Moisture content of Timber Structures in Varying Ambient Climates

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Abstract

Glued Laminated Timber (Glulam) is a common building material used today in timber structures, also in large span applications such as in roof structures of ice rinks, swimming pools, storage halls, sports halls, but also in open structures such as bridges crossing obstacles such as roads and rivers. As timber itself is a hygroscopic material, it adsorbs and desorbs moisture, following increases or decreases in relative humidity around the structure itself. Daily up to annual variations in ambient climate affect the moisture content distributions in the structures. Since moisture affects the physical and mechanical properties of wood, monitoring moisture content, and its variations, is of interest to have an indication of the building's structural health. Knowing these is also an important design parameter for design and planning engineers, as standards prescribe strength parameters to expected average moisture content. Available monitoring data is analysed into more detail as only an average annual moisture content, using measurement from different monitoring campaigns. Moisture contents in heated buildings were clearly lower than those in non-heated buildings. Based on relative humidity, swimming pools could fall under Service Class 1 because the climate is commonly so stably regulated and relatively dry. Differences in occupation of sheltered/closed and unheated structures showed that occupation does not seem to affect the measured climate in the building to the degree that special measures need to be taken. Exceptions are however possible.

The monitoring of the moisture content variations is of interest, and so are the methods. Moisture content monitoring via the electric resistance method is one of the most common methods. However, the method has an accuracy of about 2 mass percent, so more exact methods are pursued. The method is also not suitable for measurement of moisture content at temperatures far below zero. An investigation is done as to what other monitoring methods could be available and recommendations for future instrumentations are made. For now, the above-mentioned uncertainty is expected to be a unimprovable uncertainty, also because conversion parameters are often determined in static environments but used in dynamic ambient climates.

Moisture content developments and distribution of moisture induced strains perpendicular to the grain have been investigated in laboratory environments. Research has mainly been performed on smaller cross sections, which has allowed practical duration of research, and has allowed to develop numerical models to calculate moisture induced stresses on larger cross sections. Simplified ambient climates are applied during the experiments. A 1-dimensional model was used to calculate the stress distributions in the cross section of an ice hall. Additionally, the measured climate was simplified using a Fourier analysis and obtaining the most important components to reconstruct ambient climate fluctuations during a year. Using just eight frequency components, and an additional daily variation, an annual climate was reconstructed. Moisture content developments and moisture induced stress simulations showed good correlation between reconstructed and original climate.

The work presented in this report was performed during an STSM between 22 January 2018 to 2 February 2018 at the Technical University of Munich, Chair for Timber Structures and Building Construction.

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1 Introduction

1.1 Moisture content in timber placed in dynamic ambient climates

Glued laminated timber (Glulam) is used in large span timber structures such as bridges, sports halls, ice rinks, and riding halls. Whenever these glulam beams are exposed to varying ambient climate, they will be subjected to continuous drying and wetting processes, generating stresses perpendicular to the grain due to inhomogeneous shrinkage and swelling of wood. Load bearing structural members are to be protected to avoid direct impact of rain and sun to reduce the extremes, either by covering the material or applying protective coating for instance. This reduces the uptake and release of moisture and the corresponding swelling and shrinkage, but will not eliminate this.

The importance of the relation between moisture content (MC) and structural reliability is shown through assessment studies where it was observed that MC changes, high MC, or low MC could implicitly be related to almost half of the evaluated cases of structural damage or failure [1]. A similar study concluded that MC changes accounted for about one third of the observed structural damage [2]. Measuring moisture content developments in damp environments can be relevant as well as risk of fungi developments can also be monitored [3]. As moisture content monitoring will continue to be done and is still an important key to understanding long term structural response of buildings and structures in operation [3][4][5][6], monitoring desorption after wetting damage, or detecting leakage in structures where this is realistic [7]. Eurocode 5 accounts for moisture in a simplified manner through the introduction of Service Classes [8].

The Technical University of Munich (TUM) and the Bern University of Applied Sciences (BFH) have both been involved in elaborate monitoring campaigns of moisture content on load bearing timber structures. The Technical University of Munich has measured moisture content developments on sheltered hall structures [9], and the Bern University of Applied Sciences has done so on bridges [7]. Through this, the relation between a structures' operation and average annual moisture content could be determined, see Figure 1.

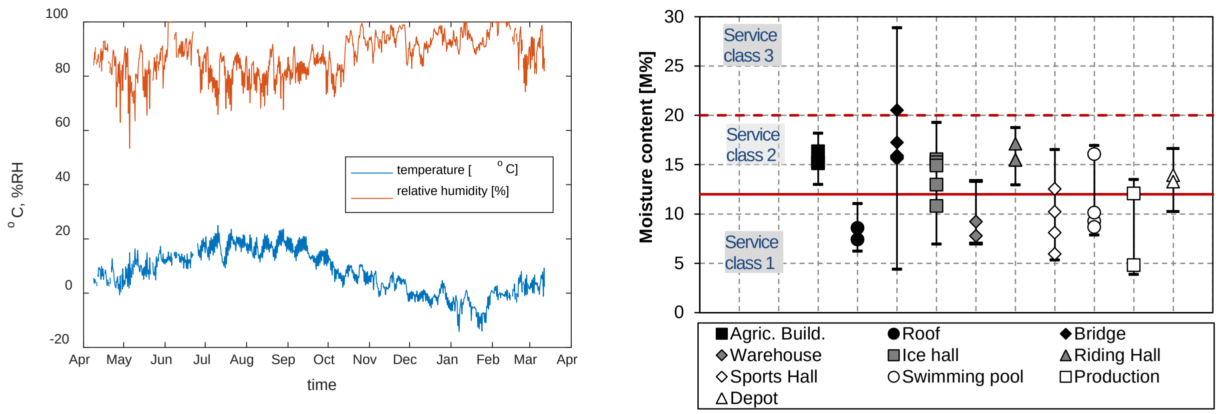

Figure 1: Measured yearly ambient climate around the Obermatt Bridge located near Langau im Emmental (CH) (left) and the plotted of average moisture content obtained from different building types and structures (right) [7][9] with relation to the Service Classes (SC) according to Eurocode 5 [8].

As structural members continuously undergo swelling and shrinkage, stresses also develop in every material direction due to constraint swelling and shrinkage. Stresses perpendicular to the grain are known to exceed the characteristic strength. Risk of crack initiation and further growth is realistic in climates where high variations in relative humidity are expected. Laboratory research has focused often on smaller cross section dimensions [10][11], and numerical tools have been developed to simulate developments of moisture induced stresses (MIS) [12][13][14]. This has allowed practical duration of experiments. Widths of structural members exceeding 200 mm cross section are however more common than exceptional and tests in laboratories with climate variations are not practical [15].

Simulations overcome that deficit and allow insight into the response of large timber elements due to dynamic climatic variations [11][16][17][18].

1.2 Goal and objectives

The goal is to develop better insight into the annual moisture content developments of a structure. This can be a structure that is either heated with a insulated building envelope, covered with a relatively closed building envelope, or fully ventilated like a bridge crossing either a road or a river. These values are generally known already, however discussion often lead to questions such as if building occupation affects the climate in a structure to that degree that special measures need to be taken during design. Possible effects of the dynamic moisture content developments are also investigated.

The first objective is to examine the annual and seasonal climate and moisture content developments in structures. This has been done already, usually to a level of annual averages. Data from different long-term monitoring campaigns will be used, both in large span structures and in bridges.

Former instrumentations will be evaluated and recommendations for future instrumentations will be made. Recommendations could also be made for locations where to measurement of moisture content developments in the future can be made to measure more realistic or extreme climates and to avoid structural damage.

Laboratory experiments have often focused on applying simple ambient climate variations in timber cross sections to know their response to moisture content developments and moisture induced stresses. Actual measured climate is simplified and simulations are performed with a 1-dimensional model to know the effects on the moisture content distributions and the moisture induced stresses.

1.3 Report setup

First, available monitoring data will be evaluated in Chapter 2. Available sources will be used to obtain the relation between relative humidity and moisture contents. Then, methods in which monitoring of moisture content can be done are compared and suggestions for future projects are made in Chapter 3. Chapter 4 contains simulations using measured ambient climates to develop insight into annual developments of moisture content distributions and MIS. Conclusions and recommendations are listed in the last section.

2 Monitoring data, buildings and bridges

2.1 Monitoring campaigns

The TUM monitored climate and moisture content in 21 different buildings. These could be categorized into seven different building types, monitored for one year [9]. Some were monitored for a second period:

- Three swimming pools,
- Four ice rinks,
- Three riding rinks,
- Three sports halls,
- Two production halls,
- Three agriculture halls, and
- Three storage halls.

