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INFLUENCE OF EXPOSED STEEL STRUCTURE AREA ON THE THERMAL PERFORMANCE OF ARTIFICIALLY CONDITIONED BUILDINGS

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Abstract. *When a material with high thermal conductivity, such as steel, is placed in parallel with a less conductive material, most of the heat transfer occurs through the steel by conduction, characterizing an effect known as a thermal bridge. Thermal bridges reduce the thermal resistance of the external envelope, increasing energy costs for environmental heating or cooling. On these considerations, this research aims to evaluate the thermal performance of artificially conditioned environments using computational simulations using the EnergyPlus program. The analyzes are made considering all Brazilian bioclimatic zones. The results showed the effects of thermal bridges were more evident in the evaluation made for Bioclimatic Zone 4. There was a maximum increase of 10.6% in the environment total cooling thermal load and, as a consequence, a maximum variation of 12.5% in the building energy consumption, evidencing that the larger the exposed steel area in the building closing system, the greater the effect caused by this thermal bridge.*

Keywords: *thermal performance, steel structures, thermal bridge, thermal load, air conditioning*

1. INTRODUCTION

The increasingly common use of steel structures in commercial buildings leads to an increase in the complexity of design constraints. During the architectural design phase, the project should be defined more carefully, taking into account the energy efficiency of the building in accordance with climatic conditions (Gomes and Souza, 2013). In this context, simulation of the thermal behavior of buildings with the use of computer programs has generated several constructive advantages for the establishment of energy-efficient buildings. By means of these computational resources, it is possible to simulate the electric energy consumption and the peak of the thermal load of the building cooling, allowing a correct estimation of the capacity of the various components of the air conditioning system, besides optimizing the system's operation through more efficient strategies.

When a high thermal conductivity material is placed in parallel with a less conductive material, or if the area of the exposed steel structure is large, most of the heat transfer occurs by conduction through the steel profile or exposed structure in an effect known as thermal bridging. This mechanism characterizes a reduction of the thermal resistance of the closed system, which causes an increase in energy costs for environment heating or cooling.

A thermal bridge offers a less heat-resistant area through the building envelope, and the adverse effects associated with it are the greater heat loss and the reduction of the internal surface temperature in the affected area, which, as well as increasing the energy costs, also increase the risk of condensation and mold growth (Sierra, Bai and Maksoud, 2015).

The first Brazilian standard on the study of thermal performance of buildings was published in 2005, named NBR 15220 (ABNT, 2005). Part 3 of this standard presents the Brazilian bioclimatic zoning and some building guidelines for social interest buildings. The purpose of such construction guidelines is to optimize the thermal performance of buildings, through their better climate suitability (ABNT, 2005). In 2013, the Brazilian standard NBR 15575 (ABNT 2013) was released, which establishes the requirements and performance criteria that apply to residential buildings for evaluation through computational simulation. Nevertheless, none of these standards addresses the effect of thermal bridges.

Gomes, Souza and Tribess (2013) assessed the impact of thermal bridges across enclosure elements on the thermal performance of air-conditioned buildings designed in Light Steel Framing (LSF) in Brazil. The results showed that the increase in the temperature difference between the inside and the outside of the building caused by the air conditioning system makes the effects of thermal bridges more evident. The thermal peak load increases by approximately 10% when considering metal frames in the numerical simulation. Besides, there was an increase of about 5% in the annual energy consumption of the building.

Freitas and Cunha (2018) evaluated the impact of thermal bridges of reinforced concrete structure on the thermal energy performance of a residential building in South Brazil climate, considering three different approaches to model the thermal bridge using the EnergyPlus software. The results show that the type of modeling influences the energy consumption and the thermal comfort indexes in the building, being able to reach a consumption difference of up to 20%, depending on the level of the building insulation.

Theodosiou and Papadopoulos (2008) claim that because construction practices in many countries do not apply all the insulation measures provided in its national regulations, thermal losses become greater than those foreseen in the design of the project. In their study on the impact of thermal bridges on the energy demand of buildings built using double brick walls in Greece, it was found that the actual thermal losses in the buildings analyzed were about 35% higher than initially estimated. This problem, therefore, has not been properly addressed since it leads to an underestimation of thermal losses or gains during the project design process or during insulation studies and calculations by various methods in general.

