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MOISTURE MONITORING TECHNIQUES FOR THE PROTECTION OF TIMBER STRUCTURES

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ABSTRACT

Moisture protection of timber structures is of high importance for a sustainable built environment. This paper provides an insight into moisture protection concepts and international regulations for moisture monitoring with permanently installed sensors. Comparative experiments for the method of long-term electrical resistance measurements and the sorptive method are conducted in both, in-vitro and in-situ measurement campaigns in CLT. Based on oven-dried samples, electrical resistivity conversion seems to tend to give too low values for wood moisture content, while results after conversion from sorption isotherms tend to be too high, depending on the equation used. Thus, the investigations show significant discrepancies and the need for further laboratory measurements. Finally, the paper outlines the further potential of moisture monitoring concepts based on European standardization work.

KEYWORDS: moisture protection, wood moisture monitoring, standardization, electrical resistance measurements, sorption method, temperature gradient, cross-laminated timber

INTRODUCTION

Moisture monitoring systems might constitute a decisive part in future holistic concepts for the protection of multi-storey timber buildings. Moisture variations can lead to constraints within built structures. Furthermore, moisture affects the mechanical properties of building materials such as strength and stiffness. In unfavourable temperature ranges, a certain moisture content can lead to deterioration by wood-destroying fungi. As a consequence, concepts for the moisture protection of timber structures have existed for centuries. Moisture monitoring is considered a part of structural health monitoring and could be described as a preventive concept based on permanent technical equipment within building structures [1]. Moisture monitoring is usually conducted to acquire information when progressive phenomena are suspected, to prevent or reduce the cost of interventions during maintenance or renovations and to evaluate long-term effects [2]. Especially structural changes in existing buildings or changes in use have an influence on the ambient conditions. Those changes mainly influence safety, serviceability and durability of timber structures but similar problems also arise with wooden objects, e.g. cultural heritage or art.

MOISTURE MEASUREMENTS AND FUTURE EUROPEAN REGULATIONS FOR TIMBER STRUCTURES

According to mandate M/515, issued by the European Commission, the second generation of European structural design standards – the Eurocodes – is currently under preparation [3,4]. Future Eurocode 0 categorises moisture and temperature variations among the so-called indirect actions [5]. The effects of those actions can be verified e.g. according to the timber design rules for buildings in EN 1995, see Fig. 1. Design values of resistance of timber structures in [6] depend on several conversion factors, such as k_{mod} and k_{def} which include effects of moisture. The completely new draft of EN 1995-3 *Execution rules* for the design of timber structures (see Tab. 1) contains minimum requirements for moisture control [7]. It recommends the designer a documentation of (i) expected moisture content in service, (ii) permitted moisture content range during execution, (iii) assumptions about protection during execution and (iv) information whether a moisture control plan is required. This plan comprises, among other things, information on (1) how moisture content gets measured, (2) whether it gets measured at depth, (3) when it gets measured and (4) how the measurements are assessed. Moisture content measurements should be taken (5) at locations at risk of high moisture and where the moisture level is critical for the structure (6) in accordance with the relevant product standard. Additionally, it should be documented (7) how temperature and relative surrounding humidity of the surrounding air get measured in parallel. In certain cases, it seems possible to obtain additionally needed average air temperate and relative air humidity over the relevant period from local weather data [7]. If required, EN 1995-3 proposes the inspection of moisture content at delivery, during execution and on completion of the structure. Besides the rules for new structures, the pre-normative CEN/TS 17440 for the assessment and retrofitting of existing structures states that testing and monitoring may be used to verify and improve the assumptions of the structural analysis for existing structures [8]. Based on such information, the basic variables of the materials may be updated. This leads to the conclusion that whether in existing structures or new buildings, moisture measurement plays a crucial role in European timber design. It thus supplements, e.g. structural wood preservation by the assessment of sensitive parts of built structures and in execution. However, the assessment of technical methods suitable for such moisture monitoring is beyond the scope of current standardization.

