11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

INFLUENCE OF CLOSURE SYSTEM AND VOLUME ON AUDITORIUM THERMAL AND ACOUSTIC PERFORMANCE

ROVADÁVIA A. J. RIBAS[*], JOSIMAR J. ADRIANO[*], HENOR A. SOUZA[†] AND LUIZ JOAQUIM C. ROCHA[†]

[*] Department of Civil Engineering – School of Mines (DECIV/EM),
Federal University of Ouro Preto
Campus, Ouro Preto, MG, Brazil
e-mail: roviaaline@gmail.com, josimarjunioradriano@hotmail.com, www.propec.ufop.br

[†] Department of Control and Automation Engineering – School of Mines (DECAT/EM)
Federal University of Ouro Preto
Campus, Ouro Preto, MG, Brazil
e-mail: henorster@gmail.com, ljoaquim@em.ufop.br, www.em.ufop.br

Key Words: *Closure Systems. Thermal and Acoustical Performance. Numerical Simulation. ESP-r. Reverberation Time.*

Abstract. In this study, we evaluated the influence of closure systems used in steel-structured construction consisting of cement slabs panels, autoclaved cellular concrete and expanded polystyrene, applied in multilayers with noise absorbing material such as glass wool between panels, and masonry ceramic bricks for thermal and acoustic performance of an auditorium, considering three different volumes: the original volume, its half and its double. For this proposed assessment, the ESP-r (Energy Simulation Program-research) software is applied, whereby temporal variation of the internal temperature (Ti) and reverberation time (RT) versus frequency are determined with numerical simulation. The effect of temperature variations in the volume and reverberation time of the room as well as the variation of sound absorption due to the air is also analyzed.

1 INTRODUCTION

Structured steel buildings require closure systems that have the same philosophy as prefabrication. An inappropriate selection of these systems can compromise the overall efficiency of the constructed area can compromise the overall efficiency of the built environment and can result in the need for further interference and resistance to the adoption of steel-structured construction.

In the Brazilian market, there are several industrial closure systems, which, being lighter, have questionable heat and sound insulation. It is important to research closure materials that present integrated thermal and acoustic performance solutions.

Thermal performance can be verified by determining the temporal variation of the internal ambient temperature of the building and its acoustic performance by calculation of the reverberation time (RT) of the surfaces encountered in the ambient.

2 PURPOSE

In this study, we evaluated the influence of closing applied in multilayers, with sound absorbing material between panels, and masonry ceramic bricks in thermal and acoustic performance of an auditorium.

3 METHODOLOGY

This study involves a large number of thermal and acoustic variables and the numerical simulation approach presented is an appropriate and efficient tool for evaluation in the pre-project phase or when building is being used [1, 2].

Thus, the ESP-r (Energy Simulation Program-research) software is applied to determine the temporal variation of the internal temperature (Ti) and reverberation time (RT) versus frequency with numerical simulation. The effect of temperature variations on the volume, reverberation time of the room, and the variation of sound absorption due to the air are also analyzed.

3.1 The ESP-r

The ESP-r software applies mathematical models that solve problems by finite element and finite difference methods in order to simulate the thermal behavior of the ambient. These models consider the effect of the closure element's thermal storage and the heat exchanges caused by the radiation, conduction and convection processes occurring in the interior of the building. This software permits the evaluation of temperature gradients and air fluxes with a great degree of refinement [3].

The thermal and acoustic simulations are integrated, because storage of the thermal effect of the closure elements, translated into temperature and humidity of the internal air, obtained in thermal simulation contributes to the calculation of sound absorption due to the air used in the determination of RT calculated by the Sabine method in acoustic simulation [4].

For simulation, a geometric model of the building is created in three dimensions. Then, to evaluate thermal and acoustic performances, the necessary parameters are: the mass and thermal properties of the elements composing the external and internal closure systems of the building; their geometric characteristics (shape, dimensions, layer thicknesses, and direction); the acoustic absorption coefficients of the constructive components (α_i) and the building; local climatic data; and typical building ambient information that characterizes its thermal capacity (i.e. occupational conditions during a 24-hour period, number of occupants, their typical activities, the amount and type of equipment used, and lighting facilities).

3.2 Edification and materials

The auditorium that is under evaluation is the main building of the Convention Center of the Federal University of Ouro Preto, in Brazil. This building is adequate for medium-scale sized conferences and artistic events. It has an area of 825.38 m², and a floor-to-ceiling height of 6.0 m. The auditorium has a 77 m² stage and 510 stuffed chairs (Fig. 1).

