

Preliminary investigation on the transient hygrothermal analysis of a CLT-based retrofit solution for exterior walls

V Costanzo¹, G Evola², L Marletta², G Roccella¹

¹ Department of Civil Engineering and Architecture (DICAr), University of Catania, via S. Sofia 64, 95123 Catania, Italy

² Department of Electrical Electronic and Computer Engineering (DIEEI), University of Catania, viale A. Doria 6, 95125 Catania, Italy

Abstract. This paper investigates the transient hygrothermal performance of an innovative energy and seismic renovation solution for reinforced concrete (RC) framed buildings, based on the addition of Cross-Laminated Timber (CLT) panels to the outer walls, in combination with wood-based insulation. This solution is being developed in the framework of a four-year EU-funded project called e-SAFE. The investigation relies on numerical simulations in DELPHIN 6.1, by considering combined heat and mass transfer (HAMT) due to water vapour diffusion and capillary transport. The proposed solution is tested in three different climates in Italy, to verify whether the CLT layer and the outer waterproof vapour-open membrane, inserted to protect the wood-based insulation from rain, still allow the effective drying of the vapour accumulated in liquid form in the walls, while also preventing mould formation. The results show that the increased thermal resistance of the wall assembly significantly reduces the total water content, although moderate risks of mould growth in the wooden materials may occur in coldest climates.

1. Introduction

It is widely known that the greatest part of the EU building stock is largely energy inefficient: indeed, as highlighted by the EU building stock observatory, around 90% of the European buildings were built before 1990, while about 35% of them are more than 50 years old [1]. Most of these buildings have not yet undergone energy renovation: this means that, in order to reach the targets set by EU for 2030 and 2050, the deep renovation of the existing building stock is a key issue [2]. The four-year e-SAFE innovation project, financed by the EU in the framework of the H2020 programme, aims to contribute in this direction: for this reason, the e-SAFE Consortium is investigating and demonstrating some innovative solutions for the combined energy and seismic building renovation. Indeed, nearly 50% of the European territory is earthquake-prone: in seismic countries, such as Albania, Greece, Turkey, Italy, Croatia and Romania, a destructive earthquake would make any energy renovation solution alone unsustainable from a social, economic and environmental point of view [3]. In these countries, combining energy and seismic renovation is a key point also for boosting market uptake.

This paper deals with one of the solutions investigated in e-SAFE, called e-CLT. This solution envisages the adoption of structural panels made of Cross Laminated Timber (CLT), which are connected to the existing RC beams with specifically designed friction dampers, and thus increase seismic performance. In fact, the CLT panels make available additional lateral stiffness, while the dampers dissipate seismic energy in case of moderate and strong ground motions. The CLT panels

also include an outer layer of insulating material (preferably natural or recycled ones), in order to comply with the U-value required by national and European regulations concerning buildings' energy performance [4].

More specifically, the paper addresses the hygrothermal performance of e-CLT, based on dynamic heat and mass transfer simulations with DELPHIN 6.1. Indeed, wooden building components are particularly sensitive to moisture, since wood has a high vapour sorption capacity and – being an organic material – is particularly prone to decay caused by fungi and mould formation. This risk occurs especially in cold and rainy climates, and deserves detailed hygrothermal analysis during the design stage of a wooden building component [5]. Previous studies have underlined that, in retrofitting systems based on multifunctional facade components, the addition of non-vapour-open materials to the existing façade can increase the risk of interstitial condensation, leading to the need of a micro-ventilated cavity behind the insulating layer in cold climates [6]. In CLT-based walls insulated on the outer side, the choice of the correct insulating material emerges as a key issue: recent studies have highlighted that very vapour-open materials, such as mineral wool, are expected to increase the risk of mould formation if compared to expanded (EPS) or extruded (XPS) polystyrene boards [7–8].

