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ORIGINAL ARTICLE

Monitoring climatic impacts on the moisture uptake of the first Swiss wildlife bridge made of wood

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Abstract

Wildlife bridges represent a major component of any sustainable strategy to counteract the negative consequences of cutting the natural habitat of wildlife into disconnected parts by motorways and rail. This is especially true for a small and densely populated country such as Switzerland with diverse wildlife scattered through its territory. Up to now all wildlife bridges in Switzerland have been made of concrete with steel reinforcement. The wildlife bridge under investigation here is the first one in Switzerland made of wood-based materials. The idea of building a wildlife bridge by using wood-based materials represents besides a challenging technological endeavor also an ecological progress regarding embodied energy. A further advantage which resulted after realizing the construction, was the short interruption time it needed for installation on a motorway in operation. The most urgent question with respect to the wood-based elements is their moisture uptake when subjected to weather conditions. The present paper reports on a long-term monitoring of this wooden wildlife bridge over a period of approximately 2 years. Different kind of sensors, data from a nearby meteorological station, data regarding hourly number of different kind of vehicles passing beneath the wildlife bridge as well as lab measurements have been used to enable a robust and reliable statement on wooden wildlife bridges subjected to Swiss flatland weather conditions.

1 Introduction

The usage of wood and wood-based materials and combinations thereof with other materials in construction has experienced worldwide an unprecedented increase in the last decade and the trend is continuing. This applies to different construction types such as single houses, high-rise buildings, bridges, overpasses etc. A further possibility to use wood-based materials instead of concrete or steel is the case of wildlife bridges. These are special bridges built over motorways or railway lines to reconnect the disconnected wildlife habitat. Most such bridges have been made of concrete.

The presently investigated wildlife bridge (Fig. 1) is the first one in Switzerland made of wood-based materials and was completed in spring 2021. Its construction and installation procedure were reported by Timbatec (2021). This was a major achievement despite the old prejudice against wood in such constructions and a result of the motion «Research and innovation of wood as a material for use in infrastructure construction as a contribution to decarbonization» accepted in the Swiss Council of States and the National Council.

It must be mentioned that some previous experiences regarding a wood-based wildlife bridge in Luckenwalde/Germany have been reported by Bauer (2016) including extensive details on the construction steps and protective measures but without any monitoring of the long-time behavior of the moisture content which represents a key issue with respect to durability. This property is of utmost importance when wood-based materials in one way or another come in contact with the outdoor climate.

There is a considerable number of scientific publications dealing with monitoring timber structures in general

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Fig. 1 An element of the wooden wildlife bridge on its way to the installation site (top left), the finished construction with the bitumen layer before filling the roof with earth (top right), and finally the frontal view of the entry (bottom)

and specifically the influence of the moisture content and methods to measure it, out of which only a selected number will be briefly reviewed here to represent the state of the art. Dietsch et al. (2015a) have monitored and assessed 245 large-span timber structures and found that in almost half of the cases damage can be attributed to moisture content and its variations over time. The study takes only indoor climate into account and makes use of the electrical resistance method.

Brischke et al. (2008) reported on a robust measurement system for long-term recording of wood moisture content with internal conductively glued electrodes. After several years of natural weathering with many extreme climatic conditions and moisture variations, no loosening or other detectable abnormality in 541 pairs of electrodes was observed by the authors. Another study pointed to the possibilities of applying electric measurements for moisture content of different types of wood modification and preservative treatments, highlighting a strong need to determine material-specific resistance characteristics when precise moisture content estimation is required (Brischke and Lampen 2014).

Lanata (2015) reports on long-term behavior of timber structures also taking the moisture content into account. There is an interesting focus on how connections and details are designed to avoid moisture trapping when exposed to outdoor conditions. A case study on a timber bridge has been reported by Franke et al. (2015) showing that moisture in timber members subjected to outdoor climate conditions varies in the range of 12 to 22%, which is considered well below the critical amount of 25% for decay hazards. An extensive review on structural health monitoring of timber structures has recently been published by Palma and Steiger (2020). In this report, several Non-Destructive Test (NDT) methods have been presented with respect to the determination of the moisture content including the advantages and disadvantages of each method. The review closes with several case studies from different parts of the world. More specific literature exists on the influence of moisture content on the mechanical properties of glulam beams and laminated veneer lumber. Franke et al. (2019) have reported on moisture-induced stresses of large glulam members using laboratory tests, in-situ measurements, and modelling. They investigated sun and rain-protected structures and found that the outdoor climate load influences mostly the outer zone of the cross-section the so-called active zone which is around 50 to 70 mm if the limit of permissible average moisture variations is set at 3 M%. A concise review on the long-term effect of humidity on the mechanical properties of wood-based materials has recently been published by Wang et al. (2021) where accelerated aging tests and their correlation to outdoor exposure have been reviewed. There is also the question of protecting timber bridges which can be done by design, by special preservative treatment, by wood modification, and by monitoring and inspection. A short but informative review on this topic has been published by Mahnert and Hundhausen (2018).

The present study reports and discusses the measured results of a rigorous monitoring installed in the first wood-based wildlife bridge in Switzerland over a period of approximately two years. It is noteworthy to mention that the wildlife crossing spans one of the busiest stretches of highway in the ASTRA network, passage of approx. 60,000 vehicles per day. The study investigates the influence of boundary conditions such as weather and traffic on the moisture uptake. It is anticipated that the level of moisture content will be well beneath the critical value causing damage in wood-based materials.

2 Materials and methods

2.1 The moisture monitoring system

The main part of the monitoring system consists of sensors measuring moisture and temperature of enclosed air cavities at different depths of the wood-based material (Fig. 2). This method is also called sorption method, bore hole method or hygrometric method (Flexeder et al. 2022).

This in-situ measurement method was regarded as advantageous over the more common electrical measurements, due to reported artefacts measured in wood (mature heartwood of Norway spruce) caused by non-uniform moisture distributions (Fredriksson et al. 2021). A more straightforward reason for this choice is the fact that the electrical resistance method applied to laminated veneer lumber needs a case-by-case recalibration according to Grönquist et al. (2021). An instructive and comparative overview on methods to determine moisture content and their suitability for long-term monitoring has been reported by Dietsch et al. (2015b). Therein the authors mention that the indirect monitoring of the moisture content using the sorption method is especially applicable to treated timber elements and the known correlation between moisture content and electrical resistance is not valid anymore. Schiere et al. (2022) have compared the two moisture content measurement methods for monitoring of a timber bridge in Andelfingen, Switzerland. The timber elements of the bridge were shielded from direct precipitation while still being exposed to outdoor conditions, like the here investigated wild-life bridge. The relationship between the two measuring methods was determined by auxiliary laboratory experiments. The measurements on the bridge over a period of two years resulted in overlapping values for both methods. Flexeder et al. (2022) also compared these two methods but found that the sorptive methods result in higher values of moisture content (2–3 M%) and that the electrical measurement is biased by the presence of strong temperature gradients. It is worth noting that a correct approach to mitigate this bias and obtain accurate temperature corrections is to install a thermistor at the same depth as the electrodes.

