



Article The Relevance of Surface Resistances on the Conductive Thermal Resistance of Lightweight Steel-Framed Walls: A Numerical Simulation Study

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Abstract: The accurate evaluation of the thermal performance of building envelope components (e.g., facade walls) is crucial for the reliable evaluation of their energy efficiency. There are several methods available to quantify their thermal resistance, such as analytical formulations (e.g., ISO 6946 simplified calculation method), numerical simulations (e.g., using finite element method), experimental measurements under lab-controlled conditions or in situ. Regarding measurements, when using the heat flow meter (HFM) method, very often, the measured value is based on surface conditions (e.g., temperature and heat flux), achieving in this way the so-called surface-to-surface or conductive thermal resistance (R_{cond}). When the building components are made of homogeneous layers, their R_{cond} values are constant, regardless of their internal and external surface boundary conditions. However, whenever this element is composed of inhomogeneous layers, such as in lightweight steel-framed (LSF) walls, their R_{cond} values are no longer constant, depending on their thermal surface resistance. In the literature, such systematic research into how these R_{cond} values vary is not available. In this study, the values of four LSF walls were computed, with different levels of thermal conductivity inhomogeneity, making use of four finite elements' numerical simulation tools. Six external thermal surface resistances (R_{se}) were modelled, ranging from 0.00 up to 0.20 m²·K/W. The average temperature of the partition LSF walls is 15 °C, while for the facade LSF walls it is 10 °C. It was found that the accuracy values of all evaluated numerical software are very high and similar, the R_{cond} values being nearly constant for walls with homogeneous layers, as expected. However, the variation in the R_{cond} value depends on the level of inhomogeneity in the LSF wall layers, increasing up to 8%, i.e., +0.123 m²·K/W, for the evaluated R_{se} values.

Keywords: lightweight steel-framed (LSF); conductive thermal resistance; computational tools; external surface resistances; level of inhomogeneity; walls' layers

1. Introduction

Since 2002, European Directives have progressively set out requirements to enhance the energy performance of building stock, culminating in 2024 with the Energy Performance of Buildings recast [1,2]. This latest update underscores the ambition for a zero-emission building stock by 2050, accentuating energy efficiency and the reduction in greenhouse gases. It stipulates new minimum standards, integrating life-cycle emissions assessments, solar energy utilization, and formulating comprehensive national renovation strategies, marking a significant step forward in sustainable building practices.

The complexities in building performance design analyses necessitate numerical simulations, which offer practical and reliable means for enhancing design, energy efficiency, and comfort. At the same time, the proliferation of more rigorous building performance codes and standards [2] acts as a key catalyst for increasing reliance on computer simulation



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). tools. These tools are essential for verifying compliance with building performance benchmarks, reflecting a shift towards more advanced evaluation methods in the construction and design industries [3,4].

The push towards achieving high-performance energy-efficient buildings (i.e., nearly Zero-Energy Buildings, Zero-Emission Buildings, net Zero-Energy Buildings, and others) [1,2] necessitates the expanded use of simulation tools in building design, construction, and operation. Concurrently, there is growing scrutiny of the accuracy of building simulation models and predictions, highlighting the importance of trust in the reliability of these simulation techniques, encompassing both the mathematical models and the input parameters used [3,5].

In terms of establishing the thermal performance of the building envelope components, previous studies, such as the one conducted by Kim et al. [6], have underscored the need to assess the surface heat transfer coefficient under various conditions to enhance our understanding of wall thermal performance. In their research, Kim et al. utilized laboratory measurements to assess the thermal transmittance of walls, employing both the Heat Flow Meter (HFM) method, as outlined in ISO 9869-1 [7], and the Air–Surface Temperature Ratio (ASTR) method. The findings of their research highlight the importance of further investigating the surface heat transfer coefficient under various conditions to understand global wall thermal performance more accurately.

On the same note, the investigation performed by Evangelisti et al. [8] on the constant value of the total internal heat transfer coefficient revealed that the actual values obtained in their experimental campaign differed significantly from the value suggested by the standard ISO 6946 [9]. The percentage differences ranged from about 40% to around 143%. This indicates that the constant value recommended by ISO 6946 may not accurately represent the heat transfer mechanisms of walls in different environmental conditions and with different surface finishes. The study also found that the total heat transfer coefficient varied with height, suggesting that the convective part is not constant.

Another interesting related study was performed by De Rubeis et al. [10]. They evaluated the influence of environmental boundary conditions (temperature and air velocity) on the surface thermal resistance of walls under controlled lab conditions, making use of experimental measurements through a Guarded Hot Box (GHB). They found lower experimental convective coefficients in comparison to the conventional values suggested by ISO 6946 [9]. The differences between the measured convective heat transfer coefficient (h_c) and the constant conventional value provided by ISO 6946 (2.5 W/m²·K) ranged between -46.8% and -32.4%. They also concluded that in real environments, the radiative and convective heat transfers could lead to even greater deviations; therefore, this issue needs to be further investigated. These studies [6,8,10] underscore the complexity of assessing overall wall thermal performance, pointing to significant deviations from standard predictions under varied conditions.

