Heat and Mass Transfer Modelling for Moisture-Related Risks in Walls Retrofitted by Timber Materials

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Abstract

The e-SAFE innovation project financed by the Horizon 2020 Programme and led by the University of Catania, is developing, testing and demonstrating an innovative combined energy-and-seismic renovation solution for Reinforced Concrete (RC) framed buildings based on the addition of Cross Laminated Timber (CLT) boards to the outer walls, in combination with wood-based insulation. In this paper, the proposed renovation solution (called e-CLT) is investigated in terms of moisture-related risks, i.e., the mold growth and the increase in heat losses due to Liquid Water Content (LWC) within building materials. To this aim, dynamic simulations are performed by means of Delphin 6.1, thus including combined heat and mass transfer (HAMT) due to water vapor migration and accumulation. The results show that, although there is no significant risk of mold growth in the e-CLT for climate conditions prevalent in Northern Italy, the moisture content within the materials implies an increase by about 10 % in the heat losses if compared with a dry wall. Furthermore, inaccurate material properties and boundary outdoor climate conditions can affect the reliability of the results: for this reason, a more appropriate hygrothermal characterization of materials is recommended, as well as the identification of suitable climate datasets, which, however, are not always available.

1. Introduction

Since around 80 % of the building stock in the European Union was built before 1990, i.e., before the enforcement of most EU regulations regarding the energy performance of buildings, it is apparent that deep renovation is a key challenge towards the decarbonization of the existing building stock.

In this framework, the e-SAFE innovation project financed by the Horizon 2020 Programme and led by the University of Catania, is developing, testing and demonstrating an innovative combined energy-and-seismic renovation solution for Reinforced Concrete (RC) framed buildings based on the addition of Cross Laminated Timber (CLT) boards to the outer walls, in combination with wood-based insulation. In this study, the proposed renovation solution (called e-CLT) is applied to a building with infill walls made of two leaves of lightweight concrete blocks with an intermediate air gap, a very common envelope solution in Italy for the residential buildings from the 1960s to the 1980s.

While the seismic performance ensured by the e-CLT solution is addressed in other studies, this paper aims to investigate moisture-related risks by means of Delphin 6.1 software, which allows transient simulations considering combined heat and moisture transport (HAMT). In fact, wood-based components are particularly prone to moisture storage due to their cellular structure, and – being wood an organic material – they are more sensitive to decay caused, e.g., by mold.

Preliminary investigations by means of Glaser's method revealed that, although the application of the e-CLT solution improves both thermal and hygrothermal behavior of the walls (Evola et al., 2021), interstitial condensation may occur in cold climates in case of high indoor humidity values (Costanzo et al., 2021a). A following study (Costanzo et al., 2021b) tested the e-CLT solution in three different climates in Italy, performing transient hygrothermal simulations and reaching similar conclusions: wood-based materials are likely exposed to mold

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growth – although moderate – especially in colder climates.

Building on these previous research experiences, this paper focuses on the reliability of the results, which may be affected by inaccuracy of hygrothermal materials properties and climatic boundary conditions. To this aim, a literature review highlights the dispersion of the hygrothermal property values for wood, and the consequent effects on the simulation results. Moreover, the paper underlines the effects of using different weather datasets, such as a typical meteorological year (TMY) and a weather file available in the Delphin database for the same location. In particular, the simulations refer to Milan, a cold and humid climate in Northern Italy. Finally, moisture-related risks are investigated by looking not only at mold growth, but also at the increase in the heat transfer through the wall due to the liquid water content within building materials.

2. Methodology

The hygrothermal performance and the moisture-related risk of the e-CLT solution are investigated by means of dynamic finite element analyses performed in Delphin 6.1, a commercial program developed at University of Dresden.

The software allows the combined heat and moisture transport (HAMT) within porous building materials to be considered. To this aim, it requires hygrothermal material properties and functions (e.g., porosity, density, specific heat capacity, thermal conductivity, water vapor resistance factor, liquid conductivity, moisture storage curve), and indoor and outdoor climatic boundary conditions (e.g., temperature, relative humidity, driving rain, wind speed, wind direction, short and long wave radiation). The selection of appropriate material properties and climate data is a paramount issue due to their effect on the reliability of the results; for this reason, this paper pays particular attention to these issues, as highlighted in this Section.