A better view of the wooden ceiling is given in Fig. 3 (left). A zoom into a part of the ceiling instrumented with sensors and node boxes for wireless transmitting of data is given on the right part of the same figure. There are sensors in each of the three elements of the ceiling namely the

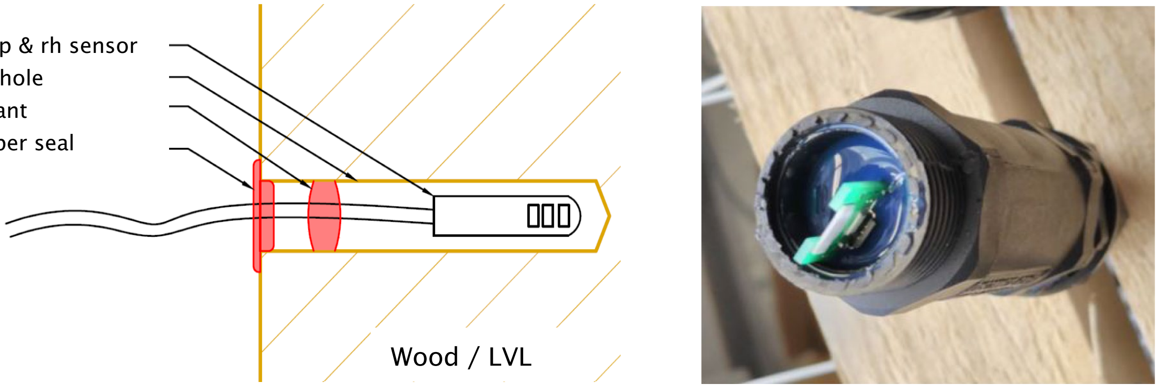


Fig. 2 Sensor for measuring the relative humidity at different depth of the wood-based material by the sorptive method

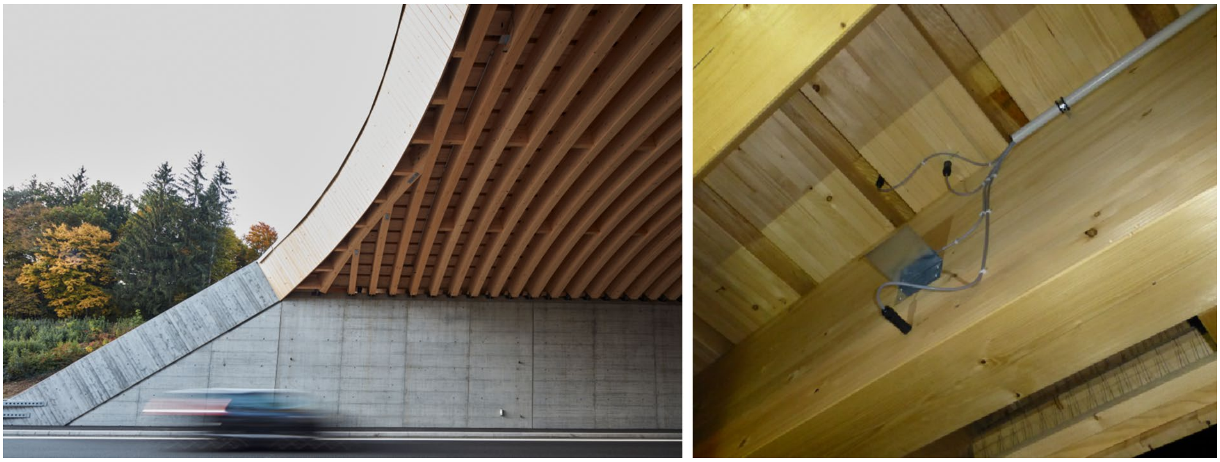


Fig. 3 View onto the ceiling at the entrance of the wild-life bridge (left) and some installed sensors to monitor moisture content in different parts and depths (right)

primary load-bearing glulam crossing the lane, the secondary load-bearing glulam parallel to the lane (on top of the first one), and finally in the cover layer and along the lane (laminated veneer lumber LVL). An overview of the sensor installation sites is given in a schematic representation in Fig. 4.

A detailed description of the built-in sensors, and their position at different sites A, B and C (Fig. 4) is given in Fig. 5. The reason for this large number of sensors is to get representative results from this monitoring project and to be able to cope with the unpredictable loss of some sensors on the one hand and the eventual

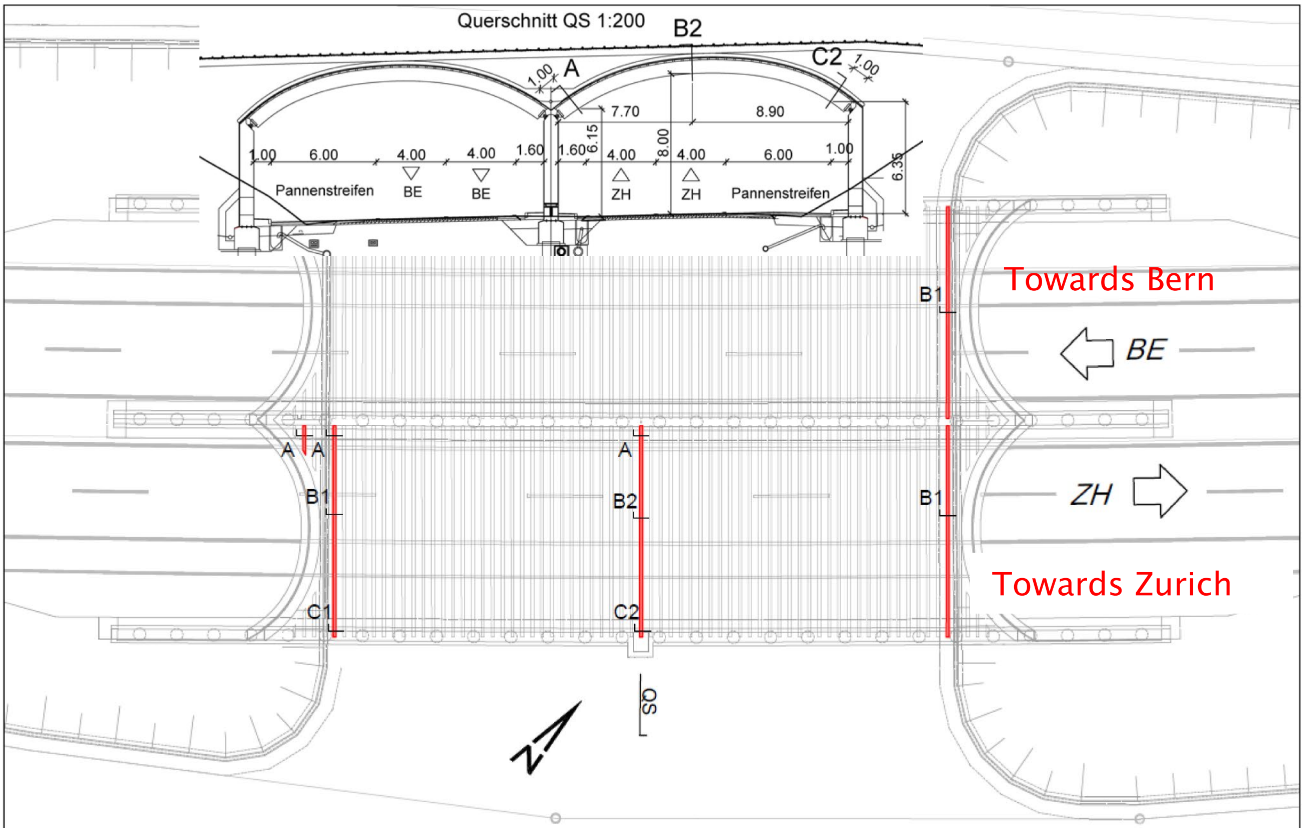


Fig. 4 Schematic representation of the sensor distribution in the wild-life bridge