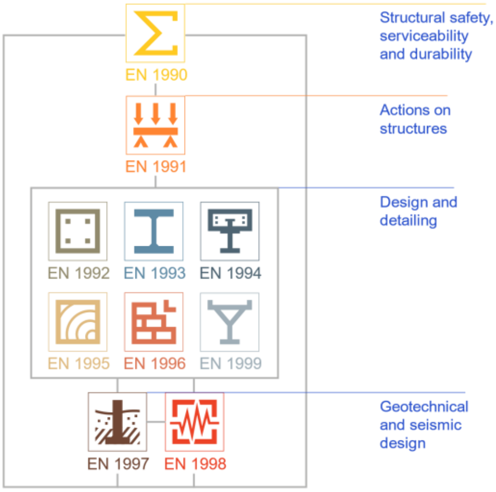

Figure 1 – Structural Eurocodes at a glance (© European Commission)

Table 1 - Overview of the Eurocode 5 series

Standard	Title
EN 1995-1-1	General rules and rules for buildings
EN 1995-1-2	Structural fire design
EN 1995-2	Timber bridges
EN 1995-3	Execution rules

PREVIOUS FINDINGS ON DIFFERENT WOOD MOISTURE MONITORING TECHNIQUES

A number of techniques and instruments are used in practice to determine the moisture content of timber. Three of them are standardized in EN 13183: Part 1 - *Determination by oven dry method*, Part 2 - *Estimation by* electrical resistance method and Part 3 - Estimation by capacitance method. It is noted that EN 13183 generally does not provide guidance on moisture monitoring. For direct wood moisture measurement, only the oven dry method [9] is used in the timber engineering practice. All other measuring methods are considered indirect [10]. Two of them are discussed in the investigation on hand with regard to their suitability for monitoring projects: The repeated measurement of electrical resistances (here method b) is based on the standardized method for estimating the moisture content of a piece of sawn timber [11]. However, there are no regulations how to conduct the same measurements over a long period with built-in electrodes. Furthermore, there is still no widespread technical solution for the monitoring of moisture gradients in timber elements, especially when influenced by thermal fluctuations. Tilleke & Fouad show measurement series with electrical resistance measurements used on a single spruce beam for experimental long-term observation over 25 years [12]. They proof their results in comparison with simulated expected values. Consequently, in the last two decades, numerous monitoring projects have been undertaken with the electrical resistance measurement of engineered timber components, for examples see [13–16]. Even if the individual research projects differ slightly in the design of the electrodes, they all have in common that the temperatures in the components examined were always sufficiently balanced.

The sorptive method (here method a, also *sorption method* or *bore hole method* or *hygrometric method*), could be a possible alternative for monitoring in the future. In order to improve techniques for the preservation of wooden objects, [17] compare both, the sorptive method and electrical resistance measurements with expected results by a Fickian model for moisture diffusion. They only obtained very inconsistent results from the comparative laboratory measurements on *Scots Pine* for the electrical resistance measurements. It could therefore be suggested that the electrical resistance method is not suitable for examining cultural heritage. Regarding the investigation of engineered timber products, Schiere et al. [18,19] compared these two methods in terms of their suitability for in-situ monitoring. In their literature review they state that the sorptive method is more suitable for the lower hygroscopic range, while the electrical resistance method can also be used above the hygroscopic range with larger uncertainties. However, for monitoring projects on beech LVL they achieved similar results with either method. Even if the authors mentioned above obtain different results, they have in common that their monitoring techniques are mainly used for wooden elements surrounded by a similar ambient climate. But how do the two methods compare under thermal gradients such as those found in exterior cross-laminated timber (CLT) walls?

