Moisture storage and water uptake experimental data for three-layer and five-layer Cross Laminated Timber specimens

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Abstract

This paper reports the results of an experimental campaign carried out on a series of three-layer and five-layer Cross Laminated Timber (CLT) specimens, aimed at measuring their water absorption coefficient and their moisture storage function. These data are very important in the transient Heat, Air and Moisture Transfer (HAMT) simulation of CLT-based walls, but few reliable data are currently available to modellers, also showing a certain dispersion. Based on the comparison of the experimental results with available literature data, and on a simulation exercise, the paper allows understanding the effect of reliable material properties on the results of transient HAMT simulations for wood-based assemblies.

Highlights
- Almost identical behaviour for three- and five-layer CLT specimens.
- The measured moisture content at RH = 80\% is slightly below any available literature data.
- Marked hysteresis is observed for both types of specimens.
- Simulations with different sorption curves produce slightly different results in terms of moisture content.

Practical implications

HAMT simulation practitioners should always consider looking for reliable hygrothermal properties of CLT, being aware of the possible range of values occurring for similar kinds of woods, especially when dealing with moisture storage function. This means avoiding a blind use of the data available in software tools’ databases.

Introduction

Nowadays, transient HAMT simulation tools are widely available to investigate moisture-related risks in building materials. These simulations are particularly relevant in case of historical buildings insulated from the inside, and when moisture-sensitive wood-based materials are used, such as Cross Laminated Timber (CLT).

However, despite the undisputed usefulness of HAMT simulation tools, in many cases the reliability of the results suffers from the lack of sound and detailed experimental data concerning the hygrothermal properties of the building materials, amongst which the water uptake coefficient, the moisture storage function and the vapour permeability are particularly important. This issue is even more relevant when a certain material can show a variety of different options: this is the case of CLT, which can be produced with several tree species, and is available in different formats (e.g., with three-layer or five-layer boards). Several studies have reported the hygrothermal properties of various CLT species; for instance, if one only considers experimental data referred to spruce, the density ranges from 370 kg/m\(^3\) (AlSayegh, 2012) to 530 kg/m\(^3\) (Libralato et al, 2022), whereas the water uptake coefficient ranges from 1.9 g m\(^2\cdot s\(^{0.5}\)) (AlSayegh, 2012) to 11 g m\(^2\cdot s\(^{0.5}\)) or even slightly more (Lepage, 2012).

To further elaborate on this issue, this paper reports the results of an experimental campaign carried out on a series of three-layer and five-layer spruce-based CLT specimens. In particular, a first test allowed to determine, on a total of twenty-four specimens (50 × 50 × 100 mm), the moisture storage functions for sorption and desorption, i.e. the curves describing the moisture content in the CLT at equilibrium with different Relative Humidity values, from dry conditions to RH = 95\% (and back); these tests comply with the procedure described in the EN ISO Standard 12571 (CEN, 2021). Then, a second test was conducted to determine the water uptake coefficient (in g m\(^{-2}\cdot s^{0.5}\)) on a total of eight specimens (250 × 250 × 100 mm), according to the EN ISO Standard 15148 (CEN, 2002). The relevance of these tests relies in the great number of specimens used, and in the differentiation between three-layer and five-layer ones. The availability of sorption and desorption curves allows highlighting moisture sorption hysteresis, which is often neglected. An interesting contribution of the paper consists in a systematic comparison of the resulting experimental data with those available in other reliable sources, thus underlining data dispersion and inaccuracy.

Finally, the simulation of a CLT based wall, carried out with Delphin 6.1.2 (Delphin, 2021), suggests that the choice of an inappropriate CLT type, for instance the one already available in the software database, is likely to generate small variations in terms of temperature and relative humidity, but slightly more evident variations in the moisture content. In all cases, at least in the climate of Southern Italy, limited or no moisture related risks occur.

