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Heat transfer analysis of the vertical closing system in light steel framing using the isothermal planes method and finite element method

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Abstract

The use of steel in construction is an alternative that has changed the panorama of this sector, contributing to an increase in productivity, and a reduction in waste and construction time. The *Light Steel Framing* (LSF) system, introduced in Brazil at the end of the 1990s, is undergoing a process of technical development and acceptance in the national civil construction market, but there are still shortcomings regarding the design, itemization and implementation of the complementary closing systems, and also regarding its thermal performance. This study employs an analytical approach that uses the isothermal planes method to calculate the resistance and thermal transmittance, and a numerical approach that uses the ANSYS software (version 15) to verify and compare these analyses. Multi-layer closures are considered, with the outer layer being made up of cement board and the inner layer of gypsum board, brokered by fiber glass insulation and air, with studs formed by C-section profiles in galvanized steel. The isothermal planes method revealed the value of 0.77 $(m^2.K)/W$ for the equivalent thermal resistance, 1.3 $W/(m^2.K)$ for the thermal transmittance, and 13.04 W/m^2 for the heat conduction flux. The difference of the results when comparing the isothermal planes and numerical solution methods was 9% for thermal resistance and 8% for heat conduction flux. The obtained results showed that the heat flux is equivalent to a value around 54% greater than the heat flux value for a closure without the presence of steel profile.

Keywords: *Light Steel Framing*, thermal resistance, thermal transmittance, isothermal planes method, numerical simulation.slate waste.

1. Introduction

The current trend in the construction sector is towards integrated techniques that must meet numerous requirements in terms of eco-efficiency, safety, health, and comfort, without neglecting economic aspects. From this perspective, buildings with lightweight steel frames (LSF) are attracting attention thanks to their advantages (Atsonios *et al.*, 2018).

In Brazil, civil construction still predominantly uses the conventional system of concrete and masonry, characterized by low productivity and, especially, by a lot of waste. However, the domestic market has signaled that this situation is changing and that the use of new technologies is the best way to enable the industrialization and rationalization of construction pro-

cesses. In this regard, the use of the LSF construction system presents itself as one of the alternatives to change the industry's landscape (Santiago *et al.*, 2012).

LSF is characterized by frames of cold formed galvanized steel, which constitute a structural skeleton capable of withstanding the loads of the building and of the several inter-related components and subsystems that enable an industrialized construction (Santiago *et al.*, 2012; Rodrigues; Caldas, 2016).

The galvanized steel profiles are used for structural or non-structural panels, floor beams, secondary beams, scissors roofs and other components. The structural panels are formed by galvanized C-section profiles, with tracks at the base and at the top of the panels, and by C-section profiles called "studs" which are regularly spaced at 400 mm or 600 mm according to the modulation defined in the structural calculation. However, it is common to use 600 mm spacing in single-story buildings, 400 mm in multi-story buildings, and 200 mm in areas supporting the water tank. The fixed plates in the structure form the internal or external closures. The other LSF components are light elements that are compatible with the system's concept, which is the formation of a structure with low own weight.

In Brazil, the products available for the closure of buildings made with LSF are provided on plates or metal sheets with various thicknesses and the most commonly used are cement board and gypsum board, of which the latter should only be used in indoor applications. Such closures should be interspersed with a thermal insulator layer (fiber glass) and air.

The use of the LSF system implies an increase in civil construction technology, enabling a strict control of the processes. As a rationalized system, it is suitable for industrial production, contributing to the design of more efficient buildings from various perspectives, such as sustainability, as a result of the possibility of recycling the materials and rationalizing the loss of material (Crasto, 2005; Campos, 2010).

However, there are still shortcomings in the design, itemization and implementation of the complementary closing systems (Santiago *et al.*, 2012). To improve the performance of the LSF system in Brazil, it will be necessary to adjust it to Brazilian culture and climate so it can be viable from a cost perspective. Reducing the costs and increasing the efficiency of the system is a concern in all the countries that use the system.

