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Hygrothermal performance of historic massive wall: when is 2D simulation necessary?

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ABSTRACT
Hygrothermal analysis of historical building envelopes is crucial in ensuring their durability and enhancing their performances. The use of hygrothermal dynamic simulation is the most effective approach to predict moisture related damages or risk of mould growth on ancient masonry envelopes. However, simulating the hygrothermal behaviour of a historic wall composed by stones or bricks and mortar joints, with a detailed two-dimensional (2D) model, is typically a complex and time-consuming process. For this reason, in numerical models, composite walls are often simplified with a one-dimensional (1D) layer, neglecting the mortar joints. An oversimplified numerical model could affect the evaluation of a retrofit intervention and lead to inadequate design choices. This study evaluates when the description of a historic wall as a 1D homogenous layer leads to an acceptable level of accuracy and when it is necessary the use of a more precise 2D model. We quantified the error by comparing 1D and 2D simulations of different massive walls in three Italian climate conditions. We examined a possible retrofit intervention with different internal insulation systems considering vapor tight, vapor retardant and capillary active solutions. Although simplified 1D models are reliable for thermal parameters, we have identified a different behavior regarding the hygric parameters. Whereas for a capillary active insulation system the 1D and 2D simulations show a reasonable agreement, the 1D approximation is no longer acceptable in the case of vapour closed insulation systems as it leads to large deviations. Knowing when it is possible to implement a simplified 1D model and quantifying the introduced error will support architects and energy consultants in the design process. It will guide them in the choice of the most suitable model depending on their specific requirements.

KEYWORDS
Hygrothermal simulation, Interior insulation, Performance evaluation, Moisture related issues, Historic stonewall.

INTRODUCTION

Historic buildings are highly energy-consuming parts of the city center, and their energy consumption provokes large CO_2 emissions due to the low performances of their thermal envelopes. A possible strategy to reduce this impact is to decrease the thermal transmittance of the outer walls. In the case of aesthetically valuable historic buildings, interior insulation has proven to be a reliable solution, but dynamic hygrothermal simulations are needed to avoid possible hygrothermal risks. In fact, the change of the original thermal and moisture balance could lead to a higher moisture accumulation into the wall [1] with a consequent spalling and cracking due to hygric expansion and contraction or frost-thaw cycles, or visual deterioration due to salt efflorescence [2]. A thorough understanding of the moisture transport is also primary to make an accurate choice of the correct inner insulation system. It is common practice, while performing a hygrothermal simulation, to simplify the historical wall as a homogeneous stone or brick layer. This simplification gives the user the possibility to have quicker results, but has the effect of neglecting mortar joints, which could play a significant role in terms of moisture storage and transport; the resultant deviations are investigated in this paper. A previous study [3] analyzed the impact of the mortar joints for a massive brick wall exposed to real climate conditions showing that they have a negligible impact and concluding that typically the approximation to a homogenous brick layer is allowed. In the present work, we extend previous analysis considering a broader range of variants and situations. We analyze a historic wall that is retrofitted with the application of different types of internal insulation, we consider several materials for the composition of the historic wall, ranging from stone to bricks, and finally we examine different climates zones.

METHODS DESCRIPTION

Hygrothermal simulation tool

In order to perform a full hygrothermal assessment, the commercial software Delphin 6.0.16 is employed. We considered a full hygrothermal simulation, which includes heat transport, liquid convective transport and vapor diffusion [4].

Boundary condition: Outdoor

In this study we focus on Italian climate; in particular we selected three locations to consider North, Middle and South latitudes and cover different climate zones. The hourly climate data files were generated with Meteonorm 7.0. They include hourly data of temperature, relative humidity, direct and diffuse short wave radiation, long wave radiation, wind direction, wind velocity, and rain. In Table 1, we summarize the main characteristics of the three selected climates, Udine, Ancona and Messina for a North-facing wall.

	Annual Wind Driven Rain [l/m^2]	Annual Global Radiation [kWh/m^2]	Winter T average [°C]	Summer T average [°C]	Winter RH average [%]	Summer RH average [%]
Udine	44.29	326.54	4.72	23.95	71.95	66.86
Ancona	31.53	344.76	6.51	23.22	72.69	69.24
Messina	50.14	358.08	10.07	24.75	72.22	68.49

Table 1. Environmental conditions highlights. Annual radiation is calculated on the wall.

The thermal resistance of the exterior surface was set to 0.04 m²K/W. The absorption coefficient for short wave radiation was set to 0.6 and the emissivity for long wave radiation exchange to 0.9. The rain exposure coefficient was set at 1.00 assuming no sheltering, since worst-case scenarios were assessed.