Over recent decades, the design of building envelope systems has seen significant changes. Though still in use, traditional heavy materials like brick or concrete have increasingly given way to lighter construction techniques [11]. These modern methods, such as timber [12] and lightweight steel-framed (LSF) constructions [13,14], are favoured for their speedier build times and less bulky structures, especially in low-rise and residential buildings [15]. Simultaneously, the capacity for system integration within wall thickness, along with minimized and recyclable construction waste, significantly reduces structural load and, consequently, construction costs [14,16,17]. This shift reflects a broader trend towards efficiency and practicality in building practices.

However, from the energy efficiency and thermal behaviour perspective, these lightweight buildings exhibit several possible drawbacks, such as reduced thermal inertia and high thermal bridges effects (e.g., due to the steel frame), when not correctly designed and executed [15,17]. Additionally, the accurate computation of thermal transmittances (*U*-values) or thermal resistances (*R*-values) of LSF components is more challenging,

since the simplified analytical methods prescribed in the ISO 6946 standard [9] are not applicable whenever the steel frame goes through the thermal insulation.

Santos et al. [18] performed a review of the calculation procedures for analytical methods to estimate the thermal transmittance of LSF walls, and made a comparison of accuracy between six analytical methods previously identified in the literature, which were applied to 80 different LSF wall configurations. They found good precision in all the studied analytical methods, the worst accuracy being offered by cold frame walls, wherein all the thermal insulation is located within the air cavity. Unexpectedly, it was found that two analytical methods, namely, the ASHRAE Zone Method (7.7%) and Gorgolewski Method 2 (9.9%), developed explicitly for LSF elements showed worse average precision (root mean square *U*-values errors) than the ISO 6946 Combined Method (7.1%).

It is common sense that the surface-to-surface or conductive thermal resistance (R_{cond}) is a unique value for a specific building component (e.g., wall), regardless of the boundary conditions, i.e., ambient temperature difference and surface thermal resistances. This approach is much more versatile, since the total thermal resistance (R_{tot}) could be easily computed by adding the corresponding surface thermal resistances (R_{si} and R_{se}) to the provided R_{cond} value. This why some technical R-value catalogues [19], as well as some research works (e.g., experimental [20] or parametric studies [21]), provide the R_{cond} values as results, instead of the R_{tot} value.

The previous approach is suitable and accurate for building components with homogeneous layers, i.e., having a unidirectional heat flow. However, the previous methodology may encounter some inaccuracy whenever the thermal bridge effect is relevant, such as in cold frame LSF walls [22,23]. We did not find in the literature any systematic research study assessing the influence of the surface resistances on the conductive thermal resistance of walls, such as LSF walls.

In this article, the relevance of surface resistances to the conductive *R*-values of lightweight steel-framed walls is assessed by performing a numerical simulation study. To this end, four LSF walls were computed, with different levels of thermal conductivity inhomogeneity, making use of four finite elements' numerical simulation tools. Moreover, six external thermal surface resistances (R_{se}) were modeled, ranging from 0.00 up to 0.20 m²·K/W, giving rise to 96 different evaluated models. The average temperature of the partition LSF walls is 15 °C, while for the facade LSF walls it is 10 °C.

This paper is structured as follows. First, the materials and methods are described, including wall descriptions (e.g., geometry and dimensions), material characterization (e.g., thermal properties) and a brief overview of the adopted methodology. Next, the main features related to the numerical simulations performed are explained, such as a brief description of the four evaluated Finite Elements Method (FEM) computational tools, a short explanation regarding the domain discretization and boundary conditions used, and, lastly, the model accuracy verifications and validation processes are described. After this, the computed results are displayed, analysed and discussed. Finally, the main conclusions of this research work are listed.

2. Materials and Methods

2.1. Walls Description and Material Characterization

In Figure 1 is presented the horizontal cross-sections of the partition and facade loadbearing LSF walls that are studied in this paper. The partition LSF wall is 126.5 mm thick and possesses vertical steel studs spaced 400 mm apart (with a web of 90 mm, a flange of 43 mm, a lip return of 15 mm and a thickness of 1.5 mm (C90 \times 43 \times 15 \times 1.5)), Mineral Wool (MW) filling the entirety of the 90 mm air cavity, one oriented strand board (OSB) structural sheathing panel 12 mm thick on both sides of the steel studs, and a gypsum plasterboard (GPB) sheathing layer 12.5 mm thick on the inner surface. The facade LSF wall, besides having the same configuration as the partition wall, also has on the outer surface an internal thermal insulation composite system (ETICS), with expanded polystyrene (EPS) insulation 50 mm thick and a 5 mm layer of ETICS finishing, adding up to a 181.5 mm wall thickness. It should be noted that the LSF wall configurations evaluated in this study are existing ones, which are widely recognized in the field. They are usual LSF wall configurations for cold frame (Figure 1a) and hybrid (Figure 1b) construction systems [17], and have been already studied in previous research [20–22].



Figure 1. Evaluated load-bearing LSF walls' horizontal cross-sections: (a) Partition; (b) facade LSF wall.

Besides these two LSF walls arrangements, another two simplified configurations were assessed to evaluate the relevance of the inhomogeneity of the material layer's thermal conductivity. Thus, in these two additional wall configurations, the steel frames were removed to obtain a partition and a facade wall with homogeneous layers.

