Moisture monitoring of nine protected timber bridges in Germany

Johannes KOCH
Research assistant
Fachhochschule Erfurt
University of Applied Sciences Erfurt, Germany
johannes.koch@fh-erfurt.de

Johannes Koch, born in 1991, received his M.Eng. by Fachhochschule Erfurt - University of Applied Sciences (FHE) in 2015. Since 2016, he is a scientific researcher in the project “Protected Timber Bridges” at FHE.

Ralf W. ARNDT
Prof. Dr.-Ing. Chair for building material science and building diagnostics
Fachhochschule Erfurt
University of Applied Sciences Erfurt, Germany
ralf.arndt@fh-erfurt.de

Ralf W. Arndt, born in 1970, received his diploma and his doctor’s degree by TU Berlin. After being a PhD student and scientist at the Federal Institute for Materials Research and Testing in Berlin (BAM), he was postdoc at US Federal Highway Administration and Rutgers University from 2008 to 2012 and assistant professor at FIU in Miami till 2013. Since 2014 he is at FHE.

Antje SIMON
Prof. Dr.-Ing. Chair for timber construction
Fachhochschule Erfurt
University of Applied Sciences Erfurt, Germany
antje.simon@fh-erfurt.de

Antje Simon, born in 1970, Civil Engineer since 1994, Project leader and head of design of civil engineering structures at an engineering office for 10 years, Thesis in the field of timber-concrete-composite road bridges in 2008, Professor for timber construction since 2011

Markus G. JAHREIS
Research assistant
Fachhochschule Erfurt
University of Applied Sciences Erfurt, Germany
markus.jahreis@fh-erfurt.de

Markus Jahreis, born 1975, is a Civil Engineer since 2001 and was seven years employed as engineer and site manager in a company for rehabilitation. For ten years he was a research assistant at the chair of timber and masonry engineering at the University of Weimar and since 2017 at the FH Erfurt.

Summary
Timber bridge construction has a millennia-old tradition in building history. Even though other building materials have become more popular in the last century, timber is still able to compete, especially if it is protected against precipitation and moisture ingress. This is the most important prerequisite for designing durable timber structures because a low moisture content is the key to durability. In fact, load-bearing members of timber bridges should be designed as protected members to prevent the negative influence of precipitation and moisture ingress [1]. To raise the acceptance of timber bridges, the efficiency of structural protective measures is evaluated in field tests under real boundary conditions. Therefore, a monitoring program was initiated to investigate the moisture content and ambient climate conditions of nine protected timber bridges by long-term measurements. This paper describes set-up and application of the monitoring system. First measurement results will be presented.
1. Introduction

Timber bridges have been seldom built in Germany in recent years. Building owners often have considerable reservations to invest in timber bridges. High maintenance costs as well as low durability and a short service life are often their concerns.

However, wood is a great building material because it is the only renewable raw material that can be used for engineering structures. Produced in sustainable forest management, it will be also available in the future. One more big advantage is the ability of carbon storage for the whole service life of a structure. This property can help to counteract the global climate change. Hence, the usage of timber should be increased in general and particular in bridge construction.

Durability should not be a problem for timber bridges if the members are structural-protected. This principle has been established in the German-speaking countries as a modern and ecological method for designing timber bridges without chemical wood protection measures. The German national annex of Eurocode 5 Part 2 [1] requests the protection of load bearing members of timber bridges. Structural timber protection measures are roofs and roof overhangs as well as claddings and coverings, examples of which can be seen in Fig. 1. Hence, low durability, short service life and high maintenance costs should be not an issue if the principle of structural protection is followed. A monitoring program has been initiated to verify this approach and increase the acceptance of the natural building material timber as a real option for new bridge structures.

2. Monitoring nine protected timber bridges

2.1 Initiation of a monitoring program

The most important aim of the monitoring program is the demonstration of durability of well-protected timber bridges. Therefore, nine structural protected timber bridges were equipped with a monitoring system for measuring moisture content and ambient climate conditions for a period of two years or more. The concept of the monitoring is to evaluate the durability on basis of the long-time timber moisture level.