Boundary condition: Indoor

The interior climate was calculated based on external daily temperature data, according to the adaptive indoor climate model presented in the standard UNI EN 15026 [5]. The selected temperature range is between 20 and 25°C, while relative humidity varies between 35 and 65% following the recommendation of the WTA leaflet 6.2 [6]. The thermal resistance of the interior surface was set to 0.125 m²K/W.

Historical wall characterization

The construction technique chosen for the reference hygrothermal model is a traditional core masonry wall. It is a widely used technology of the ancient Italian buildings [7]. The materials for the simulations are chosen among the most commonly spread over the Italian context. Four different stones are selected: granite, limestone, sandstone and tuff. The brick masonry, generally widespread in the Center-North of the country, is also included in this study. The mortar and the plaster chosen for the reference wall are a Lime Cement Mortar and an historical Lime Plaster; their hygric characterization parameters, as for the other materials, are selected from Delphin Material Database 6.0. In Figure 1 and Table 2, we report the main hygrothermal characteristics of the chosen materials.

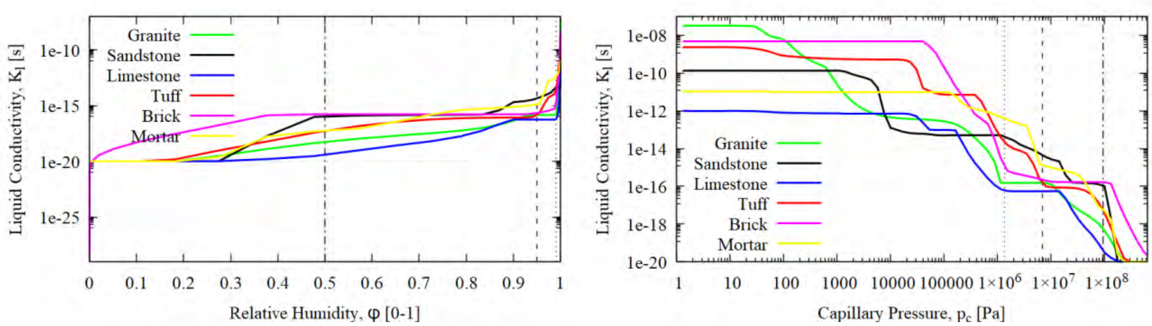


Figure 1. Liquid water conductivity, K_l, as a function of the relative humidity (left) and as a function of the capillary pressure, p_C (right). The three vertical dashed lines are drawn at the relative humilities 0.50, 0.95 and 0.99 in both graphs.

The 2D model includes irregular mortar joints of maximum 20 mm thickness. In figure 2 we show the full 2D description used in Delphin as well as the 1D approximated model.

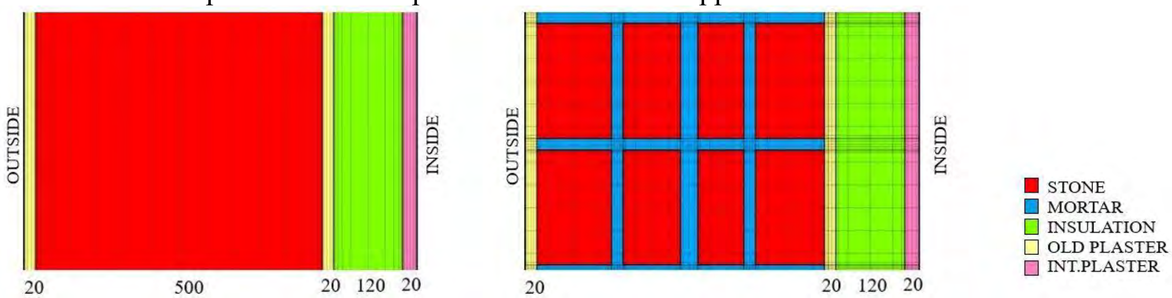


Figure 2. Schematic of the 1D and 2D models (elevation view of the section) of the historical wall section, with dimensions (mm).

Insulation systems

Three kind of insulation systems were investigated in this paper, classified by their vapor permeability: Vapor Barrier (VB), Vapor Retardant (VR), Vapor Open (VO). The thickness of each insulation layer is set to 120 mm. The VB insulation system consist of a mineral wool insulation layer plus a low permeability vapor barrier on its inner side. Two 12.5 mm gypsum board are used as surface coatings. As VR insulation system, we chose an extruded Polystyrene board installed with 20 mm of glue and a surface coating of 20 mm lime plaster. The VO insulation system is composed by a Calcium Silicate board, with 20 mm glue to attach it to the existing plaster, plus a surface coating of 20 mm lime plaster. The most relevant hygrothermal parameters of the insulation material are summarized in Table 2.