Each building was instrumented in two separate locations: one reference point and one point of special interest, for instance under a row of windows, in a building's corner, or in a heated building's entrances. At each location the moisture content was measured through resistance type methods at four different depths, the closest to the surface being at 15 mm depth, similar as to what is seen in Figure 2. The material temperature was also measured at the surface of each location. The climate was measured

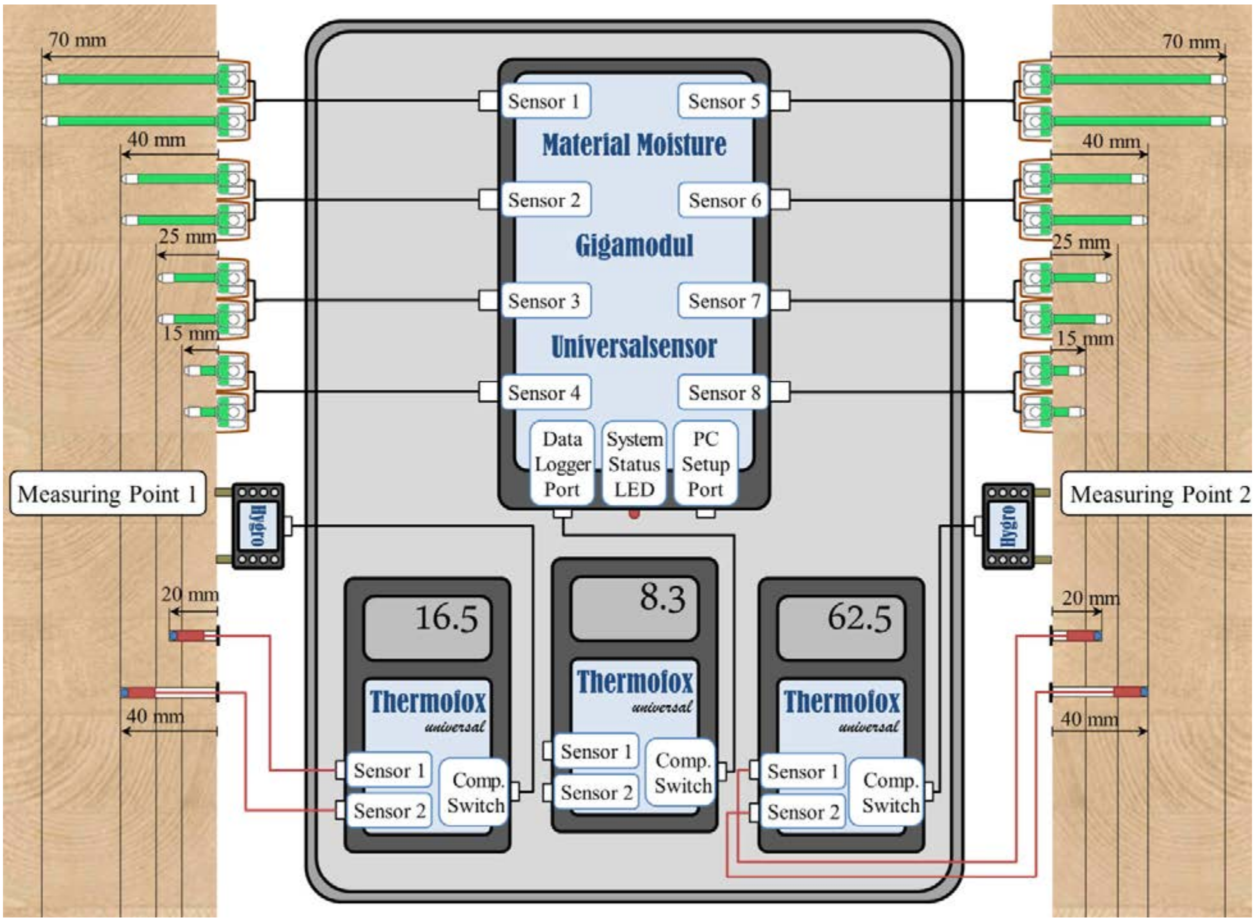

Figure 2: Example setup used for the measurement of moisture content, including pin type gauges for the measurement of moisture content (green), climate (hygro sensors) and temperature sensors (red), and logging equipment [9].

either at the point of reference, the point of interest, in between, or on both locations. Measurements were logged every hour over a span of one year.

The BFH monitored a total of five bridges during a couple of years [7]. Since the data was obtained through different monitoring campaigns, data was not gathered through a systematic measurement setup as applied by the TUM. Since risk of moisture contents building up through leaking road decks is realistic, moisture can build up in parts of the structure that cannot easily be inspected visually. Monitoring moisture content is an excellent way of detecting early damage and preventing significant repair costs, avoiding downtime, etc. [7]. Sensors were placed for instance in the middle of cross sections, or at a minimum depth of 50 mm from the surface.

2.2 Dynamic ambient climate and moisture content variations in buildings and bridges

Measurements from the different reports are obtained to show possible envelopes of climate in and around structures and give practicing engineers and planners a support towards design of a building. The envelopes allow quick overview to evaluate if measured moisture contents are in ranges where the relative humidity is measured. Figure 3 shows the annual developments of relative humidity and moisture content over a year (left) and a comparison between the two (right). The moisture content was measured at 15 mm depth. The winter and summer operation in this ice rink are rather subdivided into the period either with and without ice, i.e. from 1st September to 15th of April. The data shown in the figure was filtered with a moving average.

If moisture content directly on the surface would be compared to the relative humidity, the envelope would theoretically follow the equilibrium moisture content (EMC) of the hysteresis curve plotted in the figure. Dynamics of measured moisture content at 15 mm depth however is delayed, with a smaller amplitude. It is observed as well that the minimum out of the relative humidity was left out of the

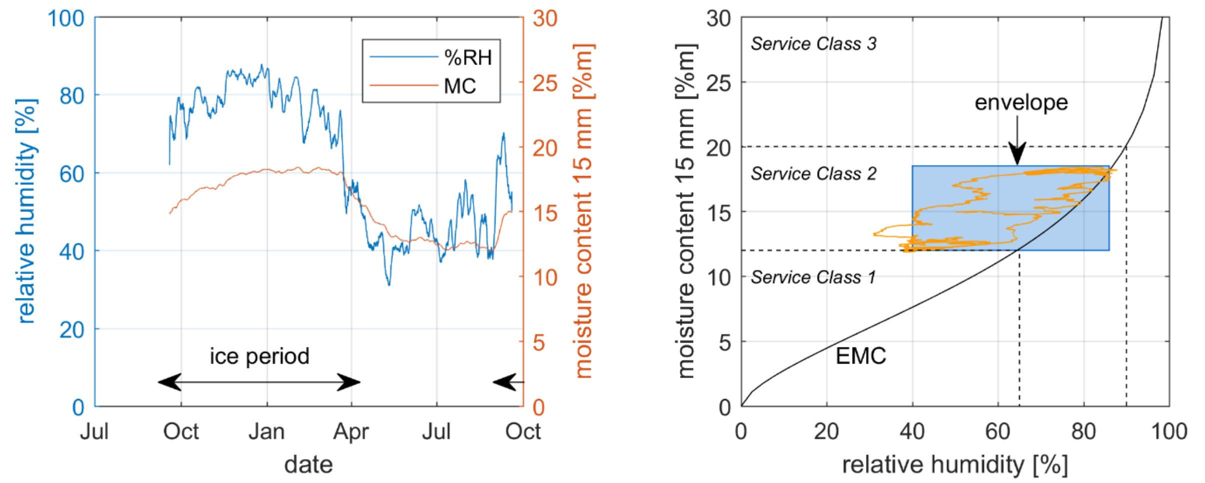

Figure 3: Example of data extraction of the data from ice rink B2 at measurement location M2 with the time series (left) and the comparison of relative humidity and moisture content at 15 mm depth (right)

envelope. Since the minimum is observed in only one peak, it is expected to be more of a special event and it did not affect the moisture content much. If it would occur a second or third time, it would be included in the envelope. The curve of the EMC was formulated as follows [4]:

$$\boldsymbol{u_{emc}} = \left(\frac{\mathbf{0.01} \cdot (-\boldsymbol{T} \cdot \boldsymbol{log}(\mathbf{1} - \boldsymbol{h}))}{\mathbf{0.13} \cdot \left(\mathbf{1} - {}^{\boldsymbol{T}}\!/_{\mathbf{647.1}}\right)^{-\mathbf{6.46}}}\right)^{{}^{\mathbf{1}}\!/_{\mathbf{110} * \boldsymbol{T}^{-.75}}} \tag{1}$$

In which T and h are temperature and relative humidity respectively and u_{emc} is the EMC.

