2D-Hygrothermal Simulation of Historical Solid Walls

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Abstract: The analysis and the knowledge of the historical building masonries are key elements in preserving and enhancing their heritage value in a conscious way. The paper aims at simulating the hygrothermal behaviour of several traditional masonry structures, using a dynamic simulation program (Delphin 5.8.3) for coupling heat, moisture, and matter transport in porous building materials. Traditional walls have different geometries, characteristics, construction techniques, and materials. The most important difficulties in the simulation concern: (i) graphic simplification of complex structures, (ii) definition of the boundary conditions; (iii) layout discretization; and (iv) selection of the materials from the existing databases. In addition, the influence of wall orientation, climate data, and boundary conditions is relevant for the results. The focus of this paper is the comparison between the hygrothermal simulations and the *in situ* heat flow meter measurements of some traditional Italian solid walls. In this way, we can understand the influence of different assumptions, parameters, and simplifications on the virtual models. *Keywords:* graphic simplification, hygrothermal simulation, historical masonry.

Introduction

Each historical period produced a specific architecture that represents a unique experience for the human history, showing a symbol of different cultural evolutions. It follows well-defined and differentiated characteristics, according to the territory, the local resources, the cultural values, the economic opportunities, and the skills of workers. Each building is "*un unicum*" that should be known and analysed, in order to preserve and to update properly its cultural features and appearances. Although common elements have been found in structures from the same geographical areas or historical periods, normally there are many differences related to construction techniques, selection, and processing of materials. For this reason, the widespread knowledge of history, dimensions, structures, shapes, building techniques, materials, environmental behaviours, energy concepts, and conservation state,

management procedures is a necessary starting point to work properly on cultural heritage. The deep knowledge of distinctive characteristics and complexities of a historic building needs a systematic approach from general to particular. The work on historical buildings requires an accurate identification of thermal properties, damage problems, moisture contents, local and seasonal environmental conditions, and so on. This information can be challenging, particularly for historical masonries, due to the presence of several materials, layers, and thickness variability across the wall. In this context, the hygrothermal simulation of historical walls can be a valid tool for supporting a conscious design. Nowadays, several hygrothermal simulation software are available, such as Wufi (Fraunhofer Institute for Building Physics) and Delphin (Dresden University of Technology). Nevertheless, the estimation of the thermal performances of the historical envelope encounters the difficulties of non-availability of appropriate criteria, parameters and tools for hygrothermal and energy simulations. For this reason, the assessment of these instruments and their comparison with the experimental measurements, particularly for historical building could help architects and engineers in understanding their thermal performance and solving specific problems.

Aims and methodology

The paper aims at understanding the influence of different geometrical simplifications, discretization, and material selections on the thermal performances of traditions stone walls. Furthermore, for verifying the reliability of the simulated results, the hygrothermal simulations have been compared with the *in situ* heat flow meter measurements. The assessment of the hygrothermal behaviour of historical walls is somehow still unresolved because of the attempt to use the same evaluation methods and criteria used for modern constructions and the limited knowledge of historical construction techniques that are far different from the modern ones. The methods normally used for assessing the hygrothermal performance of the building components are: (i) tabulated thermal values from standards, literature or software libraries; (ii) performance calculation using standard proprieties of the materials; and (iii) *in situ* heat flow meter (HFM) measurement. The first one is considered not adequate for historic masonries, due to the complexity and the variety of traditional materials and structures compared to standard simplifications [1 & 5]. Therefore, the paper aims at comparing the hygrothermal behaviours obtained by the simulation and the HFM measurements, using the same climate and boundary conditions. The work is structured in the following phases:

- Selection and analysis of a traditional Italian masonries widely used in historical buildings;
- *In situ* HFM measurement of the thermal conductivity of the wall;

- 2-D (dimensionally) hygrothermal simulation of the wall obtained using the software Delphin 5.8.3 with different geometrical simplifications, discretization, and material properties;
- Comparison between measured and simulated results.

Case-study

The case study is the Public Weigh House, a building of Romanesque origins located in the city center of Bolzano (Italy). Here, we select a traditional stonework from the Renaissance period. It presents a complex pattern composed by irregular ashlar and a nucleus formed by raw and mixed materials, such as igneous rocks, mortar, bricks, and woods. It is covered in most parts on both sides with historic lime plaster, partially with wall paintings and frescoes. The wall section has a thickness of about 62 cm. The historical research, the petrographic studies, and the diagnostic campaigns (made by different techniques as IR-thermography and coring) allow to do accurate hypothesizes about the structural morphology. We considered: (i) age of the masonry; (ii) technical construction; (iii) type of stone; and (iv) physical characteristics and hygrothermal proprieties of the materials used. In this way, we collect enough data to suppose the shape and the dimensions of the stone elements and to theorize the manufacture of the nucleus.