2.1 Materials

The e-CLT solution is here applied to a typical Italian wall structure composed of (from internal to external side): cement plaster (20 mm), hollow concrete blocks with volcanic aggregates (80 mm), non-ventilated air cavity (100 mm), hollow concrete blocks with volcanic aggregates (120 mm) and cement plaster (30 mm).

As regards the e-CLT solution, this is composed of (from internal to external side): CLT (100 mm), low density wood fiber (60 mm), scarcely-ventilated air gap (20 mm) and a fiber cement cladding (12 mm).

The proposed solution also includes a vapor-open foil (s_d = 0.04 m) to protect the insulation layer from the effect of wind-driven rain, applied to the external side of wood fiber. Materials are selected from the Delphin database; some properties have been modified according to technical sheets and standards in case of missing materials. Table 1 and Table 2 show the hygrothermal properties of the selected materials. In case of air gaps, the thermal conductivity is defined as an equivalent value calculated from the air gap thermal resistance.

Table 1 – Thermal properties of selected materials: "id" is the identification code on material database, (*) indicates modified properties

id	Material	ρ	c_p	λ_{dry}
		$kg \cdot m^{-3}$	$J \cdot kg^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$
242	Plaster	1390	850	0.75
508	Hollow blocks (80 mm)	845	1000	0.29*
15	Non-ventilated air gap	1.3	1050	0.56*
508	Hollow blocks (120 mm)	667*	1000	0.39*
712	CLT	450*	1843	0.12*
1762	Wood fiber	50*	1000	0.04
15	Scarcely-ventilated air gap	1.3	1050	0.22*
654	Fiber cement cladding	1160	1188	0.60*

Table 2 – Hygric properties of selected materials: "id" is the identification code on material database, (*) indicates modified properties

id	Material	μ	A	θ80	θeff
		-	$g \cdot m^{-2} \cdot s^{-0.5}$	$kg \cdot m^{-3}$	$kg \cdot m^{-3}$
242	Plaster	33	30	40.7	430.0
508	Hollow blocks (80 mm)	15	177	11.4	319.4
15	Non-ventilated air gap	1	-	-	-
508	Hollow blocks (120 mm)	15	177	11.4	319.4
712	CLT	186	2- 5 - 12*	59.8	728.1
1762	Wood fiber	1.1	5	12.7	590.3
15	Scarcely-ventil. air gap	1	-	-	-
654	Fiber cement cladding	26	14	70.9	283.6

The hygrothermal characterization of the CLT requires a more detailed literature review, both because it is a missing material from the Delphin database, and because there are some discrepancies amongst the various sources surveyed. In particular, those parameters related to moisture transport, namely the water vapor resistance factor (μ-value) and the water uptake coefficient (A-value), show a high dispersion of their values. Thus, CLT is represented through the database material Spruce radial (id.: 712), experimentally tested by the Technical University of Dresden. However, since the manufacturing process can make CLT denser than the original wood (Lapage, 2012), density is replaced by the value supplied by manufacturers ($\rho = 450\ kg \cdot m^{-3}$), whereas dry thermal conductivity refers to EN ISO 10456 Standard (CEN, 2007a) ($\lambda = 0.12\ W \cdot m^{-1} \cdot K^{-1}$).

As regards moisture transport parameters, the glue between lumber boards in a CLT panel can affect the μ-value and A-value because it acts as a seal. Nevertheless, some studies show good agreement between CLT and transverse wood's hygric properties (AlSayegh, 2012; Lapage, 2012): Table 3 sums up experimental μ-value and A-value for softwoods and CLT, based on different species as reported in the literature. As shown in Table 3, moisture transport parameters depend firstly on species and fiber direction. The EN ISO 10456 Standard (CEN, 2007a) reports $\mu = 50$ for timber, i.e., the proposed resistance to vapour diffusion is about four times lower than spruce radial and ten times lower than spruce tangential as gathered from the Delphin database. However, if compared with literature values (AlSayegh, 2012; Kordiziel et al., 2020), the μ-value varies from 146 to 456 for softwoods and CLT boards made of softwood with transverse fiber direction. This means that μ-value of spruce radial ($\mu = 186$) can be assumed as a reliable value for simulations.