A simple method was set up to obtain data from all the structures mentioned in the report. The data was obtained from the figures:

- Minimum and maximum values of moisture contents at the two instrumented locations, M1 and M2, at 15 mm depth are obtained. These values are already analyzed and visualized.
- Minimum and maximum values of moving average of relative humidity are estimated from the plots. The value obtained corresponds to a reasonable minimum and maximum value, excluding the lowest valley or highest maximum if this spanned only a short period. In this way the minimum and maximum reasonably affects the developments of the moisture content below the surface of the timber element. The minimum and maximum are not calculated in the report and since they are read from the figures, the expected accuracy is expected to be around 5%, excluding experimental accuracies, etc.
- Minimum and maximum values of the moisture content at 15 mm depth during winter period spanning from 1st October to 31st of March. Evaluation is done similarly as mentioned under the second bullet point. It should be noted that in case of the ice rinks, the winter period was calculated over the period in which ice was present on the ice rink floor. Expected accuracy is around 0.5 %m.
- Minimum and maximum of relative humidity during the winter period. Time span is the same as mentioned under the third bullet point. Minimum and maximum are the same as under the second bullet point.
- Minimum and maximum of theoretical EMC over the year. Evaluation is done according to method mentioned under the second bullet point.
- since data obtained from the bridges was measured deeper in the structure, ranges of the measurements are shown. Normally, yearly amplitudes of around 1 %m to 2 %m were found.

Results are plotted in Figure 4 for all the afore mentioned building types. The following observations and comments are made:

- Swimming pools: the measured climate contained several blind spots, but graphs with moisture content show stable conditions. The climate in the structures is strongly regulated. One of the three objects was not plotted as the instrumented location is not representative for the whole structure.

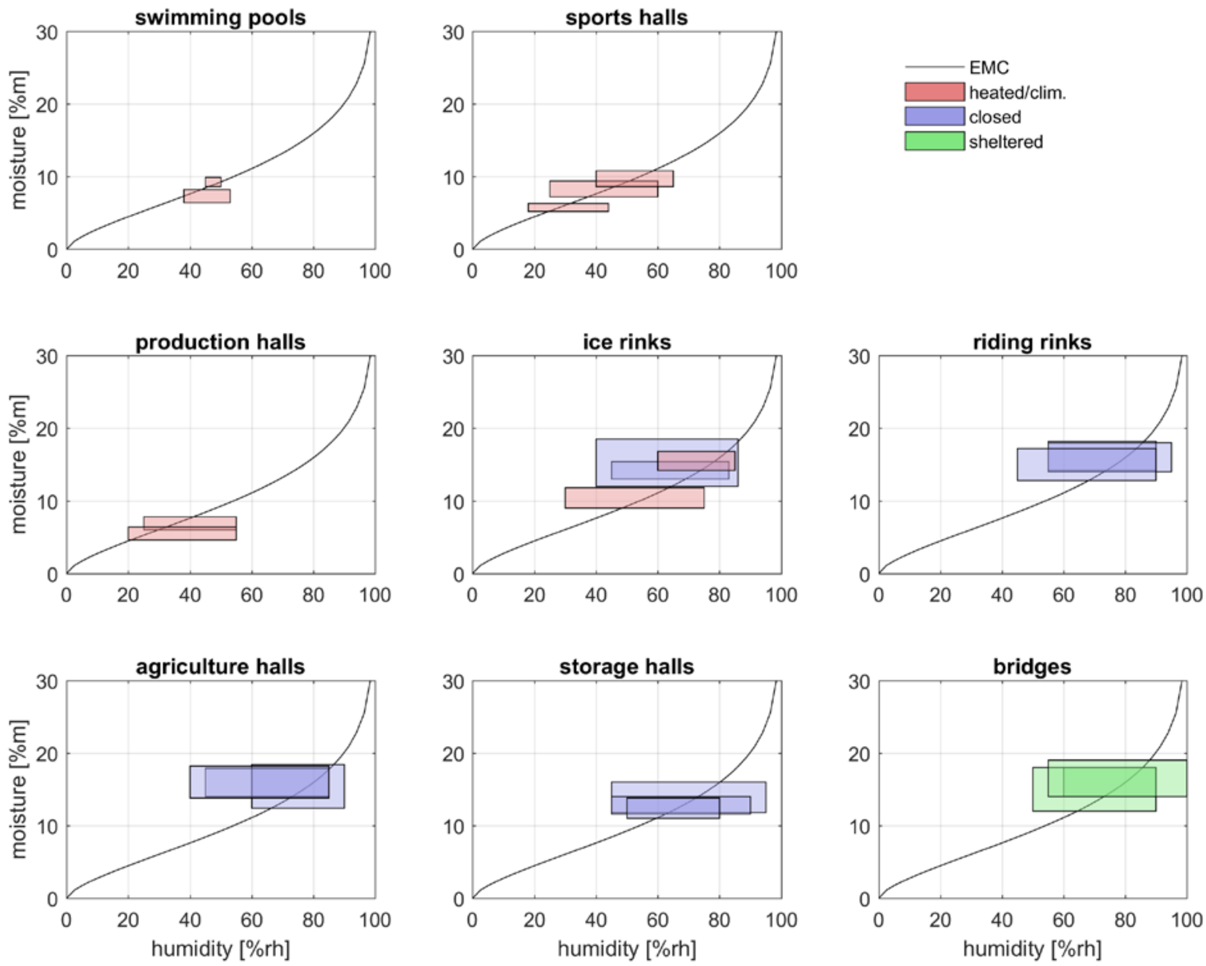

Figure 4: Comparison of measured relative humidity with the measured moisture content at 15 mm depth, moisture in the bridges shows a range of reasonable moisture contents that are to be expected at different depths.

- Sports halls and production halls: Relative humidities and corresponding moisture contents are low to very low. The relative humidity does not exceed 65%, but does show a large range of operation over the year.
- Ice rinks: Two ice rinks were actively heated/climatized. The winter periods concern the period with ice.
- Riding rinks: Although the structures are closed, large variations in climate are observed. Climate in the building presumably follows the climate around the building to a large extent.
- Livestock halls: The agricultural buildings contain livestock and were often well ventilated through one side of the building being fully open.
- Storage halls: The storage halls contained a closed building envelope, but through which smaller doors or windows ventilation was possible.
- Bridges: Operated in Switzerland instead of Bavaria. One of the three objects plotted here crossed a road, and two crossed rivers. There is no observable difference between the measured moisture content and the obstacle.

The maximum relative humidities inside the ice rinks are lower than those observed in the rest of the closed but unheated buildings, i.e. riding rinks, agriculture halls, and storage halls. Ice rinks can be a point of concern as high relative humidities can easily develop due to the low air temperatures above the ice. Subsequently, high moisture contents develop and load bearing capacity of the structure is at stake. Halls have been closed for public before even though maximum snow loads were not achieved yet [20].

The figure also shows that moisture content variations in unheated buildings are larger than those in heated buildings.

Figure 5 shows similar data as to what is shown in Figure 4, except that the EMCs at the surface are now represented on the horizontal axis instead of the relative humidity. Distinction is made as to whether the building is heated or not. The earlier mentioned bridges were excluded here. The figure suggests that a relation between the EMC at the surface and that measured at a depth of 15 mm can be set up, these are calculated in Table 1. This is calculated as follows:

$$r = \frac{\Delta EMC}{\Delta MC} \tag{2}$$

Average values between 1.83 and 2.51 can be calculated for five of the seven different building types, regardless if it is heated or not. Swimming pools have a lower ratio, storage halls a larger one. Individual values however range between 0.89 and 4.0.