Considering the above, it is important to quantify the heat losses or gains caused due to the presence of thermal bridges in the building envelope, since they directly interfere in the thermal performance of buildings. In this context, this paper aims to evaluate the influence of the steel structure area on the thermal performance of artificially conditioned commercial buildings in Brazil.

2. OBJECTIVE

This paper aims an analysis of the impact caused by an exposed steel structure area on the thermal performance of buildings, focusing on studying a commercial environment artificially conditioned.

3. MATERIALS AND METHODS

The adopted method consists of numerical simulations using the EnergyPlus program (version 8.6.0), which will predict the cooling thermal loads and the annual building electrical energy consumption. The building is simulated drawing directly the surfaces where the thermal bridges occur, considering two situations: building with the presence of exposed steel structure and building without the presence of exposed steel structure, replacing structural steel with a conventional closure system.

The EnergyPlus was developed by the US Department of Energy (LBL, 2016; Crawley, et al., 2008). This software includes some innovations in the simulations, such as shorter time slots in the simulation process, modular and plant systems integrated with each zone's energy simulation, multi-zone airflow, thermal comfort, and photovoltaic systems. Furthermore, allows the calculation of the impact of heating, cooling, ventilation, complex types of lighting, and window shutters to maximize the energy efficiency of the building and the comfort of the occupants.

The characterization of a model in EnergyPlus requires that a large number of variables (input data) be known, increasing the precision of the results, but it can also generate uncertainties, which result in errors. It is of fundamental importance that there is a deep understanding of the program used and the behavior of the building to be simulated, thus guaranteeing a greater precision of the results (Gomes, 2012).

In this paper, the proposed model is a 10-floor building similar to commercial buildings typical of large urban centers, with two well-defined sectors: vertical circulation (core) and office space, as exemplified in Figure 1.

The typical floor plan presented in Figure 1 was designed considering the structural system in reinforced concrete. Therefore, adaptations of the dimensions were made to adapt it to the system in steel structure, as shown in Figure 2.

