed at Bern University of Applied Sciences. Some timber bridges were equipped with monitoring systems that logged timber moisture content, timber temperature as well as temperature and relative humidity of the ambient air [9 – 11]. For this electrical-resistance-based system, stainless steel screws were used as electrodes. The electrodes were implemented at various positions and depths. At one of the bridges, a data transmission device was used additionally. The results of this project show that the equilibrium moisture content differs in relation to seasonal climatic variations over the cross section. Peripheral zones adapt relatively fast to climatic changes while centre zones adapt significantly time-lagged. It was also shown that the moisture content at the protected timber bridges was significant lower than 20 M%. The system worked reliably over several years.
Other methods were used in Scandinavian countries. A monitoring system based on the sorption method was implemented at some bridges in Norway for monitoring the moisture content over a long time period [12]. The moisture monitoring is a part of a comprehensive study which was initiated to collect also data about ambient climate, displacement of the bridges and development of steel bar forces of prestressed members. The moisture content was significant lower than the 20 M%-limit at most of the monitored bridges.
Overall, in the last few years some data about moisture monitoring at timber bridges were collected. But the more outstanding issues like the influence of close proximity to waters on the timber moisture content and the efficiency of protective measures have not been

investigated so far. Therefore, additional studies are required.

2.3 SELECTION OF AN APPROPRIATE MONITORING SYSTEM

At FH Erfurt - University of Applied Sciences, research has been done to develop an appropriate moisture monitoring system for timber bridges. An objective was to find a system, which is suitable for outdoor usage. Furthermore, it was necessary that the system provides the possibility of various measurement depths. For a permanent and current observation of the moisture content development, it was also necessary to add a remote data transmission device to the system.

Finally, a system was chosen, which was used successfully in other research projects [6 – 11]. This system works on the principle of the electrical resistance method, which is based on the dependence between electrical resistance and material moisture. The electrical resistance is lower if the material moisture is higher [13]. A generated measuring current flows through two electrodes which have to be in contact with the wet medium (wood). A resistance measuring device (also called ohmmeter) measures the voltage drop which will occur as a result of the electrical resistance of the wood. This fact allows conclusions regarding the timber moisture content.

Most of the devices utilising in this system are housed in an installation box to protect them from weather and vandalism (Figure 2).

Figure 2: *Measuring devices in installation box*

In regularly defined intervals moisture measurements are carried out. Parts of the system are measuring electrodes. Various types of electrodes were tested in frame of a master thesis [14]. Electrodes made of stainless steel screws (Figure 3) are advantageous, because various lengths are available and the handling is relatively simple. It can be seen that the screws are isolated with a shrinking tube to create the required measuring depth. Similar electrodes were used in a research project at Bern University of Applied Sciences [9].

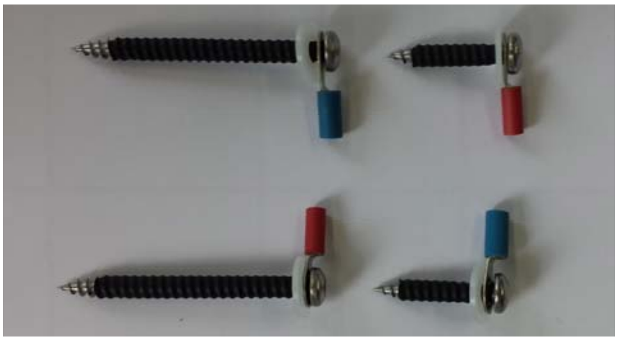

Figure 3: *Electrodes made of stainless steel screws*

Additionally, for precise measurement results the timber temperature is required to calculate the temperature compensation. Therefore, another device is used for measuring the timber temperature close to the electrodes. For correlations between climate and timber moisture content, climatic data collecting is required. Therefore, other devices measure the climatic parameters temperature and relative humidity of the ambient air.

The whole collected data of timber moisture content, timber temperature and climatic parameters are temporarily saved at data loggers for days up to weeks or months. The data is periodically transferred by a remote data transmission device in defined intervals. This device uses the GPRS mobile network. The thus collected data is available all over the world as an e-mail attachment.