Materials	**ρ [Kg/m³]**	**C_p [J/KgK]**	**θ_{eff} [m³/m³]**	**λ_{dry} [W/mK]**	**μ_{dry} [-]**	**A_w [Kg/m²s$^{1/2}$]**
Mineral Wool	67	840	0.9	0.04	1	-
Extruded Polystyrene	35	1500	0.9	0.027	225	8e-06
Calcium Silicate	270	1158	0.9	0.069	3.8	1.114
Granite	2453	702	0.054	1.71	53.8	0.085
Limestone	2440	850	0.127	2.3	140	0.003
Sandstone	1967	264	0.12	0.95	106.9	0.012
Tuff	1450	925	0.299	0.48	10.4	0.098
Brick	1788	800	0.24	0.81	28.3	0.031
Lime Mortar	1878	758	0.223	0.8	36.9	0.036
Lime Plaster	1800	850	0.285	0.82	12	0.127

Table 2. Hygrothermal proprieties of the chosen materials. Density (ρ), Specific Heat capacity (C_p), Theta effective (θ_{eff}), thermal transmittance (λ_{dry}), vapor resistance (μ_{dry}), and water absorption coefficient (A_w).

Investigated outputs

The choice of the output to analyze in this assessment is based on the prescriptions of the WTA leaflet 6.5 [6]. The analysis of frost damages is neglected, since in the studied locations temperatures barely go under zero. Moreover, this study had shown a good correspondence of surface temperature and relative humidity values between 2D and 1D simulations, so the mold germination risk is not strongly influenced by this simplification. Therefore, the most interesting outputs to discuss, as proposed in WTA leaflet 6.5 [6], are relative humidity and temperature behind insulation, averaged on the first 10mm behind the insulation layer.

Error calculation

Outputs are evaluated on an hourly basis, in particular we compare the results of 1D and 2D simulations. The deviation between the two simulations is evaluated calculating the absolute error. In particular, for a given quantity X (that can be either the temperature, T, or the relative humidity behind the insulation, φ) we define the absolute error as

$$\Delta X(t) = |X_{2D}(t) - X_{1D}(t)| \tag{1}$$

where $X_{2D}(t)$ and $X_{1D}(t)$ represent the parameter X calculated as a function of time in the 2D and in the 1D simulation respectively. Then we define the absolute mean error, $\langle \Delta X \rangle$, as the time average of $\Delta X(t)$ over the last year of simulation and the maximum absolute error, ΔX_{max} as the maximum over the all simulation.

RESULTS

The thermal analysis shows a high correspondence of the simulation results between 2D and 1D case. In particular for the calculation of the temperature behind the insulation we get the following typical errors: $\langle \Delta T \rangle = 0.12$°C and $\Delta T_{max} = 1.4$ °C. Contrariwise, more deviations exist for the hygric behavior reaching mean absolute errors up to 7% for the relative humidity behind the insulation. Figures 3, 4 and 5 show the average relative humidity behind the insulation in the simulations of Udine for each case: Vapor Barrier, Vapor Retardant and Vapor Open insulation systems. A similar behavior is observed also for the simulation performed in Messina and Ancona.