METHODOLOGY OF THE EXPERIMENTAL INVESTIGATIONS (IN-VITRO AND IN-SITU)

The moisture gradients in CLT differ significantly from simple solid wood due to the different fiber directions and the diffusion-retarding effect of the glue lines [20, 21]. Still, the moisture content of CLT walls could be estimated by periodic measurements in the individual lamellas based on the electrical resistance method according to EN 13183-2:2002 [11]. Pairs of electrodes (galvanized steel, completely insulated except for the tips, see Fig. 2b, are drilled in at a distance of 30 mm each and with the measuring direction transverse to the grain. The method used for electrical resistance measurement in this paper corresponds to that described in detail in [2]. The further processing of the raw resistance values is carried out by means of a wood-specific calibration curve and a generic temperature compensation, both as specified by the manufacturer. The temperature values of the different depths for this are taken from the combi-sensors, which are also used for the sorptive method.

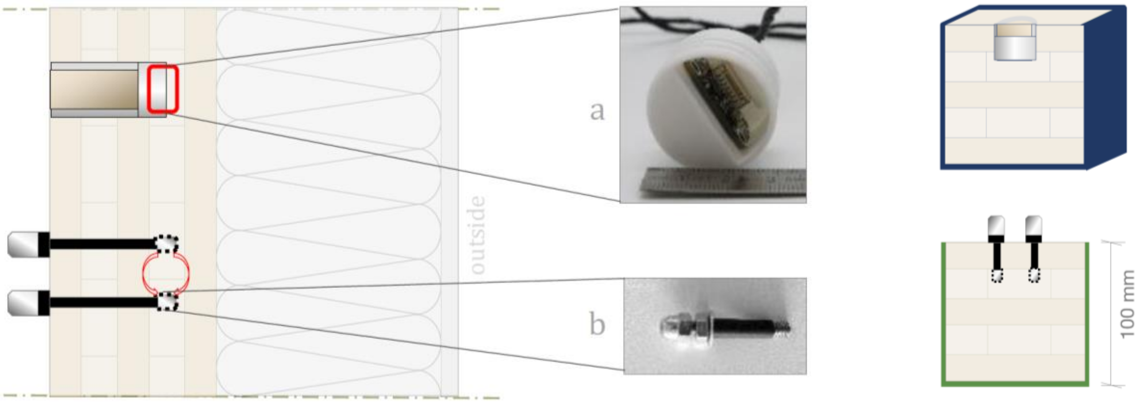

Figure 2 –Two measurement techniques in comparison in-situ in an exterior CLT wall (left) and in-vitro in lab experiments with test specimens of five-layer CLT and five sides covered with a vapor barrier film (right)

For the alternative sorptive method (see Fig. 2a) a small, closed air chamber is drilled into the material at a defined layer depth and tightly sealed by specially designed sensor casings and additional aluminium tape [22, 23]. Here, the relative water vapor partial pressure and the temperature of the enclosed air are measured. Then the corresponding equilibrium moisture content is inferred. The conversion of the input variables relative humidity h and air temperature T to an equilibrium moisture content EMC

could be performed using various equations [24]. In the context of this paper, two approaches are used, both of which are based on the sorption model by Hailwood and Horrobin [25] and the sorption data for *Sitka Spruce*. With equation (1) *EMC* is derived according to the formula of [25, 26], herein referred to as a1 (see Fig. 3). Equation (2) is a more simplified approach based on the findings by [27, 28], results are marked as a2 (see Fig. 3). In both equations, the inputs are relative humidity h as a decimal ($0 \leq h \leq 1$) and air temperature T [°C]. The individual values of the parameters W, K, K_1, K_2 and A, B, C, D fitted for *Sitka Spruce* can be found in [28, 29].

$$EMC\ [m.-\%] = \frac{1800}{W}\left(\frac{Kh}{1-Kh} + \frac{K_1Kh+2K_1K_2K^2h^2}{1+K_1Kh+K_1K_2K^2h^2}\right) \tag{1}$$

$$EMC\ [m.-\%] = 100\left[A(T+273{,}15)\left(1-\frac{T+273{,}15}{647{,}1}\right)^{B}\ln(1-h)\right]^{C(T+273{,}15)^{D}} \tag{2}$$