The thicknesses of each material layer and the corresponding thermal conductivities of these materials are listed in Table 1.

Table 1. Thickness, *t*, and thermal conductivity, λ , of materials [21].

Material	<i>t</i> (mm)	λ (W/(m·K))	Ref.
Gypsum Plaster Board (GPB)	12.5	0.175	[24]
Oriented Strand Board (OSB)	12.0	0.100	[25]
Mineral Wool (MW)	90.0	0.035	[26]
Steel Studs (C90 $ imes$ 43 $ imes$ 15 $ imes$ 1.5)	90.0	50.000	[19]
ETICS ² Insulation (EPS ¹)	50.0	0.036	[27]
ETICS ² Finish	5.0	0.450	[28]

¹ EPS—expanded polystyrene; ² ETICS—external thermal insulation composite system.

2.2. Adopted Methodology

After defining the four LSF walls' configurations ((1) partition; (2) facade; (3) simplified homogenous partition, and (4) simplified homogenous façade), it was decided to model these walls by making use of four different FEM computational tools, as listed and explained later (please see Section 3.1), and as illustrated in Figure 2. Further details on the performed numerical simulations are provided in Section 3, including: (Section 3.2) domain discretization and boundary conditions, and (Section 3.3) accuracy verifications and validation.



Figure 2. Implemented methodology scheme.

The implemented models allowed us to compute the overall (or total) thermal resistance for each assessed wall, assuming six external surface resistances (R_{se}), ranging between 0.00 and 0.20 m²·K/W, and one internal surface resistance (R_{si}), i.e., 0.13 m²·K/W. The conductive thermal resistances (R_{cond}), or surface-to-surface *R*-values, have been obtained by subtracting the considered R_{se} and R_{si} from the previously computed overall *R*-value. Next, the conductive thermal resistances for the 96 implemented models are analyzed, compared and discussed (Section 4). Finally, the main conclusions and remarks about this research work are presented in Section 5.

3. Numerical Simulations

3.1. Evaluated FEM Computational Tools

The numerical simulations of the evaluated LSF walls were performed using four different types of finite elements method (FEM) software: THERM (version 7.8) [29]; FLIXO (version 8.2) [30]; PSIPLAN (version 2024) [31], and ANSYS (student version 2022 R1) [32], where the first three are bi-dimensional (2D), and the last one allows for three-dimensional (3D) models. In the following subsections, some of the details of these software types and the respective numerical models are explained.

Starting with the THERM software [29], this is a state-of-the-art computer program, which is being developed in the Lawrence Berkeley National Laboratory, United States

Department of Energy, and makes use of an FEM algorithm to analyse bi-dimensional heat-transfer effects in a steady-state regime. This computational tool creates an automatic mesh for the FEM analysis, which is based on two parameters. The first one is the threshold for the error of the iterative calculations ("*Maximum* % *Error Energy Norm*"), which, in this research, is set at 2%. The second one is the relative size of the finite element mesh of the model ("*Quad Tree Mesh Parameter*"), which was set to a standard value of 6. Regarding the definition of boundary conditions, besides the environmental temperatures, this software uses film coefficients (or surface heat transfer coefficients), which are the inverse of the surface thermal resistances.

FLIXO software [30] is a finite element analysis computational tool used for assessing 2D thermal bridges in a steady-state. This tool employs four main input features to create an automatic mesh for the implementation of the FEM model. The first is that the mesh can automatically consider the requirements prescribed in standard ISO 10211 [33]. Next, a minimum inside element angle of the triangular shape, set to 20 degrees, is required. After that, a maximum element size should be defined, which was set to 1:150 for this research. Lastly, both maximum values for the relative error and the heat flux error were defined as 1.0×10^{-30} and 1.0×10^{-4} , respectively.

Regarding the PSIPLAN 2D [31] software, this was designed to analyze two-dimensional heat transfer within a steady-state thermal regime, employing the plane heat transfer differential equation as its foundational computational model. The input of data is facilitated through a graphical module, offering an intuitive interface for users to define the spatial, geometrical, and thermo-technical characteristics of the subject under investigation. This includes specifying boundary conditions through superficial thermal resistances, interior and exterior temperatures, and relative humidity levels.

The program automates the meshing process for thermal bridge junctions by determining the meshing steps according to the specific requirements of the element under study and the simulation's objectives, as outlined in Annex C, subsection C.2.c. of standard ISO 10211 [33]. This process involves formulating equilibrium equations at each node within the mesh, leading to the determination of temperature fields upon the resolution of the equation system.

Furthermore, the software adheres to stringent numerical validation criteria for meshing, as detailed in Annex C, subsection C.2. [33]. This section elucidates the methodology for deciding the number of subdivisions and establishes the necessary convergence criteria to ensure the accuracy and reliability of the simulation outcomes. The same discretization network was used for both the homogeneous element case and the inhomogeneous element case, using the same discretization steps and, implicitly, the same total number of discretization axes in the two directions.

To enhance the precision of the PSIPLAN simulations, specific attention was paid to the mesh size step, opting for a finer resolution starting from 0.2 mm. This choice is crucial to ensuring the accuracy of the results, and is particularly relevant to the domain discretization process described in Section 3.2. of ISO 10211 [33].