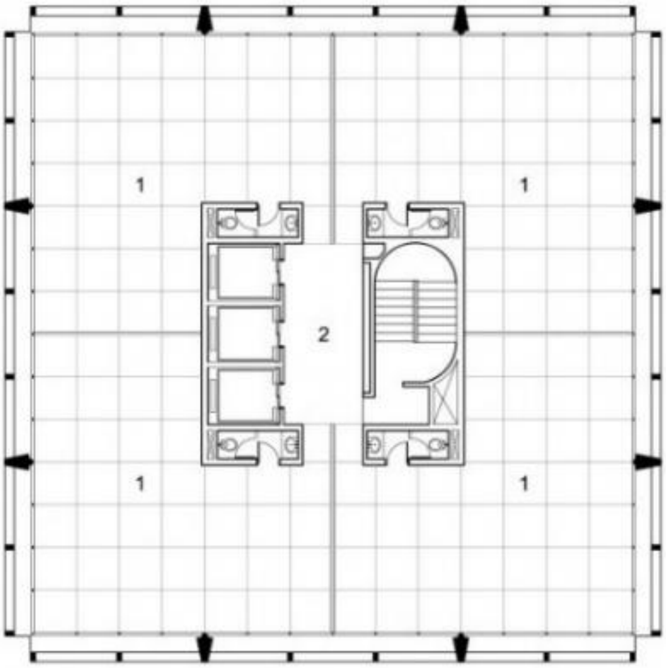

Figure 1: Typical floor plan.
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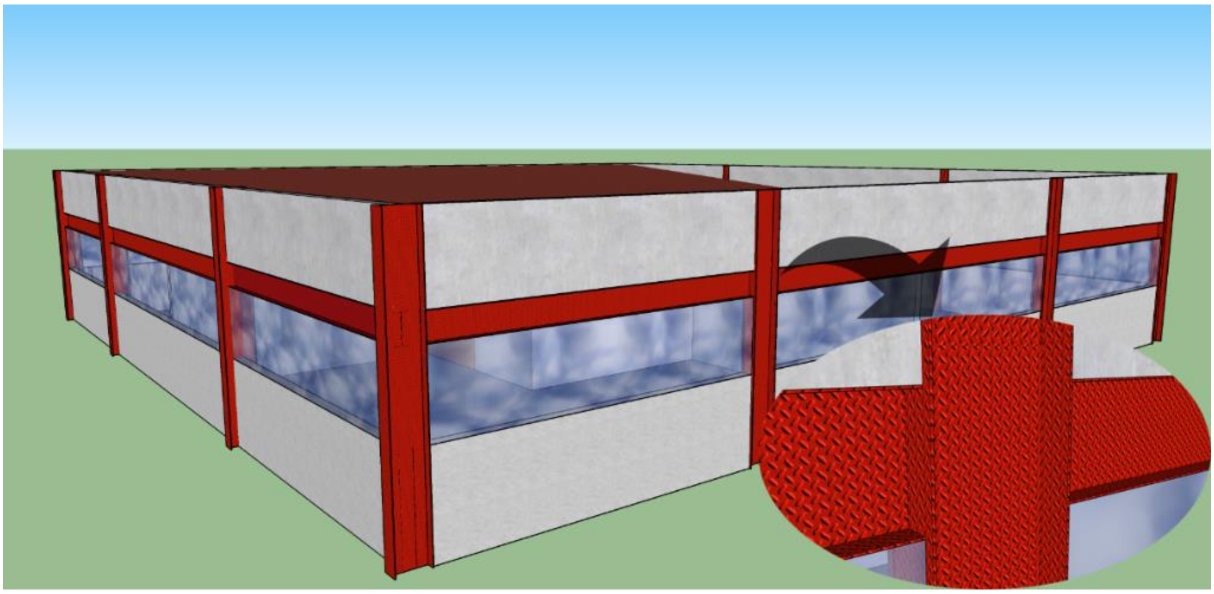

Figure 2. Adapted steel structure.

In any case, the model consists of five thermal zones: Thermal Zones 1 - 4 (Z1, Z2, Z3, and Z4) as office areas and Thermal Zone 5 (Z5) as the central core or circulation zone (Figure 3).

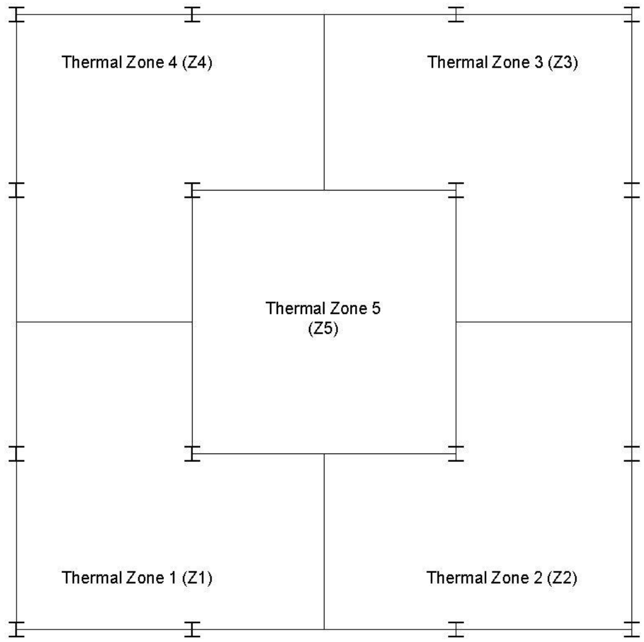

Figure 3. Thermal zones of the top floor.

In this study, only the thermal bridge's effects on beams and pillars of the building are considered, and to assess their overall effect on the building thermal performance, three cases are studied:

i. Case 1: beam height equal to 30 cm;
ii. Case 2: beam height equal to 35 cm;
iii. Case 3: beam height equal to 40 cm.

in which it is assumed that pillars made of steel profiles have a constant height equivalent to 50 cm. The windows were considered in the computer simulation with tempered glass and without the presence of window frames. Therefore, the frames were not considered in the analysis.

The closure system consists of walls with an outer layer of mortar plaster (1.5 cm thick) followed by a layer of bricks in cellular concrete blocks (15 cm thick) and an inner layer of mortar plaster (1.5 cm thick), giving a total thickness of 18 cm. The thermophysical properties of the materials used, in addition to the previously detailed walls, were taken from the Brazilian standard NBR 15220 (ABNT, 2005) and are specified in Table 1.