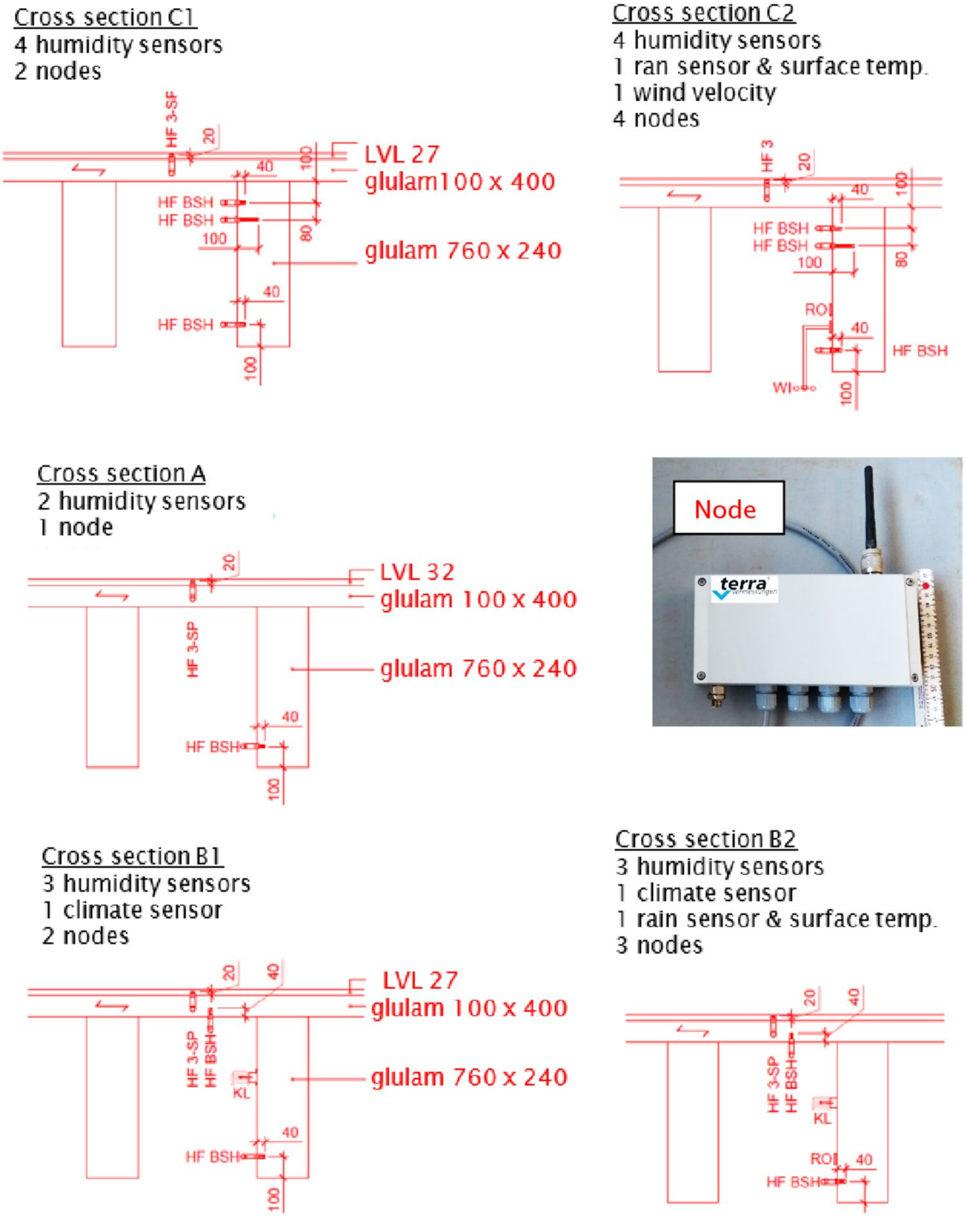


Fig. 5 Details of the positioning of sensors at different sites A, B and C within the three components of the wooden ceiling (LVL, upper glulam, lower glulam). Each node (identified by the name given by the system HF BSH, etc.) sends its measured data via wireless technology to a central logger

non-homogeneity of moisture distribution in the wooden parts on the other. The indicated climate sensors incorporate a combined temperature and humidity sensor for the air. The temperature of the air is measured by a Pt 1000 B Sensor (accuracy of 0.3 K at 20 °C) and the air relative humidity by A T14 SMD sensor (accuracy of 3%).

The instrumentation was carried out using wireless measurement systems with nodes (Fig. 5). The LoRaWAN technology allows data transmission over several kilometers but is only limited to low measurement frequencies. When monitoring wood moisture levels or climate changes, a measurement frequency of one to 3 h is considered as sufficient.

2.2 Sorption isotherms of the wood-based elements

It has to be mentioned that the wooden lamellas used for the glulam were pressure-impregnated prior to their assembly. This was done by using “Impralit BKD5”, a colorless and heavy metal-free impregnation based on aqueous salt with a preventative effect against wood-destroying insects and rotting fungi. In addition, the glulam elements were hydrophobized by using Samiperl, a colorless hydrophobic and oleophobic finish containing a fluor-carbon component. The LVL has not been hydrophobized.

As the hygric properties of wood and especially treated and glued wooden elements vary and might differ from the values stated in the literature and in the data set of hygrothermic simulation tools, it was decided to measure the sorption isotherms at 20 °C of glulam and 3-layer solid wood samples to obtain comparative values. Figure 6 shows the four sets of samples cut out of spare elements of glulam (edge D and core C), the LVL 32 (E), and the LVL 27 (F). The image on the left side of Fig. 6 shows how the edge and core samples were cut out of the impregnated glulam element. In total there were 15 C and 15 D samples of 50 × 40 × 12 mm each, 9 E samples of 50 × 50 × 33 mm, and finally 9 F samples of 50 × 50 × 28 mm.

In a first step, the samples were dried according to ISO 12570 (2000). The samples were dried in a drying oven for 7 days. The equilibrium condition of the standard was then met i.e., mass change < 0.1% after three consecutive measurements, each 24 h apart. Then the dry density of each sample was determined. In the next step, the sorption isotherm of each sample was determined according to EN ISO 12571 (2021). The dried samples were stored in a climate chamber under preset temperatures and relative humidity. The actual values were checked with calibrated sensors (Elpro Ecolog) as shown in Fig. 7.