3 MONITORING OF A PILOTE BRIDGE

3.1 IMPLEMENTATION OF THE MONITORING SYSTEM

After gaining more experience with the system in some base tests, it was set up at a protected timber bridge in August 2015. This pilot bridge is situated in Höngesberg near Cologne. As shown in Figure 4, it is a road bridge that crosses the river Agger. The bridge is a combination of a timber arch bridge and two timber-concrete-composite foreland bridges. It is a full-protected construction.

Figure 4: *Timber bridge in Höngesberg (North-Rhine-Westphalia, Germany)*

Measuring points of timber moisture content, timber temperature and ambient climate have been implemented at the load-bearing structure of the bridge. The measuring points of the timber moisture content have been implemented at various positions and in various depths to gain a comprehensive picture of the distribution of the timber moisture.

Figure 5: *Measuring points of timber moisture and timber temperature above the river*

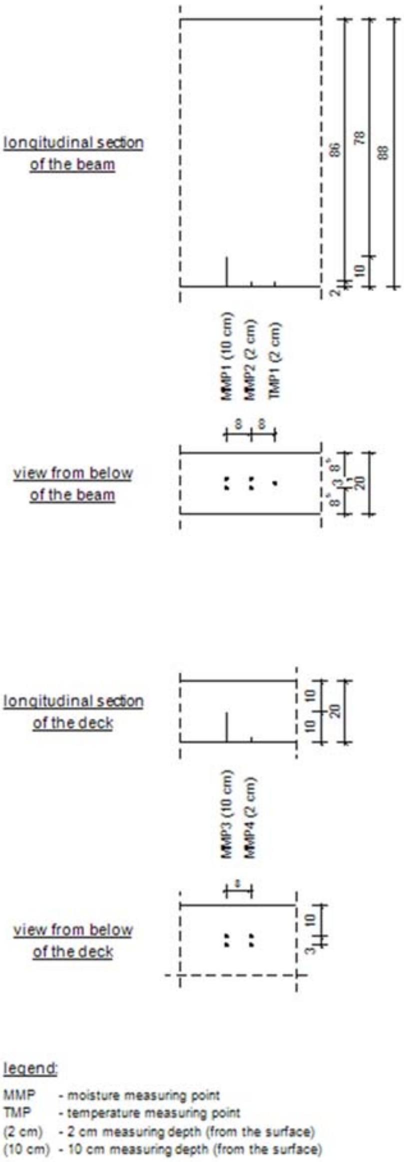

Figure 6: *Position and depth of the measuring points above the river*

Figure 5 shows four of the eight points measuring timber moisture as well as one of the two points measuring timber temperature. The picture shows the situation above the river. Measuring points are installed at the bottom of a main beam and the bridge deck. The measuring depths of the electrodes are 2.0 and 10.0 cm from the surface of each member (Figure 6).

Figure 7: *Measuring points of timber moisture and timber temperature at a block-glued laminated timber beam at one of the foreland bridges*

Figure 7 shows the other four measuring points of the timber moisture content and the second point measuring timber temperature. These measuring points have been set up at a block-glued laminated timber beam at one of the foreland bridges. The depths of the electrodes vary between 2.0 and 13.5 cm as shown in Figure 8.

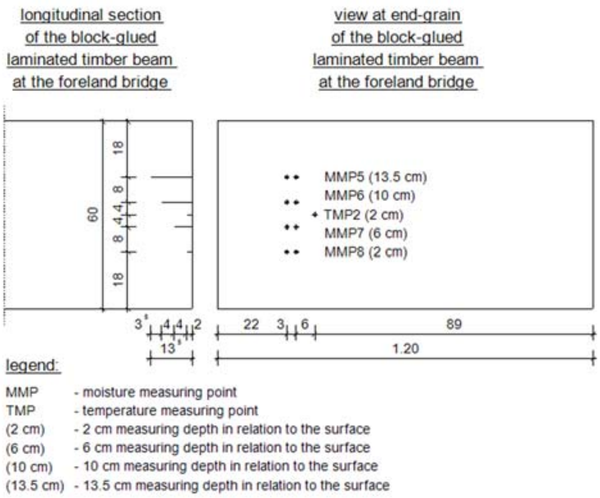

Figure 8: *Position and depth of the measuring points at one of the foreland bridges*

Most of the measuring instruments are housed in an installation box that was set up at the underside of the bridge. This box was hidden at the construction to protect it against precipitation and vandalism (Figure 9).