Coming to the A-value, this varies between 1.6 $g \cdot m^{-2} \cdot s^{-0.5}$ and 14 $g \cdot m^{-2} \cdot s^{-0.5}$ for transverse fiber direction. The wide range of values covered in the literature mainly depends on the preparation of test specimens. For instance, the presence of wood imperfections (e.g., checks, cracks, holes) could make wood more permeable to moisture, as confirmed by (Raina, 2021) by means of the visual evaluation of absorbed water from a surface with a small hole during the water uptake test. For this reason, (AlSayegh, 2012) selected test specimens that are more representative of the material without checks, thus obtaining A-value = 1.9 – 2.0 $g \cdot m^{-2} \cdot s^{-0.5}$. In contrast, (Lapage, 2012) tested samples including "checks, cracks, pitch pockets and other deviations from ideal conditions", and determined higher A-values (4 – 14 $g \cdot m^{-2} \cdot s^{-0.5}$). The size of the sample can also affect the experimental results: indeed, small samples are likely to minimize the effects of checks and gaps in the boards (McClung et al., 2014). This could explain A-values (2.1–2.8 $g \cdot m^{-2} \cdot s^{-0.5}$) found out by (Kordiziel et. al., 2020), who used samples with smaller surface area than the minimum set in the Standard.

Table 3 – Softwoods and CLT features from literature (SPF: Spruce-Pine-Fir)

Source	Type	ρ	μ*	A
		$kg \cdot m^{-3}$	-	$g \cdot m^{-2} \cdot s^{-0.5}$
Delphin database	Spruce (radial)	395	186	12
	Spruce (tangential)	395	488	5
	Spruce (longitudinal)	395	5	12
EN ISO 10456 (CEN, 2007a)	Timber	450	50	-
(Lapage, 2012)	CLT, Eastern SPF	486	-	4 - 7
	CLT, Western SPF	500	-	12
	CLT, European softwood	340	-	10 - 11
	CLT, Him-Fir	522	-	14
(Alseyeg, 2012)	CLT, Eastern SPF	370	328	2.0
	CLT, Western SPF	440	456	1.9
	CLT, European softwood	340	311	1.6
	CLT, Him-Fir	380	277	2.5
(Cho et al., 2019)	CLT	602	630	-
(Kordiziel et al., 2020)	CLT, SPF + Douglas Fir	423	-	2.5 -2.8
	SPF without adhesive	426	146	2.8
	SPF with adhesive	426	168	2.4
(Raina, 2021)	CLT, European spruce	-	-	1.9 – 3.6
	CLT, European spruce – without covered edges	-	-	7 - 12
(Chang et al., 2020)	Larch (radial)	570	75	-
	Larch (tangential)	570	109	-
	Larch (longitudinal)	570	5	-
	CLT, larch and plywood	600	79	-

*dry cup, RH chamber = 50 %

Lastly, the sealing of edges could also influence test results. To this purpose, (Raina, 2021) tested various samples with and without sealed edges, demonstrating that the A-value can reach 12 $g \cdot m^{-2} \cdot s^{-0.5}$ due to water absorbed from longitudinal fiber of the cut uncovered edges. Not surprisingly, the results are close to those reported by (Glass & Zelinka, 2010) for softwood in longitudinal direction (10 – 16 $g \cdot m^{-2} \cdot s^{-0.5}$). In view of this, and considering A-values of 2 and 12 $g \cdot m^{-2} \cdot s^{-0.5}$ as reasonable extreme conditions, this paper assumes 5 $g \cdot m^{-2} \cdot s^{-0.5}$ as an intermediate value for spruce. However, simulations are repeated for other A-values to perform a sensitivity analysis.

2.2 Climate Boundary Conditions

The simulations are carried out for Milan (lat: 45°, long: 9°, altitude: 103 m) a cold and humid climate in Northern Italy. In order to assess the most appropriate available dataset for this location, the paper considers: i) the weather file from the Delphin database and ii) the TMY weather file from Linate (2004 – 2018) downloaded from the website (Climate.OneBuilding.org, 2022) (Fig. 1). In both cases, the investigated wall is oriented facing north, thus excluding the effect of direct solar radiation. For this reason, the plots in Fig. 1 only report the mean diffuse solar radiation.

