

Numerical simulation and sensitivity analysis of a steel framed internal insulation system

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ABSTRACT

The increase of thermal insulation of existing buildings is considered a fundamental operation for reducing building energy consumption for heating and cooling. Internal insulation systems represents, in some cases, the only possible solution. Historical refurbished buildings represent a typical case when local regulations forbid external insulation placement. However, sometimes designers compute insulated wall thermal conductance disregarding the effect of structural elements employed to fix the insulation layers to existing walls. In the present paper, we analyse a typical internal insulation system made of steel studs fixed to the wall with interposed insulation layers covered by plasterboard. Using previously obtained experimental measurements of the heat flux at the centre of insulation and on steel studs, the validation of a three-dimensional numerical model and a parametric analysis has been carried out. Five cases have been analysed, showing that the main parameter to be taken into account is the radiation heat exchange between the steel studs and the wall, on the contrary, air convection inside the stud resulted less important in evaluating heat transfer. The numerical model has been used to compute a mean conductance of the wall showing that neglecting the steel stud leads to the underestimation of wall conductance by about 20 percent.

1. Introduction

A large part of energy consumed in industrialized countries is due to building climatization. In Italy, the final energy consumption share in civil and services sector accounts for nearly the 39% of the total national amount, the household accounting alone for over 26%. Heating, cooling and hot water preparation is accountable for the great part of this energy. An additional problem, strictly correlated with energy consumption, is the increase of dangerous emissions in atmosphere, especially in city centres. This picture is common to all European countries, which share similar patterns of final energy utilization [1]. Therefore, European and National regulations impose increasingly tight limits on energy consumption for building climatization, and often this situation increases the responsibilities of designers, especially if involved in building refurbishment. However, energy reduction in existing buildings represents a challenge, due to technical reasons and national or local regulations; therefore, different solutions must be searched and compared case by case. Ascione [2] searched different refurbishment solutions for an historical building located in Naples,

the investigated strategies consisted in increasing the insulation of walls but other solutions proved to be more cost efficient, due to the mild climate of Naples. Nevertheless, for colder climates increasing the thermal efficiency of building fabric is one of the preferred approaches. However, when dealing with historical or old buildings featuring particular facades, attention is required as described in a guideline by De Santoli [3]. Galatioto et al. [4] reviewed some technologies for retrofitting historical buildings emphasizing the difficulties in adopting renewable energy sources in historical city centres and the particular attention required to preserve the cultural heritage. However, the main approach considers as a priority the reduction of building thermal losses by increasing envelope insulation. This approach is considered a key activity in order to reduce energy consumption; furthermore, it is recognized as a way to increase the benefits in economic, environmental and social area as described by Adamczyk et al. in [5]. Insulation at the internal or external side of opaque facades are both refurbishment options to be considered; the two solutions are compared by Kolaitis et al. in [6] where it is highlighted that for identical insulated wall area internal insulation requires less investment cost than the external one. However, internal insulation can result as the unique solution for historical buildings as pointed out by Murgul et al. [7] when

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dealing with historical buildings in Saint Petersburg. They pointed out that external insulation can be used in closed courtyards only, but internal insulation must be adopted on the facades. Similar constraints are highlighted by Walker et al. [8] stating that any thermal upgrading should not alter the special character of historical buildings. The situation is typical in historical Italian city centres, composed mainly by historical buildings, where internal insulation often appears to be the unique adoptable solution to contain energy losses through building fabric.

U-value, or its inverse R-value, is the standard measure of the energy efficiency of a building, therefore national regulations declare, directly or indirectly allowable values. Designers reduce wall U-value by adding insulation layers; the result depends on used materials and adopted techniques to position insulation layers. Designers have a broad range of selectable materials for internal insulation; for example, Walker [8] performed on site measurements using heat flux pads and thermocouples analyzing different materials such as lime plaster, aerogel, lime and hemp, lime and cork, Calcium silicate boards, PIR, showing improvements of U-value by 34–61%. However, a common mistake occurs when computing the thermal losses in refurbished buildings with internal insulation. If the U-value is computed neglecting the effect of structural elements used to fix the insulation to existing wall, also known as clear wall values, non-real favourable results are obtained. Martinez et al. [9] considered the effect of super-insulation materials and the effect of materials and geometries applied to provide mechanical stability to the system, they introduced the Relative Insulation Ratio (RIR) for various frame materials showing that metal and wooden frame can affect dramatically the performance of the insulation system.

In author's knowledge, little information is available in literature about the effect of frames in internal insulation applied to massive constructions, however, the problem is well known in the Light Frame constructions (LF) and Light Steel Frame (LSF) context. Kosny [10] analysed numerically twelve metal frame walls with different configurations, the authors highlighted the difference between clear wall and frame R-values. They also studied the effect of framed area ratio in walls. In a following study Kosny et al. [11] analysed experimentally and numerically the effect of framing on typical light walls. They considered wooden and metal studs and found that clear wall R-values were significantly higher from the measured overall R-values suggesting that the centre values are not suited for code approvals, load calculations, or whole-building energy simulations. Mayer et al. [12] tested three types of walls using a guarded hot-box, they performed then a 3D FEM simulation of the walls, they emphasize the requirement of a 3D simulations in case of highly conductive materials. They also found different values from numerical simulation and experimental data due to uncertainties in setting material properties in FEM models. Viot [13] analysed the effect of a wooden stud on the performance of a wall in dynamic simulation, the authors highlighted some common errors resulting from the application of simplified methods and they emphasized the effect of not considering the real space between studs and the presence of rounding errors. De Angelis et al. [14] analysed light frame walls with single and double cold metal frames. They encouraged the use of numerical methods to obtain the U-values of such structures; furthermore, they highlighted also the difficulty in applying simplified methods.