Figure 9: *Installation box*

3.2 FIRST RESULTS AND DISCUSSION

Since the implementation of the monitoring system in August 2015, data have been sent by remote data transmission. The following results are referring to the evaluation period from August 2015 until March 2016. The interval of data collection was 30 minutes to create the possibility of drawing a daily curve if necessary.

The transmission of data was adjusted to an interval of five days, but the data transfer was sometimes not successful. Probably the low network coverage at the pilot bridge was the reason for this problem. Data was not lost, because it was saved in the temporary memory at the data loggers and was sent the following day of transfer.

The following results show the development of the timber moisture content of the three measuring areas. The values have been modified by temperature compensation.

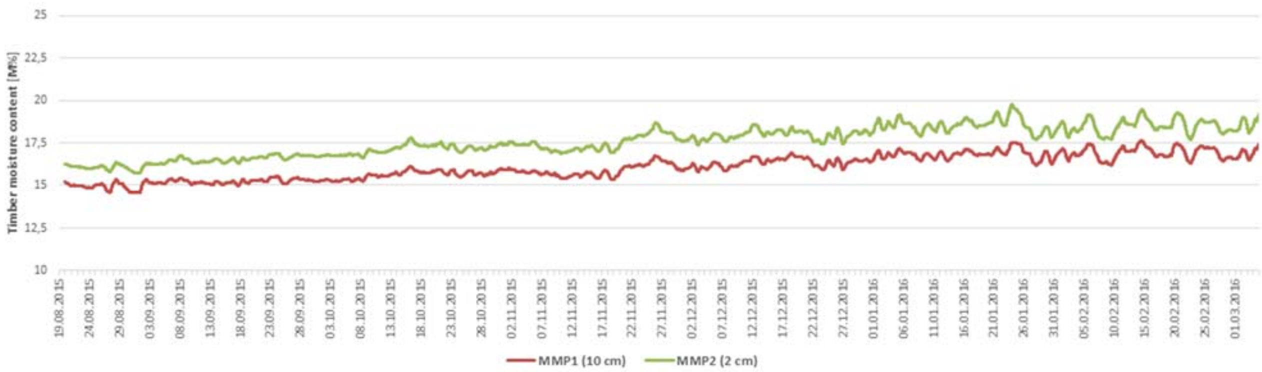

Figure 10: *Development of the timber moisture content of the main beam above the river as daily average values*

Figure 10 shows the development of the timber moisture content of one of the main beams. The moisture content was measured in depths of 2.0 and 10.0 cm from the surface. As expected, it can be seen that the moisture content is lower in the central zone than in the peripheral zone. Furthermore, Figure 10 shows a rise of the moisture content to about 2 M% as a result of the changed climate values in winter. However, the moisture content is constantly lower than the critical 20 M%-limit. The values vary between 15 and 18 M%. In consequence, there is not a risk of fungal growth or organic destruction. Furthermore, the measured moisture content is verifying a reliable efficiency of structural timber protection of the member. The protection was realised with a sheet-metal covering and side cladding.