Considering yearly mean values, the Delphin dataset shows 13 % higher diffuse solar radiation, but it appears colder (by 3 °C on average), more humid (by 6 % on average) and rainier (by 20 % on average) than the Linate dataset. This suggests that it will more likely induce moisture-related risks. Nevertheless, the long wave sky radiation (LWR) data is missing in all Italian weather files within the Delphin database, which implies excluding long wave radiation exchange from the simulation, thus affecting the reliability of results. On the other hand, Linate TMY is not built *ad hoc* for hygrothermal simulations, i.e., it is not representative of the worst climate conditions from the point of view of moisture-related risks. The selection of the most appropriate dataset thus requires preliminary simulations, as discussed in Section 3.1.

The outside heat transfer coefficient and surface vapor diffusion coefficient are 25 $W \cdot m^{-2} \cdot K^{-1}$ and $7.5 \cdot 10^{-8}$ $m \cdot s^{-1}$, respectively, while their indoor values are 8 $W \cdot m^{-2} \cdot K^{-1}$ and $2.5 \cdot 10^{-8}$ $m \cdot s^{-1}$, respectively. The solar absorption coefficient is set to 0.6. The incident wind-driven rain (WDR) is calculated by Delphin according to EN ISO 15927-3 Standard (CEN, 2009), using a splash coefficient of 0.7. In addition, a water source is assigned to the side of the insulation protected by the water-proof membrane, set equal to 1 % of the rain flux incident on external surface. This setting simulates rain leakage through the cladding.

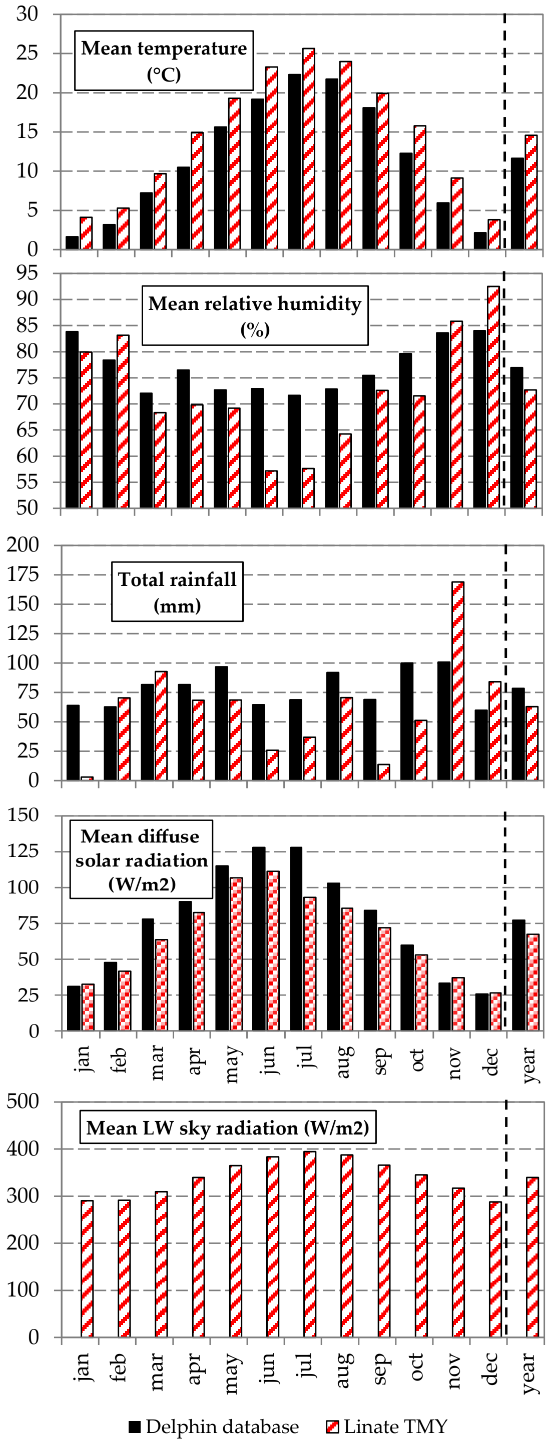

Fig. 1 – Comparison between weather data from Delphin Database and from a web service (Climate.OneBuilding.org, 2022)

On the other hand, the indoor conditions are set according to EN ISO 15026 Standard (CEN, 2007b). The standard offers a simplified approach to take the change in indoor temperature and relative humidity as a function of external conditions into account (Fig. 2). It is here relevant to highlight that moisture-related risks may also depend on the indoor conditions (Brambilla & Gasparri, 2020). This issue will be investigated in future studies.