Methodology

Moisture storage function

The moisture storage function of a porous material measures the moisture content that the material is able to store when it is in equilibrium with the environment
where it is placed, at various relative humidity values for the ambient air. In particular, the sorption curve describes the increasing trend of the moisture content as the relative humidity increases, while the desorption curve describes the opposite trend. According to EN ISO Standard 12571 (CEN, 2021), the moisture storage function of a specimen can be determined through the “climatic chamber method”, which consists in:

- Drying the specimen in an oven until it reaches constant mass, which happens if the change of mass between three consecutive weighing, each made at least 24 h apart, is less than 0.1% of the total mass. This also allows establishing the dry weight of the specimens, indicated as \( m_0 \) hereafter.
- Placing the specimen in a climatic chamber capable of keeping, throughout the experiment, the temperature at 23 °C with a tolerance of 2 °C, and the relative humidity at the lowest of the selected range of values.
- Periodically weighing the specimen until it is at equilibrium with the air in the climatic chamber, i.e. it shows constant mass \( m \) (according to the same principle used for drying the specimens).
- Repeating the procedure for increasing relative humidity values.

The balance used in the experiment has an accuracy of 0.01 g, which is in line with the requirements of the Standard. The Standard also imposes that at least four approximately evenly spaced humidity values are selected in increasing order, in the range of 30% to 95%. In this study, six different values were investigated, namely 18%, 30%, 46%, 62%, 78% and 95%, obviously keeping the temperature constant at 23 °C inside the chamber.

Furthermore, the Standard requires that a minimum of three specimens is tested; their mass must be at least 10 g, and their surface area at least 100 mm \( \times \) 100 mm if the dry density is less than 300 kg/m\(^3\). In this study, the sorption curve was determined by working on six three-layer CLT specimens, plus six five-layer CLT specimens. Since the density of CLT is well above 300 kg/m\(^3\), the surface of the specimens is reduced to just 50 mm \( \times \) 50 mm; their thickness is 100 mm, which is fully representative of commercial CLT products. Figure 1 shows two of the specimens used in this experiment. The twelve specimens were tested simultaneously inside the climatic chamber. The same number of specimens with the same size and features was then used to determine the desorption curve: in this case, the specimens were initially placed inside the climatic chamber at \( T = 23 ^\circ C \) and \( RH = 95% \). Once constant mass was reached for all the specimens, the relative humidity was set at 78%, leaving the temperature unchanged. The experiment continued until equilibrium at \( RH = 18% \) was reached, and finally the specimens were placed inside the drying oven to know their dry weight.

In order to determine the moisture storage function, the **Equilibrium Moisture Content** (EMC) of each specimen in each test condition is calculated as in Eq. (1):

\[
EMC = \frac{(m - m_0)}{m_0} \text{ (kg/kg)} \tag{1}
\]

Finally, for each set of six specimens of the same type (three-layer and five-layer), the mean EMC values is calculated, as well as the standard deviation: this allows drawing an average sorption (and desorption) curve by linking all data points in a RH – EMC diagram, while also providing information about the dispersion of the results.

**Water absorption coefficient**

The water absorption coefficient measures the attitude of a material to absorb liquid water on its surface and, at present, is considered the most accessible indicator of the capillary liquid transport intensity inside a material. According to EN ISO Standard 15148 (CEN, 2003), the water absorption coefficient can be measured through a partial immersion test, where a specimen of the material is kept with its bottom surface steadily in contact with water, while measuring the rate of increase in its mass, due to water absorption. The Standard requires that at least three specimens are tested, and that each specimen has a minimum surface of 50 cm\(^2\) in contact with water: in this study, four three-layer and four five-layer CLT specimens were used, each with a square section of 250 mm \( \times \) 250 mm (\( A = 625 \text{ cm}^2 \)) and a thickness of 100 mm. The use of much bigger specimens than in the moisture storage experiment is justified by the need to reduce the edge effect: to this aim, a sealant was applied along the side walls, which did not react chemically and did not enter the pores significantly, thus avoiding water absorption along these side surfaces.