In LSF constructions, the structural elements can generate such problems as the excessive transmission of heat between the external and internal environment and moisture condensation on the inner part of the external closing panels.

In the LSF system, the set of steel bars corresponds to less than 0.5% of the closure area. However, since the thermal conductivity of steel can be 1500 times higher than that of the insulating material, ignoring the thermal performance of these bars in buildings in rigid climatic conditions can lead to an overestimation of the building's thermal resistance of up to 50% (Gorgolewski, 2007).

Thermal performance refers to how well a building responds to changes in the external environment to maintain thermal comfort conditions in the internal environment. These conditions should be achieved while demanding the least possible energy for heating and/or cooling. Building energy efficiency means using less energy to provide the same indoor thermal conditions (Soares *et al.*, 2017).

An accurate evaluation of the thermal resistance and transmittance of the building's enveloping elements is fundamental for a reliable evaluation of its thermal behavior and energy efficiency (Santos *et al.*, 2020). This calculation can be done through simplified methods and through numerical simulation. This work presents a study of the isothermal planes method to calculate the equivalent thermal resistance of a closure in the LSF system. It also uses an assessment through numerical simulation to calculate the heat conduction flux through the closure.

2. Materials and methods

Two approaches were adopted to obtain the equivalent thermal resistance and thermal transmittance of the closures in LSF: an analytical approach and a numerical approach.

In both cases, a vertical closure was used with an area limited to 0.045m² to configure a simulation cell that was in accordance with the modulation of the LSF constructive system, in which studs are spaced at 400 mm. The adopted spacing refers to a common closure for a two-story building (Santiago *et al.*, 2012; Rodrigues; Caldas, 2016), as illustrated in Figure 1.

Figure 1 - Simulation cell of the closure in *Light Steel Framing*.

The composition used for the closure was made up of an outer layer of 10 mm thick cement board and an inner layer of of gypsum board with a thickness of 12.5 mm, interspersed by fiber glass and air, and a gal-vanized steel C-section profile (90x40) with a thickness of 0.95mm. The assembly of the layers of the external panels is done from the outside in. The cement board is fixed externally on the structure of the panels.

The fiber glass insulation is then fixed on the inside face of the cement board. And, lastly, the gypsum board is applied on the structure. The thermophysical properties of these materials are presented in Table 1.

Table 1 - Properties used for thermal analysis for the closure in Light Steel Framing.

Material	Thickness (mm)	Thermal conductivity [W/(m.K)]	Specific mass [kg/m³]	Specific heat [J/(kg.K)]
Cement board	10	0.95	2200	840
Gypsum board	12.5	0.35	1000	840
Fiber glass insulation	50	0.042	100	700
Profile	0.95	55	7800	460
Air	40	0.0263	1.1614	1007

Source: adapted from NBR 15220-2; Incropera *et al*, 2007; Rodrigues; Caldas, 2016.

For a permanent thermal analysis, a temperature of 40°C (313K) was used for the outer face of the closure and 30°C (303K) for the inner face, obtaining a temperature gradient of 10. The conditions adopted represent the typical thermal behavior of an insulating closure applied in buildings in Brazil's tropical climate.

2.1 Analytical approach

There were developed some simplified methods for calculating the equivalent thermal resistance and thermal transmittance for closing in LSF. The results of these methods are often compared with the results obtained experimentally and, for the most part, exhibit good precision (Muzzi *et al*., 2020). The Modified Zone method is the one recommended by the ASHRAE standard (2013, ch. 27), but this method does not consider the layer of air in the intermediate layers of the vertical LSF closure, as it is used outside of Brazil. Another efficient method recommended by the standard, is the isothermal planes method, which allows the use of the air layer as an intermediate layer in the vertical closure, as it is used here in Brazil.