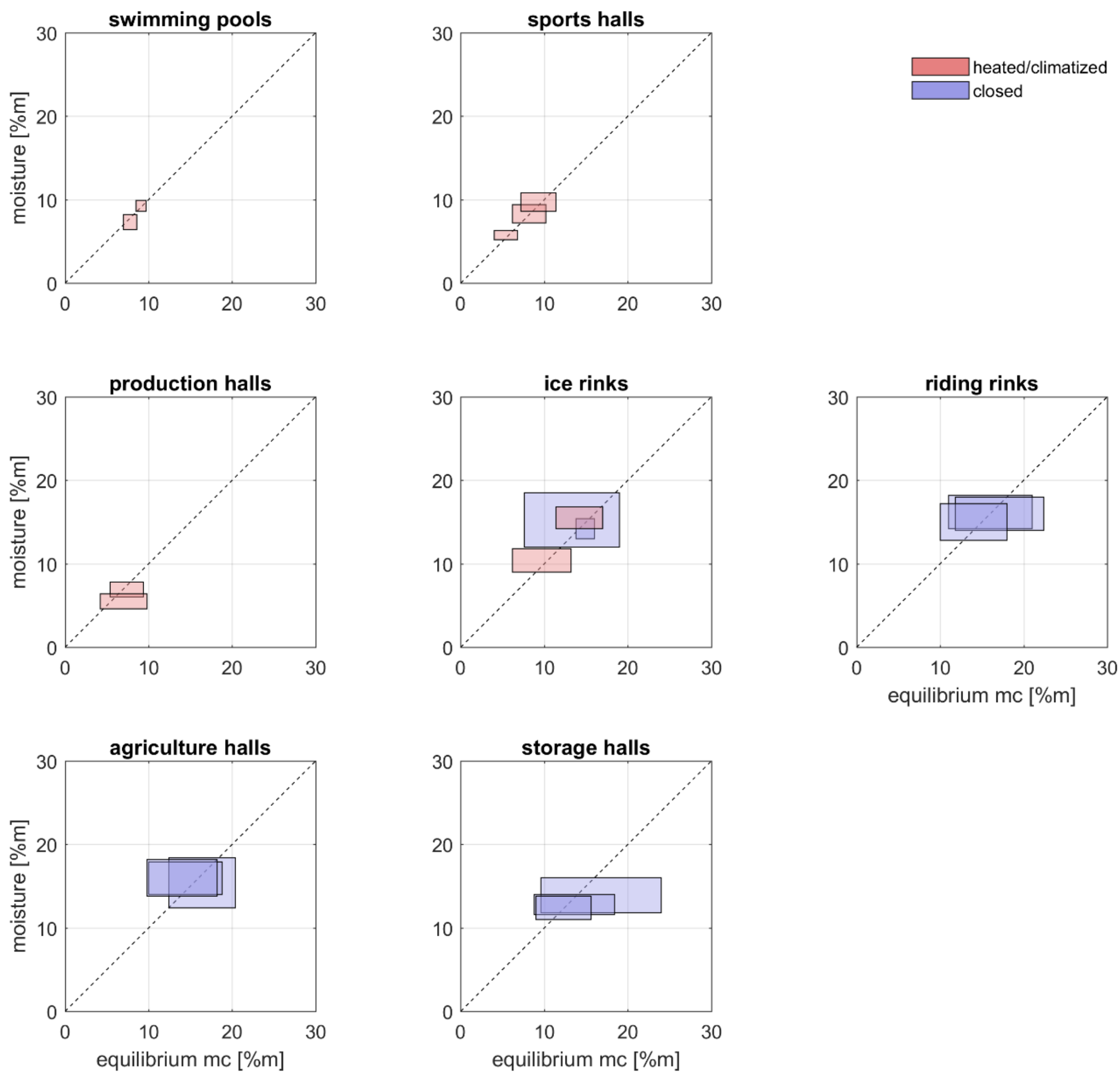

Figure 5: Comparison of minimum and maximum EMCs at the surface with the moisture contents measured at 15 mm depth of the monitored buildings.

Table 1: Summary of building properties and reference measurements along with the calculated ratio between EMC and measurement at 15 mm depth. (H) indicates the building was heated/climatized.

Building	Object 1	Object 2	Object 3	Object 4	Mean
Swimming pool (A)	0.92 (H)		0.89 (H)		0.91
Ice rinks (B)	0.91	1.75	2.50 (H)	2.15 (H)	1.83
Riding rink (C)	2.50	2.65	1.81		2.32
Sports hall (D)	2.55 (H)	2.00 (H)	1.91 (H)		2.15
Production hall (E)	2.22 (H)	2.80 (H)			2.51
Agriculture Hall (F)	1.33	2.26	1.91		1.83
Storage hall (G)	3.42	4.00	2.36		3.26

2.3 Winter operation and point of interest

All previous data was plotted for the reference locations. Data showing the operation during winter, as well as the envelopes of the points of interest, explained in Section 2.1, is plotted in Figure 6. It shows that heated buildings are dry during winter and wetter during summer. Unheated buildings are wetter during winter and dry during summer. The moisture contents in the points of interest in the buildings do not differ much from that of the reference points. If they do, these differences could be argument for closer inspection. In case of structure G1, the moisture content was measured right under a row of windows in the roof.

Finally, the winter and summer operation of only six structures is visualized in Figure 7. In heated buildings, the winter leads to lower moisture contents than in summer, although the range over which this varies is limited. In the non-heated buildings, the winter lead to higher relative humidities and higher moisture contents. These variations are higher than in heated structures.

2.4 Results and discussion

Observing the results, it is obvious that year-round operation is reflected in the climate inside the structure. This is related to the outside ambient climate as well. Climate in the swimming pools however is very stable. The analyzed data shows that moisture contents in unheated buildings show higher variations than in heated ones.

When looking towards the possible damage in the structure, i.e. cracks perpendicular to the grain, it is suggested that shrinkage cracks could be found in the sports halls and the production halls, year-round. In case of the ice rinks, riding rinks, the agricultural halls and the storage halls, inspection of possible cracks should focus on swelling and shrinkage cracks and that surface cracks should be found primarily in dry periods.

A factor left out of any of the above-mentioned analyses is the construction period. This is often considered to affect crack growth as well. A tree is felled, timber is kiln dried, planed and assembled into glulam beams. After this, it will be transported to the building site, and until roof is covered or envelope is closed, exposed to influence of ambient weather [9]. This is not visualized at all in the figures. Neither is effect of maintenance periods in which a normally heated structure could for instance be left to fully interact with climate, introducing moisture gradients in the structural members that are normally not found.

Sometimes, buildings are set for new uses due to changing demands of a community or business. A change of Service Class could negatively affect the structural integrity of the building due to developments of new cracks on top of existing ones. An example of such a significant change in building operation or occupation is the Richmond Olympic Oval in Vancouver, Canada. The speed skating rink was converted into a sports hall after the Olympic games. Still, one part of the hall serves as an ice rink. As observed though from the available data, this does not necessarily need to create a conflicting situation.

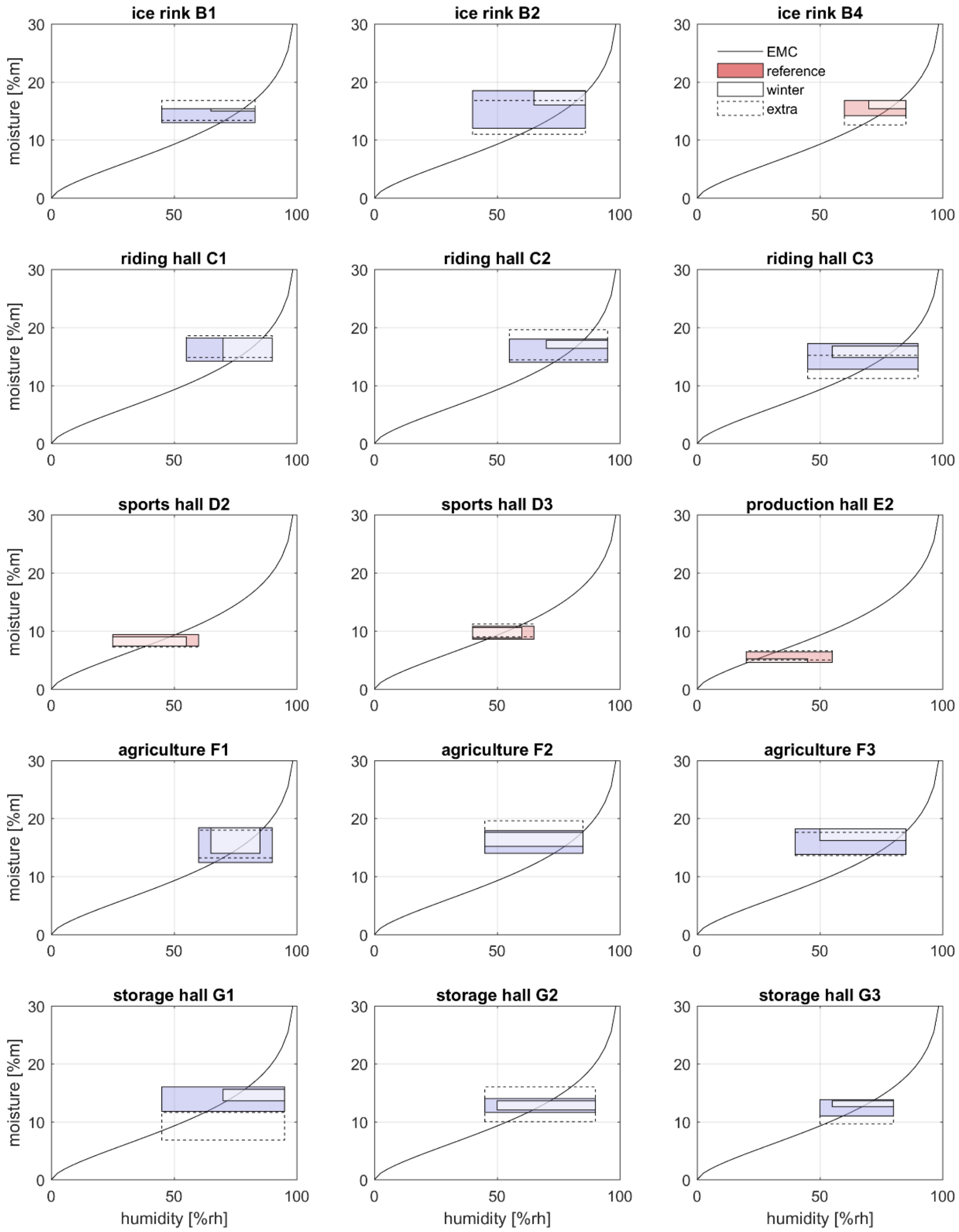

Figure 6: Comparison of year-through operation and summer operation of different heated (red) and non-heated buildings (blue)