Before starting the experiment, the specimens were conditioned in a climatic chamber, with a temperature of 23 °C and a relative humidity of 50%, until constant mass was reached (indicated as \( m \) hereafter). Then, they were placed inside a large tank filled with water, installed in a large chamber maintained at 23 °C (with a tolerance of 2 °C) and relative humidity of 50 ± 5%. A metal grid was placed below the specimens to position them properly on the same plane, and to take care that a free space of at least 5 mm was available, where water could circulate. The water level was kept at no more than 5 mm above the base of the specimens, with a tolerance of 2 mm (Figure 2).
After 5 minutes, the specimens were extracted and dried externally with a damp sponge previously squeezed, so as to absorb the water droplets. The specimens were then weighed with an accurate balance (accuracy 0.01 g), and finally placed again inside the water tank. This procedure was repeated after 20 minutes, 1 h, 2 h, 4 h, 8 h, 16 h and 24 h from the start of the experiment: at each time step \( t \), the mass of each specimen is identified as \( m_t \) and the mass gain per unit area exposed is calculated as in Eq. (2):

\[
\Delta m_t = (m_t - m_0)/A
\]  

(2)

By plotting \( \Delta m_t \) against the square root of the weighing time, a straight line can be drawn after a short initial period of stabilisation: the slope of this curve measures the water absorption coefficient \( A_w \). For each set of four specimens of the same type, the experiment ends with the definition of a mean \( A_w \) value and of the corresponding standard deviation.

## Results

### Specimens and preliminary operations

As described in the Methodology, the preliminary operations in the moisture storage test allow identifying the dry mass of the CLT specimens. Figure 3 reports, for each CLT specimen used to study the sorption process, the time trend of the mass measured throughout the drying process, and demonstrates that constant mass is reached already after a few days. The resulting dry mass ranges from 90 g to 100 g for the three-layer specimens, and from 98 g to 104 g for the five-layer ones; this variation is most probably due to the uncertainty in the size of the specimens (estimated in ± 1 mm on each side), which leads to an uncertainty of ± 5% for the volume.

Then, by dividing the dry mass of each specimen by its volume (including the twelve specimens used to investigate the desorption process), it was possible to calculate the dry density: its mean value and the standard deviation are reported in Table 1, which refers to the entire set of specimens. As one can observe, the mean dry density of the three-layer spruce CLT specimens is around 5.5% greater than that of five-layer specimens.

### Geometric features

<table>
<thead>
<tr>
<th>Size</th>
<th>50 × 50 × 100 mm (± 1 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean density in dry conditions</td>
<td></td>
</tr>
<tr>
<td>Three-layer specimens</td>
<td>398.1 kg/m³ (( \sigma = 11.3 ) kg/m³)</td>
</tr>
<tr>
<td>Five-layer specimens</td>
<td>376.3 kg/m³ (( \sigma = 21.5 ) kg/m³)</td>
</tr>
</tbody>
</table>

However, both types of CLT are quite lightweight, if compared with other CLT products traditionally used in the building construction sector, whose density normally ranges from 400 kg/m³ to 500 kg/m³: this issue will be further debated in the Discussion.

Coming to the specimens used in the partial immersion test (CEN, 2003), Figure 4 shows the time trend of their mass during the preliminary conditioning at \( T = 23 ^\circ C \) and \( RH = 50\% \), until equilibrium was reached (i.e. a mass variation smaller than 0.1% for three consecutive days). Due to the larger size of these specimens, in this case two weeks were needed to achieve this condition. The plot also shows that one three-layer specimen, identified as Specimen C, behaves as an outlier, and for this reason it was excluded by the calculation of the mean density. Once again, by dividing the mass of the specimens by their volume, it was then possible to calculate the density of each specimen (at \( T = 23 ^\circ C \) and \( RH = 50\% \)), as well as the mean value. In this case, the two types of CLT show practically the same mean density, with a very low standard deviation; the presence of vapour in the CLT has increased the density to around 438 kg/m³, 10% more than in dry conditions.

