Dynamic hygrothermal assessment of a stone wall for the installation of a novel bio-based multi-purpose insulation material

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Abstract. A new era of sustainable construction products centered on human comfort improvement and energy and environmental impact reduction is under development. In this context, biomaterials have an important role as they can reduce energy consumption and resource depletion from the perspective of a circular economy. In this work, an external stone wall was analysed through WUFI Pro software in different configurations to assess its hygrothermal properties and evaluate the possibility of integrating a newly developed bio-based lignin-polyurethane foam panel from lignocellulosic sources. First, the stone wall was modelled varying the thickness, and the less performing thickness was studied by adding to the traditional stratigraphy two types of thermal insulation material with different water vapor resistance factors. The case study external wall typology was selected based on the review of representative typologies of Italian historic buildings. The component-scale performance was evaluated via WUFI Pro, which allows realistic calculation of the transient one-dimensional heat and moisture transport in building components. In this study, the analyses were carried out in the Italian climate zone D (Florence). Results pertain to the modelling of all the mentioned stone wall configurations and highlight the influence of the use of thermal insulation materials in historic building refurbishment for the improvement of the hygrothermal performance of building opaque envelope components.

Keywords: Dynamic Hygrothermal Simulation, Building Refurbishment, Historic Stone Wall.

1 Introduction

The efforts of current governments aim at the development of eco-sustainable cities [1] intervening in various sectors. In particular, the construction sector has high environmental impacts during all the life cycle phases, from production to operation and end-of-life [2]. One of the solutions to reduce these impacts is acting on energy consumption for building heating and cooling by improving the thermal insulation of the building envelope with materials that are also able to reduce the environmental impact. However, to evaluate the benefits produced by the application of insulation materials in building components, it is necessary to define first the hygrothermal performance of the original scenario.

The thermal properties of an envelope opaque component are connected to two specific boundary conditions [3]: stationary conditions, where the thermal behavior is completely characterized by the thermal transmittance U ($Wm^{-2}K^{-1}$) according to EN ISO 6946:2018, and dynamic conditions, where the characteristic quantities are periodic thermal transmittance Yie ($Wm^{-2}K^{-1}$), attenuation factor or factor decrease fa (-), and time lag or delay of the thermal wave φ (h) according to UNI EN ISO 13786:2018. Regarding the hygrometric properties, the analysis of the vapor migration phenomena that pass through the opaque component allows the evaluation of the risk of humidity entering the wall, with the consequent possible formation of vapor condensation. There are two approaches for this type of analysis: the "Glaser model", based on the UNI EN ISO 13788:2013, and the dynamic approach, based on the UNI EN 15026:2023. The first proposes a stationary calculation that is easy to perform but precautionary: it analyzes only the effect of vapor diffusion and could signal condensation risks even where they do not exist. Instead, dynamic models evaluate the hygrothermal behavior more realistically. Consequently, in addition to having good thermo-physical properties (i.e., thermal conductivity λ ($Wm^{-1}K^{-1}$), specific heat c_p ($Jkg^{-1}K^{-1}$), density ρ (kgm^{-3}), and porosity ϕ (m^3m^{-3})), the materials to be developed to improve the hygrothermal performance of the building envelope need to satisfy the requirements of adequate hygrometric properties (i.e., in terms of water vapor permeability δ ($kgm^{-1}s^{-1}Pa^{-1}$) and water vapor resistance factor μ (-)) [4]. Furthermore, to support environmentally sustainable construction, they should comply with the requirements of circular economy.

When the stratigraphy is defined, the hygrothermal performance, closely connected to the comfort of the indoor environment and the risk of condensation (especially non-visible interstitial condensation), can be studied with different software. Among them, WUFI is the most used [5]. Furthermore, it is necessary to define climate boundary conditions to verify the hygrothermal performance in a realistic scenario.