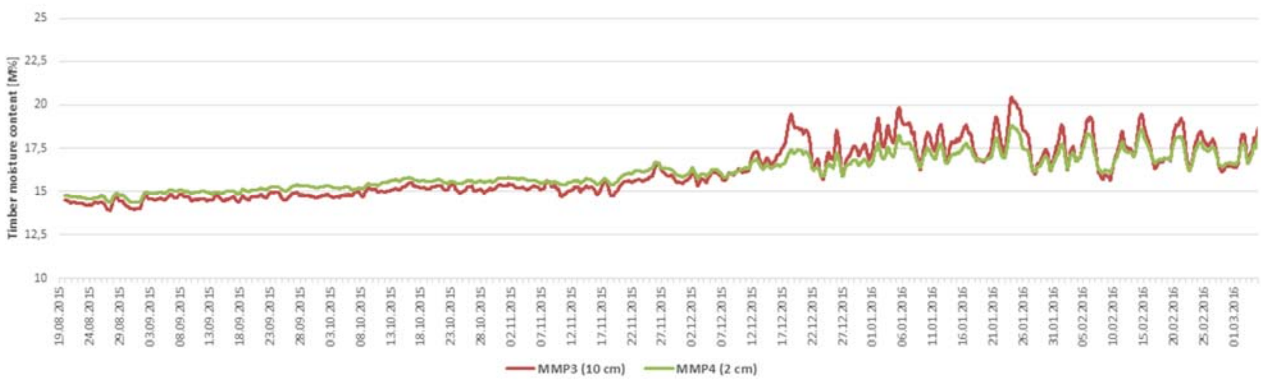

Figure 11: *Development of timber moisture content of the deck above the river as daily average values*

Figure 11 shows the development of the timber moisture content of the bridge deck. The moisture content was also measured in depths of 2.0 and 10.0 cm from the surface. It is striking that both curves show a relative similar development in the first months, while the development is differing more since December. It is surprising that the moisture content rose more in the centre zone than in the peripheral zone close to the surface. An explanation for this behaviour is currently not available. Depending on the seasonal changes, the moisture content rose general to around 2 to 3 M% in winter months. The moisture content still remained nearly always lower than the 20 M%-limit, similar to the main beam. In consequence, there is not the potential for fungal growth or organic destruction. It can be expected that the waterproofing of the pavement structure is intact and water is kept away from the load-bearing structure.

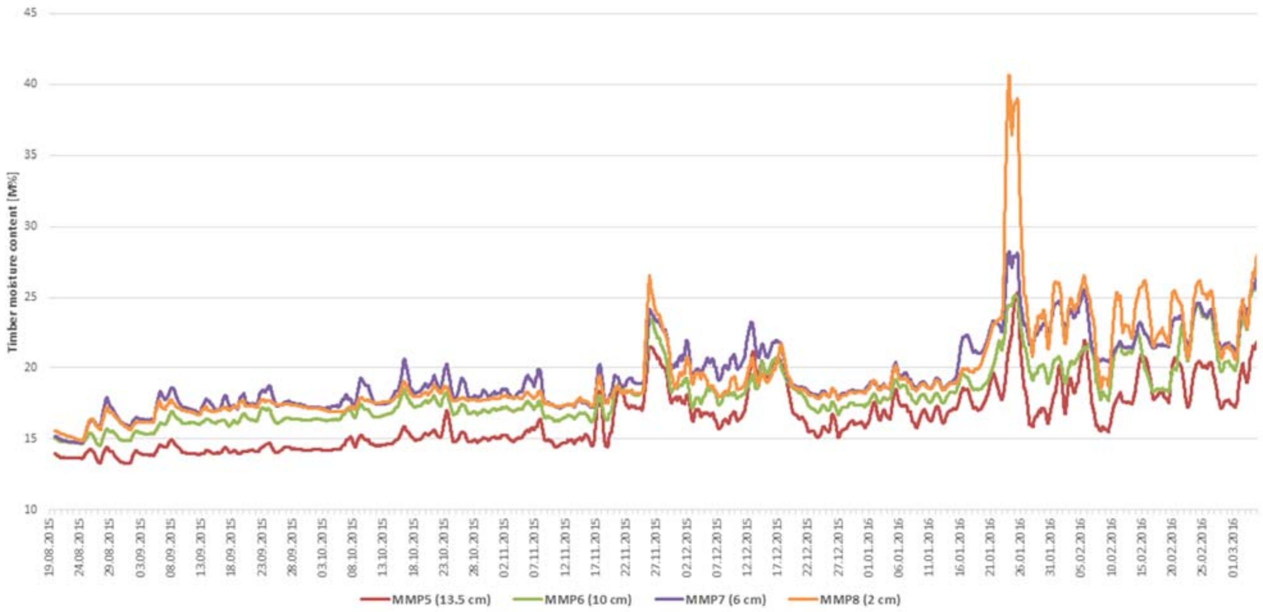

Figure 12: *Development of timber moisture content of the foreland bridge as daily average values*

Figure 12 shows the development of the timber moisture content in the beams end-grain area of a foreland bridge. The moisture content was measured in depths of 2.0, 6.0, 10.0 and 13.5 cm from the surface.