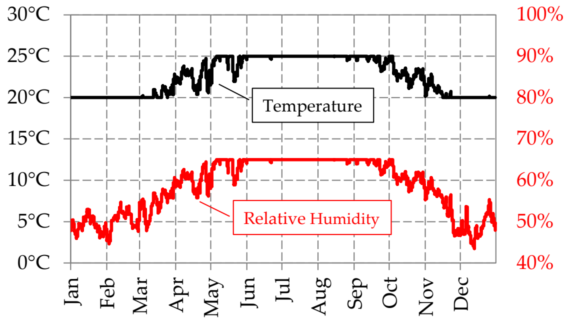

Fig. 2 – Indoor climate conditions as a function of outdoor temperature from Linate TMY, according to EN ISO 15026 (CEN, 2007b)

2.3 Initial Conditions

The simulations are performed over a 10-year-long period, in order to obtain stabilized behavior; the initial conditions correspond to 20 °C temperature and 80 % relative humidity for all materials.

2.4 Outputs

Moisture related-risks are evaluated for the e-CLT solution applied to the investigated existing wall by requesting as outputs from Delphin the time-dependent liquid water content (LWC) in both the CLT and the insulating material, as well as the temperature and relative humidity from which calculating the mold index (MI) by means of the tool PostProc 2.2.3.

In particular, the LWC ($m^3 \cdot m^{-3}$) represents the volume fraction of liquid phase accumulated in the pores of the materials (Bauklimatik Dresden, 2022). Instead, according to the VTT model (Ojanen et al., 2010), MI measures the mold growth rate in a scale from 0 (no mold growth) to 6 (very heavy and tight mold growth); the authors also suggest that MI values above 3 are not acceptable. The model also considers the sensitivity of materials to mold growth: in this specific case, the CLT and the wood fiber are set as "sensitive".

Further outputs are the mean conductive heat flux throughout the wall and the moisture-dependent thermal conductivity for each layer of the wall. They are required to assess the increase of thermal losses and U-value due to humidity within building materials.

More specifically, the moisture-dependent U-value ($W \cdot m^{-2} \cdot K^{-1}$) is calculated as follows:

$$U(LWC) = \left[\frac{1}{h_{0,e}} + \sum_{i=1}^{n} \frac{s_i}{\lambda_i (LWC)} + \frac{1}{h_{0,i}} \right]^{-1} \quad (1)$$

where $h_{0,e}$ and $h_{0,i}$ are respectively the outside and inside heat transfer coefficient, previously defined, n is the number of layers and λ_i ($W \cdot m^{-1} \cdot K^{-1}$) is the moisture-dependent thermal conductivity of each layer, computed by Delphin as a function of LWC, given the dry thermal conductivity λ_{dry} (Vogelsang et al., 2013):

$$\lambda = \lambda(LWC) = \lambda_{dry} + 0.56 \cdot LWC \quad (2)$$

This study does not consider the influence of temperature on thermal conductivity, since Delphin does not include any built-in functions for the selected materials to this scope. However, by taking into account the conversion coefficients reported in Annex A of EN ISO 10456 Standard (CEN, 2007a), the maximum variation of λ within the range of temperatures occurring in this study would be around 3 % for the insulating material, and even less for the other materials.

3. Results And Discussion

3.1 The Role of the Weather Data

As mentioned above, the influence of weather data is preliminarily investigated. The main target is to understand which dataset is more appropriate, or implies more conservative results, in terms of moisture-related risk.

The simulations are repeated with i) weather data from the Delphin database, which does not include the LWR exchanges, ii) weather data from Linate TMY, with and without LWR exchanges. The results are reported in Fig. 3 and Fig. 4.

If looking at the results obtained using the weather file from the Delphin database (grey solid line in Figs. 3-4), the yearly mean LWC is 0.054 $m^3 \cdot m^{-3}$ in the external side of CLT and 0.012 $m^3 \cdot m^{-3}$ in the external side of wood fiber. There is no risk of mold in both materials. Instead, the results from the simulations run with the TMY from Linate reveal that including LWR exchanges worsens the hygrothermal behavior of the e-CLT. In fact, using Linate TMY with LWR implies temperatures and relative humidity profiles respectively lower and higher than the case without LWR, which also means higher LWC and MI.