The isothermal planes method (ASHRAE, 2013, ch. 27) assumes that the temperature is uniform in each parallel plane of the element's side, it means, that the flow of heat through the closure is completely redistributed in each layer (isothermal planes), and that there is no lateral resistance to the heat flux, i.e. the heat flux is one-dimensional. Figure 2 shows the variables that must be considered in the isothermal planes method.
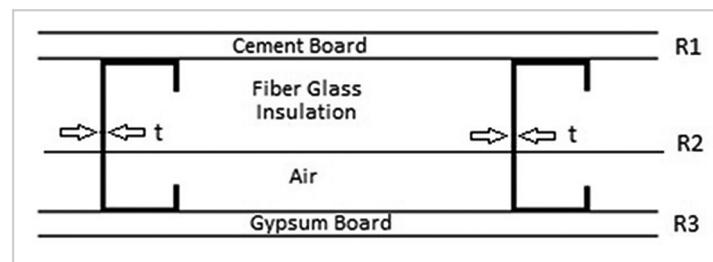
Figure 2- Isothermal Planes Method.

In equations (1), (5), and (6), the total thermal resistance, total thermal transmittance, and conduction heat flux calculations are presented, respectively.

$$R_{ip} = R_{si} + R_1 + R_2 + R_3 + R_{se} \ [(m^2.K)/W] \tag{1}$$

Where R_1 and R_3 are the thermal resistances of layers 1 and 3, respectively, calculated by equations (2) and (3), and R_2 is the resistance of layer 2, calculated by means of equation (4),

$$R_1 = \frac{d_{cement\ board}}{k_{cement\ board}} [(m^2.K)/W] \tag{2}$$

$$R_3 = \frac{d_{gypsum\ board}}{k_{gypsum\ board}} [(m^2.K)/W] \tag{3}$$

where k is the thermal conductivity of the material [W/(m.K)] and d is the thickness of the layer (m).

$$R_2 = R_{through\ briged\ layer} = \frac{1}{\left[\left(\frac{A_{frame}}{R_{steel}}\right) + \left(\frac{A_{insulation}}{R_{insulation}}\right)\right]} [(m^2.K)/W] \tag{4}$$

where A [m²] is the area of the material and R [(m².K)/W] is the thermal resistance.

R_{si} and R_{se} are the internal and external thermal resistances of the surface [(m².K)/W] and are proposed by the standard NBR 15.220 (ABNT, 2005), as presented in Table 2.

Table 2 - internal and external thermal resistance of the surface.

R_{si} [(m².K)/W]			R_{se} [(m².K)/W]		
Heat Flow Direction			Heat Flow Direction		
Horizontal	Ascendant	Descendant	Horizontal	Ascendant	Descendant
⇨|	⇧	⇩	⇨|	⇧	⇩
0.13	0.10	0.17	0.04	0.04	0.04

Source: adapted from NBR 15220 (ABNT, 2005).

$$U = \frac{1}{R_{ip}} \, [W/(m^2.K)] \qquad (5)$$

$$q = \frac{\Delta T}{R_{ip}} \, [W/m^2] \qquad (6)$$

Where ΔT is the temperature gradient of the surface in the closure [°C].

2.2 Numerical approach

The numerical approach is based on the Finite Elements method (FEM) using the ANSYS software. The FEM is based on the discretization of the closure into elements, thus generating a mesh of elements and nodes. Through convenient interpolation functions, this discrete system simulates the behavior of the original continuous system. The advantage of the finite elements method is the extent of possible uses, since the finite elements adapt themselves to the geometry of the element (ANSYS, 2013). Several analysis can be obtained with ANSYS, including structural, thermal and fluid analyses. In thermal simulation, the heat flux through the closure of the *Light Steel Framing* is calculated, which enables the calculation of the thermal resistance of the frame.

The ANSYS software has a library of various elements according to the type of analysis desired. For this thermal analysis, the element PLANE55 was used, which has unidirectional temperature in four nodes with a single degree of freedom as characteristic. This element can be applied to two dimensional thermal analyses, for both transient and permanent state conditions.

In addition to the thickness, three thermalphysical properties were loaded in the software for the thermal analysis in order to obtain the desired result. These properties are summarized in Table 2.