Table 1. Thermo-physical properties of the materials used in the closings.

Material	Thickness (m)	Specific mass ρ (kg/m³)	Specific heat c (J/kgK)	Thermal conductivity λ (W/mK)
Cellular concrete block	0.035	500	1000	0.17
Mortar plaster	0.015	2100	1000	1.15
Plywood	0.15	550	2300	0.15
Concrete slab	0.1	2400	1000	1.75
Floor tile	0.003	2000	920	1.05
Steel structure	0.00475	7800	460	55
Roof tile	0.01	2000	920	1.05
Ceiling	0.01	1400	100	0.2

Source: NBR 15220 (ABNT, 2005).

The glass that composes the building's windows were chosen to ensure the reduction of the thermal gains by direct solar radiation. In this way, a 6-mm thick reflective glass with a metallic surface coating and low thermal transmittance was chosen to increase the solar reflection.

Following the recommendations of the Brazilian standard NBR 15575 (ABNT, 2013), some guidelines were adopted for the standardization of the computational simulations of the building: two ambient ventilation rates (1 AirChanges per hour and 5 AirChanges per hour); three solar radiation absorptance of the exposed surfaces - light color ($\alpha = 0.3$), medium color (α = 0.5) and dark color (α = 0.7). Considering the analysis made for the typical summer design day, the Brazilian standard NBR 15575 (ABNT, 2013) recommends all Brazilian Bioclimatic Zones should be evaluated.

In order to carry out the computational simulations, the Brazilian data of Bioclimatic Zoning provided by the Brazilian standard NBR 15220 (ABNT, 2005) are used as climatic references. The simulations are performed considering the cities of Curitiba, São Lourenço, São Paulo, Brasília, Vitória da Conquista, Campo Grande, Cuiabá and Manaus as representative of Bioclimatic Zones 1 (ZB1), 2 (ZB2), 3 (ZB3), 4 (ZB4), 5 (ZB5), 6 (ZB6), 7 (ZB7) and 8 (ZB8), respectively.

The building occupancy profile (number of occupants, number of items of equipment, the profile of use of equipment, level of illumination, and period of occupation) directly influences its internal thermal performance. Thus, as the minimum requirements suggested by Brazilian standard NBR 15575 (ABNT, 2013) will be verified, the presence of internal heat sources will not be considered. This is why the occupancy profile is disregarded. It is defined as the standard of use the air conditioning operating from 8 am to 6 pm and a control temperature of 24º was adopted for the cooling function.

4. RESULTS AND DISCUSSION

The obtained results of the total cooling thermal loads and the energy consumption of the building obtained are presented below, highlighting the percentage of decrease and/or increase in the thermal load when comparing the case in which the steel structural system is part of the closure system and the case in which the steel structural system is disregarded.

Table 2 shows the total cooling thermal loads of Thermal Zone 1 (Figure 3), which represents the most critical case in increasing the thermal load of the environments, and the percentage of increase in thermal load when comparing the influence of structural system in the results, considering steel profiles with web heights that range between 30 cm, 35 cm, and 40 cm.

Table 2. Percentage increase of the total cooling thermal load in the most critical environment – Z1.

Total cooling thermal load (W)									
Web height	Steel exposed structure	ZB1	ZB2	ZB3	ZB4	ZB5	ZB6	ZB7	ZB8
30 cm	No	46241.2	48399.81	55744	28983.92	49580.03	70339.23	103238.52	92231.40
	Yes	48308.78	50745.49	57659.87	31479.78	51577.68	72444.05	105889.78	94629.61
	%	4.5%	4.9%	3.4%	8.6%	4%	3%	2.6%	2.6%
35 cm	No	46252.50	48408.08	55751.04	28988.53	49584.06	70344.63	103242.40	92236.01
	Yes	48547.19	51027.22	57893.86	31771.02	51814.90	72700.34	106211.60	94926.13
	%	5%	5.4%	3.8%	9.6%	4.5%	3.4%	2.9%	2.9%
40 cm	No	46264.06	48416.51	55758.22	28993.21	49588.15	70350.14	103246.45	92240.69
	Yes	48786.58	51308.66	58127.68	32064.64	52053.16	72956.44	106533.07	95222.33
	%	5.5%	6%	4.3%	10.6%	5%	3.7%	3.2%	3.2%

Figure 4 shows a comparison of the evolution of the cooling thermal load for the most critical case evaluated in Bioclimatic Zone 4, considering the three steel profiles evaluated.