Figure 1: The historical research and the diagnostic analyses conducted in the case study

HFM Measurement

The HFM measurement is a None Destructive Testing (NDT) that permits to determine the thermal transmission properties of the opaque envelope directly *in situ*. The apparatus (Ahlborn Almemo 2590-3S) is composed by a data-logger equipped with two temperature sensors (transducers) and one heat flux plate for measuring and registering the internal and external temperature and the heat flows through the walls. In addition, an adjunctive ambient temperature sensor has been used to verify the stability of the air temperature. The measurement has been carried out according to the International standard [4] on the north-facing walls and on a representative part of the whole element, to avoid the influence of the environment (e.g. sun, wind, rain, snow, localized eat sources), and the singularities (e.g. thermal bridges, different thicknesses, internal humidity, or damage). In addition, inner and outer surfaces have been protected from the variability of the boundary conditions (e.g. systems, people, direct solar radiation, and so on). To

check the uniformity of the measurement area, the location of the HFM apparatus has been investigated by the IR-thermography [2]. The sensors have been located about half-way between window and corner, and floor and ceiling. The monitoring period has been chosen to provide a stable thermal resistance (R-value) that takes into account the inertia of the walls [1]. The standard procedure [4] requires a sampling duration of an integer multiple of 24 h and at least 72 consecutive hours, dependent on the characteristics of the building component and the temperature variation. In this case, the test has been conducted continuously for 4 days (96 hours) with a climatic stability, to improve the reliability of the results on the high thickness wall. The data has been processed with the "average method", a simplified approach based on the fundamental equations of the heat transfer.

2-D simulations

The numerical simulation program Delphin 5.8.3 uses the model of coupled heat, humidity, and air transport in capillary porous building materials. The simulation of complex walls, as the historical ones with inhomogeneous material and non-standardized layouts, must be made with 2-D models. The program package consists of a user interface (data input), a solver (calculation module), and a post-processing tool for visualizing the results. The program contains several databases with climatic data, air, and material proprieties (measured directly in the laboratory). The graphic output is based on 2-D coloured image and contour plots, location and time cuts, and the post processing or further processing of the data. Physical units, axis scales, and any choice of display section are integrated. The software has very rigid options to define the graphical model that always not correspond to the real wall structure (e.g. regular geometries and shapes, orthoclastic, absence of splines, homogeneity of the material, and so on). Therefore, the simplification of the historical layout is the most important problem for modelling correctly its hygrothermal behaviour.

Discussion

The work concerns the geometric simplification of a complex masonry composed by irregular ashlar and a nucleus formed from raw and mixed materials. The first step concerns the geometric simplification of the wall, using the software AutoCAD 2014. It permits to define different wall layouts and to calculate its dimensions. The software is a necessary support for the design phase, to solve the geometric complexity of the Delphin interface layout. Four different layouts have been outlined. The initial model (1A) is the most complex: it presents several stone elements with different dimensions that reproduce the real situation of the historical walls. The stone blocks have a random design, without any standardization or orderliness. The second stratigraphy (1B) reproduce the real thicknesses and features of the wall. The external sides are formed by more regular stone blocks, while different stones compose the central nucleus. The third model (1C) is more regular than the previous one. The external sides are realized with solid stones and the central part has the same composition of the previous model. The last

model (1D) has a very simplified layout composed only by a central layer made of stone. The Delphin layouts come from these schemes. The following image shows the different steps for the simplification of the model (Figure 2).
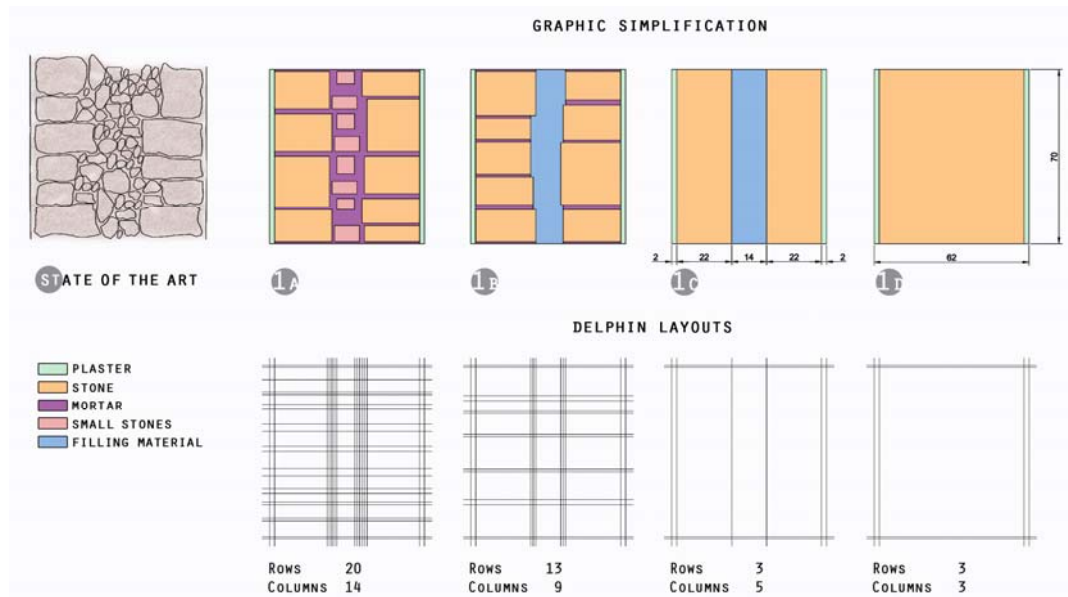