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**Figure 2:** Picture of the eight CLT specimens used in the partial immersion test

**Figure 3:** Results of the preliminary drying process for the twelve CLT specimens used in the sorption test

**Table 1:** Features of the twenty-four CLT specimens used in the moisture storage test

<table>
<thead>
<tr>
<th>Geometric features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
</tr>
</tbody>
</table>

| Mean density in dry conditions |
| Three-layer specimens         | 398.1 kg/m³ (\( \sigma = 11.3 \) kg/m³) |
| Five-layer specimens          | 376.3 kg/m³ (\( \sigma = 21.5 \) kg/m³) |

---
Figure 4: Preliminary conditioning of the specimens at $T = 23 \, ^\circ\text{C}$ and $RH = 50\%$ before partial immersion test.

Table 2: Features of the CLT specimens used in the partial immersion test (Specimen C is excluded)

<table>
<thead>
<tr>
<th>Geometric features</th>
<th>Size</th>
<th>Volume</th>
<th>Mean density @ $T = 23 , ^\circ\text{C}$ and $RH = 50%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$250 \times 250 \times 100 \text{ mm} (\pm 2 \text{ mm})$</td>
<td>$62.5 \times 10^{-4} \text{ m}^3 (\pm 3.6%)$</td>
<td><strong>Three-layer specimens</strong> $437.9 \text{ kg/m}^3 (\sigma = 1.7 \text{ kg/m}^3)$</td>
</tr>
<tr>
<td></td>
<td>$250 \times 250 \times 100 \text{ mm} (\pm 2 \text{ mm})$</td>
<td>$62.5 \times 10^{-4} \text{ m}^3 (\pm 3.6%)$</td>
<td><strong>Five-layer specimens</strong> $437.5 \text{ kg/m}^3 (\sigma = 2.6 \text{ kg/m}^3)$</td>
</tr>
</tbody>
</table>

Sorption and desorption curves

This Section presents the results of the moisture storage experiment carried out according to EN ISO Standard 12571 (CEN, 2021), leading to the definition of the sorption and desorption curves. In particular, Table 3 and Table 4 report – for both the sorption and the desorption experiment – the mean masses of the CLT specimens at equilibrium with the various RH values. The highest dispersion in these values, corresponding to a standard deviation of around 7% of the mean mass, is observed in the six three-layer specimens used to test the desorption process, while the five-layer specimens showed a significantly lower dispersion (around 3.5%). The standard deviation is almost halved in the sorption process. Then, the calculation of the Equilibrium Moisture Content for all specimens, based on Eq. (1), led to drawing the mean sorption and desorption curves reported in Figure 5. Here, the curves are proposed in two versions, namely by referring to either the mass (a) or the volume fraction (b) of moisture in the specimens.

Figure 5: Mean sorption and desorption curves determined through the moisture storage test. The EMC is expressed both in terms of (a) mass or (b) volume percentage.

Indeed, even if the Standard procedure leads to determine EMC in terms of mass percentage, some most used HAMT software tools, such as Delphin (Delphin, 2021), require their value in terms of volume. To this aim, the volume fraction of moisture inside the CLT specimens has been calculated with Eq. (3):

$$EMC_{vol} = (EMC \cdot \rho_{CLT})/\rho_w \quad (\text{m}^3/\text{m}^3) \quad (3)$$

Here, $\rho_w = 997.5 \text{ kg/m}^3$ is the water density at $23 \, ^\circ\text{C}$, and $\rho_{CLT}$ is the dry density of CLT, measured at the beginning of the experiment.
of the experiment (Table 1). The curves reported in Figure 5 show an evident hysteretic behaviour, with differences greater than 50% between the moisture content in the sorption and the desorption curves at RH = 60%. A further interesting fact is that the three-layer and the five-layer specimens show almost the same behaviour, with a small difference at the beginning of the desorption process.

Water Absorption Coefficient

This Section presents the results of the partial immersion test carried out according to EN ISO Standard 15148 (CEN, 2003), leading to the definition of the water absorption coefficient. In particular, Figure 6 reports – for each three-layer and five-layer specimen – the straight line that best correlates the mass gain per unit area with the square root of the weighing time (the markers are the experimental values). The plots also report the equations of these lines, whose slope corresponds to the water absorption coefficient.