Fig. 7 Test specimen in the climate chamber with data logger to check the actual boundary conditions (temperature and humidity)

2.3 Traffic monitoring

According to the guideline for traffic counters of the Swiss Federal Roads Office FEDRO, the data for all vehicle classes was available individually (Table 1, Swiss 10). From these, however, the truck-like vehicles (types 1, 8, 9 and 10) were combined and summarized for the two directions of travel Zurich and Bern. The reason is that these vehicles, due to their geometry, aerodynamics, and speed, can cause a much larger and higher spray over the road when it rains and can thus increase the moisture content of the wooden structure.

3 Results and discussion

The results of the investigation are summarized in the four following subsections. For the purpose of clarity wherever wood moisture is mentioned, it refers to the amount of water in the wood-based material divided by its oven-dried mass (kg/kg).

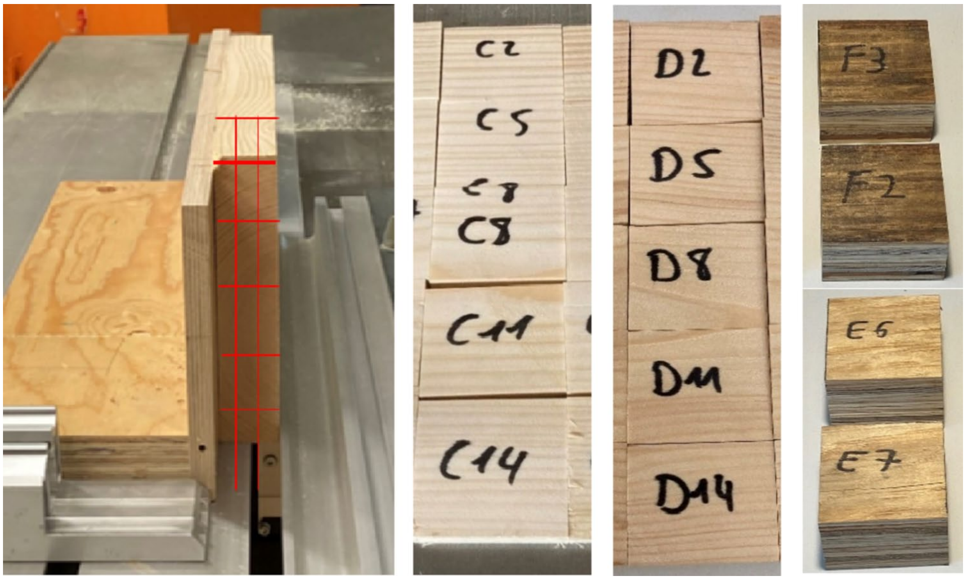


Fig. 6 Glulam core (C) and Glulam edge (D) specimens cut out of pressure impregnated glulam and specimens cut out of LVL 32 (E) and LVL 27 (F)

Table 1 Vehicle classes according to the Swiss Federal Roads Office FEDRO. In gray are those considered for the present investigation

Recording of the classes according to the "Swiss 10" scheme	Recording for the Swiss Road Traffic Census (SSVZ)	Recording for traffic management
2: motorcycle	2: motorcycle	1: Car-like vehicles (vehicles < 3.5 t)
3: passenger car	3: passenger car	
4: passenger car with trailer		
5: delivery truck	4: delivery truck	
6: truck with trailer		
7: truck with heavy trailer		
1: bus, car	1: bus, car	2: Truck-like vehicles (vehicles > 3.5 t)
8: lorry	5: lorry	
9: articulated lorry	6: articulated & trailer lorry	
10: trailer lorry		

3.1 Sorption isotherms

The resulting sorption isotherms show a lower water uptake for the investigated samples described in the previous section compared to values from the database of hygrothermic simulation tools (WUFI) and the approximative model (Simpson 1998) shown in dotted and respectively in dashed lines in Fig. 8. These lower values are due to the impregnation treatment. Pressure impregnation has a double effect on reducing the moisture absorption of wood. First, it reduces the number of –OH groups which are susceptible to attract water molecules and second, the cell walls become saturated with a monomer which is polymerized by applying pressure (Mendis et al. 2023).

It has also been reported in the literature that the moisture content of solid wood members, which are protected from direct precipitation, does not assume the equilibrium moisture content predicted from the ambient atmosphere, but dries out to a significantly lower moisture content (Dyken and Keep 2010) especially when exposed to changing temperatures, i.e., diurnal and annual fluctuations.

Nevertheless, to be on the safe side regarding the evaluation of the wood moisture from the collected data, the mentioned "Simpson" formulae have been used to determine the wood moisture based on measured temperature and relative humidity (Simpson 1998):

$$u = \frac{1800}{M_p} \cdot \left(\frac{K_1 h}{1 - K_1 h} + \frac{K_2 K_1 h + 2K_3 K_2 K_1^2 h^2}{1 + K_2 K_1 h + K_3 K_2 K_1^2 h^2} \right)$$

$$M_p = 349 + 1.29T + 1.35 \cdot 10^{-2} T^2$$

$$K_1 = 0.805 + 7.36 \cdot 10^{-4} T - 2.73 \cdot 10^{-6} T^2$$

$$K_2 = 6.27 - 9.38 \cdot 10^{-3} T - 3.03 \cdot 10^{-4} T^2$$

$$K_3 = 1.91 + 4.07 \cdot 10^{-2} T - 2.93 \cdot 10^{-6} T^2$$

where u is the wood moisture, T represents temperature and h stands for the relative humidity.

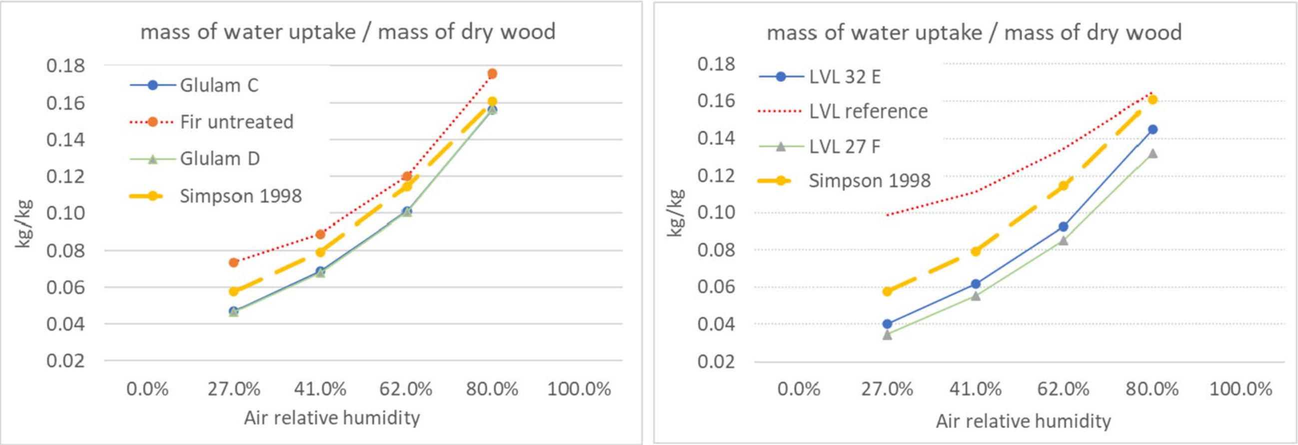


Fig. 8 Sorption isotherms of the four investigated specimens: Glulam C and Glulam D not distinguishable (left), LVL E and LVL F (right) with values from the literature and according to Simpson (1998)