Figure 2: Different steps for the graphic simplifications of the hygrothermal simulation model

The second step concerns the definition of the same boundary conditions for the simulation and the *in situ* measurement to evaluate the accuracy of the results. Standard climatic data for the city of Bolzano (temperature, relative humidity, short wave radiation, rain, vapour diffusion, heat conduction) have been used. In addition, the heat flux density and the surface temperature of internal and external sides have been inserted to reproduce the measurement configuration.

The third step considers the geometrical discretization of the walls, in order to understand the accuracy of the model. The software discretizes rows and columns using either equidistant or variable grids. In the first case, all the rows and the columns have the same thickness. Its application is not correct for the historical walls, because the original layer geometry is completely lost. Therefore, a variable grid of vertical (all models) and horizontal (1A & 1B because 1C & 1D have same vertical structure) directions has been applied. In a second step we decide to use only the vertical discretization to reduce the simulation times (e.g. both vertical and horizontal = 6-2 day; only vertical 2h-5 minutes).

The fourth step regards the selection of the stone material. The following phases has been performed: (i) definition of the age of the wall with the support of historical researches; (ii) characterization of the type of stone, using literature, geographic maps, and coring; (iii) definition of the average thermal conductivity (λ-value) of the wall, matching historical researches, petrographic results, laboratory tests, and *in*

situ measurements. Following, the characteristic of the materials are illustrated (Table 1).

Layer	Materials	λ W/mK	c J/kgK	ρ kg/m^3	1A	1B	1C	1D
Surface finish	Lime plaster	0.82	850	1800	X	X	X	X
Stone ashlar	Granite	1.72	702	2452	X	X	X	X
	Clay mortar	0.58	488	1567	X	X	-	-
Nucleus	Sandstone	0.95	264	1966	X	-	-	-
	Clay mortar	0.58	488	1567	X	-	-	-
Filling material	Sandstone	0.58	488	1567	-	X	X	-

Table 1: Proprieties of the different materials used in the geometric models

Results

First, it is necessary to define a time interval where the environmental and the wall conditions are fully operational. The software needs a period longer than the standard 72H to have a stable thermal behaviour (about 1 month). The comparison between the simulated surface heat fluxes shows very interesting results. The model 1D has the highest value, due to the simplicity of the monolithic structure composed only of granitic stone. The models 1B and 1C have similar results, thanks to the choice of the filling materials. In this case, the result is connected mainly to the material proprieties, not only to the geometry that is very similar. The model 1A has the lowest values, close to the *in situ* measurement. This is due to the complex design of the nucleus, not far from the real situation. Follow, the results are shown (Figure 3).
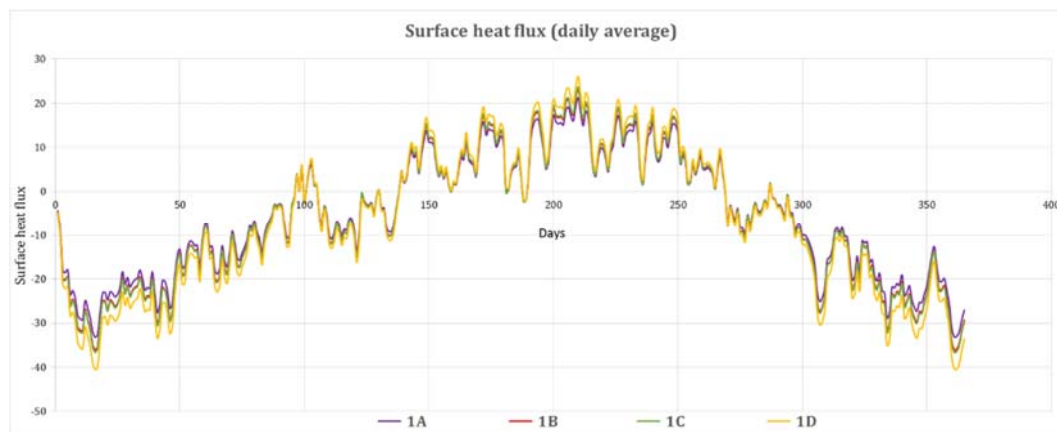

