Conference Proceedings 4th ICTB (2022)
https://doi.org/10.24451/mx3b-we02

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

Effectiveness of structural protection measures for timber bridges – results of long-term moisture monitoring

Johannes Koch[1], Antje Simon, Markus G. Jahreis

1 Introduction and motivation

Timber has many advantages. These include the high degree of prefabrication and the related, short-closure times during the construction phase, the almost matchless climate-friendly nature of the building material and, of course, its high level of efficiency in its ratio of load-bearing capacity and mass. As a logical consequence, then, it is suggested that Germany should aim for a significant increase in the use of timber in its bridge constructions.

However, an increase in the use of wood can only be achieved by overcoming the poor reputation of timber bridge construction in Germany. As result of poorly planned and inadequately maintained timber bridges in the past, these are generally seen as not being durable [1]. In order to minimise planning and execution errors in the future and to ensure the maintenance of the structures, new guidelines for the design, construction, maintenance and inspection of protected timber bridges have been developed within the research project, "Protected Timber Bridges" ("ProTimB"), at the University of Applied Sciences Erfurt (FHE). The structure of the developed guidelines is based on the existing regulations of the German federal highways. The guidelines can be downloaded from the FHE website [2] and are presented in summarised form on ICTB 2021 PLUS [3].

A second approach, "ProTimB", had the aim of creating a database on timber moisture content in timber bridges built over water. Here, the idea was to reduce the number of restrictive requirements on timber bridge inspections. A guideline for federal road bridges suggests that the durability of timber bridges crossing bodies of water is critical [4]. Therefore, annual major inspections are required for such timber bridges regardless of whether or not the bridge is protected against the ingress of precipitation and moisture. Bridges made of other construction materials need only be inspected every six years.

Short intervals of inspections of non-protected timber bridges are useful, as this type of bridge is subject to the risk of fungal decay due to the timber moisture content being higher than 20 mass%. However, structural protection enables a timber moisture content that is lower than 20 mass%, hence, fungal decay should not occur [5][6] – which would also make the necessity of annual inspections of these protected timber bridges unlikely. Furthermore, it is also very inconvenient for the building owners, as the annual inspections result in high maintenance costs. As a consequence, there is a certain reluctance to building timber bridges. "ProTimB" aimed at demonstrating that timber bridges over bodies of water are not exposed to a higher risk of fungal decay, providing they are structurally protected against precipitation and moisture ingress.

This paper describes the results of a monitoring programme of nine structural protected timber bridges in Germany.

2 Outline of the monitoring programme

2.1 Background

Fresh infestation can only occur if the timber moisture content exceeds the fibre saturation point. The fibre saturation point lies in the range of about 26–34 mass% for local softwood species [7]. Such a high level of moisture content will be reached where the structure is exposed to precipitation and other moisture ingress. A moisture content up to the fibre saturation point can also occur in timber depending on the ambient climate, as it is a hygroscopic material whose moisture content constantly adjusts to the humidity and temperature of the ambient air.

However, the German wood protection standard DIN 68800 requires a long-term timber moisture content at a maximum of 20 mass% for load bearing components [8]. Additionally, it is explained that decay is not

[1] Corresponding Author, Ph.D. student and research assistant, Fachhochschule Erfurt - University of Applied Sciences, Germany, johannes.koch@fh-erfurt.de

https://doi.org/10.24451/mx3b-we02

expected if the wood is not exposed to a moisture content higher than 20 mass% for more than four months [9].

In order to show that structurally-protected timber bridges are not at a higher risk of decay, a moisture monitoring programme was initiated as a part of the "ProTimB" research project. The intention was to demonstrate that the timber moisture content remains permanently below 20 mass%.

2.2 Overview

The monitoring programme of structurally-protected timber bridges under "ProTimB" was unique with regard to both its systematic and scope in Germany. The timber moisture content and the ambient climate were recorded at nine protected timber bridges of different construction types throughout Germany, as shown in Figure 1 below. All bridges span a river and a part of the foreland, while one bridge in Lörrach additionally spans a highly-frequented, federal road. The first measurement system was implemented in August 2015 on a road bridge in Lohmar-Höngesberg. The other eight systems were implemented in the autumn of 2016. At the bridge in Lörrach, a second measuring system with additional measuring points was set up in 2018. The monitoring systems on five of the nine bridges were removed in summer 2019, at the end of "ProTimB". Yet, the monitoring on the other four bridges that are located in Lohmar-Höngesberg, Lörrach, Wippra and Breitungen continues to the present time.