The available data is only valid for the region of southern Germany, Bavaria. Extrapolation to other regions could be done, however with care. It is expected though that the available data can provide insight into design of future buildings and to improve maintenance and inspection regimes. Even if most of this data was measured within Bavaria, it should be noted too that exceptions are always possible.

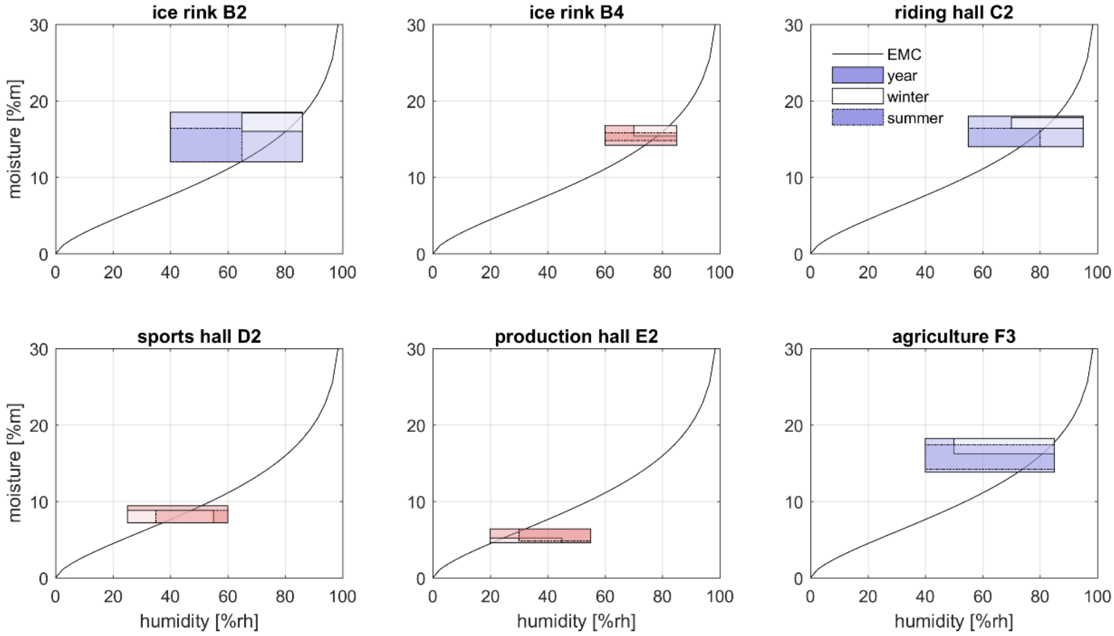

Figure 7: Comparison between the total year-through envelope, the winter and summer envelopes of measured humidity and moisture content in different buildings.

Finally, the relation between occupation type and measured indoor climate can hardly be made within a Service Class. Whether a structure is used as a riding rink or a storage hall is barely measurable moisture content wise. Similar conclusion is made with the bridges, where differences between a bridge crossing a road or a river is probably not distinguishable from the measured moisture contents.

3 Measurement of moisture content

3.1 Methods to measure moisture content through electrical resistance

Extensive comparisons between methods to measure moisture content are available [9][23][24], but not listed here. Electrical resistance measured between two pins, see also Figure 8 (left), is one of the most commonly applied methods and new gauges based on these methods are still developed [22]. Along with the electrical resistance, it is recommended to measure material temperature as well. This is done to correct for an increase of the resistance as temperature drops, or reduction as the temperature increases. A rule of thumb is that a correction of 1 %m should be made per 10 ˚C [23].

General uncertainties mentioned within this method are the material density, calibration, etc. On top of the existing uncertainties, several other uncertainties are discussed:

- Measurement of moisture content below zero degrees Celsius,
- Measurement of moisture content in salty or chemical environments,
- Effect of glue lines in moisture content measurements,
- Exact distance of pins between which the moisture content is measured, and
- Contact surface between wood and steel pin, i.e. screw or nail, dull or sharp.

Care is to be taken when using the electrical resistance methods when temperatures below zero are expected. It is suggested that moisture content can be measured, however uncertainties in the temperature correction increase and are therefore not very reliable [22]. Uncertainties can still be acceptable around -5 ºC but unreliable below -10 ºC [21]. This is explained by the conduction of electricity in water being provided by free moving ions. In ice, these are locked into crystals.

Salt positively affects the conduction of electricity in wood. Salt storage buildings, e.g. for roads, are often built in wood as risk of corrosion is too large when these are built in steel. Such effects can also be imagined in road bridges in countries or regions where salt is used to prevent ice developing on the road deck in winter. Once a leakage occurs in a road deck and salt seeps through with the water, measurements will be affected by this too.

Cured adhesive in glulam is expected to act as an insulator and increase the resistance measured between two pins. Glue lines delay perpendicular moisture transport [25]. It was observed though that the glue line had little to no effect on the measurement of electrical resistance in Beech LVL [6].

Although the distance between the gauges is mentioned as a point of concern and is often set to 30 mm, measurements were made up to 600 mm depth with screws. The tips are expected to be 25 mm apart, still maintaining an accuracy of 1.5 %m [22].

If needed and enough time is available, it is recommended to set up own calibration curves allowing the conversion from electrical resistance to moisture content. This can be done for instance when:

- conventional measurement setup cannot be used due to for instance size of the specimen or location of the measurement, or
- no proper curves are available for the material, for instance in old timber beams in structures of cultural heritage.

More examples can be imagined and listed. Setting up own calibration curves however can take time.

3.2 Measurement of relative humidity and temperature in a small void

Moisture content can also be indirectly measured using relative humidity and temperature measured in a small void in the wood [5][24], see Figure 8 (right). Mathematical formulations were set up for Nordic pine (Pinus sylvestris) and measurements were done to form a basis for a practical formula [5], not to investigate all properties of the wood or of the measuring method. It is suggested that the climate in a small void in the wood according to a moisture content and temperature is not the same as the moisture content in wood placed in an ambient climate. Therefore, new calibration curves should be determined. Measured differences resulted in values in the order of 2 %m. The method offers a good alternative to measuring with electrical resistance.

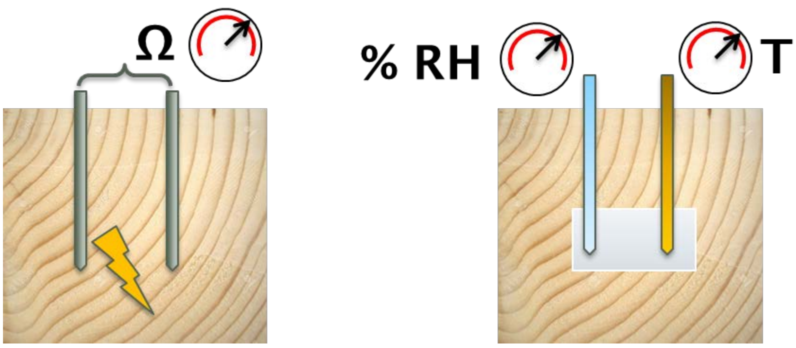

Figure 8: Illustration of moisture content measurement using the resistance method (left) and the measurement of climate within a small void (right)

3.3 Identification of non-physical effects

Calibration curves providing the correction of measured resistance or climate to moisture content have been set up in constant or semi-static climatic conditions such as a climate chamber. Corrections in the electric resistance method for a varying temperature can come down to 1 %m per 10 ºC [23]. However, monitoring campaigns deal with varying climatic conditions, measuring a constantly varying resistance, which is used to calculate moisture content. Through the different steps that are needed to finally obtain the measured moisture contents, there is a risk of non-physical effects being present in the analysis of moisture content, i.e. moisture content changes that are not real [5]. This can occur for instance to a timber member warming up due to exposure to solar radiation, through which the center of the cross section warms up quite quickly. This reduces the measured resistance and increases the measured moisture content after temperature correction. It is not realistic to expect that moisture content of larger cross sections changes in the order of 1 %m over the range of a day.