2. The e-CLT solution

In this paper, the hygrothermal performance of the e-CLT solution is investigated by supposing its application to a wall structure that is quite traditional for the residential building stock built in Southern Europe between the 1960s and the 1980s, that is to say infill walls with a double layer of hollow clay bricks and an intermediate air cavity. Starting from this wall configuration, further layers are applied on the outer side, according to the e-CLT solution, and namely a 3-ply 10-cm CLT panel plus a layer of wooden fibre and a final finishing wooden layer. A thin air-gap (2 cm) is left between the insulation and the cladding, and a vapour-open water-proof membrane (vapour resistance $\mu = 50$) is applied on the outer surface of the insulation to protect the wall from rain and wind.

Table 1 reports the main hygrothermal properties of the layers, as used in DELPHIN 6.1 for the dynamic simulations. Since the outer cladding is made of non-continuous wooden staves, which allows a slight air (and water vapour) circulation within, their vapour resistance is set to $\mu = 1$ in the simulations, while the thermal resistance of the small air cavity is set to $R = 0.09 \text{ m}^2\cdot\text{K}/\text{W}$, as for slightly ventilated cavities. The surface heat transfer coefficients are set to $7.7 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ and $25 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ respectively on the inner and the outer side.

Table 1. Hygrothermal properties of the investigated wall

	s	λ	C_p	ρ	μ	w_{80}	w_{sat}
	[m]	$[\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}]$	$[\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}]$	$[\text{kg}\cdot\text{m}^{-3}]$	[-]	$[\text{kg}\cdot\text{m}^{-3}]$	$[\text{kg}\cdot\text{m}^{-3}]$
Internal plaster	0.02	0.7	800	1500	9.3	34.2	430
Hollow clay brick	0.08	0.35	1000	720	10	11.4	319.4
Non-ventilated air cavity	0.05	*	1000	1.2	1.0	-	-
Hollow clay brick	0.12	0.35	1000	720	10	11.4	319.4
External plaster	0.03	0.70	1000	1600	11	25.2	250
Cross Laminated Timber	0.10	0.13	1600	440	50	62.6	445.1
Wooden fibre	0.065	0.04	2000	50	1.1	12.7	590.3
Water-proof membrane	$18\cdot 10^{-4}$	0.23	1000	180	50	0.3	345.1
Slightly ventilated air cavity	0.02	**	1000	1.2	1	-	-
Wooden staves	0.02	0.13	1880	630	1	-	-
* Thermal resistance $R = 0.18 \text{ m}^2\cdot\text{K}/\text{W}$		** Thermal resistance $R = 0.09 \text{ m}^2\cdot\text{K}/\text{W}$					

Other relevant parameters for the dynamic hygrothermal analysis are those related to vapour sorption, i.e. the saturation moisture content (w_{sat}) and the reference moisture content at RH = 80% (w_{80}). These values, together with the water absorption coefficient A, are available in the materials' database

included in DELPHIN 6.1. It is worth mentioning that the CLT panels are made of three separate layers, alternating transverse and longitudinal fibres: in principle, longitudinal fibres imply higher water absorption coefficient ($A = 0.012 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$) than transverse fibres ($A = 0.002 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$). In this paper, the entire CLT panel is characterized through longitudinal fibres; further analyses about the role of fibre orientation on the hygrothermal performance will be discussed in a following study.

The e-CLT solution reduces the thermal transmittance of the wall from $U = 1 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ to $U = 0.285 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, meaning that heat losses are reduced by around 70%. This is a satisfying value, if compared with regulations in force in Southern European countries (e.g. Greece, Italy, Turkey), while 3 or 4 more cm of insulation might be necessary e.g. in Central and Northern Europe.

The refurbished wall also shows excellent dynamic thermal performance, being the periodic thermal transmittance $Y_{IE} = 0.02 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ well below the threshold set by national regulations in Italy when more than 50% of the building envelope is renovated; the phase shift is $\phi > 15 \text{ h}$.