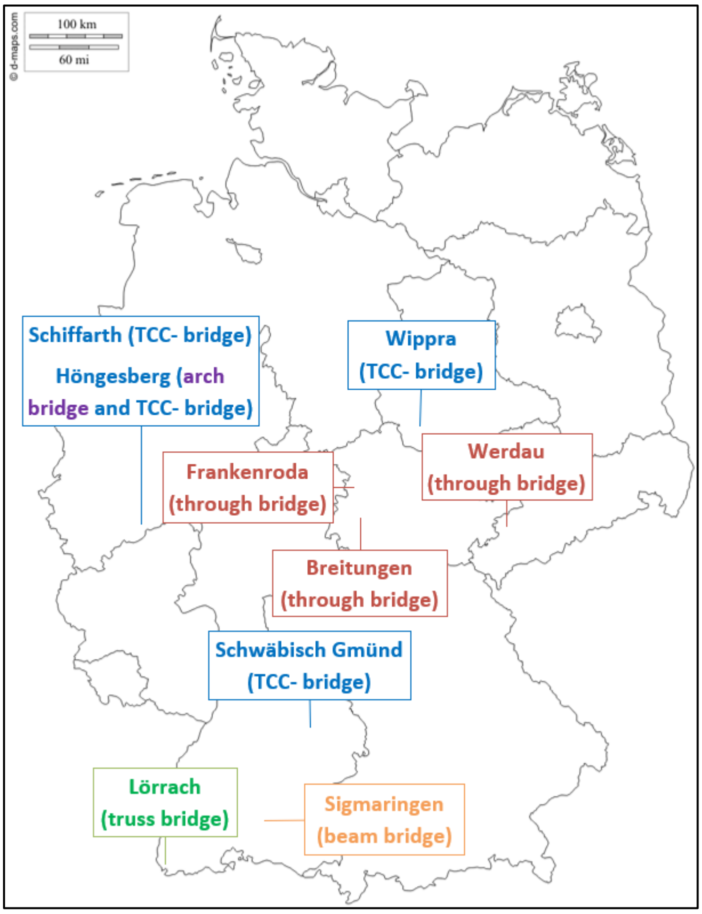

Figure 1: Location and construction type of the bridges within the "ProTimB" monitoring programme

A system with eight pairs of electrodes was implemented at each structure to measure the electrical resistance of the wood, distributed over two or three measuring areas. In each case, there were measuring points with several measuring depths above the waters and in the foreland. Furthermore, the timber temperature, air temperature and relative humidity were also logged at each of the measuring areas. Figure 2 below shows the road bridge in Lohmar-Schiffarth with the implemented equipment and four pairs of electrodes at the two measuring areas.

More details of the implementation of the monitoring systems and the bridges of the programme are given in [10][11][12].

Figure 2: View of the TCC road bridge in Lohmar-Schiffarth (top of the image); measuring area over the foreland (bottom left); measuring equipment in an installation box (bottom centre); measuring area over the River Agger (bottom right of the image)

2.3 Method

The timber moisture content is estimated by using the electrical resistance method, which is standardised for sawn timber [13]. Using experimentally-determined wood species-specific calibration curves, the moisture content of the timber can be derived from the measured resistance. However, the electrical resistance is also influenced by the temperature. Therefore, the timber moisture content has to be calculated from the measured electrical resistance using the calibration curves, and corrected using the measured timber temperature.

The equilibrium moisture content was computed according to the mathematical Hailwood-Horrobin sorption model using the ambient climate conditions, relative humidity and air temperature [14]. Theoretically, this moisture content occurs directly on the wood surface. Given that the timber moisture content is not determined at the surface, but at several depths of the cross section, it should be noted that this calculated value may not exactly match the timber moisture content directly calculated from the measured electrical resistance. Changes in climatic conditions affect the timber moisture content deeper in the cross section with a time delay. Furthermore, no material specific parameters were available for the Hailwood-Horrobin sorption model to calculate the timber moisture content for larch (*Larix decidua*) and European spruce (*Picea abies*) – the species of wood used for the bridges of the monitoring programme. Thus, the equilibrium moisture content for all structures was determined on the base of data for Sitka spruce (*Picea sitchensis*) [15].