Similarly, the resistance type method has also shown to be affected by magnetic fields around the instrumentation. Electrical systems being switched on or off result in unrealistic moisture content increases.

These types of uncertainties can hardly be corrected or accounted for. They do however affect data analysis. Moving averages have been suggested to correct for strongly varying effects, but it is not expected that that can average out all the encountered effects. It is suggested to filter moisture content measurements using a median filter for instance prior to the application of a moving averages.

3.4 Future instrumentation and monitoring

A list of recommendations is given for future instrumentations. To improve the value of future measurements and to avoid loss of data, misinterpretation of measurements, the state of the art per instrumentation is suggested as follows:

- Measurement of moisture content at least close to the surface, but deeper in the material is also possible to serve as a reference value to changes at the surface,
- Measurement of material temperature to apply temperature corrections,
- Measurement of climate around, or as close as possible to, the instrumented locations,
- Climate around the structure, either through a meteorological station in the vicinity or through a mobile station around the building if it is expected that local climate significantly differs from that of the nearest meteorological station.

Further recommendations concerning the instrumentation itself, if possible:

- A visit to the monitoring object prior to the instrumentation, possibly with building plans or description of the building in hand to have an overview of interesting measurement points. A visit prior to the instrumentation allows time to organize extra ladders of lifting platforms. Hand held moisture content measurement equipment or climate meters can be taken along to survey points of interest.
- Accessibility of the data loggers, e.g. is a ladder needed, who can access them and does a protective case need to be installed?
- Planning of a location where reference values can be measured for the structure, along with what location might be of interest. Is that a structural detail, or vicinity of ventilation systems, direct radiated sunlight, water related activities such as cleaning/washing/development of condensate.

3.5 Fiber optic methods to measure moisture content

Until now moisture content measurements are made through electrical systems. It is also suggested to measure moisture content using fiber optic methods. This can be through the Fiber Bragg Grating type system in which individual sensors can be connected to a long cable [26]. Since measurement of electrical resistance is not possible through fiber optical sensors yet, the method of measuring relative humidity and temperature in a void could be applied, requiring two sensors per location. Data could be multiplexed to the interrogator over one single cable. It is claimed that up to twelve sensors can be connected onto one cable, allowing the measurement of respectively temperature and humidity at six locations.

There is interest to measure moisture content over surfaces instead of in single points as possible through conventional methods. Leakage in large dams is identified over temperature differences or strains in bridges or high-rise buildings are measured using fiber optic cables and the Brillouin approach. It can be imagined that a single cable with many sensors can be laid in a grid over the surface of bridge deck for instance to identify a leak in the asphalt or concrete layer.

4 Modelling climate scenarios

4.1 Fourier analysis of measured ambient climate

In laboratory experiments, climate variations are often simplified, subjecting timber elements to sudden change in moisture, for instance from 40 %RH to 80 %RH and back [10][16]. In real operation, it is unlikely though that such sudden changes in ambient climate occur. However, conservative results are obtained. Large cross sections need to be exposed to periods stretching a couple of months to reach the point of maximum moisture induced stresses. Simulations however allow to apply more realistic climates and simultaneously observe developments of moisture content and moisture induced stresses.

To model such a climate, long time traces of climate are needed. It is expected that variations can be simplified into a summation of frequency components. The climate measured in ice rink B2 is used in a Fourier analysis to obtain an overview of the most important frequency components of the year-through operation. An exercise is done to see whether it is possible to build a signal using just a couple of frequency components. The climate found in ice rink B2 is used. The frequency components, along with their amplitudes are observed in Figure 8 and Table 2.

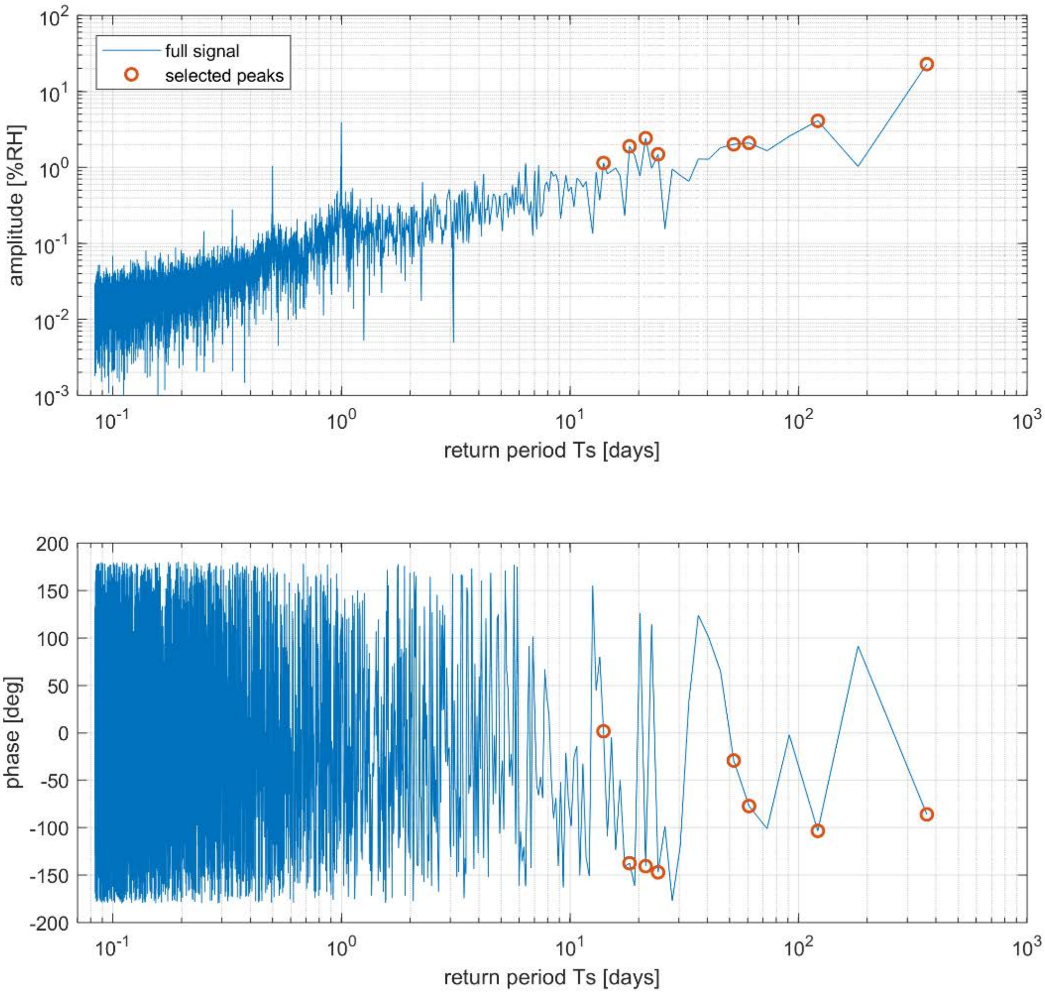

Figure 9: Frequency components of the relative humidity, along with their phases. Additionally, the selected components for further analysis are indicated.

Table 2: Selected frequency components, along with their return periods, amplitudes, and phases of both relative humidity and temperature.

Component	Return period Ts [days]	Amplitude [%RH]	Phase [deg]	Amplitude [°C]	Phase [deg]
mean	∞	62.95	-	9.82	-
2	365.04	22.72	-86.22	12.00	78.27
4	121.68	4.08	-103.6	1.57	89.15
7	60.84	2.09	-77.42	0.60	158.53
8	52.15	2.00	-29.45	0.56	165.48
16	24.34	1.48	-147.27	0.93	-5.14
18	21.47	2.41	-140.81	0.64	50.04
21	18.25	1.88	-137.67	0.36	82.41
27	14.04	1.14	1.45	0.52	-167.61
Daily amplitude	-	3.88	-	2.31	-

The selection of the frequency components was done based on the choice of all reasonable peaks larger the 1 %RH. The start time of the signal is 12 September 2010 at 12:00. The figure and table show that return period of 14 days or less consist of amplitudes of only 1 %RH or less. These could however, when arranged with the right phases, affect the signal of course. One single other peak can be found at lower periods which is the daily variation of 3.8 %RH.