In the last decades, researchers have focused on the development and implementation of new thermal insulation materials, recently focusing on biomaterials. The use of biomaterials or recycled materials in buildings pursues both the objectives of good thermo-hygrometric properties and the reduction of environmental impacts, achieving a circular economy [6]. Korjenic et al. [7] used jute, flax, and hemp to develop a new insulation material from renewable resources with physical and mechanical properties comparable to those of the most commonly used insulation materials. However, traditional materials continue to dominate the construction sector, and there is a lack of knowledge among policymakers and developers regarding biomaterials. The review by Chen et al. [8] attempted to define construction biomaterials, their policies, and life cycle assessment through case studies. Among the most common materials for thermal insulation are polyurethanes derived from the reuse of plastic materials. Hysek et al. [9] provided a solution for the use of two waste materials, namely soft polyurethane foam residues from mattress production and winter wheat husks.

In this framework, this research study aims to evaluate the hygrothermal performance of the application of different insulation materials to opaque building envelope components and, specifically, external walls using WUFI Pro software. First, bibliographic research was carried out on the most common typologies of external walls for

Italian residential buildings in different construction periods. As for historic buildings (built before 1945) stone walls were identified as representative. The traditional stratigraphy was analyzed varying the stone thickness and, then, thermal insulation materials applied. Finally, a comparison was made between the parameters obtained for the traditional stratigraphy and the insulated ones. Results show that the use of insulation materials allows improving the regulation of thermal and humidity flows inside the stone wall, paving the way for further analyses aimed at introducing new bio-based eco-sustainable panels for building envelope thermal insulation.

2 Materials and methods

This study was developed in the framework of the LIGNOCAP PRIN project. The project aims to develop a bio-based insulation panel for energy efficiency in buildings with advanced thermo-acoustic insulation performance, low environmental impact, and long-term stability. To achieve this aim, the study of the energy performance associated with the integration of the new material into the building envelope was divided into various phases:

- definition of the calculation codes for hygrothermal analysis and building dynamic simulation, considering their inputs/outputs;
- definition of components to which the new material could be applied to implement its performance and installation methods;
- identification of the most common Italian typologies of external walls of three historical periods (historic buildings, post-World War II buildings, and new buildings) and choice of different Italian climatic zones for the simulation;
- heat and mass transfer simulation of the new material when applied to the selected external wall typologies;
- building dynamic simulation when applied to prototype buildings.

In this framework, this research aims to evaluate the hygrothermal performance of a stone wall (without or with the application of two different thermal insulation materials) using WUFI Pro to assess the effect of the insulation application. The work carried out serves as a basis for identifying the necessary parameters for the software simulation and its functionalities. Next steps will analyze the new bio-based polyurethane insulation material performance for different building external wall stratigraphies.

2.1 Heat and mass transfer simulation

The choice for the numerical simulation software was made among those capable of simulating in detail the hygrothermal performance in terms of heat and mass transfer at the component scale. Among the existing tools, in this research work, WUFI Pro was considered because it is specific for 1D heat and moisture transfer analysis of building components. It refers to different standards for simulating external boundary conditions. In particular, it is possible to compare results derived from EN 15026:2023, EN 13788:2013, and ASHRAE 160:2016. First, all the inputs needed for the characterization of the component stratigraphy in the software were identified. The definition of the geometry of the stratigraphy (position and thickness of the individual layers, and the associated materials) was carried out using the software database of building materials.

2.2 Opaque components description and properties

The definition and choice of building types to be analyzed was carried out considering the most recent ENEA study [10], which reports Italian statistical data relating to properties, divided by climate zones and construction periods. The data relating to buildings highlight that about 85% of the buildings are registered as residential. Therefore, it was decided to use this typology due to its greater diffusion in Italy compared to other types. Regarding the climate zone, in this work, the Italian zone D was considered for the high number of residential buildings present (24.10%), and Florence was selected as the example case study climate context. Climate zone D, according to the Italian Legislation (DPR 412/93) is characterized by Heating Degree Days (HDD) between 1411 and 2100. HDD are used to estimate the energy needed for heating; the higher the value of HHD, the colder is the location. Florence is characterized by 1821 HDD.