However, a comparison between the equilibrium moisture content and the timber moisture content can be used to understand how the ambient climate influences the timber moisture content. Excessive discrepancies could be an indication for free water in the area of the sensors.

3 Results and discussion

3.1 Effectiveness of structural protection measures

Table 1 shows the mean values of the timber moisture content (TMC) and the equilibrium moisture content (EMC) of all nine bridges of the "ProTimB" monitoring programme. It can be observed that at none of the nine bridges do the mean values exceed 20 mass%. Generally, this is a positive trend as concerns the risk of decay.

Table 1: Mean values of the timber moisture content (TMC) and the equilibrium moisture content (EMC) in mass% of the bridges of the "ProTimB" monitoring programme

Location of the bridges	**Evaluation period**	**TMC above foreland [mass%]**	**TMC above river [mass%]**	**EMC above foreland [mass%]**	**EMC above river [mass%]**
Lohmar Höngesberg	19.08.2015 - 13.11.2019 04.05.2021 - 31.01.2022	18.6 18.5	17.1 18.2	15.9 15.6	16.3 16.2
Lohmar Schiffarth	21.10.2016 - 18.06.2019	16.0	15.9	16.5	15.7
Wippra	13.10.2016 - 21.01.2022 13.10.2016 - 28.02.2021	18.1	17.8	no sensor	17.8
Schwäbisch Gmünd	28.10.2016 - 30.04.2019	15.7	16.1	14.7	15.3
Breitungen	26.10.2016 - 31.01.2022	15.9	15.9	16.6	16.0
Sigmaringen	04.11.2016 - 14.05.2019	16.6	15.9	16.5	16.4
Lörrach System I	03.11.2016 - 31.01.2022	19.1	19.5	15.6	16.2
Lörrach System II	01.02.2018 - 28.04.2021 15.03.2019 - 28.04.2021	16.3	16.8	no sensor	no sensor
Werdau	24.11.2016 - 06.06.2019	16.0	15.7	16.3	16.0
Frankenroda	23.11.2016 - 27.05.2019	16.5	16.7	16.7	15.9

However, it is also important to take the development of moisture content into account in shorter periods. As described above, 20 mass% should not be exceeded for longer than four months. Examples of the development of the timber moisture content and equilibrium moisture content on two bridges are given in Figures 3 and 4.

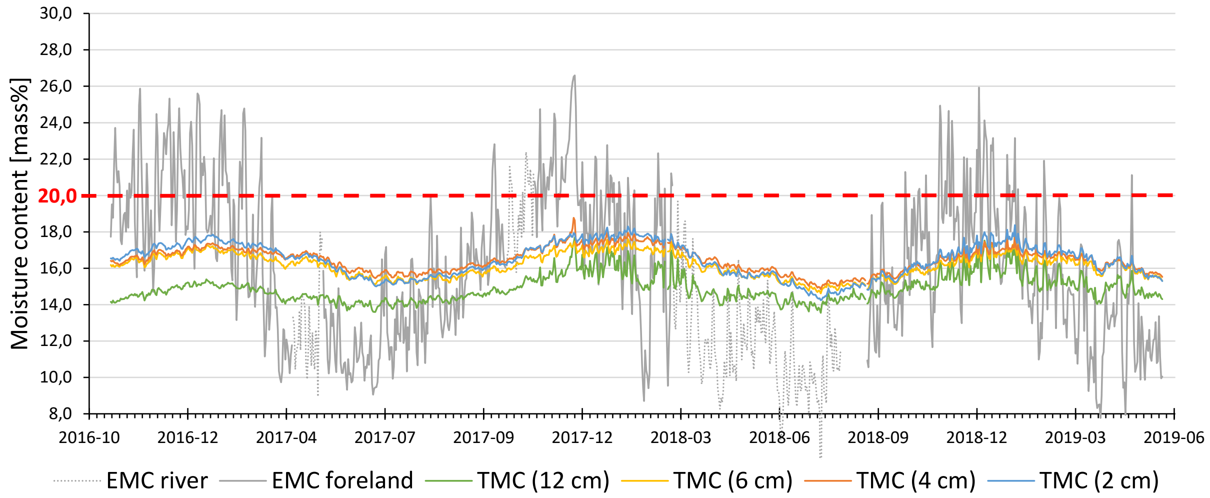

Figure 3: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the bridge in Lohmar-Schiffarth (measuring area: foreland)