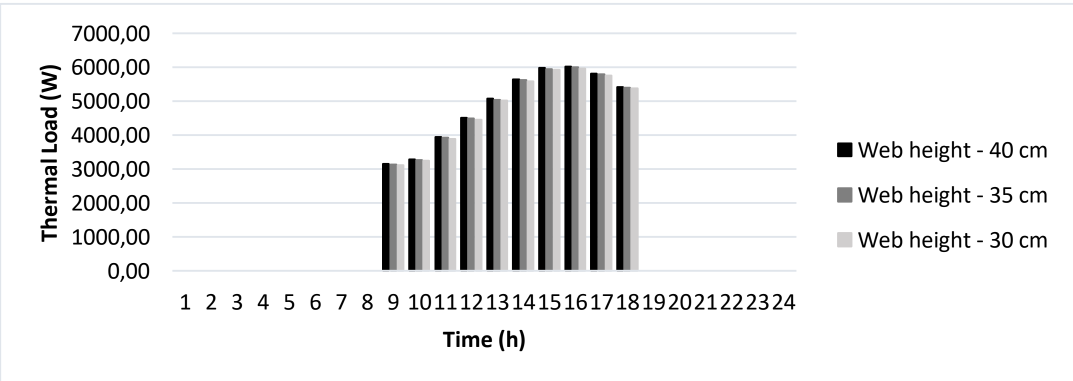

Figure 4. Comparison of the temporal evolution of the thermal load for the typical summer design (α = 0.3; 1 Airchanges/h) – ZB4.

Based on the above considerations, in the case of the representative city of Bioclimatic Zone 4, it was evaluated that the total cooling thermal load of the environment increased more significantly, reaching a 10.6% increase considering steel profile with a 40 cm web height.

Table 3 below shows the influence of the steel structure on the electric energy consumption, considering the evaluation for the typical summer design day.

Table 3. Energy consumption for the typical summer design day (α=0.3; 1 Airchanges/h), Case 3.

Energy consumption (kWh)			
Bioclimatic Zone	Closure system with steel	Closure system without steel	Percentage increase (%)
ZB1	91.67	86.11	6.5%
ZB2	100.00	91.67	9.1%
ZB3	119.44	113.89	4.9%
ZB4	50.00	44.44	12.5%
ZB5	105.56	97.22	8.6%
ZB6	161.11	152.78	5.5%
ZB7	250.00	238.89	4.7%
ZB8	227.78	219.44	3.8%

In general, the structural system is not considered in the simulations of the buildings' thermal behavior. The results presented in Table 3 show that, for the study object of this work, the disregard of the structural system in exposed steel beams can lead to an increase in cooling energy consumption of up to 12.5% for the typical summer design day in the representative city of the bioclimatic zone 4. This increase in energy consumption was also very significant for the other Bioclimatic zones evaluated.

5. CONCLUSIONS

In this study, the influence of the exposed steel structure area on the thermal performance of artificially conditioned commercial buildings was evaluated, considering a structural system with steel profiles and web heights varying between 30cm, 35cm and 40cm, disregarding the presence of internal heat sources.

It was observed that the effects of thermal bridges were more evident in the evaluation made for Bioclimatic Zone 4. There was an increase of 10.6% in the total cooling thermal load considering beams with a 40 cm web height. As consequence, the consideration of the structural steel system in numerical simulations also increased the energy consumption, reaching a maximum increase value of 12.5% in the ZB4.

These results cannot be expanded to other building types, since commercial buildings have their own characteristics such as wide and well-defined circulation areas, environments with high ceilings, light internal partitions, facades with large glass areas, and others. However, it was evident that in the structural design the thermal behavior of the closure as a whole should also be considered as a conditioning factor when choosing the structure.

This study indicates that the steel structure should be considered in the hourly numerical simulations of the thermal performance of buildings due to the effects of thermal bridges and the consequent increase in costs for cooling.

6. ACKNOWLEDGMENT

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8. RESPONSIBILITY NOTICE

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