The mesh refinement was related according to the thickness of the steel profile, 0.95mm. Refinement levels were tested, seeking the best refinement of the mesh in the C-section profile area. The tests revealed an element with approximately 32% of the thickness profile. For other areas, the mesh refinement was approximately 4% in relation to the closing area of 0.045m².

A verification of the numerical simulation was performed through ANSYS to obtain a modeling procedure that would lead to results consistent with those obtained using the analytical approach. This way, considering closures with a known exact solution, simple and multilayer finite element models for the closures were constructed (Figure 3), with 0.045m² of area, without the presence of the steel frame. The heat conduction flux for each case was then analyzed and compared with the results (Muzzi, 2014).
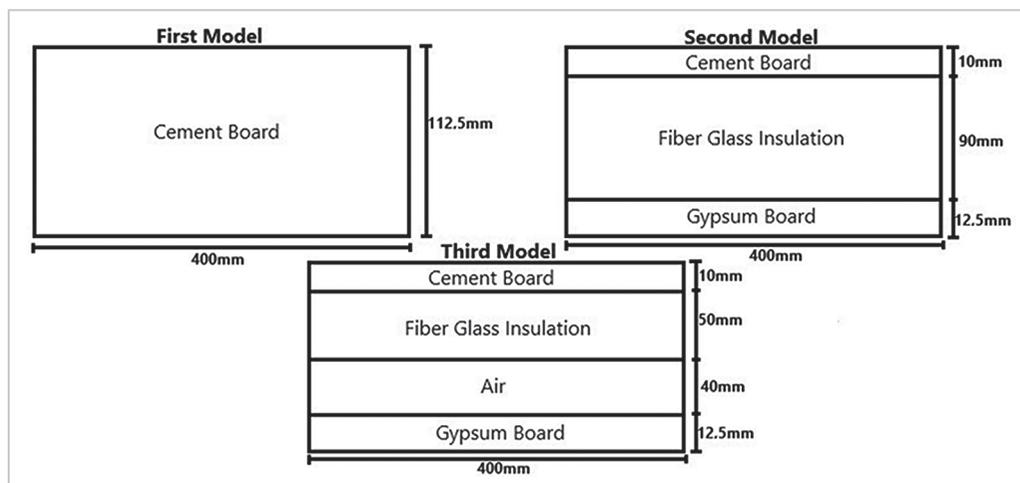
Figure 3 - Schematic of the closures used for verification of the finite elements model.

The ANSYS results reveal the heat flux values for the presented models. In the first model, composed only of the cement board, the heat flux is 84.44 W/m², in the second model it is 4.89 W/m² and the third model the heat flux is 3.6 W/m².

When compared with the results of the analytical approach, the values for the models were also 84.44 W/m², 4.89 W/m² and 3.6 W/m² for the first, second and third model, respectively. These results were obtained through equations 7 and 8.

$$q = \frac{\Delta T}{R} \ [\text{W/m}^2] \qquad (7)$$

$$R = \frac{d}{k} \ [(\text{m}^2.\text{K})/\text{W}] \qquad (8)$$

where the temperature gradient is 10^0C, d is the thickness of the closure layers (m), and k is the thermal conductivity of the materials used [W/(m.K)].

3. Results and discussion

The calculations were carried out in ANSYS for both the Isothermal Planes method and the numerical approach according to the closure presented in Figure 1, considering a permanent heat exchange regime, one-dimensional heat conduction and a temperature gradient between the surfaces of the closure equivalent to 10^0C. This temperature gradient represents the thermal behavior of a closure applied to constructions that use air conditioning systems in the tropical climate of Brazil. Only with a temperature difference between the inner and outer surface of around 10ºC is it possible to clearly observe the interference of the steel profile on the thermal bridging effects in the heat conduction flux through the closure (Gomes *et al.*, 2013).

3.1 Results obtained through the analytical approach

Through the isothermal planes method, the value of the equivalent thermal resistance is 0.77 (m².K)/W, the value of thermal transmittance is 1.3 W/(m².K), and the value of the heat flux is 13.04 W/m².