Soares et al. in [15] highlighted the problems related to heat exchange in LSF; they reviewed the strategies found in literature to reduce the repeated thermal bridges due to metal studs, such as slotted steel stud, flange stud indentation, thermal breaks for building components and thermal break strips. They reviewed also the simplified methods to calculate thermal characteristics of LSF elements, such as the one developed by Gorgolewski [16] based on EN ISO 6946 [17],

As previously noted, many authors use numerical methods to obtain heat transfer characteristics of insulation systems, sometimes this appear to be the unique method to analyse complicated heat transfer phenomena. Theodoros et al. [18] investigated the point thermal bridges of lightweight cladding systems for external facades showing that not considering their effect an underestimation of heat flow in the range from 5% up to even 20% could be obtained. Holstain et al. [19] performed an experimental and numerical analysis of nine wall sections of post-frame buildings, stating that the parallel path method [16] can lead to large errors. They quantify also in 34% the error in thermal resistance obtained by neglecting free convection and radiation heat exchanges in the wall section.

The correct evaluation of internal insulation is important in order to select the best possible solutions in building refurbishment [20], however it is common practice to ignore the effect of structural elements and to use insulation centre values as insulation values [7]. In order to increase the awareness of local operators involved in refurbishment activities such as construction companies and designers, Architects and Engineers, the Engineering and Architecture Department of the University of Trieste started a cooperation with Edilmaster, a local building school, for retrieving information about the real insulation effect of internal insulation systems. The scope of this agreement is to test insulation methodologies suited for historical buildings in Trieste, a city located in northeast Italy. The first step has been the realization and instrumentation of a test chamber with controlled internal temperatures separated with a wall specimen as described by the authors in a previous work [21]. There, the whole wall behaviour has been computed using the parallel path method of ISO 6946 [17], additionally two methods have also been tried to obtain numerically the experimental results, the former an analytical one applying a correlation to compute the thermal resistance of the studs the latter a numerical model using ANSYS Fluent [22]. Unexpectedly, the numerical approach failed to give satisfactory results with large errors. Therefore, in the present paper, we developed an improved and accurate 3D model of the internal insulation system in order to replicate, with a higher fidelity, previous experimental results and to highlight the physical phenomena involved in the heat transfer process. The parametric analysis carried on allowed highlighting the relative importance of the model parameters required by the simulation.

2. Experimental results

2.1. Measured wall

In a previous paper [21] the authors described the test chambers and the measured wall along with the used instrumentation. The specimen is a massive wall 51 cm thick made of solid bricks with cement mortar and two 1 cm plaster layers. Conductance of the wall, measured using a heat flux pad, resulted to be $C_w = 1.64 \text{ W}/(\text{m}^2 \text{ K})$. In order to improve the thermal characteristics of the wall an internal insulation had been placed at the hot side using 3 cm EPS boards and a 12.5 mm thick plasterboard. To fix the plasterboard, vertical $6 \times 3 \text{ cm C}$ shaped 0.6 mm thick steel studs are placed at 500 mm distance each other as presented in Fig. 1a), the vertical studs are also fixed by means of two U shaped profiles positioned at the top and bottom of the test wall. In [21] also the results with wooden studs were presented, and they showed better performance, however the use of wooden studs is not common and they could lead to imperfections due to off center positioning and non-planar geometry possibly leading to finished structures