For the preliminary tests in-vitro, five test specimens with sorptive sensors (a) and four test specimens with electrical resistance measurements (b) in different depths were compared. Before mounting the sensors, the CLT blocks were first pre-conditioned to mass consistency in the laboratory and weighed regularly with a precision scale to determine the equilibrium moisture content. After sensor insertion they were then subjected to several isothermal humidity jumps over a period of several months. During this period, both monitoring systems ran in parallel with a time increment of 10 minutes. Oven drying the test specimens [9]concluded the test and retrospectively determined the respective actual wood moisture contents (distributed over the entire test piece). In addition to the laboratory tests, both measuring systems were compared with regard to their long-term behavior (see Fig. 2, left). For this purpose, they were installed in a measuring cube in CLT construction in the exterior wall, i.e. with a temperature gradient, over several months and then compared. For better clarity, only the conversions according to method a1, based on equation (1), are shown when evaluating the results from the outer wall.

RESULTS AND DISCUSSION

When comparing the resulting wood moisture values, it is noticeable that those according to the sorptive method (a) are always higher than those according to the electrical resistance method (b). The results from equation 2 (a2) are again slightly higher than the results from equation 1 (a1), but they both show much more pronounced amplitudes then results from method b after the isothermal moisture jumps in the laboratory, see Figure 3. The moisture contents determined according to oven drying and thus with the only direct measurement method refer in each case to the entire test specimen, but without the weight of the sensors and the adhesive film. From these values, it can be estimated which actual wood moisture contents should have set in at the various depths at the time of measurement.

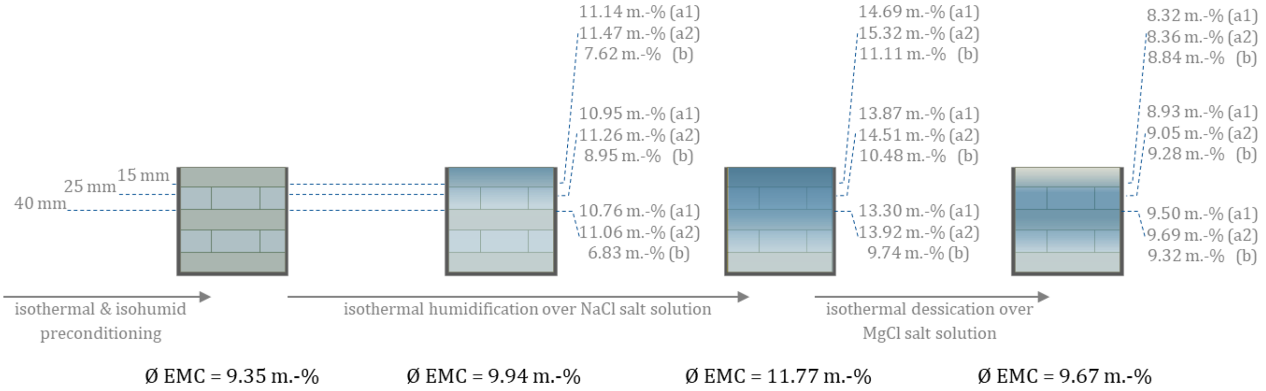

Figure 3: Results from different wood moisture monitoring techniques, obtained at three different measurement depths (15, 25, 40 mm). Sorptive measurements a1, calculated to EMC-Values acc. to equation 1 by [26]. Sorptive measurements a2, calculated to EMC-Values acc. to equation 2 by [27]. Results by electrical resistance measurements b. The average equilibrium moisture contents Ø EMC were derived by oven dry method.

Due to the lack of consideration of known phenomena such as sorption hysteresis, the available equations of the sorptive measurements are considered not suitable for in-depth scientific investigations but rather for a rough estimation [28]. However, the results according to a1 and a2 seem to depict the expected moisture distribution still more realistically than those by method b. Since the sensors used (Texas Instruments, HDC1080) can be subject to drift after prolonged exposure to high relative humidities, they were repeatedly checked for accuracy after removal from the test specimens. After completion of the lab measurement series, the deviations were still within ±2 % relative humidity.