4.2 Reconstruction of an annual climate

Then, several components are selected and a climate is reconstructed. The signal can be reconstructed using the following equation:

$$\boldsymbol{h(t) = h_0 + \sum_{i=2}^{N} h_i \cos\left(2\pi \frac{1}{T_i} t + \varphi_i\right) + N(\mu, \sigma)} \quad (3)$$

in which *h(t)* is the humidity in percentages as a function of time, h_0 is the yearly mean, and the subscript *i* refers to the used component of respectively humidity *h*, return period *T* and phase angle *phi*, see Table 2. The $N(\mu,\sigma)$ represents a random normally distributed daily variation with a mean of 0 and a standard deviation of the daily variation, listed in the last row of Table 2. Based on such an approach, several more realistic climates could be built to calculate long term stress distributions. Including these daily variation is expected to be important for the moisture content changes close to the surface at depths of 6 mm [28]. It is advised to take daily, as well as significant, changes into account.

Using the frequency components mentioned in Table 2, the climate in the ice rink is reconstructed, see Figure 10. It should be noted that the original signal was filtered through a moving average spanning a period of a day. Visually, a good overlap is observed.

4.3 Moisture content distribution and moisture induced stresses

The frequency components obtained in Table 2 were used to recreate a time trace of relative humidity and temperature in Figure 10. These were used to recreate a theoretical EMC at the surface of the cross section. This was used to perform simulations concerning moisture content distributions and moisture induced stresses (MIS). A one-dimensional model was used for the simulations.

The moisture content distributions were calculated using a single phase Fickian model. A diffusion coefficient of 2.0E-10 m^2/s was used and no hysteresis effect was considered during moisture content changes, neither was a surface emission coefficient or film resistance for coating was used during the drying processes [4][16][27][28]. An EMC at the start of the simulation of 13 %m was assumed. Fick's second law for transient diffusion is presented in Equation 3 using the first derivative of moisture content to time equals the diffusion coefficient *D* times the second derivative of moisture content to space (cross section).

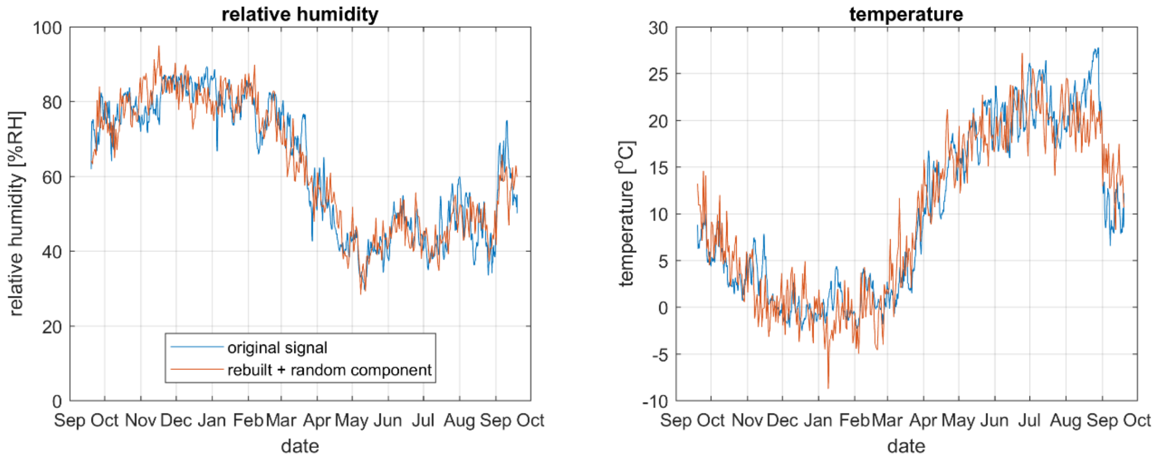

Figure 10 : Reconstructed relative humidity (left) and temperature (right) using the eight frequency components, amplitudes, and phases, along with the average and random distribution of daily effects.

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2} \tag{4}$$

The stress distributions were calculated using the elastic, hygro-expansive, and mechano-sorptive components of the strain distributions [4][13][16]. The properties over the cross section were calculated taking average angle of annual ring over the board layup, and using this to calculate elastic properties over the cross section and hygro-expansive properties over the cross section. The mechano-sorptive creep was considered differently in a wetting state than in a drying state through scalars m and β. For more details on the calculation of the effective stiffness over the cross section, the effective hygro-expansion over the cross section, material parameters, and the solution of the equation reference is made to literature [12].

$$\begin{gathered}\dot{\epsilon_t} = \dot{\epsilon_E} + \dot{\epsilon_u} + \dot{\epsilon_{ms}} \\ \dot{\varepsilon_t} = \frac{\dot{\sigma}}{E_{eff}} + \alpha_{eff}\dot{u} + (m|\dot{u}| - \beta\dot{u})\sigma\end{gathered} \tag{5}$$

Long term creep components, i.e. irreversible creep, were not considered. Neither were effects of reduction of modulus of elasticity due to increasing moisture content taken into account for instance.

A year was simulated with the reconstructed climate using:

1. all components mentioned in Table 2,
2. using only the average and the first frequency component, and
3. the original climate.

The envelope moisture contents and moisture induced stresses were calculated for the width of 180 mm, the cross section measured on in the ice rink B2. The results of this comparison over the cross section are shown in Figure 11, where the moisture content distributions are shown on the left and the moisture induced stresses are shown on the right.

The comparison of the climate (1) and (2) shows that higher frequency components only affect the outer 20 mm of the cross-section's moisture content. For the inner part of the structure, the annual moisture content variation could also be modelled using a single sinus. The moisture induced stresses are however overestimated on the midplane of the cross section. This could however also be due to the start of the simulation over which an equilibrium stress state was assumed.

The maximum tensile stresses exceed the characteristic tensile stress perpendicular to the grain used in the Eurocode [8]. This is however for a rather small volume. Weibull theory of the weakest link could be used to describe failure using the integral of the tensile stresses over the volume it represents [13].

A similar approach was used to calculate failure of curved beams loaded in bending and exposed to varying ambient climates [18].

Figure 12 shows the moisture content at the surface and at the midplane (top) and the moisture induced stresses (bottom). However now it is plotted as a function of time.

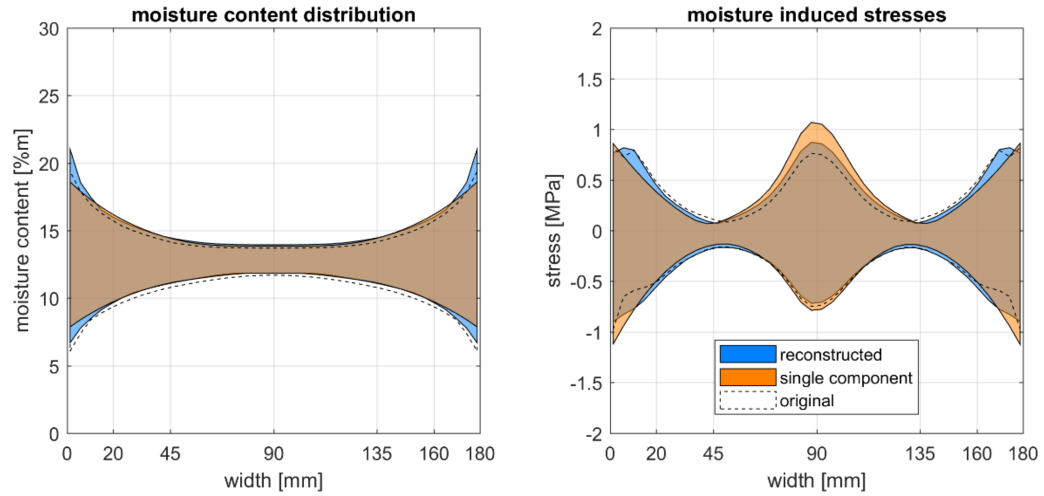

Figure 11: Comparison of envelopes of moisture content distribution and moisture induced stresses using the reconstructed climate, a single frequency component, and the original climate.