3. Methodology

DELPHIN 6.1 is a software tool developed at University of Dresden that allows a detailed 2-D numerical study of the dynamic heat and mass transfer phenomena inside building components, including vapour diffusion, vapour and liquid sorption and capillary suction. To this aim, a rich database is available, where materials are characterized through their relevant hygrothermal properties, including experimentally measured sorption curves and moisture-dependent thermal conductivity. In DELPHIN 6.1, sorption curves do not take into account hysteresis, which implies a slight deviation between adsorption and desorption processes. This feature is actually common to most HAMT tools, and in case of wooden materials this might imply a slight inaccuracy [9].

In this paper, the simulations for e-CLT are replicated in three different climatic conditions in Italy, namely those of Catania, Genova and Milan, making use of the weather data available in the DELPHIN database. Catania is representative of the warm and dry climate occurring in coastal Southern Italy, while Genova and Milan are two examples of the cold and humid climate in some regions of Northern Italy. The indoor conditions change as a function of outdoor temperature, according to EN ISO 15026: indoor air temperature ranges between 20°C and 25°C , while relative humidity ranges between 35% and 65%, which corresponds to normal internal moisture load [10].

The simulations are performed over a 10-year-long period, in order to get a stabilized behaviour; the initial conditions correspond to 80% relative humidity for all materials. The investigated wall is oriented facing north, in order to exclude the drying effect of direct solar radiation. The effect of driving rain is not considered. However, despite driving rain has generally negative effects on the hygrothermal performance of walls [11], it is also well-known that such effects are negligible when a water-proof membrane is applied on the outer side [12], as in the case of e-CLT. As an output of the simulations, the following parameters were taken for the CLT layer and the wooden fibre [13]:

- Total Water Content (TWC) in kg/m^3 , due to all liquid and vapour transport mechanisms: water accumulates in the pores of the materials, and along an annual wetting/drying cycle it oscillates between a minimum and a maximum value;
- Mould Index (MI): according to the VTT model [14–15], this index measures the possibility of mould formation in the materials and its growth rate. The model takes into account the sensitivity of materials to mould growth: treated wooden materials prove to be the most sensitive ones. $\text{MI} = 0$ implies no mould growth, while $\text{MI} = 6$ means very heavy and tight mould growth; $\text{MI} > 3$ is not acceptable, since it suggests visual findings of mould on up to 50% of the material [15].

Finally, condensation issues on the internal surface of the wall are investigated: if the internal surface temperature keeps below the dew point temperature corresponding to indoor conditions, surface condensation occurs, which is not acceptable.

4. Results and discussion

As a first result, Figure 1 shows the year-round trend of temperature and relative humidity in the CLT layer and the wooden-based insulation layer. More specifically, the reported values refer to the outermost surface of these layers, and to the tenth year of simulation. As one can observe, there is a remarkable difference amongst the selected climates, especially when looking at relative humidity: in Milan this keeps constantly around or even above 90% both in the CLT and in the wood fibre, while in Catania it ranges between 40% and 70%, the higher values occurring in the winter. Values in Genova are close to Milan, and frequently exceed 80%, especially in the wood fibre. These results suggest that mould formation issues are very likely in Milan and Genova, while being extremely unlikely in Catania: this is confirmed by Figure 2, referring to Milan, where – after two years of simulations – the Mould Index stabilizes around MI = 3 and MI = 4.5 in the CLT and the wood fibre, respectively.