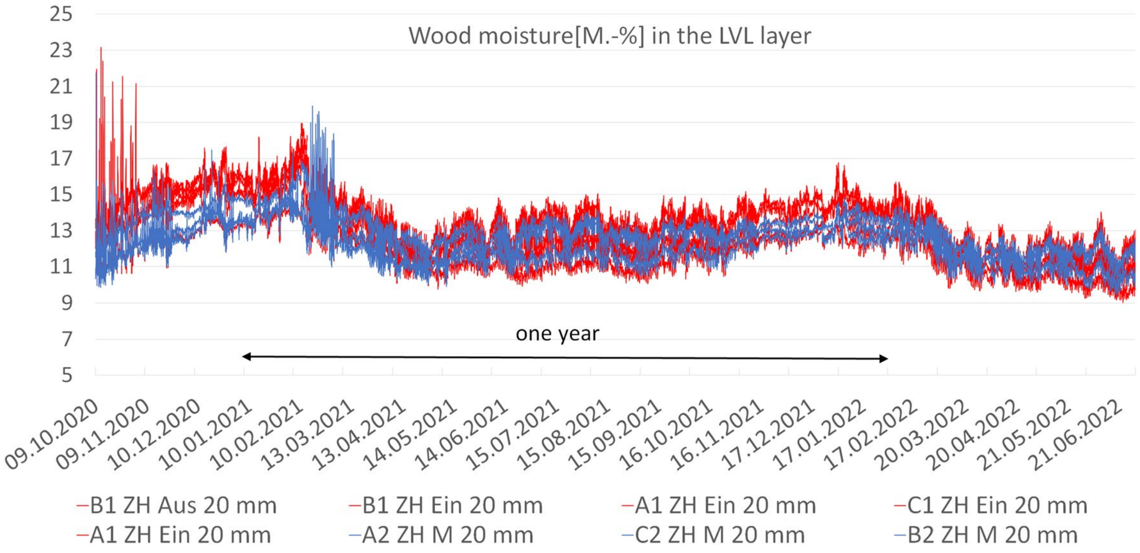


Fig. 9 Evolution of wood moisture at a depth of 20 mm at 8 different locations in the LVL layer of the wooden structure over a period of 20 months

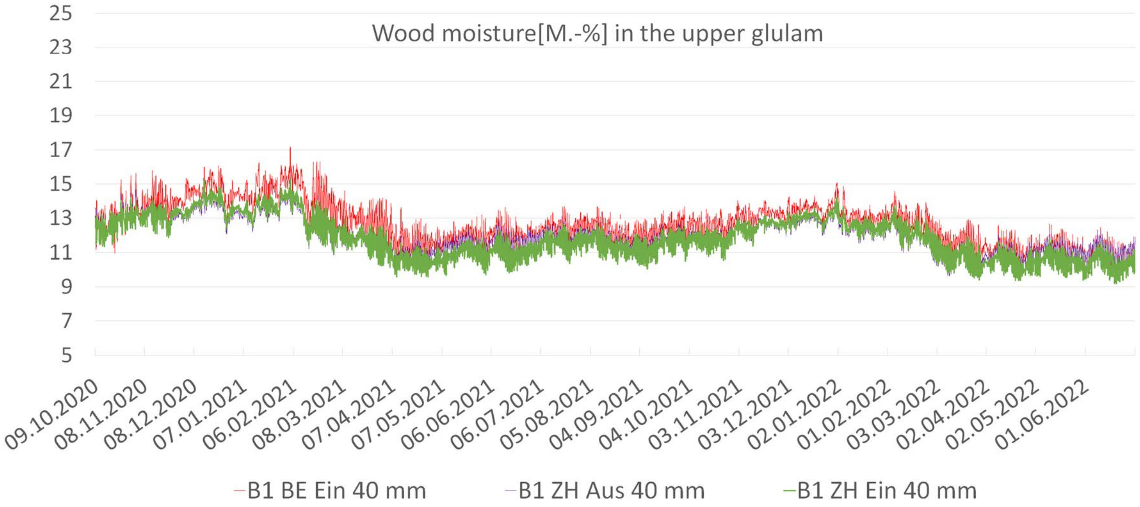


Fig. 10 Evolution of wood moisture at a depth of 40 mm at 3 different locations in the upper glulam over a period of 20 months

3.2 Moisture content

The course of the wood moisture measured at different positions of the wooden ceiling (LVL, upper glulam, lower glulam) for different depths of 20, 40 and 100 mm is shown in Figs. 9, 10 and 11 for the entire measurement period of 22 months, i.e., from October 2020 to July 2022.

In Fig. 9 the wood moisture in the LVL layer measured at a depth of 20 mm at 8 different locations is shown. For matters of comparison, all sensors positioned at the entrance (A1 ZH Ein, B1 ZH Ein and C1 ZH Ein) as well as the one at the exit (B1 ZH Aus) are shown in red color. In contrast, the sensors in the middle of the wild-life bridge (A2 ZH M, B2 ZH M and C2 ZH M) are shown in blue color. This allows to see if there is a difference between the values measured at the entrance and those measured in the middle.

None of these moisture levels indicate an upswing or a continuous increase in wood moisture content. This means that an accumulation of moisture over this period under the existing climatic conditions can be ruled out. Nevertheless, there is a slight decrease of moisture in the summer months and a slight increase in the winter months, hence a quasi-steady state can be assumed. Since the diffusive transport of moisture is a slow process, a fully settled state will only occur after several years if the climatic conditions remain

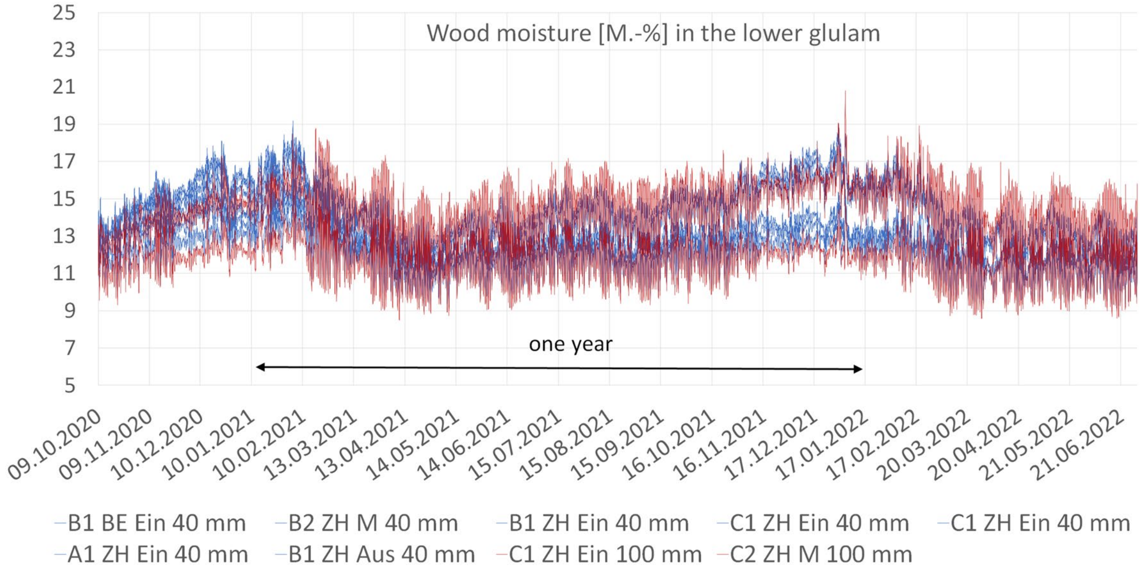


Fig. 11 Evolution of wood moisture at a depth of 40 and 100 mm at 9 different locations in the lower glulam over a period of 20 months