ANSYS Workbench [32] is a software that provides access to a suite of engineering simulation tools. It allows users to perform various simulations, such as structural, thermal, fluid dynamics, and electromagnetic simulations, among others. The ANSYS Workbench is widely used in engineering and product development to analyse and optimize designs before physical prototypes are built. In this research, the functionality of a steady-state thermal condition was used to simulate the thermal behaviour of construction elements. Among other features, this computational tool automatically creates and refines the mesh used for the FEM analysis. The main boundary conditions are the environmental temperature and the film coefficients. Regarding the mesh, in this study, an initial uniform mesh of 2 mm was used, and the borders between different materials were further automatically refined.

3.2. Domain Discretization and Boundary Conditions

As illustrated in Figure 1, only a 400 mm representative width segment of the LSF walls' cross-section was modelled, so as to reduce computation time and effort. The dimensions and thermal conductivities of the materials used in the simulations are displayed in Table 1.

To perform the numerical simulations, the environmental air temperatures and surface thermal resistances have been defined. In this research, the interior air temperature was set to 20 °C, while the exterior one was set to 0 and 10 °C, for the facade and partition LSF walls, respectively. Therefore, the average temperature of the partition LSF walls is 15 °C, while for the facade LSF walls it is 10 °C. Table 2 displays the surface thermal resistances adopted. For the internal surface thermal resistance (R_{si}), we adopted the default value of 0.13 m²·K/W, recommended in standard ISO 6946 [9] for horizontal heat flow. To compare their influence over the computed thermal resistance, six distinct values, ranging from 0 to 0.20 m²·K/W, were simulated for the external surface thermal resistance (R_{se}). One of these was the ISO-recommended conventional R_{se} , i.e., 0.04 m²·K/W. The conventional surface thermal resistances suggested by ISO 6946 [9] range from 0.04 to 0.17 m²·K/W. Thus, we sought to cover this interval, starting at 0.00 (theoretical) and extending up to 0.20 m²·K/W.

Table 2. Evaluated internal (R_{si}) and external (R_{se}) surface thermal resistances.

$R_{\rm si}~({\rm m}^2\cdot{\rm K}/{\rm W})$	0.13					
$R_{se} (m^2 \cdot K/W)$	0.00	0.04	0.08	0.13	0.16	0.20

To demonstrate that the mesh configuration and calculation approach employed are sufficiently robust for the simulation, a sensitivity analysis case study for the inhomogeneous partition wall using the PSIPLAN program is here presented. The boundary conditions were $R_{si} = 0.13 \text{ m}^2 \cdot \text{K/W}$ and $R_{se} = 0.04 \text{ m}^2 \cdot \text{K/W}$, while the interior temperature was 20 °C and the exterior temperature was 10 °C. Therefore, the sensitivity analysis was conducted in two stages, as is presented below. The choice of the rectangular discretization network has been validated over the years through the program's development, demonstrating that it provides quick convergence in the resolution of the system of energy balance equations.

First stage

The first step was to select a discretization mesh in accordance with criterion C2.d of standard ISO 10211 [33], which mandates that the number of subdivisions should be determined based on a process whereby the sum of the absolute values of all the thermal fluxes entering the object is assessed twice, once for *n* nodes (or cells) and then for $2 \times n$ nodes (or cells). The variation between these two assessments must not surpass 1%. If it does, the number of subdivisions must be expanded until the requirement is fulfilled.

In the tabulated data presented (see Figure 3 and Table 3), various discretization node counts are employed to elucidate the impact of mesh refinement on the thermal flux, which serves as a critical parameter in the sensitivity analysis. Upon careful scrutiny of the thermal flux alterations consequent to the doubling of discretization nodes, it can be concluded that there is an inverse correlation between the increase in discretization nodes and the percentage deviation in heat flux (ϕ_{si}). This trend is indicative of the system's convergence characteristics.

As can be observed, the condition is met starting from node count of 1739 onwards. Beyond this threshold, any augmentation in node count, characterized by doubling, yields a variance in the calculated thermal flux that is within the permissible limit of less than 1%, thereby affirming the adequacy of the mesh configuration for the thermal simulations conducted. The final row in Table 3 lists the *R*-values for all evaluated cases, capturing the impact of thermal bridges on the detailed thermal performance.





Figure 3. Mesh refinement stages in thermal simulation with visualization of temperature field for the LSF partition wall: (a) 16.0 mm; (b) 8.0 mm; (c) 4.0 mm; (d) 2.0 mm; (e) 1.0 mm; (f) 0.5 mm; (g) 0.2 mm; (h) temperature field at 0.2 mm.

Table 3. Analysis of convergence of thermal flux sensitivity to discretization node variation, regarding the LSF partition PSIPLAN model, for R_{si} and R_{se} values equal to 0.13 and 0.04 m²·K/W, respectively.