3.2 Results obtained through the numerical approach

In Figure 4, the stratification of the closure's temperature with intermediate insulating and air layers is presented.
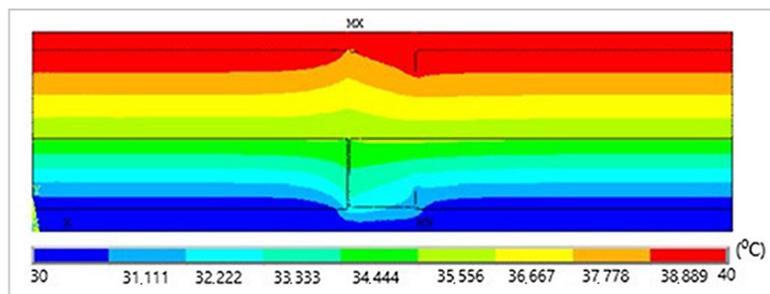
Figure 4 - Temperature distribution of the closure with insulating and air layer.

As can be seen in Figure 4, there is a difference in the temperature distribution in the steel profile region in relation to the region further away from this element. There is a relationship between the high conductivity of steel and the two-dimensional heat conduction, for in the profile region one can see that the flux goes in more than one direction; while in the rest of the closure, the heat flux goes in a single direction (from the outer surface to the inner surface of the closure). Since the thermal conductivity of steel is far superior to that of other materials, it becomes clear in this region that the heat conduction mechanism is two dimensional (Figures 5 to 7).
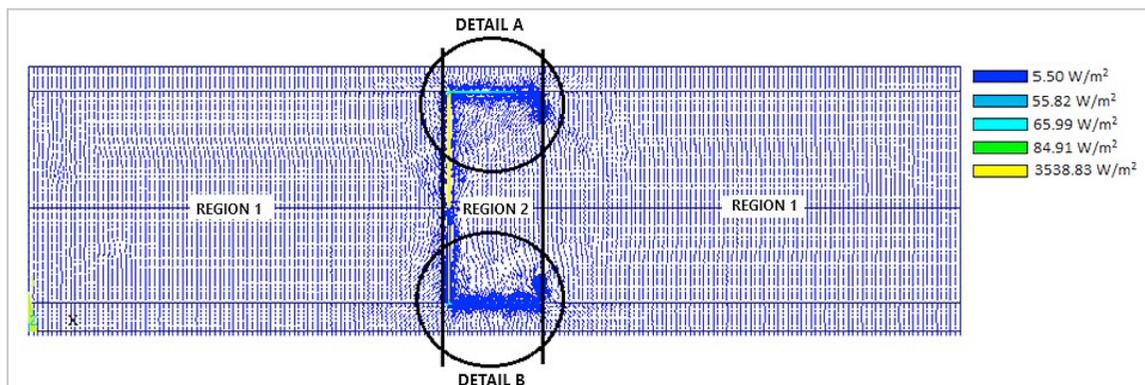

Figure 5 - Distribution of the heat flux for the closure with insulating and air layers.

The heat conduction flux in this region of the steel profile is (59.9 W/m² - Region 2) around 11 times greater than the heat conduction flux in a wall without a steel profile (5.5 W/m² - Region 1).