Figure 3 shows the development of moisture content at the bridge in Lohmar-Schiffarth near Cologne at the measuring area above the foreland. The timber moisture content follows the equilibrium moisture content that represents the climate conditions with a time delay. The seasonal climate changes are clearly visible. It can also be seen that the timber moisture content does not exceed the limit of 20 mass% during the whole evaluation period from October 2016 to Jun 2019. Figure 3 is representative of the measuring results of the bridges in Schwäbisch Gmünd, Breitungen, Werdau and Frankenroda. At all of these, the timber moisture content remains below 20 mass%. Therefore, decay is not expected in the measuring areas. It should be taken into consideration that the measurements are only punctual and not distributed over the whole superstructures. However, the results show that the structural wood protection measures are effective.

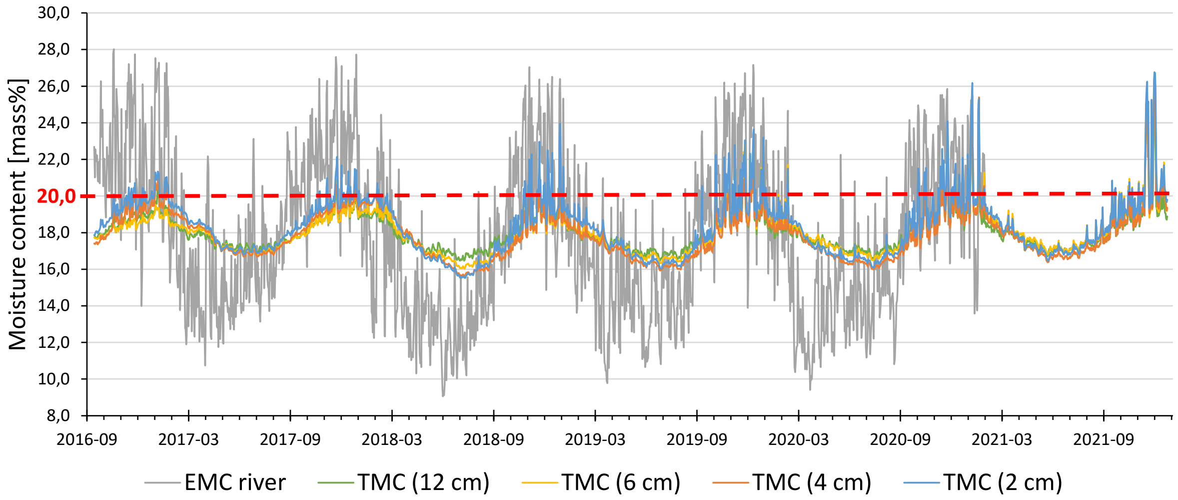

Figure 4: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the Birkberg bridge in Wippra (measuring area: foreland)

On the other hand, there are areas with exceeded moisture content in the winter periods, which is shown in Figure 4. This occurs at the bridges in Wippra, Lohmar-Höngesberg and Lörrach, as well as Sigmaringen in certain periods. In the graph it can be seen that the period of higher moisture level over 20 mass% is limited to three or four months per year. The wood usually dries back to an acceptable level after February. These short periods of higher moisture level are also acceptable in preventing the risk of decay.

However, when looking at the mean values of the moisture content in Table 1, a number of other questions arise. Most bridges have a mean value of 16 mass%. The bridges of Lohmar-Höngesberg and Wippra are at 18 mass%, and at Lörrach a little higher at 19 mass%. The question here is why this is the case.

Figure 4 shows that the moisture content is directly related to the climate conditions represented by the equilibrium moisture content. There are no unusual offsets on the graph. Thus, the continuously 2 mass% higher moisture level at the Birkberg bridge in a valley near to Wippra appears to be a consequence of the more humid and colder climate in the Harz mountains. The higher equilibrium moisture content for this location confirms this.