N. of nodes	234	500	910	1739	3795	7546	19,468
Step size (mm)	16.0	8.0	4.0	2.0	1.0	0.5	0.2
ϕ_{si} (W/model length) Differences	2.436365	$2.373234 \\ -2.7\%$	$2.346557 \\ -1.1\%$	$2.331952 \\ -0.6\%$	$2.322983 \\ -0.4\%$	$2.318495 \\ -0.2\%$	2.315669 -0.1%
$\frac{R_{\text{cond}} (\text{m}^2 \cdot \text{K}/\text{W})}{R\text{-value} (\text{m}^2 \cdot \text{K}/\text{W})}$	1.471790	1.515464	1.534625	1.545301	1.551924	1.555257	1.557363
	1.641790	1.685464	1.704625	1.715301	1.721924	1.725257	1.727363

Second stage •

Based on the results presented in Table 3, the second step of the analysis involved confirming the computational precision of temperature and flux values to meet the criterion specified in condition C2.e of standard ISO 10211 [33]. This condition necessitates that for iterative solution methods, iterations should proceed until the ratio of the sum of all thermal fluxes (positive and negative) entering the object to the semi-sum of their absolute values is below 0.0001.

Taking into account the stipulation in section C.2.b of standard ISO 10211 [33], which states that the subdivision degree of the object (specifically, the number of cells or nodes) is at the discretion of the user rather than being predetermined by the computational method, and referring to the outcomes highlighted in stage 1, a subdivision size of 0.5 mm was consistently utilized throughout this case study.

Observing the precision row in the results (see Table 4), it can be seen that the precision of the iterative calculations consistently improves, eventually achieving and surpassing the required threshold of less than 0.0001. This is evidenced by the final entries in the precision row, which meet the rigorous precision requirement laid out in condition C2.e of standard ISO 10211 [33].

Table 4. Evaluation of iterative calculation precision in thermal flux analysis at 0.5 mm subdivision (7546 nodes), regarding the LSF partition PSIPLAN model, for R_{si} and R_{se} values equal to 0.13 and 0.04 m²·K/W, respectively.

Iterations	1st	2nd	3rd	4th	5th	6th	7th
ϕ_{si} (W/model length)	2.359532	2.322598	2.318905	2.318536	2.318499	2.318495	2.318495
ϕ_{se} (W/model length)	2.259720	2.312617	2.317907	2.318436	2.318489	2.318494	2.318495
Precision	0.043215	0.004307	0.000431	0.000043	0.000004	0.000000	0.000000
$R_{\text{cond}} (\text{m}^2 \cdot \text{K/W})$	1.526944	1.552381	1.554969	1.555228	1.555254	1.555257	1.555257
<i>R</i> -value (m ² ·K/W)	1.695252	1.722209	1.724952	1.725227	1.725254	1.725257	1.725257

3.3. Model Accuracy Verifications and Validation

The authors already have a large degree of experience in using three of these computational tools, as can be verified in the following published papers, regarding THERM [18,20–23,34–40], ANSYS [21,22,34,38,39,41,42] and PSIPLAN [12,43–49]. Only the FLIXO software is being used by the authors for the first time, but with excellent results, as can be checked afterwards.

Nevertheless, several accuracy verifications and one validation by comparison to measurements were performed. The accuracy verifications that were performed were based on the test cases defined in Annex C of standard ISO 10211 [33], as well as in the analytical calculation procedures defined in standard ISO 6946 [9], for homogeneous layers. Moreover, the implemented models were validated by comparing some results with laboratory measurements under controlled conditions. These verification and validation procedures will be briefly described in the following paragraphs.

To ensure the precision of the computational tools used and the models implemented, the first two bi-dimensional test cases prescribed in Annex C of ISO 10211 [33] were simulated, and the following 3D test cases (3 and 4) from the same standard [33] were modelled in ANSYS (the only three-dimensional tested algorithm). The obtained results were within the permitted bounds, the difference between temperatures calculated and listed not exceeding 0.1 °C and the difference between heat flow values not exceeding 0.1 W/m.

The second verification was a comparison of the obtained thermal transmittances for the models previously presented in Figure 1, but simplified (i.e., without steel studs), with the results provided by the analytical calculation procedures provided in standard ISO 6946 [9] for walls with homogeneous layers. The material properties were the ones previously specified in Table 1, and the boundary conditions have also previously been described (please see Section 3.2), the values of the implemented surface thermal resistances being equal to the conventional ones defined in ISO 6946 [9], i.e., 0.13 and 0.04 m²·K/W for R_{si} and R_{se} , respectively. Notice that for the partition, we adopted R_{se} , equal to R_{si} (0.13 m²·K/W), since both walls' sides are internal (it is a load-bearing partition, instead of a facade).

Table 5 displays the overall thermal transmittances obtained for the analytical and numerical approaches, for both types of evaluated walls (simplified partition and facade).

As expected, for each wall type, the *U* values are equal until the third decimal place, ensuring the excellent accuracy of the evaluated algorithms and models.

Table 5. Thermal transmittance calculated for the simplified partition and facade LSF walls, assuming homogeneous layers (i.e., without a steel stud).