The moisture content rose generally to around 3 to 4 M% in winter, similar to the other members. Timber moisture content developed how expected, until the end of November 2015. The moisture content was lowest at a depth of 13.5 cm and higher close to the surface. The values of the measuring depths of 2.0, 6.0 and 10.0 cm were relatively close together. However, it can be seen that the moisture content rapidly rose to a high level after 25th of November and degreased to a more acceptable level of around 20 M% only a few days later. A second rise was in the middle of December. However, the largest increase was at the end of January. Values of timber moisture far beyond the fibre saturation point have been reached.

A malfunction of the monitoring system can be probably ruled out, because each curve shows large fluctuations. There is an expansion joint between the main part of the bridge and the foreland bridge. If this member is defect, it might be possible that water runs to the end-grain area of the beam where the electrodes are placed. Water stripes are supporting that assumption that can be seen in Figure 7. If there are unfavourable wind conditions, driving rain could be an additionally explanation.

The authors informed the owner about the high moisture content. They recommended to survey the affected areas in detail during the next inspection to protect the member from fungal growth and organic destruction.

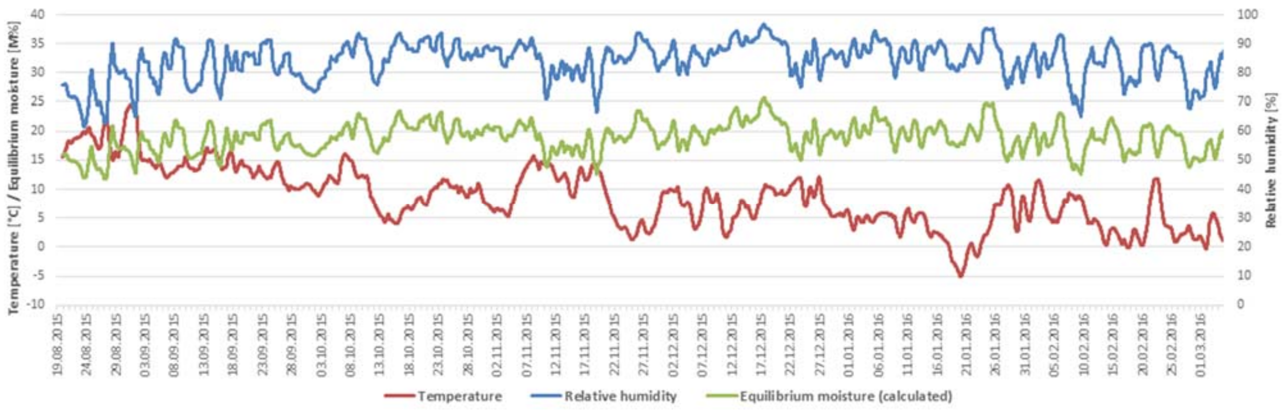

Figure 13: *Development of the climatic parameters temperature and relative humidity as well as the calculated equilibrium moisture as daily average values*

Figure 13 shows the development of climatic parameters temperature and relative humidity. These parameters have been measured close to the points measuring timber moisture of the main beam and the bridge deck above the river.
It can be seen, that the relative humidity was rising during the autumn and winter months. The values are lower in August and September. As expected, the temperature is decreasing in winter. The temperature reached negative values just in the middle of January. These climatic seasonal changes ensured a general rise of the moisture content of a few M%, as can be seen in Figure 13.
It is necessary to set up a second climatic measuring point a few meters away from the river to investigate the influence of close proximity to waters.
Furthermore, there is an equilibrium moisture curve plotted in Figure 13. This curve is calculated by using the "two hydrate sorption model" from A. J. Hailwood and S. Horrobin in combination with the material specific parameters, which were calculated by W. T. Simpson in 1973 [15, 16]. The curve was computed according to Equation (1).