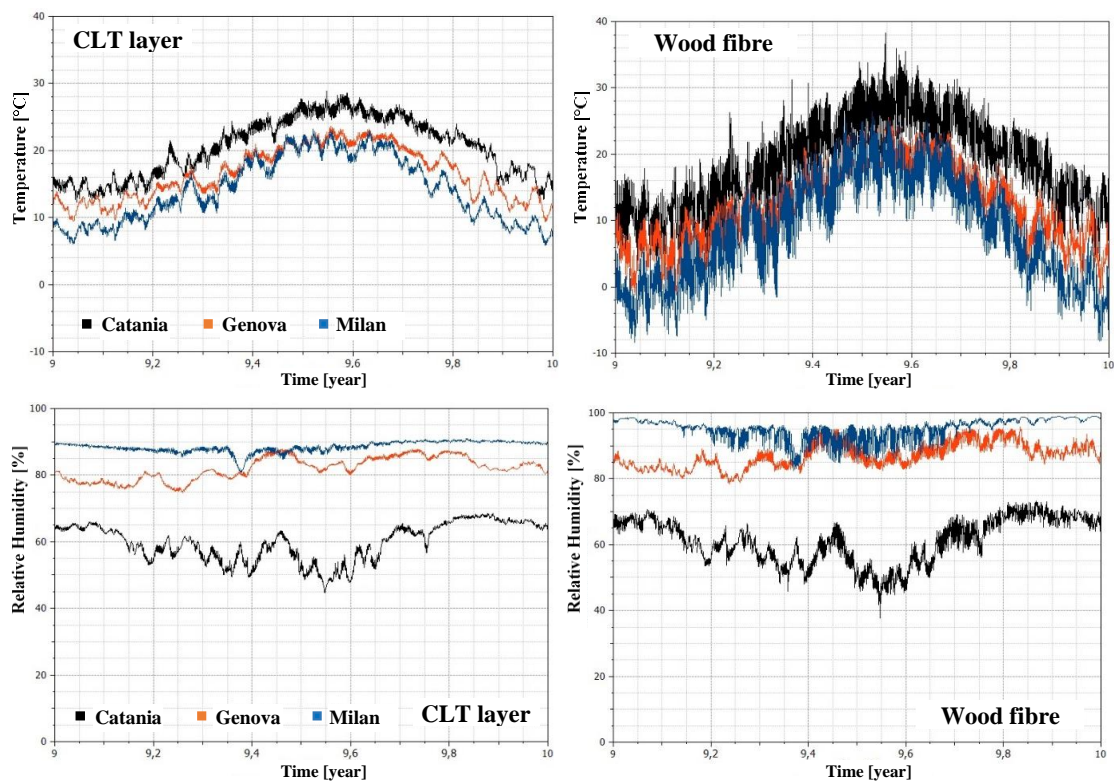


Figure 1. Year-round profile of temperature (top diagrams) and relative humidity (bottom diagrams) in the CLT (left-hand) and the wood fibre (right-hand). The curves refer to the outermost surfaces.

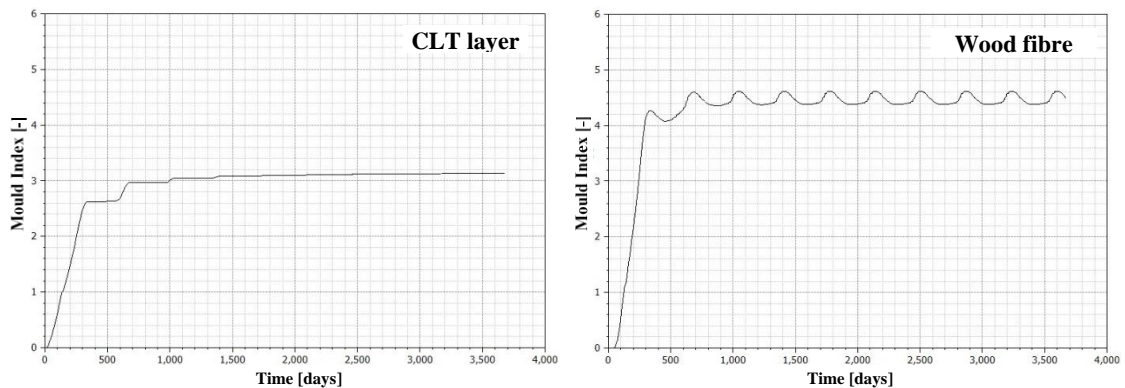


Figure 2. Time trend of the Mould Index in Milan: CLT (left-hand) and wood fibre (right-hand)