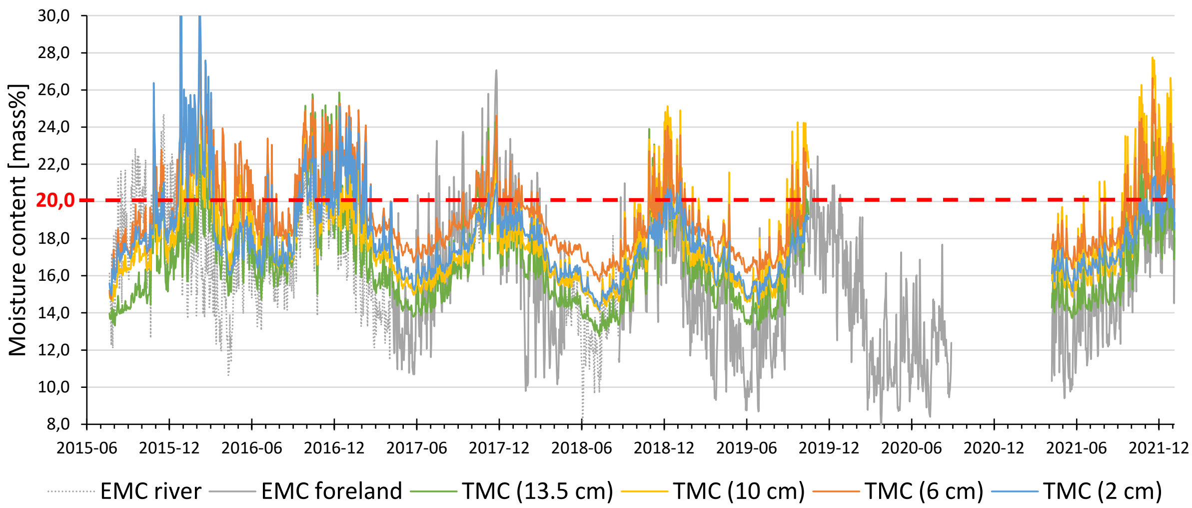

Figure 5: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the bridge in Lohmar-Höngesberg (measuring area: foreland)

The situation is different at the bridges in Lohmar-Höngesberg and Lörrach. In the first case, a high timber moisture level was already noticed in the first winter of the monitoring in 2015/2016. Specifically, it was then noted that an expansion joint situated above the measuring area had failed. This resulted in rainwater running over the measuring points, meaning that, in certain cases, the measured timber moisture content reached a high value (Figure 5). As a first act to remedy this, cladding was installed to protect the wood from the rainwater. It is also evident that the moisture content is higher than 20 mass% during some winter months. This contrasts with the results of the measurements at the other two measuring areas above the river. In Figure 6 below, the graph shows shorter periods of moisture contents higher than 20 mass%. It is assumed that the rainwater creates a more humid climate in the measuring area above the foreland. Therefore, it is necessary for the failed expansion joint to be replaced as soon as possible.

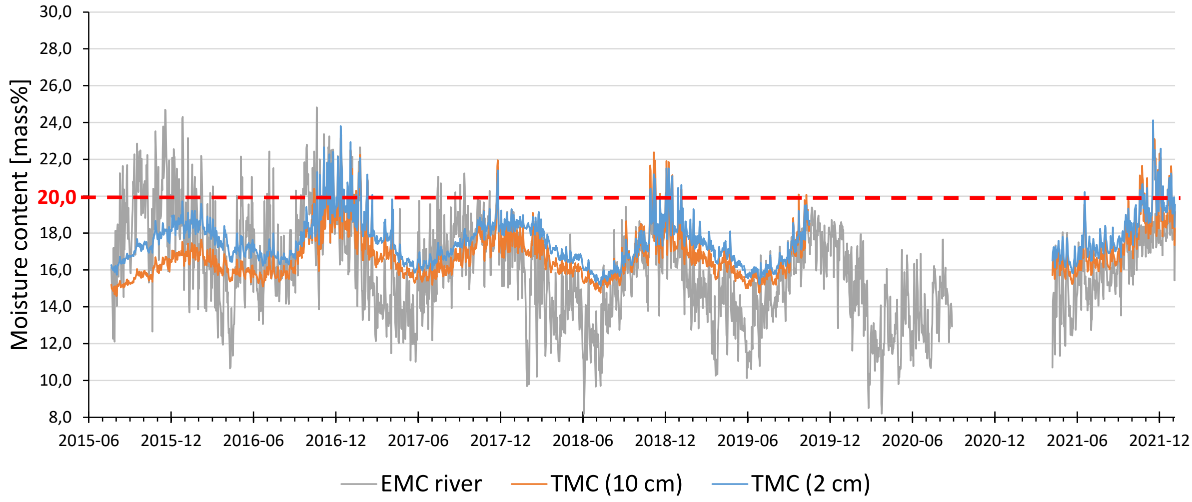

Figure 6: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the bridge in Lohmar Höngesberg (measuring area: river - arch bridge tension member)