This is based on the fact that high moisture content above the fibre saturation point (around 30 mass %) could be dramatically for timber structures because fungal decay could occur. Also, even lower moisture contents of more than 20 mass % over an extended period of time could be problematic. Fungal growth and organic destruction could not be ruled out [2]. Hence, if the moisture level is permanently lower than 20 mass %, fungal growth in unlikely and might even be impossible. The bridge would be durable and a long service life should be reached.

Fig. 1: Examples of structural protective measures – roof, housing, cladding, metal sheet, roof overhang and timber concrete composite structure
Another aim of the monitoring is the investigation of the influence of specified local climates on the timber moisture content. Close distance to waters and spray over roads or waterfalls could be the reason for problematic climate conditions. It is investigated how much the moisture content increases as a result of these influences in contrast to other locations, without those influences.

2.2 Operating principle of the monitoring system

The monitoring system works on the principle of the electrical resistance method and has been used in other research activities before [3], [4], [5]. This method is based on the dependence between electrical resistance and material moisture content. The electrical resistance decreases if the moisture content increases.

To measure the moisture content, electrodes have to be installed in the timber members of the bridges. The electrodes are made of stainless steel screws of different lengths. Preliminary, other types of electrodes were tested. It turned out that screws are more convenient for exact and comprehensible results compared to sharpened threaded rods and glued-in steel cables [6] [7]. The screws are partly insulated with a shrinking tube to measure the moisture content in a well-defined depth of the cross section. The aim is to gain more information about the moisture distribution within the cross section, because there is an active and a passive zone. In the inner passive zone, there is a small variation of the moisture content, while the outer active zone is characterised by a larger range of changing moisture content. As a result of this behaviour strong internal stresses can happen. Therefore, cracks in the members cannot be ruled out [8].

The wood species have an influence on the measuring principle. Therefore, calibration curves are required for each wood species. Seven of the nine bridges that are part of the program were built with glulam made of spruce. Two bridges are made of larch.

Another relevant influencing factor is the temperature of the material [9]. Therefore, additional sensors are required for measuring the timber temperature close to the electrodes. This allows a temperature compensation of the measured timber moisture values to produce more precise results.

Climate sensors were additionally installed to investigate the local climate conditions. These sensors were placed close to the moisture and temperature measurement points at the most measuring areas.

All measured values are saved by data loggers and sent by a remote data transmission device via mobile network, week by week. Only for one of the bridges, this way of data transmission is impossible, because it is located in an area, where no mobile network is available. The data has to be downloaded manually two times a year.

2.3 Bridges of the program

The nine selected bridges are spread out all over Germany, as shown in Fig. 2. Furthermore, different typical structure are taken into consideration, as there are timber concrete composite (TCC) bridges, through bridges, arch bridges, truss bridges and beam bridges. They are also shown in Fig. 2 by different colours.

The bridges in Höngesberg, Schiffarth and Wippra are road bridges. The other bridges are pedestrian bridges and cycle path bridges.

All bridges span over rivers and the truss bridge, which is located in Lörrach, spans additionally over a road. These locations were selected to investigate some specified climate conditions resulting from moisture exposition by waters or spray as a result of the traffic.
2.4 Implementation of the system

The first bridge, which is located in Höngesberg, has been equipped with a monitoring system in August 2015. The other bridges have been equipped in October and November 2016.

Each bridge contains a minimum of two measuring areas at load bearing members. One measuring area has always been placed above a river. The second one has been placed above the foreland, usually near to the abutment. This arrangement should enable the investigation of influence of close distance to waters on the ambient climate conditions and on the timber moisture content. At a few bridges, a third measuring area has been implemented at points of special interest e.g. at secondary members beneath the bridge deck or above a road in an area of spray exposition.

The measuring areas have been equipped in a similar way as shown in Fig. 3. From two up to four pairs of electrodes were always implemented in several depths. Four pairs of electrodes can be seen in Fig. 3. The measuring depths in this example are 20, 40, 60 and 100 mm. As
shown in the figure, a temperature sensor (red cable) is usually implemented close to the electrodes. That is a necessity for the temperature compensation of the moisture values. Last component is the sensor for measuring the ambient climate conditions, air temperature and relative humidity. Fig. 3 it can be seen as the small black case between the electrodes and the temperature sensor.

![Figure 3: Example of a measuring area at the cycle path bridge in Frankenroda](image)

2.5 Analysis of the data

The collected data is analysed with the following steps. First, the timber moisture content is calculated from the measured electrical resistance by using the calibration curve for the respective wood species. The second step is the temperature compensation to correct the moisture content.