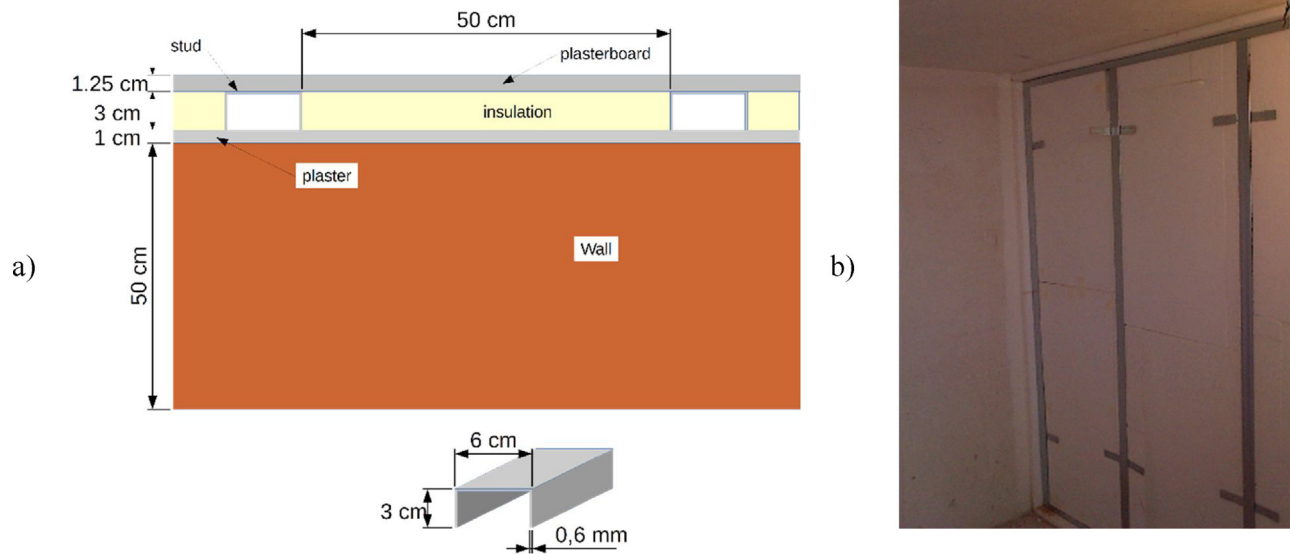


Fig. 1. internal insulation system a) layers distribution b) picture of the internal assembly without plasterboard.¹

Table 1
Experimental Results.¹

		Clear wall (cw)	Stud (st)
θ_C	$^{\circ}\text{C}$	6.1	6.2
θ_H	$^{\circ}\text{C}$	24.3	22.9
q_j	W/m^2	11.1	23.5
C_j	$\text{W}/(\text{m}^2 \text{ K})$	0.61	1.41

affected by irregularities [11]. Therefore, present research focused on metal studs only.

Fig. 1b) presents a picture of the test wall with steel studs before the installation of the plasterboard cover layer. Vertical studs are fixed to the underneath wall by bent metal ribbons which realize the thermal contact. It is worth noting that this disposition creates a thermal bridge between the cold wall and the internal warm plasterboard. For instance others solutions exist, but the one analyzed here is characterized by fast realization times and low thickness of the entire insulation system.

2.2. Experimental results

In [21] the authors presented two measures using heat flux pads for characterizing the insulation performance on the test wall. The specific heat flux and surface temperatures had been measured on the centre of insulation panel, obtaining clear wall values, and on the plasterboard covering metal studs. Table 1 reports the measured values: two surface temperatures for cold and hot sides of the test wall had been obtained and the value presented in Table 1 are the averaged values of each one. Temperature and heat flux values reported in Table 1 can be used to compute the one-dimensional experimental thermal conductance, also reported in Table 1, at clear wall and stud positions using Eqs. (1) and (2).

$$C_{cw} = \frac{q_{cw}}{(\theta_H - \theta_C)_{cw}} \quad (1)$$

$$C_{st} = \frac{q_{st}}{(\theta_H - \theta_C)_{st}} \quad (2)$$

Table 2
Material properties.

	λ $\text{W}/(\text{m K})$	ρ Kg/m^3	c $\text{J}/(\text{kg K})$
Wall	0.833	1200	840
plaster	1.056	1800	1000
Insulation	0.035	1450	30
cardboard	0.2	700	1000
steel	50	7800	500

In Eqs. (1) and (2) θ_H and θ_C represent hot and cold surface temperatures respectively, while subscripts “cw” and “st” refer to clear wall and stud measures respectively. In Table 1 C_j is the one dimensional conductance, q_j the specific heat flux while the subscript j can take the values “cw” and “st” for clear wall and stud position respectively. A large difference exists between the one dimensional conductance obtained in the two positions. The results highlights the requirement to evaluate a “real” mean conductance and hence transmittance of the insulated wall taking into account the effect of the supporting studs.

3. Numerical simulation

A three dimensional model has been developed to accurately represent the heat transfer process in the insulation system. The employed studs are made of steel with a higher conductivity respect the other materials employed as reported in Table 2, leading to the formation of a thermal bridge. While realizing the internal insulation system, metal studs are first positioned on the wall and then blocked using two clamps. This method creates a narrow vertical cavity where air is free to move allowing convection heat transfer as presented in Fig. 2a). An additional heat transfer is due to radiation heat exchange between the stud and the underneath wall section. In order to replicate the experimental results and to highlight the relative importance of the different phenomena involved, accurate three-dimensional simulations have been carried on.

The simulations have been performed using ANSYS Fluent [22]. The code employs a finite volume discretization for analysing convective problems and it has been selected due to the ability to couple convection and radiative heat transfer. Furthermore, Fluent implements conductive two-dimensional thin layers needed to