Figure 3: Comparison among simulated surface heat flux

The surface temperature changes within the walls, in the horizontal and vertical sections. The simplest models (1C & 1D) made a 1-D simulation, with constant temperature along the vertical axis. This does not correspond to the reality, as shown by the IR-thermography. In the other models (1A & 1B) the temperature varies in the 2-D section. In both cases, the simulation shows the temperature fluctuation during the year (Figure 4).
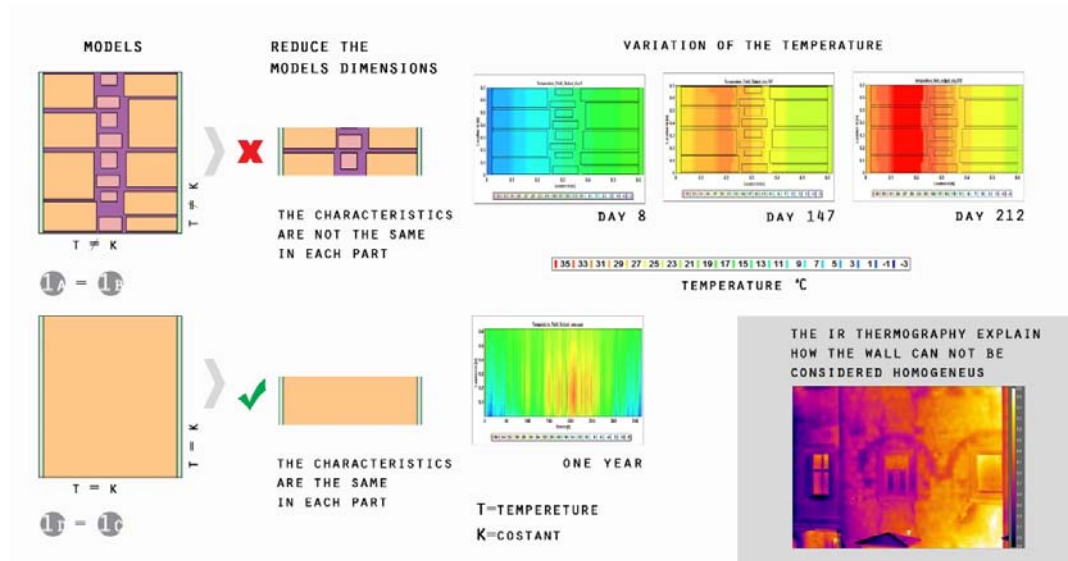

Figure 4: Temperature fluctuations inside the wall

The static calculation of the thermal conductance on one year shows the following results (Table 2).

Thermal conductance (m²K/W)				
Monitored data	1A	1B	1C	1D
1.37	1.45	1.58	1.62	1.86

Table 2: Comparison among the monitored and simulated thermal conductance

The thermal conductance of the complex model (1A) is the most similar to the reality. The simple walls are more deviate from the actual case. The variability is in the range 5.5-35%.

Conclusions

The paper aims at understanding the influence of different geometrical simplifications, discretization, and material selections on the thermal performances of traditions stone walls. Furthermore, the comparison with the in situ measurements permits to evaluate the flexibility, the adaptability, and the accuracy

of the results. The features of the traditional masonries are hardly represented in the current software, due to the differences of materials, technologies, and morphology from contemporary architectures. The most important difficulties for the simulation concern: (i) the graphic simplification of complex structures, and (ii) the material selection from existing databases. The excessive simplification (1A) of the model leads to unreliable results, while there are many similarities between the models 1B & 1C. More complex is model, more reliable are the results. Likewise, the calculation databases are too much simplified for describing correctly the pre-industrial materials. In addition, the influence of wall orientation, climate data, and boundary conditions is relevant for the result. This calculation tool has good flexibility to the application on historical walls, but its modelling is reliable only from adjusting the data on material propriety appropriately to obtain results close to the experimental data. The problem is real: as the matter of fact, the application of inadequate models causes risks and disadvantages for the buildings related to damage, corruption, and degradation. In addition, retrofit actions based on an incorrect understanding of the energy performances can cause serious physical damage and possible legal claims.

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