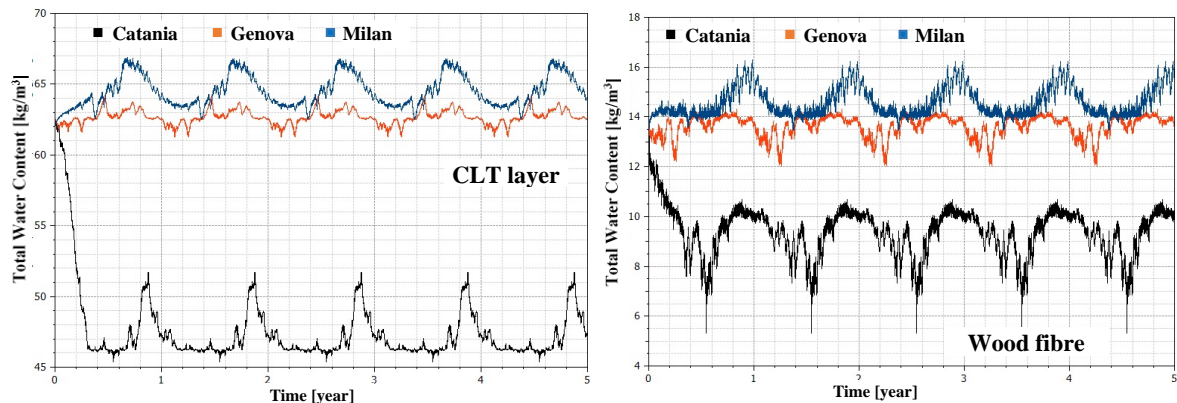


Figure 3. Total Water Content in the CLT (left-hand) and the wood fibre (right-hand)

According to the scale of MI introduced by the VTT model, this corresponds to visually evident mould formation on a significant portion of the material, which is not acceptable. The Mould Index in Genova is slightly lower than in Milan, but it still implies mould growth issues in the wood fibre, that need to be solved. On the contrary, no mould formation occurs in Catania (MI = 0 in both layers). Finally, Figure 3 reports the time trend of the TWC along the first five years, which is confirmed up to the tenth year. The TWC in Catania is much lower than in the cold climates for both layers. Catania is also the only context where the structures dry starting from their initial water content, but in any case the peak TWC occurring in the first year reappear in the following years, as in the other climates. The most relevant results are finally summarized in Table 2. The highest TWC competes to the CLT, most likely because the wood fibre can more easily dry out through mass and heat transfer processes with the outdoors. If compared with the saturation moisture content (w_{sat}) reported in Table 1, the TWC in the CLT corresponds – in Genova and Milan – to slightly less than 15% of the maximum moisture content, and slightly exceeds the w_{80} , while in the wood fibre this only amounts to around 8%. Table 2 also suggests that no surface condensation occurs in all climates; the hygrothermal performance of the proposed wall solution is totally satisfying only in Catania (Southern Italy), while in cold climates mould formation risks and excessive TWC are likely to occur, especially in the CLT.

Table 2. Hygrothermal properties of the investigated wall

Criterion	Layer	CATANIA	GENOVA	MILANO
Total Water Content	CLT	52 kg/m ³	64 kg/m ³	67 kg/m ³
	Wood fibre	10.6 kg/m ³	14.2 kg/m ³	16.2 kg/m ³
Surface Condensation	Inner surface	NO	NO	NO
Mould Index (max)	CLT	0	1.8	3.2
	Wood fibre	0	3.8	4.6

5. Conclusions

This paper has discussed the hygrothermal performance of a retrofit solution where a CLT panel plus a wooden-based insulation layer are applied on exiting infill walls made with a double layer of hollow clay bricks, based on HAMT modeling with DELHIN 6.1. While in warm climates of coastal Southern Italy the proposed solution does not show any hygrothermal issues, in cold climates (Northern Italy) visible mould formation – and the consequent wood decay – is likely to occur, especially in the CLT layer. Here, the maximum total water content reached in the CLT during annual wetting/drying cycle is slightly above the 15% of the maximum (saturation) moisture content in the material.