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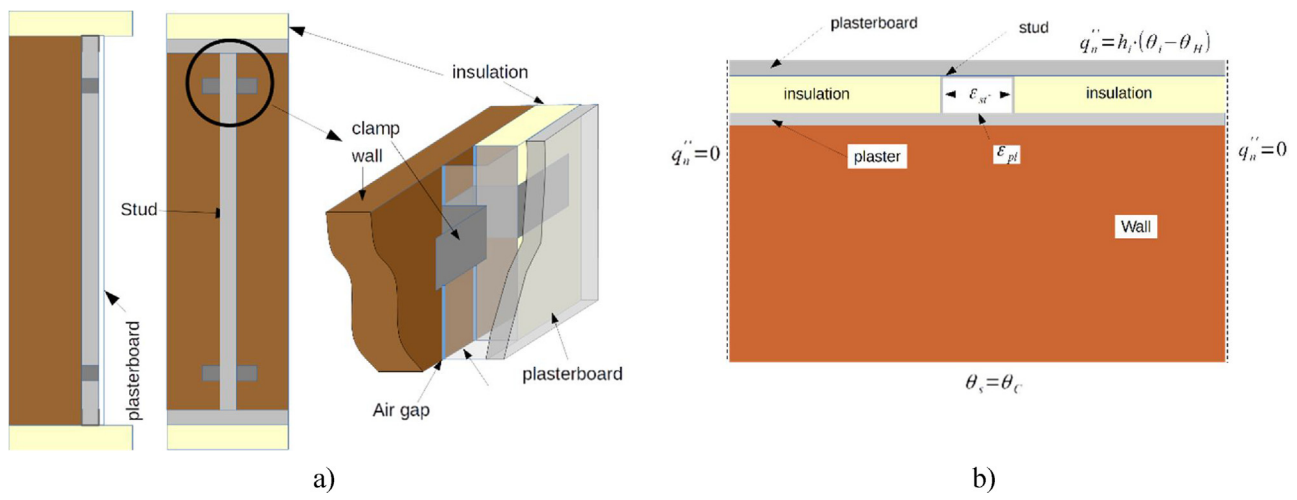


Fig. 2. geometry and boundary conditions a) stud fixing and clamp detail b) thermal boundary conditions.

represent the conduction in metal studs without generating a true three-dimensional geometry with excessively thin thickness. To replicate the experimental layout some additional design features have also been implemented in the model.

3.1. Model geometry

Fig. 2 a) reports a sketch of the geometry and a detail of the employed method to fix metallic studs to the wall by means of clamps. The clamps are fixed to the wall using screws and then the studs are fixed to the clamps using nails. Insulating panels are inserted between the studs and the cardboard is fixed to the vertical studs at the internal side. It is worth noting that due to the fixing system it is not assured a contact between the metal studs and the wall, only the clamps assure the thermal continuity between studs and the underneath wall. In order to interrupt the continuity between wall and stud a thin conductive layer, with the properties of the air, has been introduced between the stud and the wall as presented in Fig. 2a).

In order to reduce the computational burden the realized model exploits symmetries and considers one vertical stud only and half the insulation and cardboard between studs at each side. Two slices of the horizontal U steel profiles highlighted in Fig. 1b) have been simulated as well, the model is completed by two slices of insulation layers at the bottom and top of the wall, part of the test room.

A multi block regular grid has been developed. Particular attention has been given to the development of the grid inside the cavity formed by the stud and plaster. The adopted grid allows simulating the convective heat transfer, which develops due to the temperature difference between the wall and the internal side of the metal stud.

3.2. Boundary conditions

The great part of the domain is subject to conduction heat transfer, only inside the narrow channels created by the metal studs the air is free to move, therefore, no slip conditions have been applied for moment equation. Thermal boundary conditions are reported in Fig. 2 b). The plasterboard is in contact with the hot chamber air, therefore, a convective heat transfer condition has been applied. The heat transfer coefficient has been computed using the measured values of temperature and specific heat flux obtained at the level of insulation board where a one dimensional heat transfer is expected to occur. Using the measured internal temper-

ature $\theta_i = 26.3^\circ\text{C}$ the convective heat transfer coefficient resulted $h_i = 5.55 \text{ W}/(\text{m}^2 \text{ K})$. The wall has been modelled for the entire thickness and at the cold side the measured temperature $\theta_c = 6.2^\circ\text{C}$ has been imposed as boundary condition. At the other sides of the domain, adiabatic conditions are considered.

Long wave radiation between channel surfaces has been computed using the surface to surface model. The emissivity of stud's metal surfaces has been set to $\epsilon_s = 0.23$, a recommended value for galvanized steel, while the plaster facing stud's cavity emissivity has been considered as $\epsilon_{pl} = 0.9$ [23]. Material properties used for the simulation are reported in Table 2, wall and plaster conductivity have been computed in order to obtain the uninsulated wall thermal conductance obtained by the experimental results.

3.3. Simulation models

A sensibility analysis has been carried on in order to identify the relative importance and the impact on accuracy and computational times of different models.

Inside the channel created by the vertical stud and wall's plaster convective heat transfer occurs, therefore laminar Navier Stokes equations and Energy equation have been solved. In solid domains, conductive energy equations are of interest. The metal studs and clamps have been modelled as conductive thin layers. Five cases have been identified by switching different models. Case 1 simulates only the conduction in the metal studs, no air circulation is considered inside the vertical channels. This is a simplified model, and it is not expected to generate reliable results. However, it has been considered in order to make a comparison with more complex and numerically expensive models. Case 2 introduces natural convection into the channels using a 1st order approximation for convective terms. Case 3 is similar to Case 1 but with added radiation heat exchange, in this case, no convection is present inside the channels and the air is treated as a conductive only material. Case 4 has been generated by merging Cases 2 and 3, convection with 1st order upwind is considered along with long wave radiation heat exchange. In Case 5, the 1st order upwind scheme of Case 4 is replaced with a less diffusive 2nd order upwind. The solution in this case, required a transient simulation due to the development of non-stationary eddies inside the vertical channel.