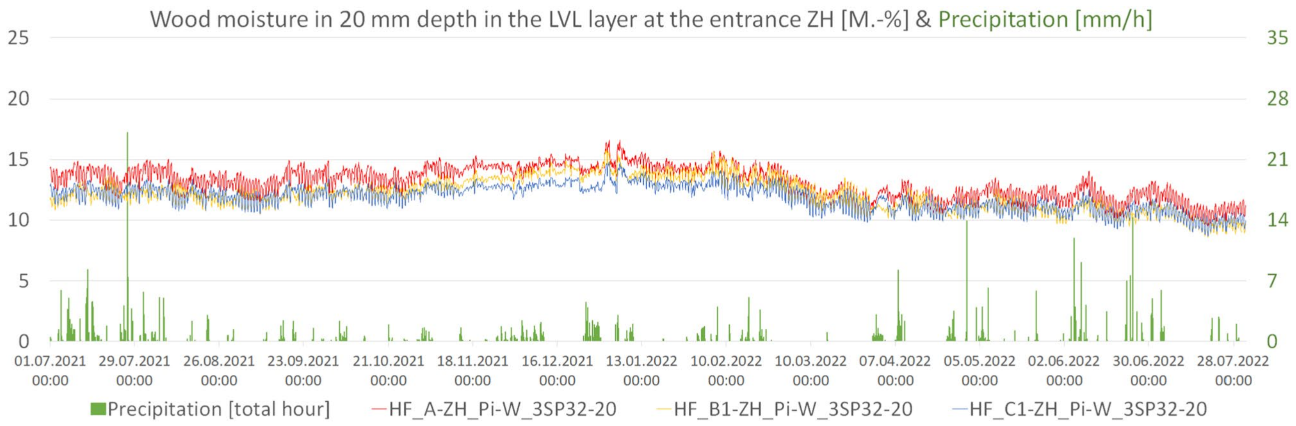


Fig. 12 Evolution of wood moisture at the entrance (A, B1 and C1 in Fig. 4) at a depth of 20 mm in the LVL layer over a period of 22 months and the occurrence of precipitation (green, right axis)

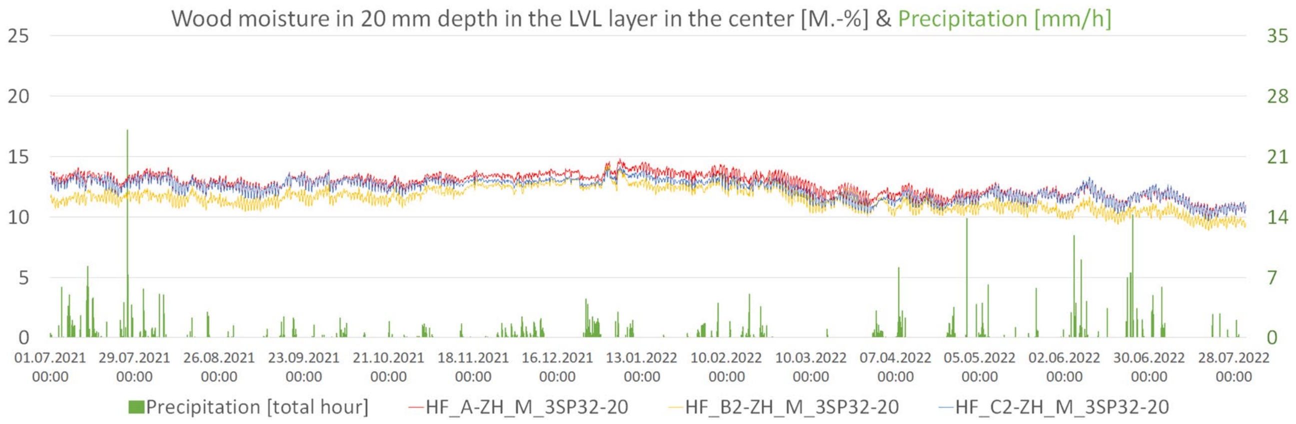
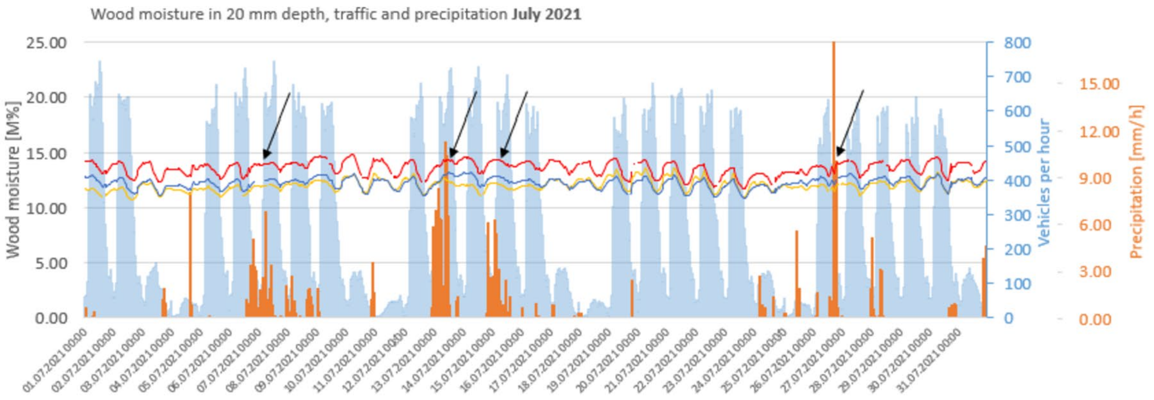


Fig. 13 Evolution of wood moisture at the center (B2 and C2 in Fig. 4) at a depth of 20 mm in the LVL layer over a period of 22 months and the occurrence of precipitation (green, right axis)