$$u = \frac{1800}{M_p} \cdot \left[\frac{K \cdot h}{1 - K \cdot h} + \frac{K_1 \cdot K \cdot h + 2 \cdot K_1 \cdot K_2 \cdot K^2 \cdot h^2}{1 + K_1 \cdot K \cdot h + K_1 \cdot K_2 \cdot K^2 \cdot h^2}\right] \quad (1)$$

where
h = relative humidity of the ambient air and
M_p, K, K_1, K_2 = material specific parameters by W. T. Simpson shown in Equations (2 - 5)

$$M_p = 330 + 0{,}452 \cdot T + 0{,}00415 \cdot T^2 \quad (2)$$

$$K = 0{,}791 + 0{,}000463 \cdot T - 0{,}000000844 \cdot T^2 \quad (3)$$

$$K_1 = 6{,}17 + 0{,}00313 \cdot T - 0{,}0000926 \cdot T^2 \quad (4)$$

$$K_2 = 1{,}65 + 0{,}0202 \cdot T - 0{,}0000934 \cdot T^2 \quad (5)$$

where
T = temperature of the ambient air

3.3 FURTHER INVESTIGATIONS

At the pilot bridge, a lot of information was gained regarding the handling of the measuring devices, the implementation of measuring points, data transmission as well as data interpretation.
Based on these results, the monitoring of protected timber bridges will continue and expand in the frame of the research project "**Pro**tected **Tim**ber **B**ridges (ProTimB)". ProTimB is funded by the Federal Ministry of Education and Research (BMBF) and several companies. Executing firms, engineering offices and scientists work together in this project to define a new standard for the planning, execution and inspection of protected timber bridges.
In course of this research project up to eight other protected timber bridges will be equipped with monitoring systems to monitor the timber moisture content over a time period of more than two years. The objectives are to analyse the difficult structural details of the load-bearing structure and investigate the distribution of timber moisture over the cross section. Therefore, the efficiency of the structural timber protection measures could be evaluated and scientific knowledge can be obtained to define an appropriate interval for inspections of timber bridges. Furthermore, special features of local climates like spray zones as well as the influence of close proximity to waters should be considered. It is planned to gain more experience about durability of protected timber bridges close to waters. These scientific investigations are necessary, as comparable information is not available at this time.

4 CONCLUSIONS

In this paper, general aspects of protected timber bridges have been shown. Compared to non-protected timber bridges only protected timber bridges might be able to compete with bridges of other building materials functionally and economically.
To get more information about the development of moisture content of timber bridges at close proximity to waters, also the combination and handling of the measurement equipment has been investigated. Therefore, a protected timber bridge has been equipped with a monitoring system measuring moisture content, timber temperature as well as ambient climate conditions (air temperature and relative humidity). The first results of the monitoring at the pilot bridge prove that protective measures at the load-bearing structure guarantee an acceptable timber moisture content. Therefore, it can be summarised that the structural timber protection is mandatory in building durable timber bridges.
In the context of the research project "ProTimB", an exhaustive investigation will be carried out by extending the monitoring to validate the preliminary results. Furthermore, the influence of special features of local climates on the timber moisture content will be investigated extensively.

ACKNOWLEDGEMENT

The research project "Protected Timber Bridges" is funded by the Federal Ministry of Education and Research (BMBF) and several companies. Therefore, many thanks are owed to the Federal Ministry of Education and Research, Schaffitzel Holzindustrie GmbH + Co. KG, Schmees & Lühn Holz- und Stahlingenieurbau GmbH, Grossmann Bau GmbH & Co. KG and to Setzpfandt Beratende Ingenieure GmbH & Co. KG. We also wish to thank Qualitätsgemeinschaft Holzbrückenbau e. V., Studiengemeinschaft Holzleimbau e. V., Harrer Ingenieure GmbH and HSW-Ingenieure Schiermeyer Wiesner GbR.