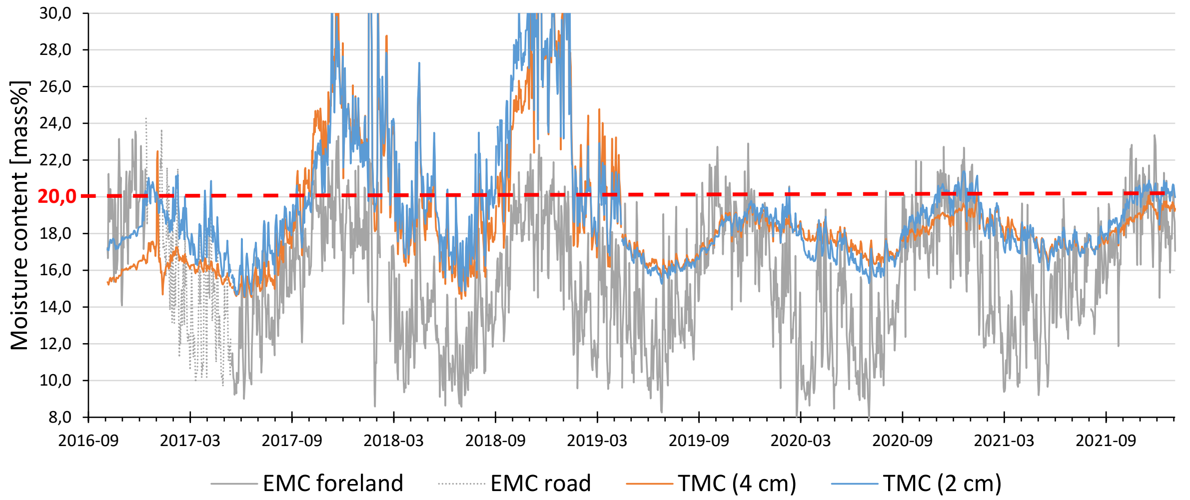

Figure 7: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the bridge in Lörrach (measuring area: foreland)

It can be noted that moisture monitoring at bridges or other structures can help to explore or monitor neuralgic points in the wood protection or waterproofing concept of a structure. Monitoring also proved to be a benefit for the future of the bridge in Lörrach. As the graph in Figure 7 shows, during the period between October 2017 and April 2019, moisture content reached a high level for a long time, sometimes beyond the fibre saturation point. It was found that the angle of precipitation is sometimes almost horizontal due to an unusual air flow in the valley where the bridge is situated. Despite the carefully-planned wood protection concept in accordance with the current standard specifications (see [8] [16]), the lower load bearing components of the bridge were regularly exposed to weather. Rain and snow penetrated the structure between the roof and the cladding (see Figure 8). This resulted in the lower chord of the truss being wetted. To solve the problem, a number of variants for improving the structural wood protection concept were investigated.

The preferred option was a sensor-controlled curtain that closes the gap between roof and cladding in times of precipitation [17].

Figure 8: View of the bridge in Lörrach

In summary, the structural wood protection measures show positive effects at the observed bridges. Problems only occurred at two of the nine bridges. The failure of the expansion joint at the bridge in Lohmar-Höngesberg should be replaced as soon as possible in order to ensure the full functionality of the structural wood protection concept of this bridge. Only in the case of the bridge in Lörrach was the wood protection insufficient in its original design for the extraordinary exposure. This problem was identified by the monitoring and an innovative solution was developed.

3.2 Moisture exposure of timber bridges spanning waters and roads

All bridges of the monitoring programme span over rivers. They span smaller rivers such as the Agger, the Wipper and the Pleiße, or larger rivers such as the Danube and the Werra. However, at none of the sites was an unusually high moisture level observed that can be associated with the waters.

In Table 1 above, the difference can be seen between the timber moisture content of the measuring areas above the river and the measuring areas above the foreland, which for all bridges is a maximum of 0.7 mass%, except for the bridge in Lohmar-Höngesberg in the period between October 2015 to November 2019. As described above, the difference there is twice as high as a result of the failed expansion joint. Nevertheless, the timber moisture content at all bridges is at a tolerable level.