The water absorption coefficients attributed to all specimens are reported in Table 5 and Table 6, together with the mean values and the standard deviation; all values are provided with two different units, since both are commonly used in the literature and in the HAMT software tools. Similar to the moisture storage functions, the two types of CLT specimens show almost the same water absorption coefficient (3.86 g·m⁻²·s⁻⁰·⁵ for five-layer CLT and 3.91 g·m⁻²·s⁻¹⁄₂ for three-layer CLT), with a difference below 1%.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>A_ν [kg/(m²·h⁰·⁵)]</th>
<th>A_ν [g/(m²·s⁻⁰·⁵)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen 1</td>
<td>0.2836</td>
<td>4.73</td>
</tr>
<tr>
<td>Specimen 2</td>
<td>0.2165</td>
<td>3.61</td>
</tr>
<tr>
<td>Specimen 3</td>
<td>0.2276</td>
<td>3.79</td>
</tr>
<tr>
<td>Specimen 4</td>
<td>0.2115</td>
<td>3.53</td>
</tr>
<tr>
<td>Average</td>
<td>0.235 ± 0.033</td>
<td>3.91 ± 0.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>A_ν [kg/(m²·h⁰·⁵)]</th>
<th>A_ν [g/(m²·s⁻⁰·⁵)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen A</td>
<td>0.1885</td>
<td>3.14</td>
</tr>
<tr>
<td>Specimen B</td>
<td>0.2543</td>
<td>4.24</td>
</tr>
<tr>
<td>Specimen C</td>
<td>0.2178</td>
<td>3.63</td>
</tr>
<tr>
<td>Specimen D</td>
<td>0.2665</td>
<td>4.44</td>
</tr>
<tr>
<td>Average</td>
<td>0.232 ± 0.036</td>
<td>3.86 ± 0.59</td>
</tr>
</tbody>
</table>

Discussion

Comparison with literature data

After describing and commenting the results of the experimental tests, it is interesting to compare them with other data available in the literature or in well-known software tool databases. To this aim, Table 7 and Table 8 collect a series of data taken from reliable references; all data derive from experimental tests and refer either to spruce or SPF lumber (a combination of spruce, pine and fir that is common in Canada). The values reported by Kukk et al. (2022) refer to the material called “Stora Enso CLT”, also available in the WUFI® database (WUFI®, 2018), and have been measured by Fraunhofer Institute for Building Physics according to the information provided by the manufacturer.

Starting from Table 7, the density of CLT specimens ranges from 370 kg/m³ to 550 kg/m³; the specimens tested in this study are very close to the lowest end of this range, but they are also close to the CLT features reported in WUFI® (410 kg/m³) and Delphin (397.3 kg/m³). Coming to the water absorption coefficient, the reported values vary from 1.9 g·m⁻²·s⁻⁰·⁵ to 12 g·m⁻²·s⁻⁰·⁵. The wide range covered in the literature mainly depends on the preparation of the test specimens: indeed, cracks and holes make wood more permeable to moisture (Lipand, 2021), while selecting specimens with no cracks leads to values around 2.0 g·m⁻²·s⁻⁰·⁵ (AlSayegh, 2012). The edge sealing also influences the experimental results: samples without sealed edges can reach 12 g·m⁻²·s⁻⁰·⁵ due to water absorbed by the fibres of the uncovered edges. Similarly, the direction of the exposed fibres in the immersed surface strongly influences the water absorption coefficient, with longitudinal fibres showing the highest values, as demonstrated by the three options available in Delphin database (Evola et al, 2022). Finally, the size of the specimen can also affect the water absorption coefficient: indeed, small samples are likely to minimize the effects of checks and gaps in the boards (McClung et al., 2014). This may explain the low value (2.8 g·m⁻²·s⁻⁰·⁵) found out by Kordziel et. al. (2020), who used samples with smaller surface area than the minimum set in the Standard.
On the other hand, Table 8 collects information about the moisture storage in CLT specimens. The asterisks indicate that the corresponding sources report both the sorption and the desorption moisture storage function, thus describing the hysteretic behaviour of CLT; in this case, for the sake of simplicity the reported values only refer to the sorption curve. Please observe that Table 8 only shows one pair of RH – EMC values: indeed, when the entire sorption curve is not known, HAMT software tools are able to build it through mathematical models based on just two EMC values (Libralato et al., 2022), corresponding to saturation conditions (EMC\(_{\text{sat}}\), which is not investigated in this study) and to another relative humidity value (normally, RH = 80%). For instance, one of the most consolidated models has been proposed by (Kuntzel, 1995), and requires the definition of a coefficient “b” that can be determined experimentally:

\[
\text{EMC}_{\text{RH}} = \text{EMC}_{\text{sat}} \left(\frac{(b-1)\cdot \text{RH}}{b - \text{RH}}\right) (m^3/m^3) \tag{4}
\]

In this case, a narrower range of variation is observed in the literature (from 13.8% to 16.7% moisture content in terms of mass, at equilibrium with RH = 80%). The CLT specimens tested in this study are slightly out of this range, since they show a percentage moisture content of around 12.7% in terms of mass, when referring to RH = 80%. The comparison of the experimental values reported in Table 7 and Table 8 suggests that the hygrothermal parameters adopted in HAMT simulations should be selected with care: indeed, even if one refers to the same category of CLT (spruce), their values can vary within a wide enough range, thus introducing non-negligible uncertainties in the results. This issue is further deepened in the next subsection, based on a simulated case study.

**Impact on the simulation results**

According to the findings of the previous section, the hygrothermal properties of specific CLT specimens may differ from the values reported both in the literature and in the databases of the most common HAMT software tools. Since the users of the tools commonly rely on these databases, without checking the conformity with the CLT they intend to use in their project, it is here relevant to understand how the results of HAMT simulations can be affected by the choice of the CLT properties.

To this aim, in this research several HAMT simulations are carried out on a typical CLT-based wall, consisting of a 10-cm spruce CLT layer (λ = 0.012 W·m\(^{-1}\)·K\(^{-1}\)) with an outer 6-cm layer of wood fibre (λ = 0.035 W·m\(^{-1}\)·K\(^{-1}\)) plus a vapour-open water-tight membrane. The resulting thermal transmittance is \(U = 0.37\) W·m\(^{-2}\)·K\(^{-1}\). The simulated assembly is discretized through a series of smaller control volumes with a stretch factor of 1.3. This means that the grid thickens towards the extreme sides of each layer: in particular, the largest element is 16 mm thick, while the smallest one is 1 mm thick.

The hygrothermal properties of both wood fibre and membrane are selected from the Delphin database, while three different sets of hygrothermal properties are considered for the CLT, namely:

1. The “Spruce Saxony Tangential CLT” available in the Delphin database;
2. A “Norway spruce CLT”, created by using the experimental density, water absorption coefficient and sorption isotherm of the five-layer CLT specimen investigated in this study (since the experiment did not include the thermal conductivity and the moisture diffusion resistance, the same values as for “Spruce Saxony Tangential CLT” have been used);
3. A “Modified Norway spruce CLT”, where the moisture storage function is described through an average between the sorption and desorption curves reported in Fig. 5.

The difference between the second and the third case rises from the impossibility to simulate the CLT hysteretic behaviour in Delphin: this means that just one moisture storage curve must be introduced. When both sorption and desorption isotherms are available, a possible strategy might consist in using an intermediate curve.

Regarding the outdoor boundary conditions, the outside heat transfer coefficient and surface vapor diffusion coefficient are set to 25 W·m\(^{-2}\)·K\(^{-1}\) and 7.5·10\(^{-8}\) s·m\(^{-1}\),
respectively. The solar absorption coefficient is set to 0.7. The simulations are run by using a weather file referring to Catania, Southern Italy, prepared by the authors according to a previous study (Costanzo et al., 2020). The weather file includes hourly data for the sky longwave irradiance and the rainfall on the horizontal plane. The wind-driven rain on the vertical surfaces is calculated by Delphin according to the standard EN ISO 15927-3 (CEN, 2009), depending on wind direction and velocity. Since the prevalent wind direction in Catania is West, this is the selected wall orientation in the simulation (azimuth angle = 270°). Moreover, the indoor climate conditions are set according to EN ISO 15026 (CEN, 2007), and consider the variation in indoor air temperature and relative humidity as a function of outdoor conditions: the indoor air temperature ranges from 20 °C to 25 °C and the relative humidity ranges from 35% to 65%. The inside heat transfer coefficient and surface vapor diffusion coefficient are respectively set to 8 W·m⁻²·K⁻¹ and 5·10⁻⁶ m·s⁻¹. Finally, the initial conditions are set to RH = 80% and T = 20 °C for each material.