Among the different sources of data that classify the building envelope components typically used in Italy, distinguished per climate context and/or construction period, this research analyzed the three main ones: the IEE projects TABULA and EPISCOPE database, the UNI/TR 11552:2014 standard, and ENEA reports. In particular, this study focuses on external wall applications that, among the main components of the building envelope (walls, floors, and roofs), are those that occupy a predominant fraction. Also, the study focuses on historical buildings applications. About the historical buildings, the most representative technology used to build external walls before 1945 in Italy was the stone wall according to the literature analysis. Therefore, the effectiveness and feasibility of implementing insulation materials was studied for this selected representative construction typology. Indeed, the new bio-based insulation material can be used to develop panels for the refurbishment of the building envelope.

2.3 Input and output parameters

First, the climate data were retrieved from the Meteonorm software and uploaded to WUFI Pro. Then, the external wall typology (stone wall) was modeled. The software has a database of materials with their thermophysical characteristics (density ρ, porosity ϕ, specific heat c_p, thermal conductivity λ, and water vapor resistance factor μ). To choose the closest materials to those in the analyzed stratigraphy, the parameters obtained from the UNI/TR 11552:2014 standard were compared with those in WUFI Pro. The analyses were divided into two parts:

- Part I: analysis of the traditional stone wall with varying thicknesses of the stone layer (0.4, 0.6, and 0.8 m);
- Part II: analysis of the less-performing stone wall varying the type of applied thermal insulation material based on the water vapor resistance factor.

The other input data were selected considering the North orientation (worst conditions in terms of temperature and incident solar radiation), interior surface resistance equal to 0.125 m^2KW^{-1} and exterior surface resistance of the wall equal to 0.0588

m^2KW^{-1}. The initial humidity and temperature conditions were 80% for relative humidity (RH) and 20°C for air temperature (T). The high humidity is due to the possibility of verifying how the component studied behaves in unfavorable initial hygrothermal conditions. The outputs obtained were calculated using the weather file from Meteonorm for the external climate conditions and the UNI 15026:2003 to set the required indoor environmental conditions, which allows the hygrothermal variables to be analyzed more precisely. The duration of the analysis was set to 5 years, which corresponds to a standard duration that allows for the verification of the stabilization of the hygrothermal behavior of the components of the analyzed stratigraphy.

3 Results and discussion

3.1 Thermo-hygrometric analysis of the traditional stone wall

The main properties of the materials in the assessed stratigraphy are reported in Table 1.

Table 1. Main properties of stratigraphy components (from the internal to the external side).

Material	ϱ (kgm^{-3})	c_p ($Jkg^{-1}K^{-1}$)	λ ($Wm^{-2}K^{-1}$)	μ (-)
Plaster	2000	850	1.2	9.61
Stone	2300	850	2.3	70
*Render	1571	850	0.8	25

*lime and cement mortar that has worse hygrothermal conditions.

The results relating to the trend of the total water content within the stone wall stratigraphy (Fig. 1a) when varying the wall thickness (0.4, 0.6, and 0.8 m) are reported in Fig. 1b for the five years of simulation. An increasing water content over the years, without reaching equilibrium, is an indication of a potential problem as it highlights that the technical solution accumulates water without the capacity to dispose of it towards the outside, with consequent problems of condensation, mold, or corrosion. The graphs show that all the configurations reach equilibrium after about 2 years and then continue to have small oscillations due to normal seasonal variations. Moreover, the initial and final water content difference has a very limited variation among the analyzed thicknesses.