Approach	T 1	U-Value (W/(m ² ·K))			
	1001	Partition	Facade		
Analytical	ISO 6946	0.3182	0.2246		
Numerical	THERM FLIXO PSIPLAN ANSYS	0.3182 0.3182 0.3182 0.3182 0.3182	0.2246 0.2246 0.2246 0.2246		

The third strategy to ensure the accuracy of the evaluated LSF wall models was an experimental validation based on laboratory measurements. Making use of two loadbearing LSF wall prototypes ((1) a partition [20] and (2) a facade, as illustrated in Figure 4), their surface-to-surface thermal resistances were measured under controlled lab conditions. The LSF wall prototypes were placed between a hot box (heated by a thermal resistance up to around 40 °C) and a cold box (cooled by a fridge down to around 5 °C). These kinds of "climatic chambers" allowed us to implement a nearly steady-state temperature difference between the tested LSF walls of around 35 °C, for a mean average temperature of the tested LSF walls equal to 22.5 °C. To mitigate the eventual flanking lateral heat losses, the perimeter for the tested LSF wall was covered with polyurethane foam insulation (80 mm thick), while it was supported by a layer of more rigid thermal insulation (100 mm thick XPS).



Figure 4. Tested load-bearing LSF facade prototype: (a) steel frame; (b) sensors' position (cold surface) [35].

The heat transfer across the tested LSF wall samples was monitored by making use of thermocouples (TC) to measure temperatures, and Heat Flow Meters (HFMs) to measure heat flux. These measurements were performed making use of the Heat Flow Meter method described in standard ISO 9869-1 [7]. However, to improve the measurements' accuracy and reduce the test duration, two HFMs were used simultaneously, for each sensor location, at both cold and hot wall surfaces, as suggested by Rasooli and Itard [50].

For each wall configuration, three tests were performed; for each test, the sensors were placed at different height locations, as illustrated in Figure 4b. Moreover, these measurements were performed along two vertical lines: (1) in the middle of the LSF wall prototype, i.e., near the vertical steel stud, and (2) between the steel studs, i.e., in the middle of the insulation cavity. This test setup allowed us to monitor the two typical thermal behaviour zones on an LSF wall: (1) a region with higher heat flux (HFM1), originated by the steel stud's thermal bridge, and (2) the remaining part of the wall with smaller heat flux (HFM2), due to the cavity thermal insulation. More details about these measurements could be found in previous research works published by the authors [20,35].

Besides the measured conductive thermal resistances, displayed in Table 6 as R_{cond} , it was possible to also measure the average surface thermal resistances for each side of the tested LSF walls. The measured values were, for the partition LSF wall, $R_{si} = 0.10 \text{ m}^2 \cdot \text{K/W}$ and $R_{se} = 0.11 \text{ m}^2 \cdot \text{K/W}$, and for the facade, $R_{si} = 0.10 \text{ m}^2 \cdot \text{K/W}$ and $R_{se} = 0.13 \text{ m}^2 \cdot \text{K/W}$. Notice that the internal surface resistance (R_{si}) was measured on the hot side of the tested wall, while the external one (R_{se}) was measured on the cold side of the same wall.

Test N.		$R_{\rm cond} \ ({\rm m}^2 \cdot {\rm K} / {\rm W})$		
	Sensors Location —	Partition	Facade	
1	Тор	1.607	3.247	
2	Middle	1.576	3.121	
3	Bottom	1.491	3.232	
	Measurement Average	1.558	3.200	
	Computed in THERM	1.594	3.200	
	Percentage Deviation	+2.3%	0.0%	
	Computed in FLIXO	1.590	3.196	
	Percentage Deviation	+2.1%	-0.1%	
	Computed in PSIPLAN	1.591	3.198	
	Percentage Deviation	+2.1%	-0.1%	
	Computed in ANSYS	1.586	3.206	
	Percentage Deviation	+1.8%	+0.2%	

Table 6. LSF walls' conductive *R*-values for both experimental and numerical methods.

Figure 5 displays the measured heat flux values and surface temperatures over time (24 h) for the facade LSF wall, when the sensors were located at the highest height, as illustrated in Figure 4b. The measured values recorded at two different sensor locations are displayed in these plots: (1) near the steel stud (Figure 5a), and (2) in the wall cavity (Figure 5b). It is clearly visible that after a couple of hours, the values stabilize, confirming the intended steady-state regime. Regarding surface temperatures, the values are quite similar at both sensor locations (around 40 °C and 5 °C). As expected, the major difference is related to the heat flux values, these being much bigger (around 19.9 W/m²) near the steel stud (Figure 5a) when compared to the cavity location (near 8.9 °C), due to the thermal bridge effect caused by the high thermal conductivity of steel.

Making use of the measured values (surface thermal resistances and environmental air temperatures on both sides of the wall), it was possible to model a similar representative partition and facade LSF wall, making use of the four tested FEM computational tools. Afterwards, we computed the predicted conductive (or surface-to-surface) thermal resistance (R_{cond}) for each wall and each software model, as displayed in Table 6.

When comparing the results predicted by the FEM models with the measurements, we can see very good agreement, whereby the differences vary between -0.1% and +2.3%. Moreover, these deviations are much smaller (almost negligible) for the facade LSF wall, this being explained by the steel studs' lower thermal bridge relevance, given the effect of the continuous external thermal insulation layer (ETICS). These results allow us to validate



the accuracy of the implemented models, making use of the four computational tools compared in this research.

Figure 5. Measured heat flux values and surface temperatures over time when sensors are located at the highest height (see Figure 4b) for the LSF facade: (a) Sensor position 1, near the steel stud. (b) Sensor position 2, in the middle of the wall cavity.