Wood moisture in 20 mm depth, traffic and precipitation **July 2021**
Wood moisture [M%]
25.00
20.00
15.00
10.00
5.00
0.00
Vehicles per hour
800
700
600
500
400
300
200
100
0
Precipitation [mm/h]
15.00
12.00
9.00
6.00
3.00
0.00
01.07.2021 00:00
02.07.2021 00:00
03.07.2021 00:00
04.07.2021 00:00
05.07.2021 00:00
06.07.2021 00:00
07.07.2021 00:00
08.07.2021 00:00
09.07.2021 00:00
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22.07.2021 00:00
23.07.2021 00:00
24.07.2021 00:00
25.07.2021 00:00
26.07.2021 00:00
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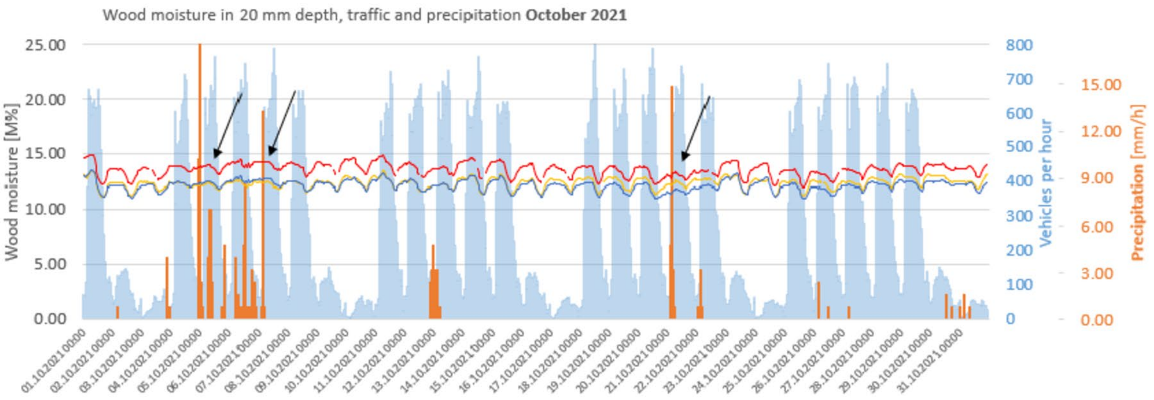
28.07.2021 00:00
29.07.2021 00:00
30.07.2021 00:00
31.07.2021 00:00


Wood moisture in 20 mm depth, traffic and precipitation **October 2021**
Wood moisture [M%]
25.00
20.00
15.00
10.00
5.00
0.00
Vehicles per hour
800
700
600
500
400
300
200
100
0
Precipitation [mm/h]
15.00
12.00
9.00
6.00
3.00
0.00
01.10.2021 00:00
02.10.2021 00:00
03.10.2021 00:00
04.10.2021 00:00
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25.10.2021 00:00
26.10.2021 00:00
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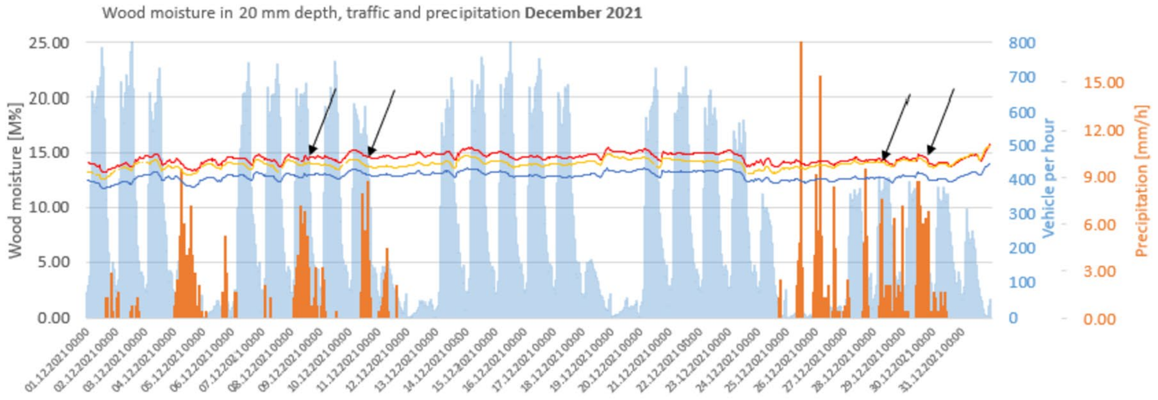
30.10.2021 00:00
31.10.2021 00:00


Wood moisture in 20 mm depth, traffic and precipitation **December 2021**
Wood moisture [M%]
25.00
20.00
15.00
10.00
5.00
0.00
Vehicle per hour
800
700
600
500
400
300
200
100
0
Precipitation [mm/h]
15.00
12.00
9.00
6.00
3.00
0.00
01.12.2021 00:00
02.12.2021 00:00
03.12.2021 00:00
04.12.2021 00:00
05.12.2021 00:00
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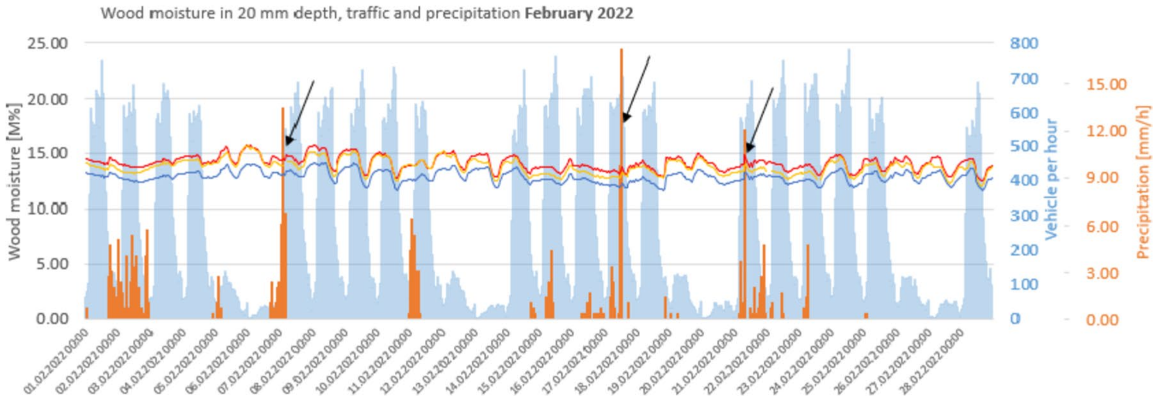
Wood moisture in 20 mm depth, traffic and precipitation **February 2022**
Wood moisture [M%]
25.00
20.00
15.00
10.00
5.00
0.00
Vehicle per hour
800
700
600
500
400
300
200
100
0
Precipitation [mm/h]
15.00
12.00
9.00
6.00
3.00
0.00
01.02.2022 00:00
02.02.2022 00:00
03.02.2022 00:00
04.02.2022 00:00
05.02.2022 00:00
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11.02.2022 00:00
12.02.2022 00:00
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14.02.2022 00:00
15.02.2022 00:00
16.02.2022 00:00
17.02.2022 00:00
18.02.2022 00:00
19.02.2022 00:00
20.02.2022 00:00
21.02.2022 00:00
22.02.2022 00:00
23.02.2022 00:00
24.02.2022 00:00
25.02.2022 00:00
26.02.2022 00:00
27.02.2022 00:00
28.02.2022 00:00

◂**Fig. 14** Wood moisture in 20 mm depth, traffic (orange), and precipitation (blue) for selected months (those with heavy traffic—precipitation coincidences) (Colour figure online)

approximately the same. The smaller fluctuations of about 2 M% may be caused by the stability of the sensors.