The climate conditions are displayed as a calculated equilibrium moisture content that would theoretically result on the surface of the members because of the hygroscopic behaviour of wood. The calculation of the equilibrium moisture curve is based on A. J. Hailwood’s and S. Horrobin’s “two hydrate sorption model” (Equation 1) [10] in combination with the material specific parameters by W. T. Simpson from 1973 (Equations 2 to 5) [11].

\[
\begin{align*}
M_{eq} & = 330 + 0.452 \cdot T + 0.00415 \cdot T^2 \\
\end{align*}
\]

\[
\begin{align*}
K & = 0.791 + 0.000463 \cdot T - 0.000000844 \cdot T^2 \\
K_1 & = 6.17 + 0.00313 \cdot T - 0.0000926 \cdot T^2 \\
K_2 & = 1.65 + 0.0202 \cdot T - 0.0000934 \cdot T^2 \\
\end{align*}
\]

where \( h \) = relative humidity and \( T \) = air temperature

3. First results of the pilot bridge

A road bridge that spans over the little river Agger has been already equipped with a monitoring system in August 2015. The bridge is located in Lohmar Höngesberg near Cologne in North Rhine-Westphalia and was built in 2014. It is a fully protected timber arch bridge with two timber concrete composite foreland bridges. All timber members of the load bearing structure are made of glued laminated spruce.
Fig. 4: Road bridge in Höngesberg

Three measuring areas have been implemented, whereby two of them are close together above the river. The first measuring area has been set up at the tie beam of the arch that is made of glulam. Two pairs of electrodes have been chosen to measure the moisture content in depths of 20 and 100 mm. The same configuration has been chosen at the second measuring area, close to the first one. It has been implemented in the bridge deck, which is completely made of glulam. Furthermore, a temperature measuring point and a climate measuring point have been placed. Both measuring areas can be seen in Fig. 5.

Fig. 5: Two measuring areas above the river at the bridge deck (left) and the tie beam (right)

The third measuring area has been placed above the foreland at the end grain of a main girder. The timber moisture content is measured in depths of 20, 60, 100 and 135 mm, a temperature sensor has been implemented nearby. The measuring area is shown in Fig. 6. A climate sensor was later set up, in October 2016.
The results of the monitoring are displayed in the diagrams of Fig. 7, Fig. 8 and Fig. 9. The diagrams show the timber moisture content at the different measuring depths and the equilibrium moisture contents, which were calculated from the ambient climate conditions. The diagrams show a three-day moving average of the determined timber moisture content and equilibrium moisture content. On the one hand, the average was chosen to smooth the day and night oscillation and very short periods of extreme climatic conditions, which are not relevant for the long-term view. On the other hand, the period of moving average was chosen as short as possible to display even unexpected peaks, e.g. as a result of penetrating water.

The measurement results of the measuring areas above the river are shown in Fig. 7 and Fig. 8. It turned out that the timber moisture content did not exceed the 20 mass % limit for most of the time of the first 14 months. During the winter 2015/16, a mean increase of 3 mass % has been recognised. In winter 2016/2017 it was much colder than in the year before. As a result, the moisture content increased partly up to 24 mass %. However, for most of the time the moisture content remains around 20 mass %. A similar development was observed at the third measuring area above the foreland in the second winter. This behaviour has to be kept in mind.

The average timber moisture content is around 17.4 mass % for the whole measuring period of both measuring areas and both measuring depths. This is close to the average of the equilibrium moisture content above the river that is around 17.8 mass %. Therefore, in the present stage of knowledge, it can be assumed that the structural protection measures achieve the expectations.
Fig. 7: Measurement results of the measuring area at the tie beam above the river

Fig. 8: Measurement results of the measuring area at the bridge deck above the river

Fig. 9 shows the development of the timber moisture content of the measuring point above the foreland. The moisture content increased strongly in November 2015 and in the first quarter of 2016. Moisture values were observed high above the fibre saturation point. An inspection revealed that the expansion joint had a leak, exactly above the measuring area. Hence, rainwater penetrated the structure and ran over the measuring area. A ventilated cladding was installed at the end grain of the beams to protect them against the penetrating water. The work was done in April 2016 and it can be seen that the timber moisture content decreased in summer. This demonstrates the high influence of structural protective measures on the timber moisture content. A simple installation of a cladding improved the situation considerably.