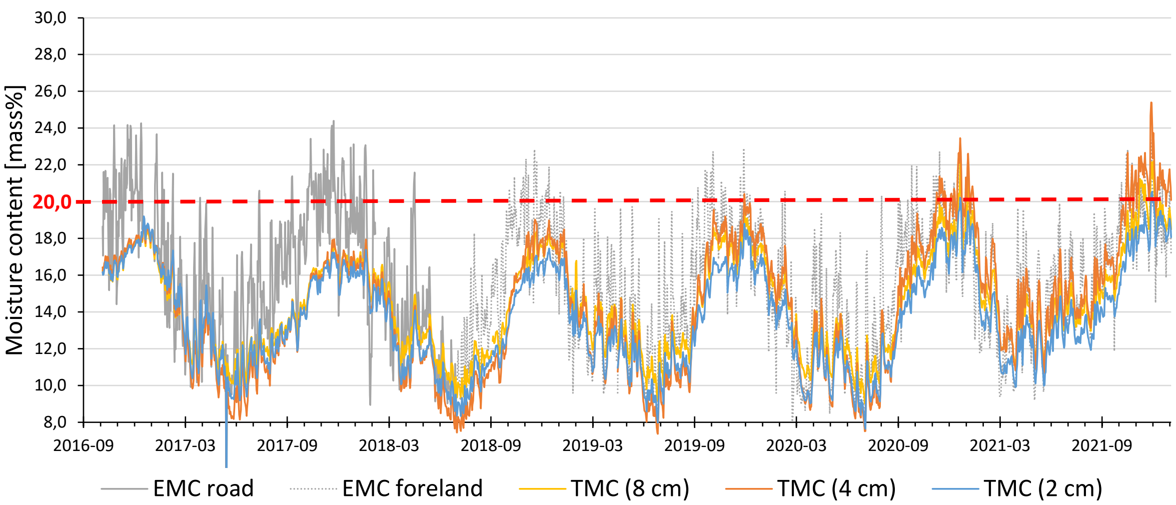

Figure 9: Daily mean values of equilibrium moisture content (EMC) and timber moisture content (TMC) at different measuring depths at the bridge in Lörrach (measuring area: road)

Conference Proceedings 4th ICTB (2022)
https://doi.org/10.24451/mx3b-we02

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

In addition to the fact that the bridge in Lörrach spans the river Wiese, it also spans a highly- frequented federal road. In order to investigate spray exposure from road traffic, an additional measuring area was set up above the road. The results can be seen in Figure 9 above. The mean value of the timber moisture content is 14.2 mass% for the whole evaluation period from November 2016 to January 2022.

Contrary to expectations, the wood moisture content is relatively low and even lower than at the other measuring areas, despite the spray exposure. Therefore, it seems that the spray is not a relevant factor for the moisture load of this structure. This assumption is supported by the results of a Swiss study, which found that the spray is almost irrelevant for the moisture content of timber components located at a distance of about five metres above a road [18]. Nevertheless, it is important to mention that only one bridge spanning a road was investigated in the "ProTimB" monitoring programme. Hence, further investigations should be conducted.

The results of the monitoring show that the moisture content of the components of protected timber bridges does not seem to be influenced to any relevant dimension by the fact that the bridges span water bodies or are influenced by spray resulting from traffic over roads. Therefore, it does not seem to be useful to conduct an expensive and complex main inspection of such bridges every year. Rather, it is suggested that adequate maintenance of the bridges is provided for, and that monitoring in the first few years after construction is carried out so as to be able to identify any unexpected vulnerabilities in the structural wood protection concept.

4 Conclusions

The idea and realisation of an extensive moisture monitoring programme of nine structurally- protected timber bridges in Germany was described in this paper. The results of the monitoring show the effectiveness of structural wood protection measures, but they also demonstrate the benefit of monitoring timber bridges in the first few years after construction. It was found that waters underneath the bridge or spray generated by traffic on roads under the bridges do not affect the moisture content of the bridge construction. Therefore, an annual inspection is not necessary. It is suggested the results of the "ProTimB" monitoring programme will contribute towards overcoming the poor reputation of timber bridge construction in Germany, and furthermore support an increased use of timber in bridge construction.