In Fig. 11 all sensors placed at a depth of 40 mm in the lower glulam are indicated in blue color and those at a depth of 100 mm in the lower glulam are shown in velvet. This shows that there is no specific distinction between the measured values which depends on the depth of the sensor placement. The only trend detectable is the slight rise of all during the colder season.

3.3 Impact of rain alone

To detect any influence of precipitation on the measured moisture content, these two variables were displayed simultaneously (Figs. 12 and 13). Precipitation is always plotted on the right y-axis in mm/h and the values were obtained from the nearby Meteo measuring station. It can be assumed that the increase in air humidity caused by precipitation becomes locally distributed and absorbed in the wooden structure with a time delay. This is the case at the portal entrance (Fig. 12), where the air is most humid. After high precipitation peaks (July 2021, April, May, and June 2022) a time-delayed slight increase in wood moisture (2%) occurs. This is also the case at the center of the wildlife bridge (Fig. 12), where the outdoor climate has a slightly weaker effect.

These findings relate to measurements at the lowest, i.e., the most sensitive depth of 20 mm in the LVL layer. Deeper layers are less sensitive and hence not shown.

3.4 Impact of the coincidence of rain and traffic

A further possibility to influence the moisture load in the wooden parts has been anticipated to be the whirling up of the rainwater to a sort of haze when there is simultaneously a high traffic load. To detect whether this effect occurs or not, a diagram was created for each individual month, from July 2021 to July 2022, to reveal the triple coincidence of wood moisture, heavy traffic beneath the wildlife bridge, and the measured precipitation. The reason for the division into individual months is the readability of the curves in the format of the present report.

From these months, only those were selected in which one or more coincidences of rain and heavy traffic occurred (Fig. 14). The sensors at the smallest depth (20 mm) were chosen because these would respond most readily to an increase in air humidity, i.e., the formation of water haze.

On July 7th, 8th, 13th, and 14th 2021, a coincidence of heavy traffic (grey blue) and precipitation (orange) can be observed. Similar coincidences occur on October 6th, 7th and 21st, on December 8th, 9th, 11th, and 29th 2021 and finally on February 3rd, 7th 12th, 18th and 21st 2022. The remaining months were not listed because they show no or only very weak precipitation- traffic coincidences and hence are irrelevant to the present argument.

On the dates mentioned above, a slight influence of the precipitation-traffic coincidence on the measured wood moisture content can be observed, in that the following minima of the daily fluctuations are less deep. In Fig. 14 these are marked with arrows. It can thus be plausibly shown that the simultaneous occurrence of heavy traffic and precipitation in this wooden wildlife bridge does not induce any relevant influence on the moisture in the wooden structure. This is of course also related to the size and height namely 6.1 m at the supportive walls and 8.1 m in the center of the construction (see Fig. 1). For lower ceilings this might be different.

The above only considered the wood moisture content measured at a depth of 20 mm in the LVL layer. In the primary structure, the lowest measuring depth is 40 mm. However, since this area of the wooden construction is at a smaller distance from the road due to the arched shape of the wild-life bridge and therefore more exposed to the moisture brought in by the vehicles, the same representation was selected for such a sensor (cross-section C1 in Fig. 5). This sensor too shows no significant influence of the precipitation-traffic coincidences on the corresponding wood moisture (Fig. 15).

4 Conclusion

During the period under investigation, no significant correlations between precipitation and moisture increase in the wooden structure can be determined. Even with the coincidence of heavy precipitation and high traffic volume, no significant increase in moisture content in the wooden structure could be determined during the period examined. This is based on a more conservative approach in which the influence of pressure impregnation (lower sorption isotherm) was neglected.

The impregnation of the wooden parts tends to result in a lower equilibrium moisture content in dry air but approaches the values of the untreated wood with increasing air humidity. In view of the wood moisture content measured at representative points and at various depths in the wooden structure of the wildlife bridge, it can be assumed that under the given climatic conditions at the location, no critical moisture

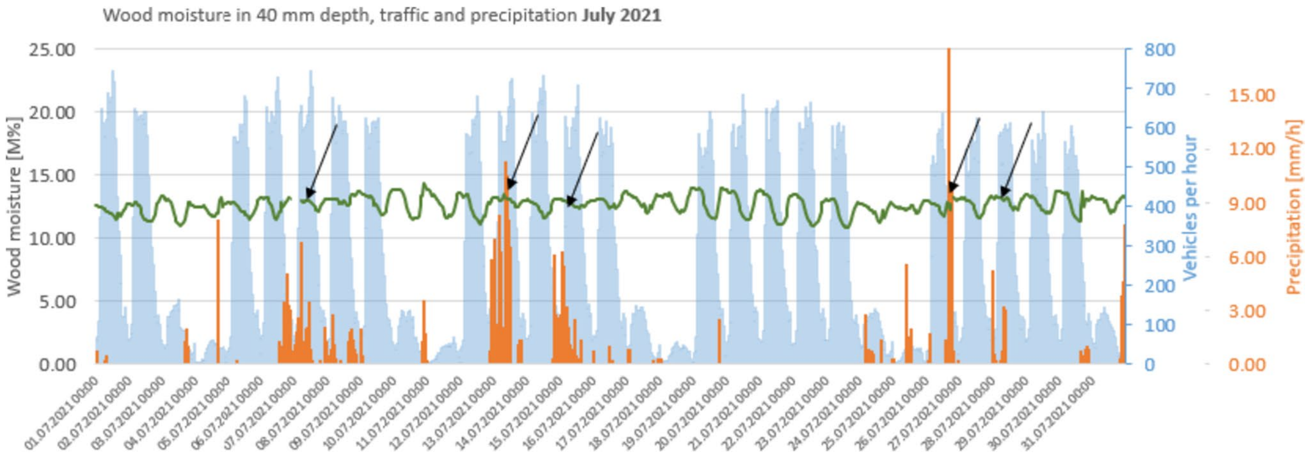

Fig. 15 Wood moisture in 40 mm depth, traffic (orange), and precipitation (blue) for July 2021 (Colour figure online)

content is to be expected even for untreated wood. This leads to the conclusion that wood can very well be used for wildlife structures in central European climatic conditions.

The sensors and the data loggers of the monitoring system have been taken over by the BFH (AHB laboratory). Monitoring is going on beyond the present project to enable the collection of long-term data relating to climate change. This can also be used to detect any slow drifting of the humidity sensors.

The primary structure and the secondary structure have been hydrophobized. Since hydrophobic treatment is only effective in slowing down the absorption of moisture in the first 2 to 3 years, a continuation of the monitoring would provide even greater certainty about uncritical wood moisture conditions.

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Author contributions K.G.W. wrote the main manuscript and was involved in the evaluation of the measurements. M.S. and A.M. wrote the proposal for the project and submitted it to FEON. U.K. and J.M. made the data collection and preparation. L.R. represented the industrial partner who accompanied the whole project and provided all needed information on the construction itself.

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Data availability All data are available upon request. Please send an explanatory email to the corresponding author.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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