To evaluate the stratigraphy with the worst performance, the isopleth graph was analyzed. In this graph, the relative humidity on the internal surface is represented as a function of the temperature. Initially, the points are clearer, and progressively darken, allowing also to have temporal information. In the graphs (Fig. 1c), also the limit isopleths (LIM B I, dashed line in the graph, and LIM B II, solid line) are reported, which define the limit combination of RH and T above which microbiological growth is possible on the wall internal surface (if the points go beyond the dashed line there is only the possibility of micro-biological formation while if they go beyond the solid line there is a certainty). For 0.60 and 0.80 m thick stone walls, the values are always below the curve representing the LIM B I limit, meaning that the formation of mold is not physically possible. Among the configurations, the one with the greatest potential risk of mold formation is the 0.40 m thick stone wall. For this reason, the 0.4 m thick stone wall was used for the following analyses.

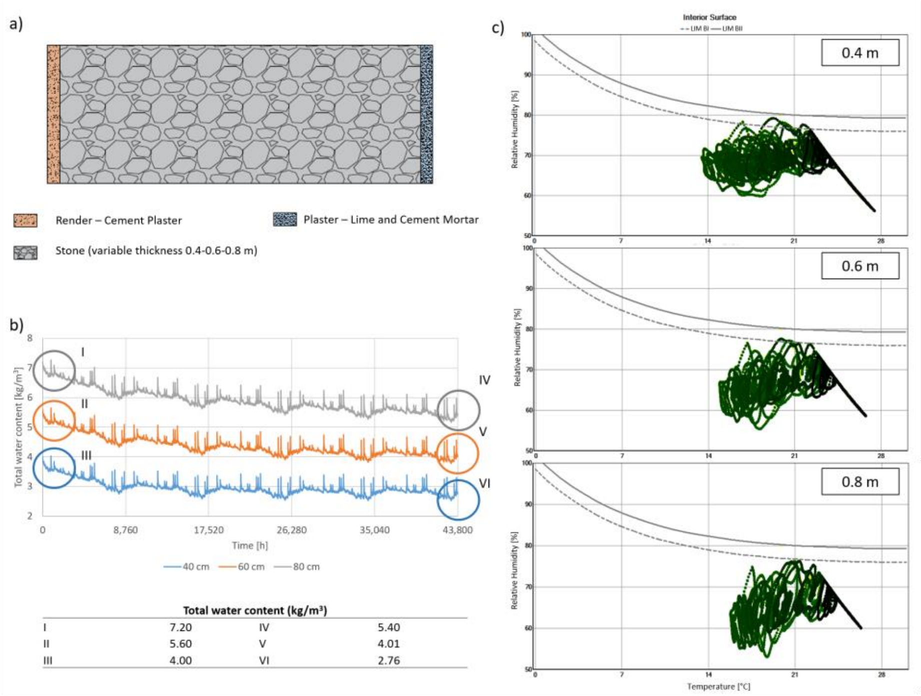

Fig. 1. a) Stone wall stratigraphy, b) total water content trend in relation to the variation in wall thickness and, c) isopleth graphs. Thermo-hygrometric analysis of the stone wall with thermal insulation

The results of the second analysis concern the hygrothermal performance obtained by applying two different types of thermal insulation materials on the internal side of the stone wall – since the intervention was hypothesized on a historic building with preservation requirements. Furthermore, a thickness of 5 cm was chosen for the thermal insulation layer as it is an average thickness for an insulation material applied on walls. The stratigraphy analyzed is shown in Fig. 2a while the data relating to the most important properties of the chosen insulation materials are reported in Table 2. These materials were selected to evaluate the influence of the variation in the value of water vapor diffusion resistance factor μ (-), which is equal to 8 and 69 for the two materials, respectively. This characteristic does not substantially affect the trend of the water content after five years within the stratigraphy (Fig. 2b).

Thereafter, temperature and humidity profiles over time were analyzed on the cold side of the insulation material layer (Fig. 3). This test allows identifying the possibility of ice formation if there is simultaneously a relative humidity between 95-100% and temperatures near 0°C. In the case of more permeable insulation material the possibility of interstitial condensation forming is higher because, despite a RH trend similar to the less permeable insulation material, the T values are much lower.