Both measuring systems were employed simultaneously in a test cube with an exterior wall of CLT in four different depths: 15, 25, 40 and 70 mm from the inner surface. They were therefore also exposed to a thermal gradient over several months. Similar to the laboratory experiments, pronounced differences between the two monitoring techniques can be seen, see Fig. 3. Nevertheless, commonalities can also be identified: the deeper layers (70 mm) of the CLT wall seem to become more humid in the course of winter and spring, although the actual moisture content is still unclear. The wood moisture content calculated with the sorptive method (a1) according to [25, 26, 29] seems to be around three to four percentage points higher than what would result from the electrical resistance measurement according to the calibration curves (b).

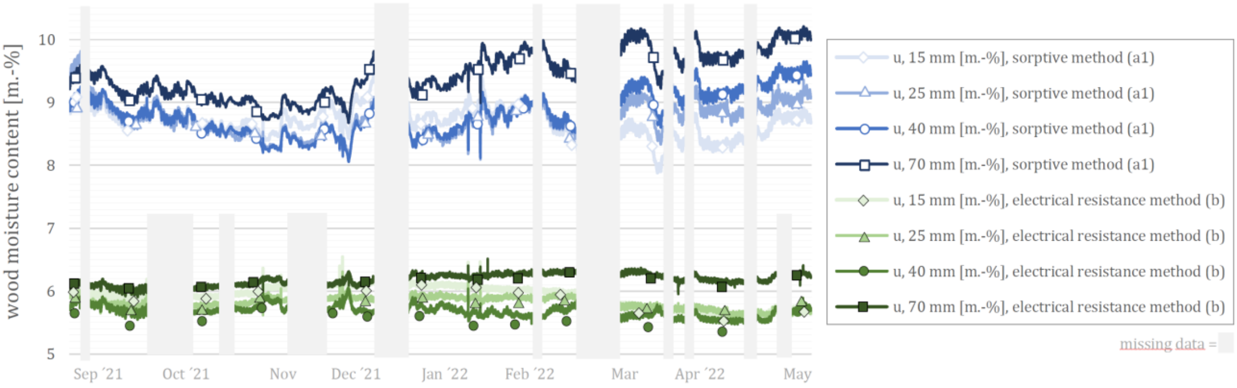

Figure 4 – Results from six months of measurements in a test cube

CONCLUSION AND OUTLOOK

The series of measurements presented here provide an insight into why it is necessary to investigate the methods of moisture monitoring in more detail. The following insights for future measurement series can be derived from the results obtained so far: It is not possible at this point to make a clear statement about the actual moisture distribution of the test specimens using the oven dry method. Due to their thickness the relatively large sample pieces (100 x 100 x 100 mm^3) would require significantly more time to achieve constant equilibrium moisture content throughout (1). Furthermore, the sample size of this preliminary test is too small (2). In addition, for clearer results, extended series of measurements with a larger number of samples as well as greatly reduced specimen thickness (20 mm) are planned for the future. Especially in the case of strong temperature gradients, a mathematical falsification of the measured values by electrical resistance measurements is suspected (3). Laboratory measurements are expected to provide a strongly improved curve fitting of the formula for temperature compensation. Typical wood characteristics such as anisotropy or sorption hysteresis could have an influence on the measurement results, which have not yet been taken into account (4).

Furthermore, it is explicitly pointed out that the two indirect methods investigated are both only estimation methods. Nevertheless, it is important for the engineering practice that the methods provide at least sufficient accuracy. Future European standards refer to moisture measurements in a multitude of application cases, either during execution or in existing structures. Hence, further information and guidelines on how to adequately conduct this monitoring on site are in heavy need. The investigations on hand and the described work in European standardisation are small but important parts in the big picture of further achieving holistic sustainability for our built environment.

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