In particular, the yearly mean LWC in the external side of both CLT and wood fiber increases by around 4 %. The risk of mold growth is higher in the wood fiber, for which the maximum MI is 2.17 – 0.27 respectively taking and not taking into account LWR exchanges. Although the MI is still below the critical threshold, in the first case its values tend to increase over the years. This means that excluding the LWR exchanges, for instance by using the Italian weather files available in Delphin, can underestimate moisture-related risks.

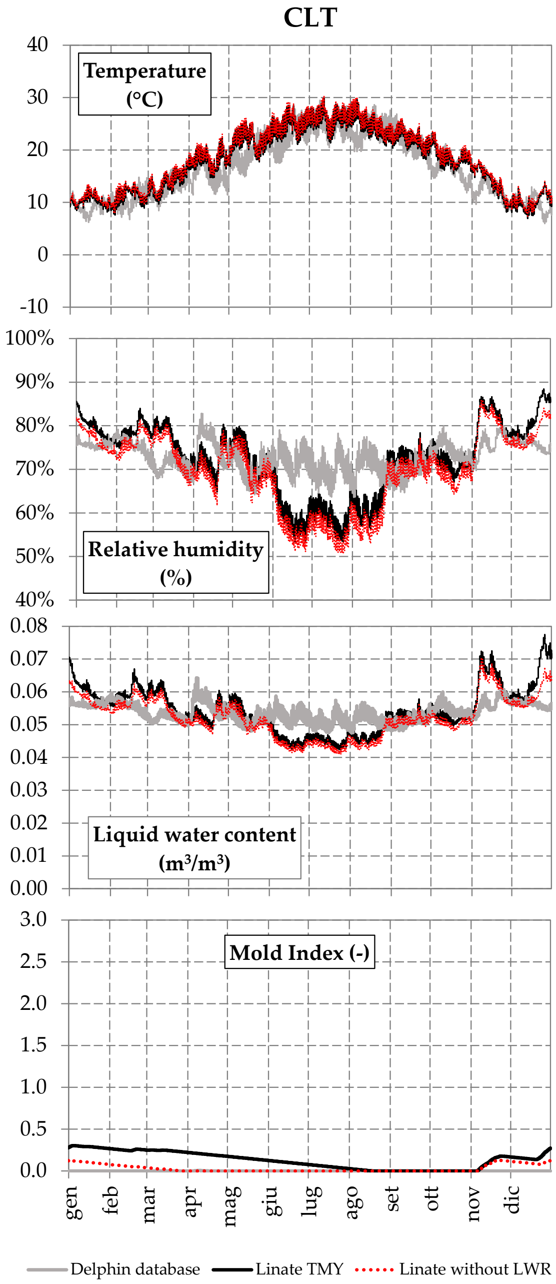

Fig. 3 – Comparison between simulations with weather data from Delphin database and from Linate TMY with/without LWR