Table 2. Main parameters for thermal insulation materials chosen.

Parameters	More permeable material	Less permeable material
ϕ (m^3m^{-3})	0.96	0.98
μ (-)	8	69
λ ($Wm^{-2}K^{-1}$)	0.042	0.031

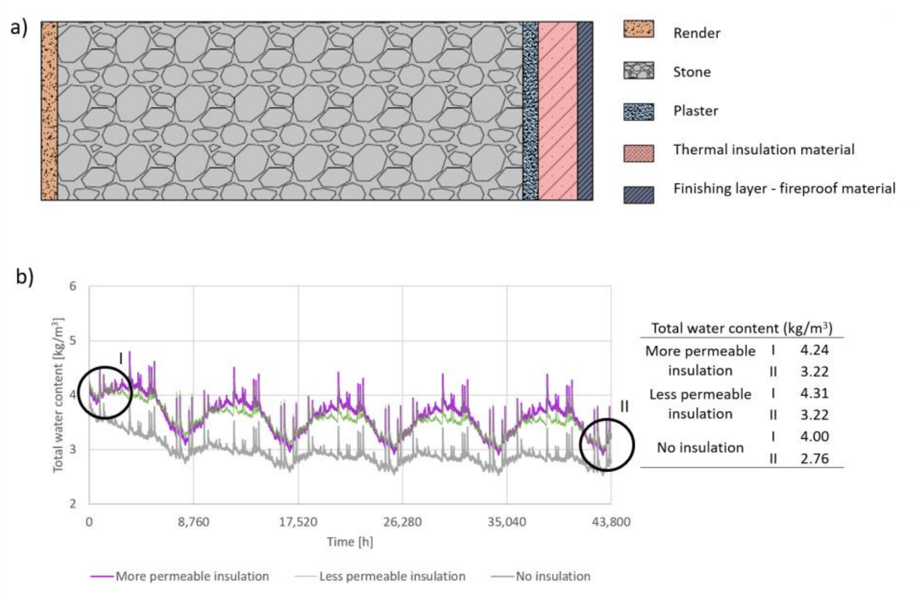

Fig. 2. a) Insulated stone wall stratigraphy and insulating materials main parameters and, b) initial and final water content trend.

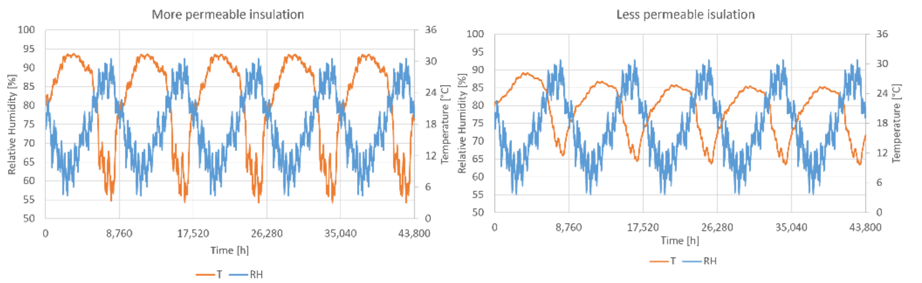

Fig. 3. Temperature and relative humidity trend on the insulation material surface (cold side).

4 Conclusion

The analyses of hygrothermal performance carried out using WUFI Pro on different stone wall configurations confirmed that a lower wall thickness (0.4 m) leads to a greater risk of mold formation on the internal surface. By adding internal insulation with different water vapor diffusion resistance factors to this stratigraphy, it was found that an insulation less permeable to water vapor is suitable to avoid the risk of interstitial condensation and, simultaneously, improve the thermal performance of the envelope. These considerations are fundamental for the production and subsequent analysis of a novel bio-based multi-purpose thermal insulation material.

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