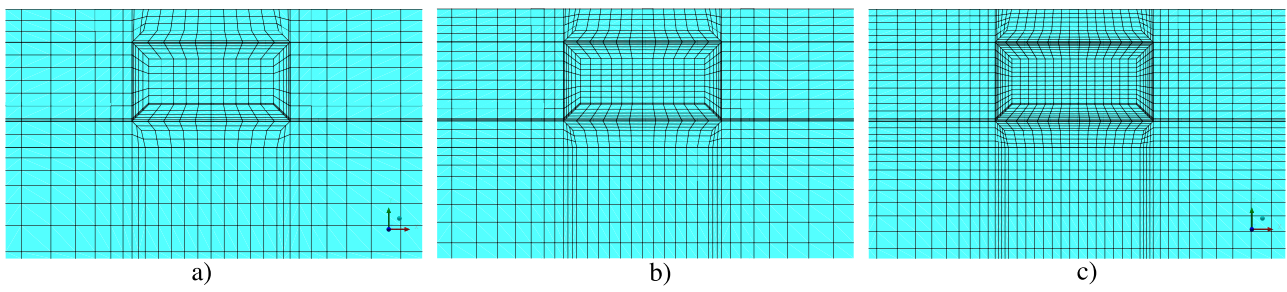


Fig. 3. comparison between grids for grid independence test a) coarse grid b) medium grid c) fine grid.

4. Results

4.1. Output parameters

Internal insulation is adopted in order to reduce heat exchanges between the interior and the exterior of a refurbished building. The transmittance of the refurbished wall represents the main parameter to consider. For instance, for some national regulations, thermal transmittance should attain predefined values. However, transmittance is not a characteristic of the wall, since depends on the external and internal thermal resistances, which can be imposed by regulations or computed in function of the exposure of the wall. Therefore, in the following the performance of the wall is computed considering conductance only. In order to compare the experimental results, one dimensional conductance of Eqs. (1) and (2), computed using the measured or simulated fluxes and temperatures, have been compared.

The experimental results report the measured specific fluxes on the insulation panel and on the metal stud, the numerical simulation provides the fluxes on the same spots as the experimental ones. However, using the numerical results the whole heat flux exchanged by the wall can be also computed. The latter parameter can be used to evaluate the error committed by designers if clear wall values of conductance are used to evaluate the transmittance of the refurbished wall.

The measured and numerical specific fluxes are utilized to compute two conductances, the one on the stud C_{st} and on the insulation panel C_{cw} . The heat flux through the whole wall surface Q_{wall} obtained with the numerical simulation lets the evaluation of a mean conductance of the refurbished wall C_{wall} . This value takes into account the effect of the vertical and horizontal studs. The value is computed using Eq. (3) inserting the heat transfer coefficient used as boundary condition on the plasterboard and the total surface area $A = 1.064 \text{ m}^2$ of the model.

$$C_{wall} = \left\{ \left[\frac{Q_{wall}}{A \cdot (\theta_i - \theta_c)} \right]^{-1} - \frac{1}{h_i} \right\}^{-1} \quad (3)$$

To evaluate the differences between numerical $C_{st,num}$ and experimental $C_{st,exp}$ values of conductance on the stud a local error E_{st} , defined in Eq. (4), is considered. To evaluate the differences committed when disregarding stud effect in computing refurbished wall conductance, a design error can be introduced E_{wall} as defined in Eq. (5) where C_{cw} represents the clear wall value.

$$E_{st} = \frac{C_{st,num} - C_{st,exp}}{C_{st,exp}} \times 100 \quad (4)$$

$$E_{wall} = \frac{C_{wall} - C_{cw}}{C_{cw}} \times 100 \quad (5)$$

Table 3
grid refinement test.

grid	size	C_{st} [W/(m ² K)]	E_{st}
coarse	238958	1.440	2.15
medium	460320	1.449	2.79
fine	900002	1.456	3.30

Table 4
results for the different cases.

	C_{st} [W/(m ² K)]	E_{st}	C_{wall} [W/(m ² K)]	E_{wall}
Case 1	1.258	-10.81	0.765	16.95
Case 2	1.260	-10.64	0.767	17.22
Case 3	1.462	3.69	0.778	19.03
Case 4	1.458	3.38	0.779	19.18
Case 5	1.489	5.60	0.7807	19.41

4.2. Grid independence test

First, a grid independence test has been carried using three grids, coarse, medium, fine and Case 4 as reference, Fig. 3 reports three horizontal sections at the mid height of the wall highlighting the grid resolution of the internal channel where flow develops. Table 3 reports the results obtained with the three grids, highlighting the local error E_{st} along with the grid sizes, Fig. 4 reports the vertical distributions with the different grids of the local one dimensional conductance and surface temperature on the plasterboard covering the stud. The error changes with grid refinement, with little difference between grid 2 and grid 3. This confirms that grid 3 is accurate enough for carrying on the sensibility analysis.

4.3. Simulation results

Table 4 presents the results of the simulations for the five different cases analysed. The table reports the conductance obtained in correspondence of the mid height of the stud, the whole wall mean conductance and the error respect the measured results as identified by Eqs. (4) and (5).