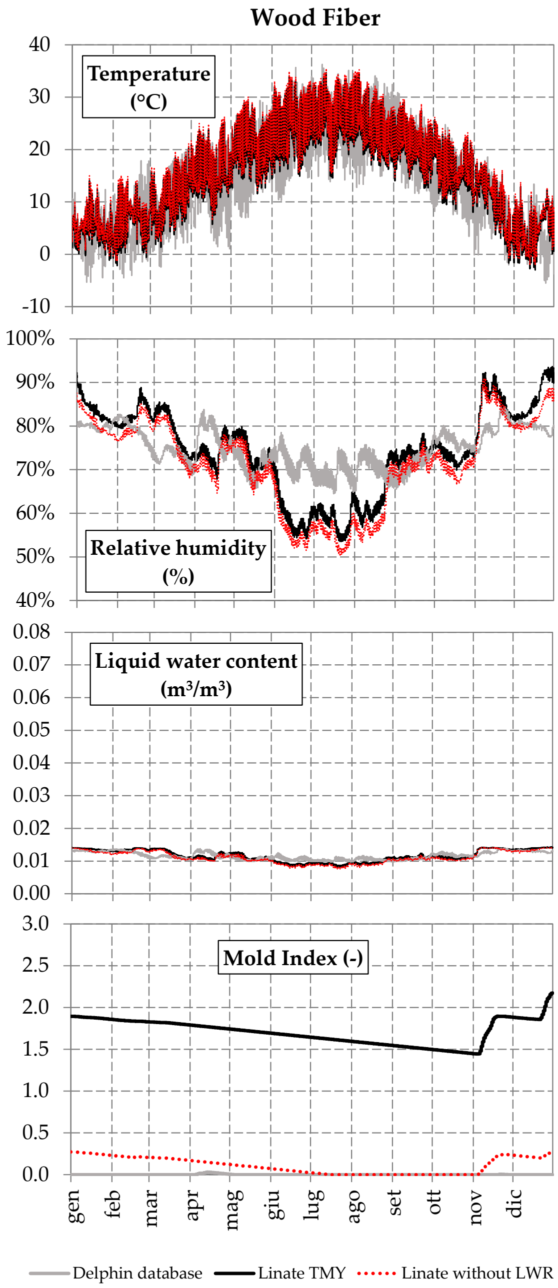

Fig. 4 – Comparison between simulations with weather data from Delphin database and Linate TMY with/without LWR

For this reason, the results discussed in the following sections refer to simulations performed with Linate TMY, even if this weather file is not built *ad hoc* for hygrothermal simulations. Future studies will rely on suitable extreme weather data for Milan, for instance created according to EN ISO 15026 (CEN, 2007b).

3.2 Humidity and Increased Heat Flux

In order to assess the increase in the heat losses due to LWC within building materials, the mean heat flux transferred through the wall is calculated considering thermal conductivity respectively dependent, or independent, on moisture content. Thus, simulations are repeated assuming for each material respectively Eq. 2 and Eq. 3.

$$\lambda = \lambda_{dry} \tag{3}$$

The results are reported in Fig. 5: not taking into account the variation in thermal conductivity due to moisture content within materials would underestimate heat losses by about 9.7 % on average. Similarly, the moisture-dependent yearly mean U-value (U = 0.326 W·m^{-2}·K^{-1}) increases by 11.0 % with respect to the U-value in dry conditions (U = 0.290 W·m^{-2}·K^{-1}).

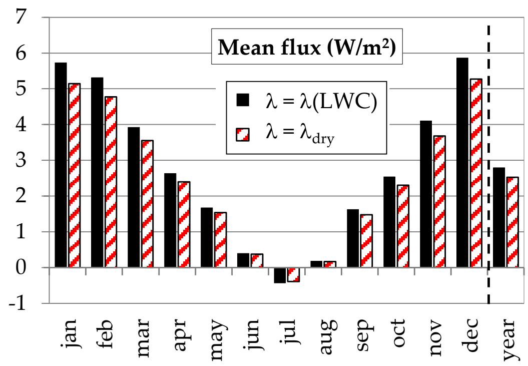

Fig. 5 – Monthly mean conductive heat flux: comparison between simulations taking and not taking into account moisture-dependent thermal conductivity

In a similar study, (Danovska et al., 2019) studied the impact of humidity and temperature on the thermal behavior of insulated timber walls for a series of Italian cities, and found out that the mean increase in heat losses – considering the actual thermal conductivity of materials – is below 6 % on average in Northern Italy locations and below 10 % in Southern Italy, the highest values pertaining to the most insulated wall structures. Finally, Fig. 6 suggests that the monthly mean U-value of the wall retrofitted through the e-CLT solution can be linearly correlated with mean LWC of wood fiber with $R^2 = 0.99$. This means that the thermal performance of the e-CLT solution applied to the investigated wall decreases linearly with the amount of the LWC in the insulation layer.

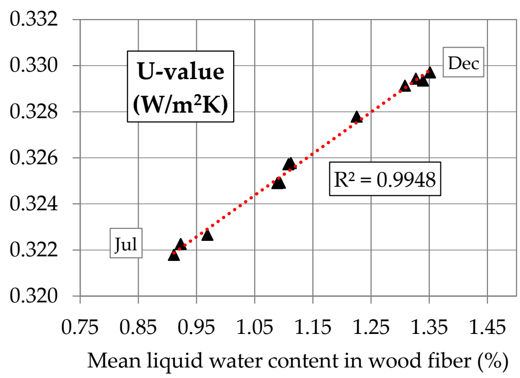

Fig. 6 – Moisture-dependent monthly mean U-value

3.3 The Water Uptake Coefficient

A sensitivity analysis is finally carried out to observe the CLT performance as a function of its A-value. The top plot in Fig. 7 shows the hourly profiles of mean LWC throughout the CLT, respectively with A-value = 2, 5 and 12 g·m^{-2}·s$^{-0.5}$ according to literature. In principle, higher A-values imply higher LWC during winter.