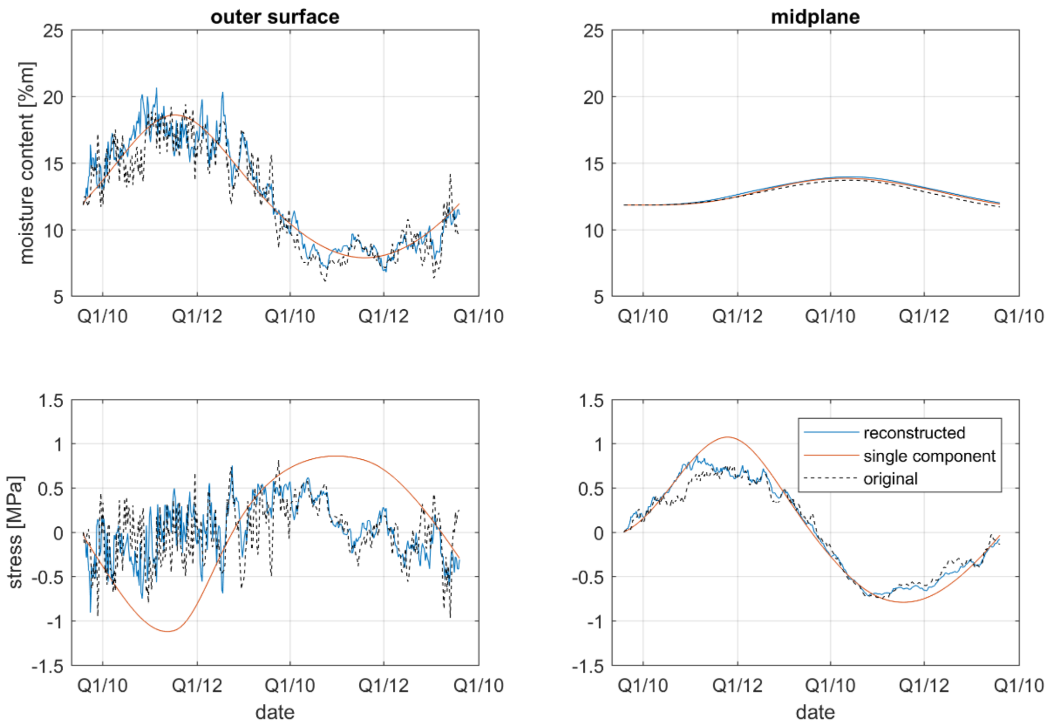

Figure 12: Comparison of moisture content distributions and moisture induced stresses using the rebuilt climate and the original climate on a cross section of 180 mm wide

Whether the stresses at the surface are realistic or not is open as the used model for moisture diffusion was simplified. This affects the distribution of the moisture induced stresses due to the large swelling and shrinkage of the material at the surface the material is exposed to. As observed, the large overestimations of the maximum and minimum of the moisture induced stresses are made when only a single frequency component in the climate modelling is used. Differences in the moisture content distribution at the surface are in the order of a couple percent moisture content if a single frequency component is used. Concerning the midplane, little difference is observed between the reconstructed climate, a single amplitude, or original climate is used to calculate either the moisture content distribution or the moisture induced stresses. Using more than one frequency component in the modelling of the climate especially affects the stress distribution at the surface of the cross section.

Daily variations in moisture content are higher in winter than in summer due to an inclination of the sorption isotherm around higher relative humidities.

4.4 Discussion

The derived frequency components suggest that climate repeats itself roughly every year in the same pattern, although this does not necessarily have to be the case. Finally, a constant moisture content distribution is assumed at the start of the simulation, so has a zero-stress state across the width.

The relation between temperature and relative humidity is in this case quite random. It could be suggested that the relative humidity and temperature could be directly related to each other through absolute humidity for instance. The daily variations are now added as a random component every day. It could be suggested that variations in relative humidity and temperature show smoother variations than suggested through this random signal.

A climate was reconstructed in which a phase angles were distributed more randomly was not possible as with these larger amplitudes, the risk of creating relative humidities over 100% was large. This was also due to the addition of the normally distributed random component, which in 2.5% of the cases was larger than 2 times the standard deviation assumed as the daily component. Certain care must be taken using these types of modelling.

Eventually, the daily components are needed to model moisture content distributions and moisture induced stresses close to the surface.

5 Conclusion and recommendations

5.1 Conclusions

Ranges of moisture content and indoor climates were analyzed for 20 different buildings. Data showed that the relation between relative humidity and measured moisture content followed hysteresis curved for sorption of water in wood. that heated buildings operate in Service Class 1 and that unheated buildings perform under Service Class 2. Relations between building occupation and measured moisture contents can hardly be made. Theoretical equilibrium moisture content at the surface of the timber was also compared to the measured moisture content variations at 15 mm depth.

Care must be taken though when generalizing the data or extrapolating the results to other buildings or locations. Building physics aspects should be kept in mind. Exceptions are always possible and building physics in corners or close to building openings must also be considered. Higher or lower moisture contents can be expected in cold corners of a heated building, such as close to an exit, or warm places in non-heated buildings, such as under roof windows, respectively. It also helps to plan maintenance in both type of buildings that causes a significant change in the experienced climate, encouraging maintenance of heated buildings to be done during summer instead of winter to reduce high fluctuations in humidity around the structure that last for a long time.

Moisture content monitoring or measurement using electrical resistance methods is not recommended below 0 °C. However, limited periods around -5 °C are accepted, although uncertainties in measurements start to increase. The measurement of relative humidity and temperature in a void in the structures seems a good alternative for temperatures that are lower, although some further research is recommended to better understand more aspects of the measurement method. There is also limited understanding of what factors really cause uncertainties in moisture content measurement through electrical resistance methods. The current uncertainty of 1.5 %m to 2 %m are values that should currently be accepted as unimprovable. This partly is related do the calibration factors are measured in static climates, whereas monitoring is often done in dynamic climates.

Reconstructing a measured climate from a limited amount of frequency components proved to be successful. Also with respect to the year-through moisture content distributions and moisture induced stress developments. It is however just one example and rather simple models were used in the simulations.

5.2 Recommendations

Data from new monitoring objects currently under supervision of the Bern University of Applied Sciences were not performed yet over a large enough period to enclose in the overview of climates in buildings. These concern two ice rinks, three ski/cable car stations, and one riding rink. These should be added to the graphs as soon as data is suitable. Representative data from other structures could be added or plotted in a similar way.

Methods of measuring moisture content at very low temperatures are not available or reliable. The measurement of relative humidity and temperature in a small void does offer an alternative to the resistance method. It is recommended however to investigate the method further.

Modelling the climate as a superposition of sinus waves looks promising and could be a step towards modelling response of structures in realistic ambient climates. It could also help to separate relevant components for different types of cross sections, i.e. would a variation of a week affect moisture induced stress levels of small beams more than that of wide beams for instance. To what extend could this affect maintenance programs or exposure to weather during construction.

5.3 Benefit to the COST Action

The outcome of the STSM is that a better insight is developed in the long-term moisture developments assessed through experiments and simulations. This will improve research concerning structural health in the future and enable a more efficient use of a renewable material such as timber in structures.

5.4 Acknowledgements

The author would like to thank the team of the Chair of Timber Structures and Building Construction of the TUM for their hospitality and fruitful discussions during the Short Term Scientific Mission.

6 Future collaboration

Further intention on collaboration has been expressed on the topics of structural monitoring and improvement of methods to determine moisture content of structures. Also, topics concerning the long-term performance of timber under regular conditions are of interest to both. Further collaboration is also intended through acquisition of research projects together, such as a Forest Value call. Long term performance of timber structures in ambient climates is also of interest to both

7 Foreseen articles

Not planned yet and probably done if more monitoring data is available.

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9 Confirmation of successful execution of the STSM

To add.

Appendix A: Overview monitoring data TUM

Building	Heated/sheltered	Approximate year	Reference	Climate	Ref. EMC/ MC 15 mm
Swimming pool A1	Heated	2012	M2	M1	0.92
Swimming pool A2	Heated	2012	M2	M1	1.87
Swimming pool A3	Heated	2012	M2	M2	0.89
Ice rink B1		2012	M2	M1-M2	0.91
Ice rink B2		2012	M2	M1-M2	1.75
Ice rink B3	Heated	2014	M1	M1-M2	2.50
Ice rink B4	Heated	2014	M2	M1-M2	2.15
Riding rink C1		2012	M2	M1	2.50
Riding rink C2		2014	M2	M2	2.65
Riding rink C3		2012	M2	M1	1.81
Sports hall D1	Heated	2012	M2	M2	2.55
Sports hall D2	Heated	2012	M1	M1	2.00
Sports hall D3	Heated	2012	M1	M2	1.91
Production Hall E1	Heated	2014	M2	M1	2.22
Production Hall E2	Heated	2014	M1	M2	2.80
Agriculture Hall F1		2014	M2	M2	0.80
Agriculture hall F2		2012	M2	M1	2.26
Agriculture hall F3		2014	M2	M2	1.91
Storage hall G1		2014	M2	M2	3.42
Storage hall G2		2014	M2	M2	4.00
Storage hall G3		2012	M2	M1	2.36