Table 4 reveals that the most important parameter affecting the results is the radiation heat exchange between metal stud sides and plaster, introduced in cases 3, 4 and 5. Convective effects inside the channels formed by studs and plaster only marginally modifies the results with a little reduction of the error E_{st} between Case 2 and Case 1. The introduction of radiation reduces substantially the absolute error between Case 3 and Case 1. Case 4 introduces convective heat transfer inside the stud, the use of 1st order upwind for energy and momentum equation allows the development of a stationary circulation flow inside the stud with a new distribution of temperatures on the plasterboard surface and a different radiation heat exchange. However, the error reduces substantially respect the value of Case 2, highlighting that the main heat transfer phenomena to be considered is the radiation heat exchange.

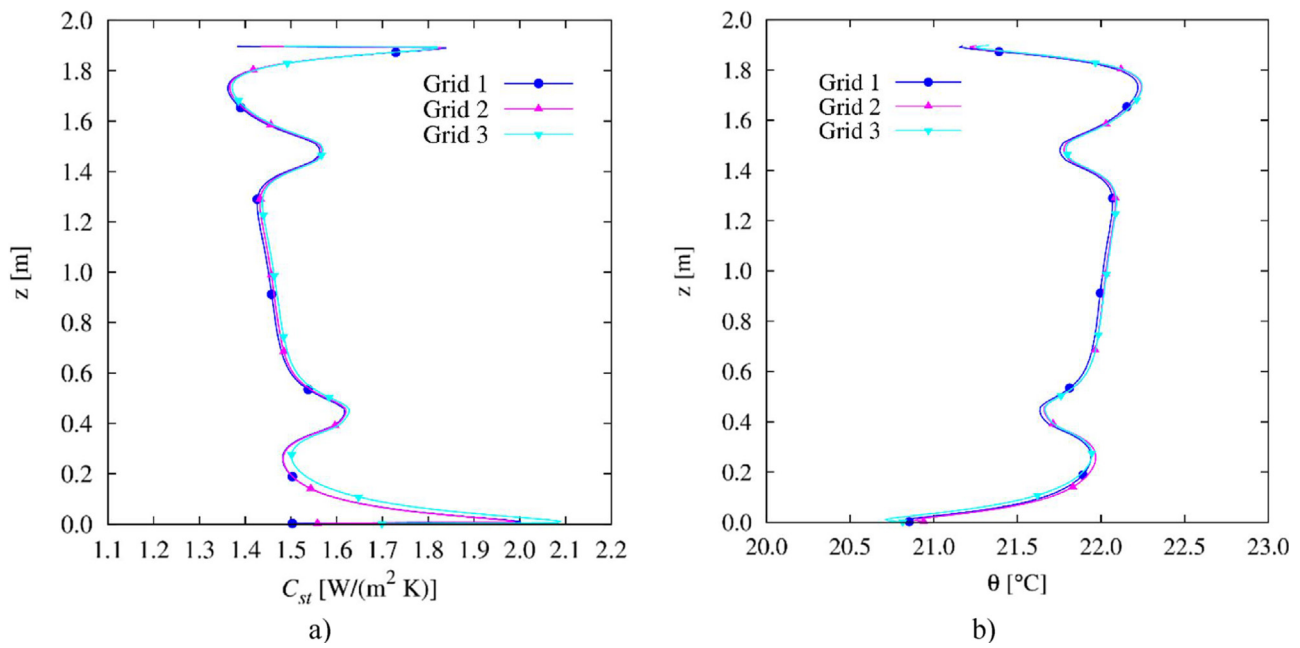


Fig. 4. comparison among grids a) local conductance along the vertical stud b) surface temperature distribution along the stud.