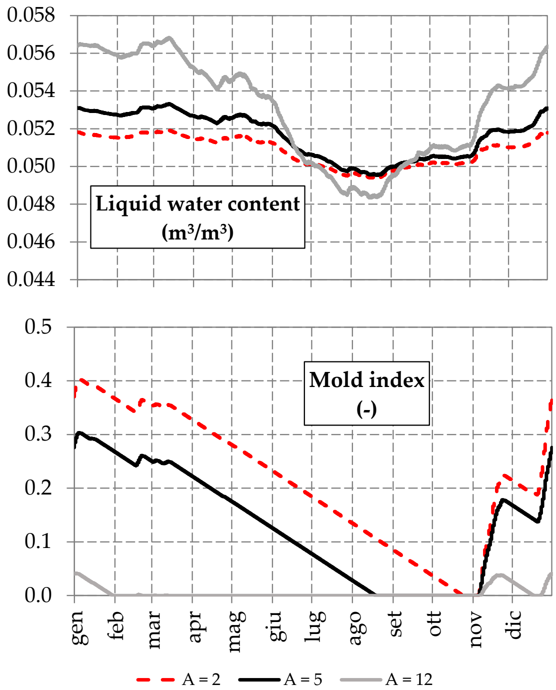

Fig. 7 – Influence of A-value on mean liquid water content and external face mold index. All values in legend are in g/m^{2}s$^{1/2}$

Overall, A-value does not significantly affect the e-CLT thermal performance: indeed, the yearly mean LWC ranges between 0.051 – 0.053 $m^3 \cdot m^{-3}$, which does not imply variations in the heat losses. Finally, looking at the MI in the CLT (bottom plot of Fig. 7), the increase in A-value determines slightly higher mold growth risk. Indeed, in this case the moisture content between CLT and wood fiber is absorbed more rapidly towards the inner side. However, the risk is negligible (MI < 0.4).

4. Conclusion

In this study, the e-CLT building retrofit solution, applied to a typical existing Italian wall, is investigated in terms of moisture related risks, i.e., the mold growth and the increase in heat losses due to liquid water content within building materials. Moreover, this paper focuses on the role of weather data and of the water uptake coefficient of the CLT material on simulations. Since e-CLT is an innovative retrofit solution, this topic is not addressed in the literature except for some preliminary analyses carried out by the same authors (Costanzo et al., 2021b). With respect to the above-referenced study, the current research confirms that a moderate mold growth risk (MI > 1) can occur in a cold and humid Italian climate, while also discussing the role of CLT hygrothermal properties in greater detail. Furthermore, the reliability of the Italian weather files within the Delphin database is assessed in a systematic way.

The conclusions can be summed up as follows:

- excluding the long wave heat transfer from the simulation, for instance, when using Delphin database Italian weather files, leads to underestimate moisture-related risks;
- the inaccuracy on the A-value of CLT does not significantly impact on the LWC and MI;
- the increased heat losses due to LWC within building materials amount to around 10 %
- the monthly mean U-value is linearly dependent on LWC in the insulation layer, and on average can vary by around 11 % if compared to an equivalent dry wall.

The next steps of this research activity will investigate the hygrothermal behavior during extreme meteorological years, selected from long-term weather acquisitions in different climate zones. In addition, further analyses are planned to better characterize hygrothermal properties of materials by means of experimental analyses.

Nomenclature

Symbols

A	water uptake coefficient ($g \cdot m^{-2} \cdot s^{-0.5}$)
CLT	cross laminated timber
c_p	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
HAMT	heat and moisture transport
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
λ_{dry}	dry thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
LWC	liquid water content ($m^3 \cdot m^{-3}$)
LWR	long wave radiation
MI	mold index (-)
μ	water vapor resistance factor (-)
ρ	density ($kg \cdot m^{-3}$)
s_d	equivalent air layer thickness (m)
θ_{80}	moisture content at 80 % RH ($kg \cdot m^{-3}$)
θ_{eff}	effective saturation ($kg \cdot m^{-3}$)
U	thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
WDR	wind-driven rain

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