The results of the three different simulations are compared by looking at the temperature and RH values in the CLT, and more specifically in the layer closest to the thermal insulation, since this turns out to be commonly the zone most exposed to moisture-related risks (Urso, 2022). Moreover, the comparison will look at the moisture content (MC) in the CLT, measured as a volumetric percentage. The results reported in Table 9 suggest that the use of different types of CLT (Saxony, Norway), as well as the adoption of an intermediate storage function between sorption and desorption ones (Norway modified), do not affect the temperature in the CLT, while there is a limited influence in terms of maximum relative humidity. Instead, a more evident variation is observed in terms of moisture content, and in this direction the change of the moisture storage function has non-negligible effects. However, it is also worth underlining that in all cases, moisture-related risks are almost absent, since the RH in the CLT never exceeds 80%; furthermore, the relatively small variations in the moisture content do not justify large changes in the thermal conductivity of the material.

Table 9: Comparison of the main results obtained with the three different CLT types

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Saxony</th>
<th>Norway</th>
<th>Norway modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min T</td>
<td>12.7°C</td>
<td>12.4°C</td>
<td>12.5°C</td>
</tr>
<tr>
<td>Mean T</td>
<td>22.2°C</td>
<td>22.1°C</td>
<td>22.2°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Humidity (%)</th>
<th>Saxony</th>
<th>Norway</th>
<th>Norway modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean RH</td>
<td>61.6%</td>
<td>62.8%</td>
<td>63.0%</td>
</tr>
<tr>
<td>Max RH</td>
<td>76.9%</td>
<td>78.0%</td>
<td>76.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moisture content (m³/m² %)</th>
<th>Saxony</th>
<th>Norway</th>
<th>Norway modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean MC</td>
<td>4.65%</td>
<td>3.46%</td>
<td>4.17%</td>
</tr>
<tr>
<td>Max MC</td>
<td>4.93%</td>
<td>3.63%</td>
<td>4.49%</td>
</tr>
</tbody>
</table>

Conclusions

This paper has shown the results of an experimental campaign on a series of three-layer and five-layer spruce-based CLT specimens. The tests were aimed to determine, based on many specimens, their moisture storage functions for sorption and desorption, and the water absorption coefficient, according to standard procedures. The results show marked uniformity and low dispersion for the various similar CLT specimens, and only slight differences were observed between three-layer and five-layer ones. On the one hand, the water absorption coefficients range between 3.86 g·m⁻²·s⁻¹/² (five layers) and 3.91 g·m⁻²·s⁻¹/² (three layers); based on the literature survey, these values approach the lowest end of the currently available range of data in the literature. On the other hand, the measured moisture storage curves are almost superimposed, even if the three-layer specimens show a slightly higher moisture content than five-layer ones during desorption. Hysteresis is evident, with differences by about 50% between the moisture content in the sorption and the desorption curves at RH = 60%. This confirms that sorption hysteresis occurs in CLT, which is often neglected in HAMT simulation tools.

The main message emerging from this study is that the hygrothermal parameters adopted in HAMT simulations should be selected with care, otherwise inaccurate results are likely to occur. This issue has been further deepened through a simulated case study, showing that using non-verified generic hygrothermal properties for the CLT can induce non-negligible variations in the CLT hygrothermal performance, especially in terms of relative humidity and moisture content, even if – at least in the selected case study – this does not modify the degree of moisture-related risk.

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