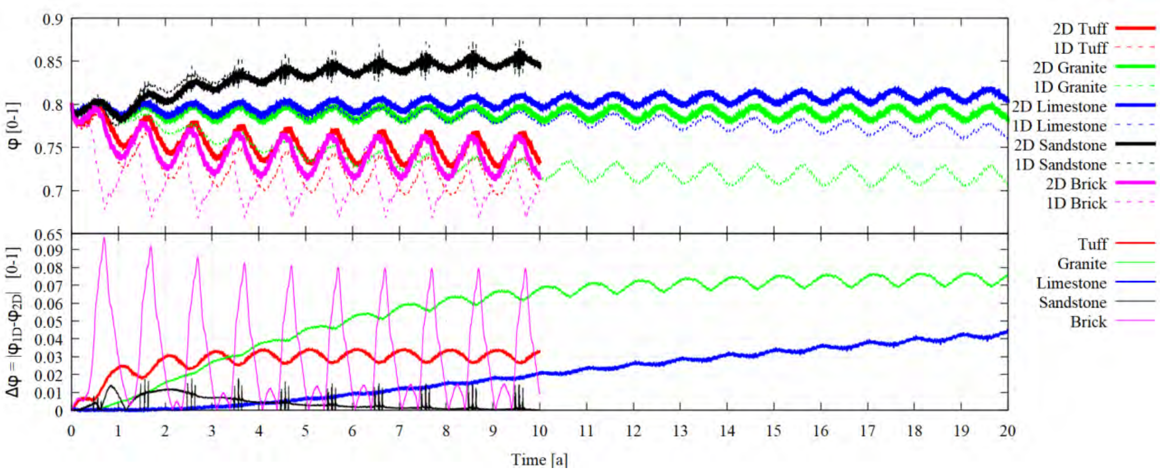


Figure 3. Relative humidity behind the insulation, φ, as a function of time (top panel) and corresponding absolute error, $\langle \Delta\varphi \rangle$, (bottom panel) for Vapor Barrier insulation system and for the climate of Udine. The different colors refer to different materials composing the historic wall.

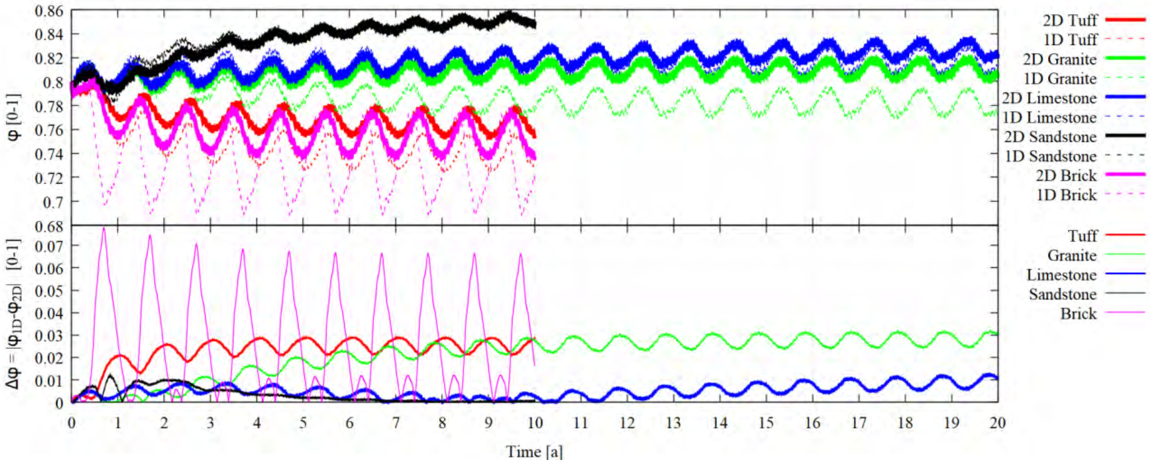


Figure 4. Same as Figure 3 but for Vapor Retardant insulation systems.

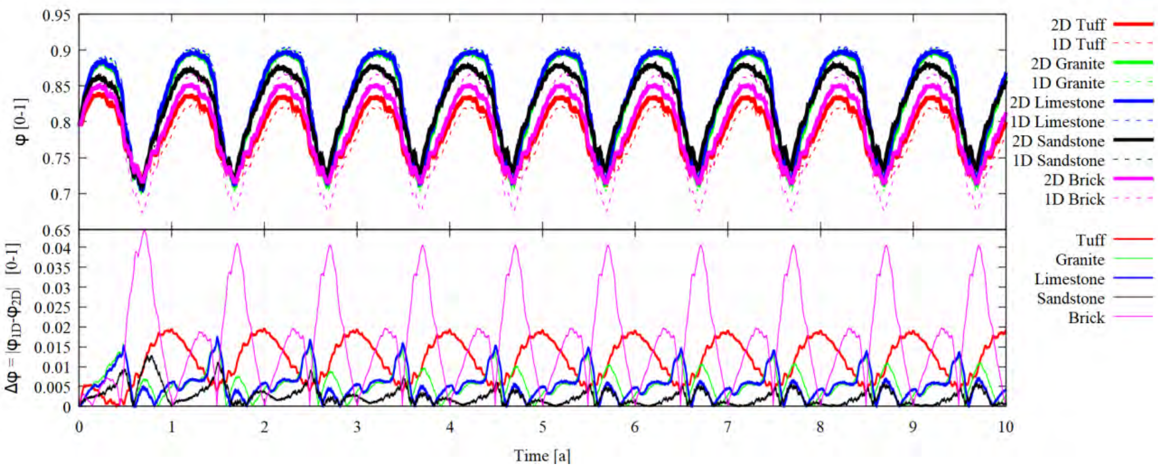
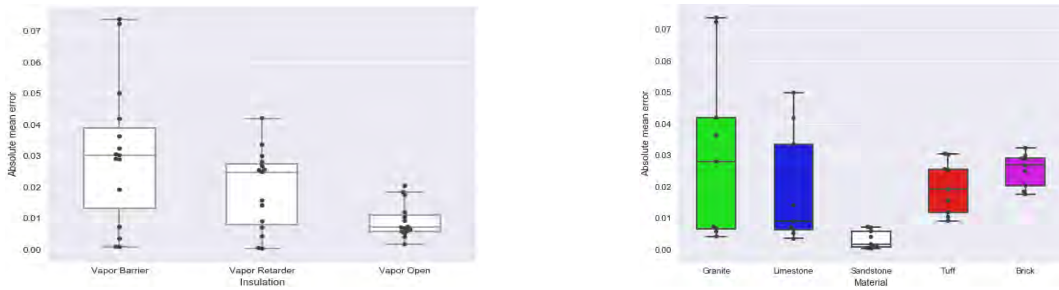