REFERENCES

[1] DIN EN 1995-1-1:2010-12, Eurocode 5: Bemessung und Konstruktion von Holzbauten – Teil 1-1: Allgemeines – Allgemeine Regeln und Regeln für den Hochbau; Deutsche Fassung EN 1995-1-1:2004 + AC:2006 + A1:2008.

[2] Graf E., Meili M.: Holzzerstörende Pilze und Insekten. Analyse, Prognose, Bekämpfung. Lignum, Schweizerische Arbeitsgemeinschaft für das Holz (Ed.), Lignatec: Die technischen Informationen der Lignum EMPA/LIGNUM-Richtlinie 14. Zürich, Switzerland, 2001.

[3] DIN EN 1995-2/NA:2011-08, Nationaler Anhang – National festgelegte Parameter – Eurocode 5: Bemessung und Konstruktion von Holzbauten – Teil 2: Brücken.

[4] Brischke C., Rapp A. O.: Untersuchung des langfristigen Holzfeuchteverlaufs an ausgewählten Bauteilen der Fußgängerbrücke in Essing. Arbeitsbericht Nr. 2007/2, Bundesforschungsanstalt für Forst- und Holzwirtschaft, Institut für Holzbiologie und Holzschutz. Hamburg, Germany 2007.

[5] Brischke C.: Untersuchung abbaubestimmender Faktoren zur Vorhersage der Gebrauchsdauer feuchtebeanspruchter Holzbauteile. Dissertation, Universität Hamburg, Germany, 2007.

[6] Gamper A., Dietsch P., Merk M., Winter S., Sieder M.: Gebäudeklima – Langzeitmessung zur Bestimmung der Auswirkung auf Feuchtegradienten in Holzbauteilen. Forschungsbericht, TU München, Germany, 2012.

[7] Gamper A., Dietsch P., Merk M., Winter S.: Building Climate – Long-term measurements to determine the effect on the moisture gradient in timber structures. Final report, TU München, Germany, 2014.

[8] Dietsch P., Merk M., Winter S.: Monitoring building climate and timber moisture gradient in large-span timber structure. *Journal of Civil Structural Health Monitoring*, Volume 5, Issue 2, pp. 153-165, 2015.

[9] Franke B., Müller A., Vogel M, Tannert T.: Langzeitmessung der Holzfeuchte und Dimensionsänderung an Brücken aus blockverleimtem Brettschichtholz. Forschungsbericht, Berner Fachhochschule, Architektur, Holz und Bau. Biel, Switzerland, 2012.

[10] Franke B., Franke S., Müller A., Vogel, M., Scharmacher F., Tannert T.: Long-term Monitoring of Timber Bridges – Assessment and Results. *Advanced Materials Research*, Volume 778, pp. 749-756, 2013.

[11] Franke B., Franke S., Müller A.: Case studies: long term monitoring of timber bridges. *Journal of Civil Structural Health Monitoring*, Volume 5, Issue 2, pp. 195-202, 2014.

[12] Horn H.: Monitoring five timber bridges in Norway – result 2012. Norsk Treteknisk Institutt, Oslo, Norway, 2013.

[13] Kruschwitz S.: Feuchtemessung im Bauwesen - ein Überblick. In: Fachtagung Bauwerksdiagnose 2014, Vortrag 5, Berlin, Germany, 2014.

[14] Koch J.: Feuchtemonitoring an geschützten Holzbrücken - Planung, Durchführung und Auswertung. Master Thesis, FH Erfurt - University of Applied Sciences, Germany, 2015.

[15] Hailwood A. J., Horrobin S.: Absorption of water by polymers: analysis in terms of a simple model. *Transactions of the Faraday Society*, Volume 42B, pp. 84-92, 1946.

[16] Simpson W.T.: Prediction equilibrium moisture content of wood by mathematical model. *Wood and Fiber*, Volume 5, No. 1, pp. 41-49, 1973.