5 Acknowledgement

The monitoring programme was part of the research project "Protected Timber Bridges (ProTimB)", which has been supported and funded by the Federal Ministry of Education and Research of Germany, the companies of the Qualitätsgemeinschaft Holzbrückenbau e. V. (Schaffitzel Holzindustrie GmbH + Co. KG, Schmees & Lühn Holz- und Stahlingenieurbau GmbH, Grossmann Bau GmbH) and Setzpfandt Beratende Ingenieure GmbH & Co. KG. The authors thank all partners and supporters for their technical and financial support.

6 References

[1] Hemmert-Halswick, A. (2012) Nachhaltigkeitsgedanken zum Holz im Brückenbau. in: Forum Holzbau [Hrsg.] 2. Internationale Holzbrückentage (IHB). DE-Bad Wörishofen, 19th and 20th Apr. 2012.
[2] Online source: https://www.fh-erfurt.de/fakultaeten-und-fachrichtungen/bauingenieurwesen-und-konservierung-restaurierung/bauingenieurwesen/projekte/protimb-ergebnisse
[3] Simon, A.; Jahreis, M.; Koch, J (2022) Design, construction and maintenance of structurally protected timber bridges. in: ICTB 2021 plus, CH-Biel, 09th to 12th May 2022.
[4] Bundesministerium für Verkehr und digitale Infrastruktur (2017) Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfungen nach DIN 1076 (RI-EBW-PRÜF). Feb. 2017.
[5] Graf, E.; Meili, M. (2001) Holzzerstörende Pilze und Insekten – Analyse, Prognose, Bekämpfung. in: Lignum, Schweizerische Arbeitsgemeinschaft für das Holz [Hrsg.] Lignatec: die technischen Informationen der Lignum: EMPA/LIGNUM-Richtlinie 14. Rüschlikon: Schück Söhne AG.
[6] Mohrmann, M.; Wiegand, T. (2015) Holzschutz bei Ingenieurholzbauten. in: Studiengemeinschaft Holzleimbau e.V. [Hrsg.] holzbau handbuch, Reihe 5 Teil 2 Folge 1.
[7] Trendelenburg, R; Meyer-Wegelin, H. (1955) Das Holz Als Rohstoff. Munich: Carl Hanser Verlag.
[8] DIN 68800-1 (2019) Holzschutz – Teil 1: Allgemeines. Berlin: Beuth. June 2019.

[9] Willeitner, H. (2013) Kommentar zur DIN 68800-1:2011-10 – Holzschutz – Teil 1: Allgemeines. in: Marutzky R. [Hrsg.] Holzschutz – Praxiskommentar zu DIN 68800 Teile 1 bis 4. 2. completely revised edition. Berlin: Beuth, p. 9–76.

[10] Koch J., Simon A., Arndt R. W. (2016) Monitoring of moisture content of protected timber bridges. In: CD-ROM Proceedings of the World Conference on Timber Engineering (WCTE 2016), AT-Vienna.

[11] Koch J., Arndt R. W., Simon A., Jahreis M. G. (2017) Moisture monitoring of nine protected timber bridges in Germany. In: 3rd International Conference on Timber Bridges, SE-Skellefteå.

[12] Arndt R. W., Koch J., Simon A., Jahreis M. G. (2018) ProTimB - Monitoring of structurally protected timber bridges. In: NDE/NDT Structural Materials Technology for Highways and Bridges (SMT) and the International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), US-New Brunswick.

[13] DIN EN 13183-2:2002-07: Feuchtegehalt eines Stückes Schnittholz - Teil 2: Schätzung durch elektrisches Widerstands-Messverfahren; Deutsche Fassung EN 13183-2:2002.

[14] 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.

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

[16] DIN EN 1995-2/NA (2021) Nationaler Anhang – National festgelegte Parameter – Eurocode 5: Bemessung und Konstruktion von Holzbauten – Teil 2: Brücken. Berlin: Beuth. June 2021.

[17] Schmees, J. (2018) Was heißt schon geschützt – Fachwerkbrücke über die Wiese und die B 317 in Lörrach in: Forum Holzbau [Hrsg.] 24. Internationales Holzbau-Forum (IHF). DE-Garmisch-Partenkirchen, 5th to 7th Dec. 2018.

[18] Finger, A.; Sell, J.: Bewitterungsversuch an Holzfachwerk. Prüfbericht Nr. 414433, EMPA, Dübendorf, 29th Oct. 2002.