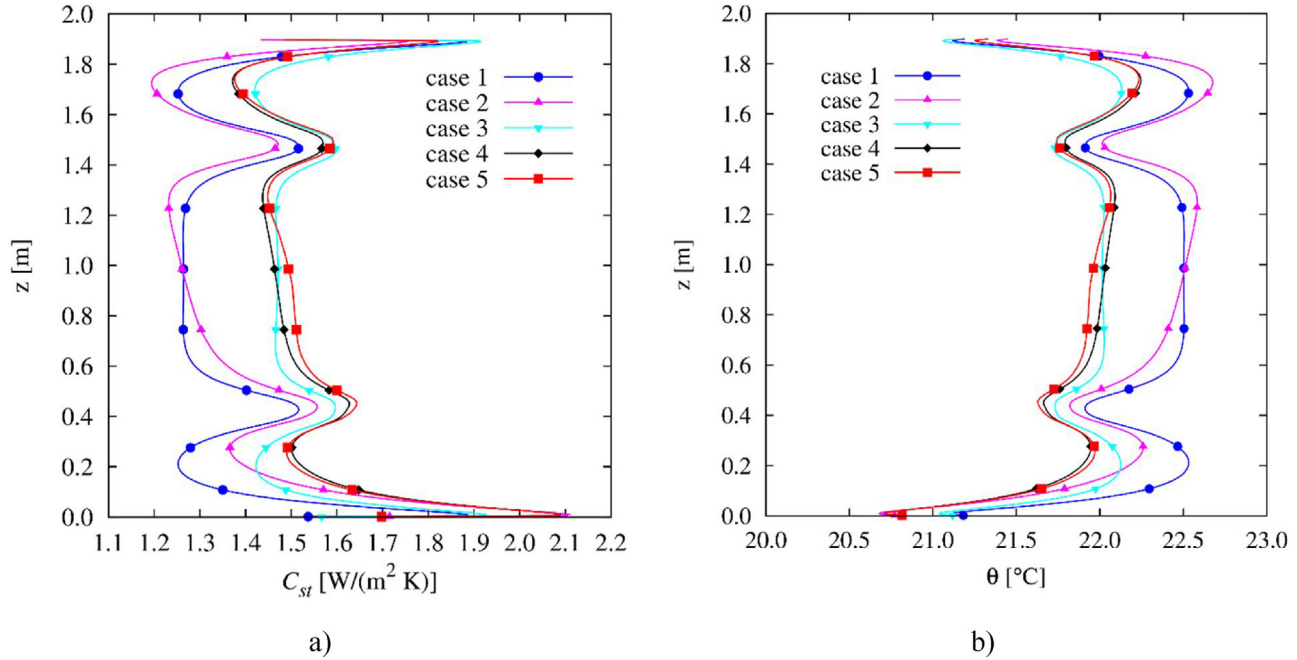


Fig. 5. a) local conductance along the vertical stud b) surface temperature distribution.

The use of a second order upwind model for energy and momentum equation inside the studs, leads to a transient solution. The large recirculation zone inside the stud of Case 4 is replaced by a series of non-stationary eddies moving inside the stud. Temperature and heat flux profiles change very little in time on the plasterboard surface, and the values reported in Table 1 are obtained by a time averaging on stabilized solutions. The result of Case 5 show a slight increment of heat transfer along the stud, which only marginally increases the mean conductance of the entire wall by a 1%.

The last column of Table 4 reports the design error E_{wall} , the error a designer commits by using the clear wall values for computing the conductance of the wall. The reported values clearly demon-

strate that neglecting the influence of studs is a serious design error, which leads to false regulation compliance and wrong economic analysis.

Fig. 5 reports the distribution along the vertical stud of the local conductance C_{st} and the corresponding temperature distribution on the plasterboard covering the vertical stud for the different cases analysed. Clamps position is identifiable with increased local conductance and low temperatures. The analysis of Fig. 5 reveals how the models affect conductance and temperature distribution. Cases 1 and 3, are pure conductive and radiative solutions without air movement. They show a symmetric behaviour, the difference between the two cases is due to radiation heat transfer inside stud cavity. Cases 2 and 4 introduce air movement and the profiles are

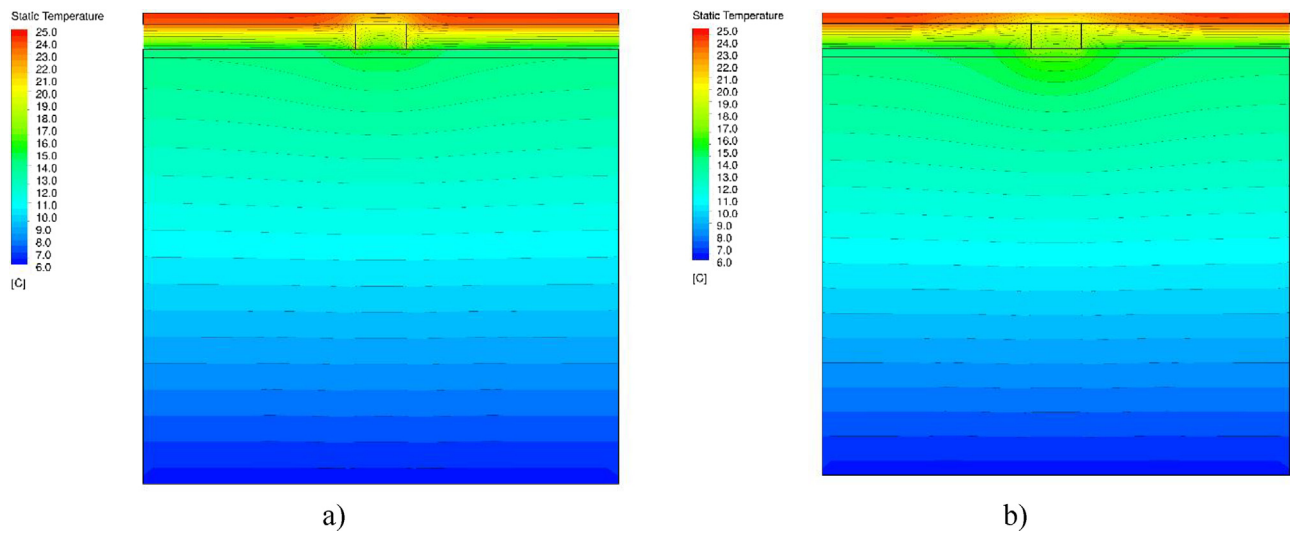


Fig. 6. temperature at the cross section of the wall a) mid height b) clamps level.