For the analyzed closure, the equivalent thermal resistance was R_t = 0.84 (m².K)/W and the total heat flux was 11.93 W/m². This heat flux is equivalent to a value around 54% greater than the heat flux value for a closure without the presence of steel profile.
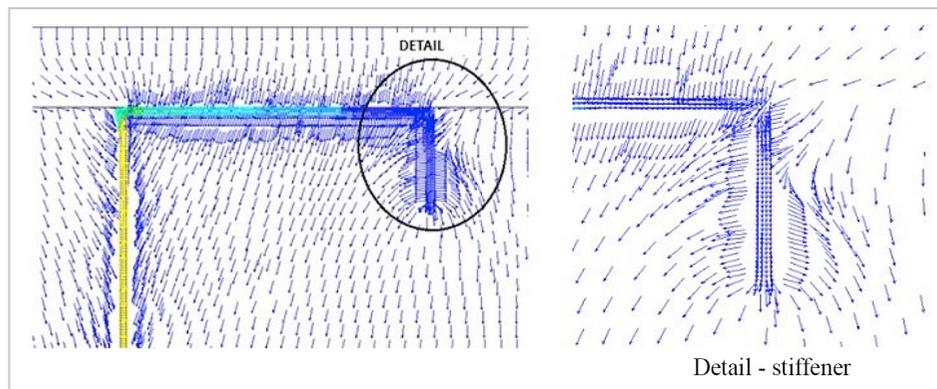

Figure 6 - Distribution of the heat flux for the closure with insulating and air layers.
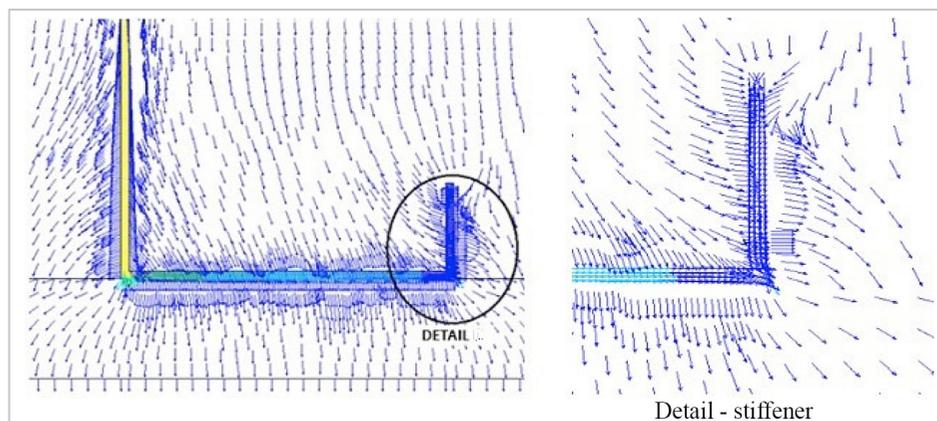
Figure 7 - Distribution of the heat flux for the closure with insulating and air layers.

A comparison between the results obtained using the analytical and numerical approach with the ANSYS 15.0 software is shown in Table 3.

Table 3 - Comparison of the analytical and numerical analysis values for thermal resistance, thermal transmittance, and heat flux.

Approach	Thermal Resistance (m².K)/W	Thermal Transmittance W/(m².K)	Heat Flux W/m²
Analytical	0.77	1.3	13.04
Numerical	0.84	1.2	11.93

When the value of the equivalent thermal resistance obtained through numerical simulation (R_t = 0.84 (m².K)/W) is compared with the value of thermal resistance obtained through the isothermal planes method (R_t = 0.77 (m².K)/W), a difference of around 9% is obtained, and when the thermal transmittance obtained through simulation is compared with the one obtained by isothermal planes, a difference of 8% is obtained, the same value as for the heat flux comparison.

4. Conclusions

Both methods, the Isothermal Plane Method and the numerical simulation in ANSYS, provide reliable results for thermal resistance, thermal transmittance and heat flux through the LSF closure system. Although the ASHRAE standard (2013, ch. 27) recommends another method (Modified Zone) to determine the thermal resistance in panels with internal cavities, the Isothermal Plane method also produces good results, similar to those of the numerical simulation, which was validated. Another point to be highlighted, as previously mentioned, is the fact that in Brazil a layer of air is used as one of the intermediate closing layers, and in those cases, the Isothermal Plane method should be applied when compared to the Modified Area method.

The numerical simulation in ANSYS should be prioritized, however, in cases where it is necessary to perform an ad-hoc study of the heat conduction flux through the closure. Another advantage of using the ANSYS software is the range of possibilities of its use.

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