Fig. 9: Measurement results of the measuring area at a main girder above the foreland
4. Further results

Another indicator for the effectiveness of the protective measures can be seen in Tab. 1. It contains the average of the measured timber moisture contents for the different measuring areas at all bridges. The evaluation period of Höngeberg is more than one and half a year from August 2015 to March 2017. The evaluation period of the other bridges is around half a year from October or November 2016 to March 2017.

<table>
<thead>
<tr>
<th>location of the bridge (structure)</th>
<th>measuring area</th>
<th>average timber moisture content [mass %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Höngeberg (arch bridge)</td>
<td>above foreland</td>
<td>19,2</td>
</tr>
<tr>
<td></td>
<td>above river at tie beam</td>
<td>17,4</td>
</tr>
<tr>
<td></td>
<td>above river at bridge deck</td>
<td>17,4</td>
</tr>
<tr>
<td>Schiffarth (TCC bridge)</td>
<td>above foreland</td>
<td>16,4</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>16,3</td>
</tr>
<tr>
<td>Wippra (TCC bridge)</td>
<td>above foreland</td>
<td>18,9</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>18,3</td>
</tr>
<tr>
<td>Schwäbisch Gmünd (TCC bridge)</td>
<td>above foreland</td>
<td>16,6</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>17,2</td>
</tr>
<tr>
<td>Breitungen (through bridge)</td>
<td>above foreland</td>
<td>16,3</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>16,9</td>
</tr>
<tr>
<td>Sigmaringen (beam bridge)</td>
<td>above foreland</td>
<td>16,6</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>17,4</td>
</tr>
<tr>
<td>Lörrach (truss bridge)</td>
<td>above foreland</td>
<td>17,5</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>18,4</td>
</tr>
<tr>
<td></td>
<td>above road</td>
<td>16,6</td>
</tr>
<tr>
<td>Werdau (through bridge)</td>
<td>above foreland at main girder</td>
<td>17,1</td>
</tr>
<tr>
<td></td>
<td>above foreland at secondary girder</td>
<td>17,8</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>16,8</td>
</tr>
<tr>
<td>Frankenroda (through bridge)</td>
<td>above foreland</td>
<td>18,1</td>
</tr>
<tr>
<td></td>
<td>above river</td>
<td>17,8</td>
</tr>
</tbody>
</table>

Tab. 1: Average timber moisture contents [mass %] at the bridges of the monitoring program

The lowest average value is 16.3 mass % in Schiffarth and Breitungen and the highest one is 19.2 mass % in Höngeberg, whereby the extreme high values are included while the water ran over the measuring area. It can be seen that the timber moisture content is generally lower than the critical 20 mass % limit at all bridges. A relevant difference between the measured timber moisture content above the foreland and the river is not obvious for the current evaluation period.

5. Conclusions and outlook

It is the most important aim of the monitoring program to demonstrate the durability of well-protected timber bridges. Another aim is the investigation of influence of specified local climates on the timber moisture content. To investigate these issues, nine timber bridges have been equipped with monitoring systems to analyse the timber moisture content and ambient climate conditions. Several structures and varying ambient climate conditions characterise the bridges. Eight of them were equipped with a monitoring system in October and November 2016. Results of a longer evaluation period are available for one bridge that was equipped in August 2015. The first results indicate that structural protective measures can guarantee acceptable timber moisture contents. Furthermore, a problem at an expansion joint was detected. A ventilated cladding was installed to protect the affected beams from penetrating...
water before secondary damage at the timber structure could evolve. This shows the potential of monitoring systems to prevent costly damages.

Currently, a great quantity of data is collected. The measuring and analysis of the data is ongoing until autumn of 2018, when the research project will be finished.

6. Acknowledgement

For funding ProTimB, many thanks go to the German Federal Ministry of Education and Research (BMBF), the companies of the Qualitätsgemeinschaft Holzbrückenbau e. V. as there are Schaffitzel Holzindustrie GmbH + Co. KG, Schmees & Lühn Holz- und Stahlingenierbau GmbH and Grossmann Bau GmbH & Co. KG and to Setzpfandt Beratende Ingeniure GmbH & Co. KG.

7. References