Figure 5. Same as Figure 3 but for Vapor Open Insulation system.

DISCUSSIONS

Figures 3, 4 and 5 show that depending on the insulation type and on the material that forms the historic wall we can get very different absolute errors between 1D and 2D simulations. For instance when considering the sandstone wall we always get very small errors, while the largest mean absolute errors are observed for the case of granite. Also in the case of the limestone wall we get significant deviations. In the specific case of the limestone wall with a vapor tight insulation system, the situation is particularly critical since the 1D and the 2D simulation have different behaviors. The 2D simulation reaches a quasi-stationary behavior, while the relative humidity in the 1D simulation keeps decreasing over the years. For the brick masonry wall we observe peaks up to 9% deviation. For the vapor open insulation system, we typically get small deviations while the largest errors are found in the case of vapor tight solutions. Conversely, we observe that the climate does not play a crucial role in the determination of the behavior of the absolute error. We only observe a small correlation between the quantity of wind driven rain that reaches the façade and the absolute error. In order to get a closer insight on the correlation between the observed error and the parameters varied in the simulations we represent in Figure 6 and 7 the distributions of the absolute mean error using box plots. In Figure 6 the absolute mean error distributions are grouped depending on the insulation type, while in Figure 7 according to the material of the historic wall.



Figures 6-7. Absolute mean error: Insulation system dependency, Material dependency.

Fig.6 confirms that vapour tight insulation systems lead to higher errors. In particular, decreasing the vapour tightness of the insulation system, we observe smaller mean absolute errors. For vapour open insulation systems the mean absolute error $\langle \Delta\varphi \rangle$ is, for almost all the cases, smaller than 2%, while for vapour barrier insulation system we get errors of up to 7%. When using a vapour retardant solution we get an intermediate behaviour. The use of a vapour tight system on the internal side of the construction strongly reduces the interaction of the wall with the internal environment and therefore the behaviour of the wall is mainly determined by the interaction with the exterior climate. This interaction strongly depends on the way in which the wall is modelled, thus a detailed description of the wall becomes more relevant in this situation. Fig.7 confirms that the material forming the wall plays a significant role in the determination of the mean absolute error. In particular, we observe smaller errors for materials that have a liquid water conductivity close to the one of the mortar in the range 80 – 99%. These observations strongly suggest that the approximation of a masonry wall to a homogenous brick or stone layer has to be used with caution, especially when looking at hygric properties of the wall.

CONCLUSIONS

This study analyzed the effect of simplifying an historical wall with a homogeneous layer in hygrothermal assessments, comparing the results of a 1D approximated simulation with those of a detailed 2D simulation. Three Italian climates and five materials were investigated, in combination with three internal insulation systems: a Vapor Barrier, a Vapor Retardant and a Vapor Open one. Results had shown a high correspondence in thermal behavior. Contrariwise, higher deviations are found in hygric results, especially in vapor tight and retardant insulation systems, which are influenced by a moisture accumulation process. Regarding the historic wall composition, those materials that have a similar liquid water conductivity to the mortar in the relative humidity range of the simulation, lead to smaller deviations. Our results show that representing an historic wall with a homogenous 1D layer could be in some situations an oversimplified model. We identified the situations that lead to larger errors in the framework of the parameters that we varied. However, further investigation are needed to develop a systematic approach for the identification of those situations.

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