4. Results and Discussion

4.1. Partition LSF Walls

Regarding the partition LSF walls, Figure 6 displays the surface-to-surface or conductive thermal resistances (R_{cond}) computed for several external surface thermal resistances (R_{se}) within the range of 0.0–0.20 m²·K/W, making use of the four evaluated FEM computational tools.



Figure 6. Partition LSF wall: conductive thermal resistances (R_{cond}) for different external surface thermal resistances (R_{se}) and their percentage variation, computed using (**a**) THERM, (**b**) FLIXO, (**c**) PSIPLAN, and (**d**) ANSYS.

As expected, the lowest R_{cond} value is provided for the smaller R_{se} , i.e., assuming a null value. Regarding the THERM software (Figure 6a), the computed surface-to-surface thermal resistance is 1.5237 m²·K/W. When the R_{se} value is increased up to 0.20 m²·K/W, there is also a non-linear increase in the R_{cond} value (greater increment for smaller R_{se} values), reaching a maximum value of 1.6467 m²·K/W, which corresponds to an increase of +0.123 m²·K/W (+8.1%). Notice that for the other evaluated computational tools, i.e., FLIXO (Figure 6b), PSIPLAN (Figure 6c) and ANSYS (Figure 6d), the trend is very similar, as are the computed values.

To better visualize and compare the results for the several tested FEM computational tools, Figure 7 displays all the obtained R_{cond} values in a single plot, as well as the averaged computed values for each external surface thermal resistance value. This graph makes it clearer that the thermal resistances computed by THERM, PSIPLAN and ANSYS are very similar, while the ones provided by the FLIXO algorithm are slightly smaller.



Figure 7. Partition LSF wall: conductive thermal resistances (R_{cond}) for different external surface thermal resistances (R_{se}) computed by different FEM softwares and their average value variations.

Looking now at the averaged R_{cond} values, the trend is very similar to the one previously observed in Figure 6, i.e., there is a non-linear increase ranging from the minimum (1.520 m²·K/W) up to a maximum conductive thermal resistance of 1.643 m²·K/W, corresponding to an increase of +0.123 m²·K/W (+8.1%). Notice that these average thermal resistance increments (absolute and percentage) are the same as those previously observed and discussed in relation to the THERM software (Figure 6a).

4.2. Facade LSF Walls

In this section, the results obtained for the facade LSF walls are presented and discussed. Notice that the main difference between the previously evaluated LSF partition (Section 4.1) and this LSF facade is that the latter has an additional ETICS layer containing 50 mm of EPS insulation, as previously illustrated in Figure 1b and listed in Table 1. This fact results in an LSF facade wall wherein the thermal bridges due to the steel studs are less relevant, given the existence of a continuous ETICS insulation layer.

Figure 8 illustrates the conductive thermal resistance values (R_{cond}) computed for the evaluated LSF facade wall. Comparing these results with the previous ones derived for the

partition LSF wall (Figure 7), the main difference, besides the higher thermal resistances obtained (around two times higher), is that now the increase in R_{cond} values for higher external surface values is greatly reduced. In fact, this average increment is only from 3.199 up to $3.205 \text{ m}^2 \cdot \text{K/W}$, corresponding to an absolute increase of $+0.006 \text{ m}^2 \cdot \text{K/W}$ (+0.2%). This feature leads us to conclude that the relevance of the surface thermal resistance values to the conductive thermal resistance in LSF facade walls, with the thermal bridges of steel studs being adequately mitigated (e.g., by an ETICS layer), is notably reduced, and is almost negligible.



Figure 8. Facade LSF wall: conductive thermal resistances (R_{cond}) for different external surface thermal resistances (R_{se}) computed by different FEM softwares and their average value variations.

4.3. Homogeneous Layered Walls

To confirm the previous assumption that the relevance of surface thermal resistance variations to the corresponding R_{cond} values significantly decreases when the thermal bridge effect in the wall also decreases or becomes non-existent (unidirectional heat transfer), we here discuss the results computed for both partition and facade homogeneous layered walls, i.e., without steel studs (no thermal bridges).

Figure 9 displays the surface-to-surface thermal resistances computed for the partition (Figure 9a) and facade (Figure 9b) LSF walls, but here assuming homogeneous layered walls, i.e., neglecting the steel frame. The values for each wall type are nearly constant, and do not depend on the surface thermal resistances. On average, the computed conductive thermal resistances are equal to 2.883 and 4.283 m²·K/W for the partition and facade walls, respectively.

These results also allow us to perform an additional verification of the implemented models and algorithms, since the provided results could be compared and should be equal to the ones provided by analytical calculations performed for homogenous layers (ISO 6046 [9]). Making use of the thicknesses and thermal conductivities previously provided in Table 1, the thermal resistance provided by each wall layer could be obtained. Summing all these thermal resistances, we obtain the same conductive *R*-values as those displayed in Figure 9a,b, ensuring again the accuracy of the implemented numerical models using the four evaluated computational tools.



Figure 9. Conductive thermal resistances (R_{cond}) for different external surface thermal resistances (R_{se}) computed by different FEM softwares and their average value variations: (**a**) homogeneous partition; (**b**) homogeneous facade.