Suitable adjustments must then be envisaged for the proposed stratigraphy when it is adopted in cold climates, such as adding a vapour barrier on the inner side of the CLT or using a different kind of

insulation [7–8]. These issues are currently being investigated in the framework of the e-SAFE innovation project, together with the effects of driving rain, which was neglected in this paper, even if the presence of a vapour-open water-proof membrane on the outer surface of the insulation is expected to properly protect the wall from rain. Further ongoing studies are also addressing the possibility of simulating the CLT panel through three separate layers with different fibre orientation, and the increase in heat transfer due to the effects of humidity on thermal conductivity.

6. References

- [1] EU Building Stock Observatory database, <https://ec.europa.eu/energy/en/eu-buildings-database>
- [2] Buildings Performance Institute of Europe, The Concept of the Individual Building Renovation Roadmap – An in-depth case study of four frontrunner projects, iBRoad, January 2018.
- [3] La Greca P and Margani G, Seismic and energy renovation measures for sustainable cities: a critical analysis of the Italian scenario, 2018 *Sustainability* **10** 254.
- [4] Margani G, Evola G, Tardo C and Marino EM, Energy, seismic, and architectural renovation of RC framed buildings with prefabricated timber panels, 2020 *Sustainability* **12** 4845.
- [5] Wang L and Ge H, Hygrothermal performance of cross-laminated timber wall assemblies: a stochastic approach, 2016 *Build. Environ.* **97** 11–25.
- [6] Paiho S, Ojanen T, Pinto Seppä I and Paavola M, Critical performance aspects of retrofitting apartment buildings using a multifunctional facade system, 2019 *Buildings* **9** 184.
- [7] Chang SJ, Yoo J, Wi S and Kim S, Numerical analysis on the hygrothermal behavior of building envelope according to CLT wall assembly considering the hygrothermal-environmental zone in Korea, 2020 *Environ. Res.* **191** 110198.
- [8] Chang SJ, Wi S, Kang SG and Kim S, Moisture risk assessment of cross-laminated timber walls: perspectives on climate conditions and water vapor resistance performance of building materials, 2020 *Build. Environ.* **168** 106502.
- [9] Libralato M, De Angelis A, Saro O, Qin M, Rode C, Effects of considering moisture hysteresis on wood decay risk simulations of building envelopes, 2021 *J. Build. Eng.* **42** 102444.
- [10] EN ISO 15026:2007, Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation. International Organization for Standardization, Geneva, 2012.
- [11] Coelho GBA and Henriques FMA, Influence of driving rain on hygrothermal behaviour of solid brick walls, 2016 *J. Build. Eng.* **7** 121–32.
- [12] Bastien D and Winther-Gaasvig M, Influence of driving rain and vapour diffusion on the hygrothermal performance of a hygroscopic and permeable building envelope, 2018 *Energy* **164** 288–297.
- [13] Ibrahim M, Wurtz E, Biwolé PW, Achard P and Sallee H, Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering, 2014 *Energy Build.* **84** 241–51.
- [14] Viitanen H and Ojanen T, Improved model to predict mold growth in building materials, 2008 *Proc. ASHRAE Conf. Buildings X*, ASHRAE.
- [15] Ojanen T, Viitanen H, Peuhkuri R, Lähdesmäki K, Vinha J and Salminen K, Mold growth modeling of building structures using sensitivity classes of materials, 2010 *Proc. ASHRAE Conf. Buildings XI*, ASHRAE.

Acknowledgments

This paper was carried out in the framework of the "Energy and seismic affordable renovation solutions" (e-SAFE) project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 893135. Neither the Executive Agency for Small-and-Medium-sized Enterprises (EASME) nor the European Commission is in any way responsible for any use that may be made of the information it contains. This research was also partially produced in the framework of the SIS-RENEW research project (Piano di incentivi per la Ricerca 2020–2022 – University of Catania).