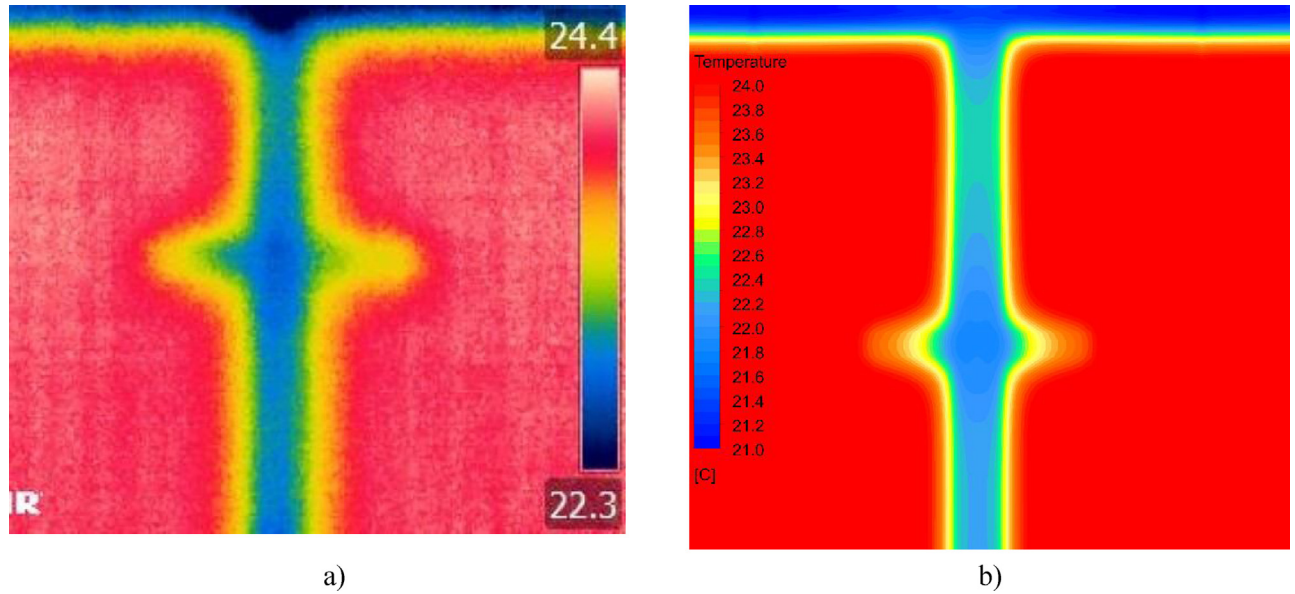


Fig. 7. comparison between a) infra-red imaging and b) simulated temperature distribution.

not symmetric, a stratification occur inside the stud leading to temperatures lower at the base and higher near the top. Conductance distribution displays a reversed behaviour: low conductance at the base and high at the top. Little difference exist between Case 4 and Case 5, the introduction of second order upwind in the energy and momentum equation doesn't modify the results, Case 5 shows a slightly increase in local conductance at the centre of the stud with lower surface temperatures than Case 4.

Fig. 6 shows the temperature distribution at two horizontal cross sections of the wall: in Fig. 6 a) the cross section is placed at the mid height of the wall, while Fig. 6 b) has been taken at clamp level. In both cases, the thermal conductance of stud and clamps can be identified. The temperature distribution on the wall is modified due to the radiation heat exchange between stud and plaster surface, and by the thermal conductance between plaster and clamp. It is worth noting that the presence of clamps strongly influences the temperature distribution inside the wall. The influence area of the stud is pretty large, therefore the application of one dimensional simplified methods for computing the overall heat transfer for this problem is questionable [10,17]. For instance the ASHRAE method

[24] in this case is clearly not applicable since the so called influence zone, covers the entire wall.

Thermographic analysis is of widespread application for identifying singularities in buildings. Infrared pictures are useful for the analysis of the temperature distribution over a large area, the benefits of the integration of numerical and thermographic analysis has been described by Taylor [25]. Fig. 7 presents a comparison between an infrared picture and the numerical simulation. Numerical simulation is able to capture the temperatures difference due to the conduction of metal studs; however, the numerical simulation shows local temperatures slightly lower than the values measured with the infrared technique. For instance, the values introduced for numerical simulation derive from literature analysis and may be slightly different from the ones of the experiment. Two major parameter influencing the results have been identified: conductivity of metal studs and the emissivity values of inner surfaces of metal studs. On the other hand, the inserted values are common in building constructions and therefore present results are representative for a wide range of situations.

5. Conclusions

An accurate numerical simulation has been carried on in order to simulate the real performance of an internal insulation system for external walls in historical buildings. It is common practice by designers to account for the insulation effect considering the insulation panels only, without taking into account the effect of studs, this has been demonstrated to be a wrong approach. A comparison between experimental results and numerical simulation has been carried on highlighting the error that can be committed adopting such approach. Using numerical simulation a sensitivity analysis has been conducted to identify the phenomena and numerical models that can affect the simulation. The sensitivity analysis revealed that the long wave radiation inside stud's cavity is the main parameter to be taken into account. The air movement inside the studs resulted a secondary effect, which does not modifies the overall heat transfer characteristics of the insulation system. The correct evaluation of the insulation performance of the system revealed a mean conductance 20% higher than the one computed using the one dimensional insulation clear wall values, this is a result that should be taken into consideration by practitioners in order to avoid overestimation of insulation effect and underestimation of heat losses in refurbished buildings.

Acknowledgement

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