4.4. Results Overview

To allow for the better and easier analysis of the results, Figure 10 shows only the averaged R_{cond} values computed using the four FEM computational tools, as well as their percentage variations. Regarding the partition LSF wall (Figure 10a), we can now even



more clearly see the increase in the conductive thermal resistance values, from 1.522 up to $1.645 \text{ m}^2 \cdot \text{K/W}$, corresponding to a percentage variation up to +8.1%.

Figure 10. Average values of computed conductive thermal resistances (R_{cond}) for different external surface thermal resistances (R_{se}) and their percentage variation: (**a**) partition LSF wall, (**b**) facade LSF wall.

Observing now the results obtained for the facade LSF wall (Figure 10b), we can see that the R_{cond} averaged values are nearly constant, showing only a slight increase from 3.199 up to 3.205 m²·K/W, which also means a minimal percentage variation up to +0.2%.

The R_{cond} values for homogeneous simplified LSF walls (i.e., without the steel frame) are constant, and do not change with the increment of the external surface thermal resistances, as previously seen before in Section 4.3.

To better understand and visualize the obtained results, Figure 11 displays the average computed conductive thermal resistances (R_{cond}) and the corresponding temperature color distribution predicted by the THERM models for the two extreme surface thermal resistances (R_{se}), these being 0.0 m²·K/W for the first column and 0.20 m²·K/W for the second (right one). Three different wall configurations were selected for this analysis, namely: (a) partition LSF wall; (b) facade LSF wall, and (c) facade, homogenous simplified wall.

Looking to the partition LSF wall cross-section temperature distributions (Figure 11a), and comparing the results for both surface thermal resistances, it is clearly visible that, near the external wall surface, there are some differences, the major ones being near the flange of the steel stud, as a result of the related thermal bridge effect. In fact, for the higher R_{se} (0.20 m²·K/W) the external surface temperatures are also higher, as expected, in comparison to the other R_{se} value.

We can also observe similar results for the facade LSF wall cross-sections (Figure 11b); given the external continuous insulation layer (ETICS), the steel stud's thermal bridge effect is now more attenuated, mainly near the external wall surface, where the temperature values are almost constant for both R_{se} values. These features elucidate the reason why, in this LSF wall configuration, the conductive thermal resistances are almost the same, with an increment of only +0.2%.

Regarding the simplified facade wall with homogenous layers, i.e., without steel studs (Figure 11c), as expected, the computed colour distribution is steady over all the layers of the wall, corresponding to a perfect unidirectional heat transfer without any thermal bridge effect. Therefore, the R_{cond} values are now fixed for all evaluated surface thermal resistances. Obviously, besides being fixed, the surface-to-surface *R*-value is now bigger (4.283 m²·K/W) when compared with the previous LSF wall configuration (3.200 m²·K/W), corresponding to an increment of 1.083 m²·K/W (+33.8%).



Figure 11. Average computed conductive thermal resistances, with temperature showing colour distribution predicted by THERM models for the two extreme surface thermal resistances (R_{se}) and for different wall configurations: (**a**) partition LSF wall; (**b**) facade LSF wall; (**c**) simplified facade wall with homogenous layers (without steel studs).

5. Conclusions

In this work, the influence of surface thermal resistance (R_s) on the conductive thermal resistance (R_{cond}) of LSF walls was evaluated. To this end, four finite elements' numerical simulation tools were used to model the four assessed LSF walls, showing different levels of thermal conductivity inhomogeneity: (1) partition, cold frame LSF wall; (2) facade, hybrid LSF wall; (3) simplified homogeneous partition LSF wall, and (4) simplified homogeneous facade LSF wall. Moreover, six external thermal surface resistances (R_{se}) were modeled, ranging from 0.00 up to 0.20 m²·K/W. The average temperature of the partition LSF walls is 15 °C, while for the facade LSF walls it is 10 °C.

Notice that the accuracy of the implemented numerical models used in this study was verified, taking as a reference the ISO 10211 test cases and the ISO 6946 analytical calculation rules for homogeneous layered simplified walls, as well as by comparing the results provided by the four evaluated computational tools. Moreover, the precision of the employed models was also validated by comparison to measurements under controlled lab conditions.

The main conclusions of this research work can be listed as follows:

• The accuracy of all evaluated computational tools was very high and similar;

- The *R*_{cond} value is nearly uniform for walls with homogeneous layers, as expected;
- The variation of the *R*_{cond} values depends on the level of inhomogeneity in the LSF wall layers;
- For the assessed R_{se} values, the conductive thermal resistances increased up to 8.1%, i.e., +0.123 m²·K/W, for the partition cold frame LSF wall;
- However, the variation in R_{cond} values was almost negligible (only up to +0.2%) for the facade hybrid LSF wall with a continuous thermal insulation layer (50 mm thick);
- When removing the steel frames, the *R*_{cond} values of this simplified facade wall do not change, regardless of the *R*_{se} values;
- However, when compared to the original LSF facade wall, the conductive thermal resistance values increased significantly (+34%);
- Numerical modelling and laboratory measurements are complementary methods, and the combination of them boosts the accuracy and the practical relevance of thermal performance analyses.

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