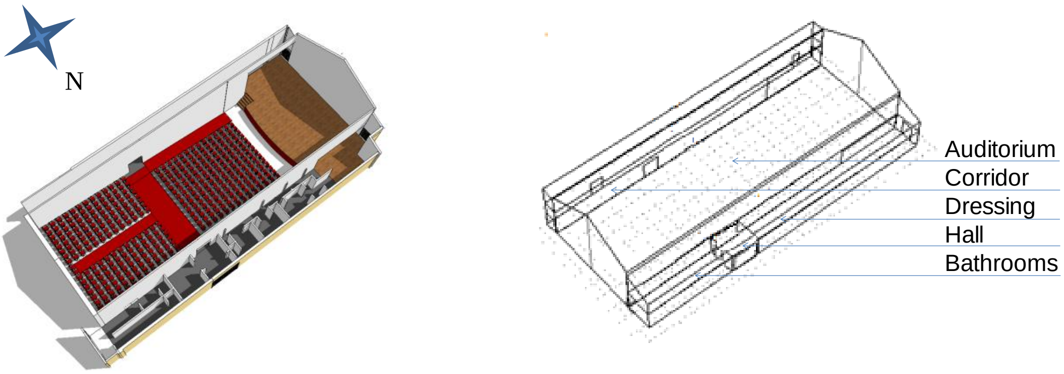

Figure 1: Auditorium perspectives

The thermal and acoustic performance of the auditorium is analyzed considering three different volumes: the original volume (4740 m³, V2), its half (2370 m³, V1) and its double (9480 m³, V3) [5].

The closures consist of cement slab (PLC) panels, aerated autoclaved concrete (CCA) and expanded polystyrene (EPS), applied in multilayers together with sound absorbing material, such as glass wool (LVI) between panels (Fig. 2), and masonry ceramic bricks coated on both sides with mortar (ATC) (Fig. 3) [5].

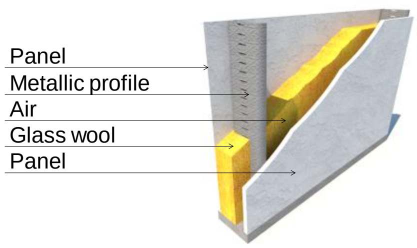

Figure 2: A multilayer closure system

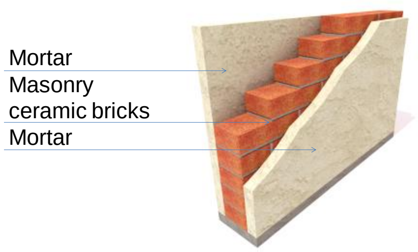

Figure 3: Masonry ceramic bricks coated mortar

Table 1 shows the horizontal and vertical closure material elements with their thicknesses expressed in mm between parentheses. The closure material properties relevant to the acoustic and thermal analyses, i.e. specific mass (ρ), thermal conductivity (k_t), specific heat (c_e), emissivity (ε) and absorptivity (α_p) are displayed in Table 2. The geometric characteristics of the building's thermal zones are shown in Table 3.

Table 1: Closure elements

Element	Composition (thickness in mm)
Lining (Roof)	Ceramic tiles (10)
Wooden floor	Medium density wood (30) laid over a layer of air (100) and concrete (20)
Outer doors	Medium density wood (25)
Inner doors	Plywood (25)

Table 2: Closure material characteristics

Panels	ρ (kg/m³)	k_t (W/(m K))	c_e (J/(kg K))	ε	α_p
Cimentitious slab	1330 [6]	0.350	1050	0.96	0.60
Aerated autoclave concrete	500 [1]	0.170	1000	0.90	0.65
Expanded polystyrene	25 [7]	0.030	1000	0.90	0.30
Ceramic tiles	1900 [1]	0.850	840	0.90	0.60
Ceramic bricks	1800 [1]	1.050	920	0.95	0.80
Mortar	2100 [1]	1.150	1000	0.90	0.50
Glass wool	100 [1]	0.045	700	0.90	0.50
Medium density wooden doors/floor	900 [1]	0.130	2000	0.91	0.70
Plywood doors	800 [1]	0.150	2093	0.91	0.65

Table 3: Geometric characteristics of the building's thermal zones

Zone	Enclosure Volume (m³)	Floor area (m²)	Wall area (m²)	Door area (m²)
Auditorium	3600.00	520.00	657.55	8.40
Bathrom	111.00	41.80	78.04	2.52
Dressing room	232.00	87.48	125.47	22.40
Corridor	761.00	286.00	661.85	15.54
Hall	35.60	13.70	25.67	13.02

To calculate the reverberation time, the coefficients for the sound absorption (α_i) of the material applied in the ambient is necessary (Table 4).

Table 4. Sound absorption coefficients (α_i) of the material applied in the ambient

	Octave band central frequency (Hz)					
Element	125	250	500	1000	2000	4000
PLC [8]	0.23	0.12	0.08	0.06	0.05	0.05
GEA [8]	0.26	0.13	0.09	0.05	0.05	0.05
CAA [10]	0.05	0.10	0.15	0.15	0.20	0.25
EPS and ATC (mortar) [8]	0.01	0.01	0.02	0.02	0.02	0.03
Stuffed chairs [9]	0.08	0.16	0.22	0.23	0.24	0.24
Lining (tiles) [11]	0.01	0.01	0.01	0.02	0.02	0.02
Wooden floor [9]	0.40	0.30	0.20	0.17	0.15	0.10
Doors [9]	0.58	0.22	0.07	0.04	0.03	0.07

3.3 Thermal simulation

For the thermal analysis, simulations were made for a typical summer day and Zone 3 climatic data, using as a reference the city of Belo Horizonte-MG (latitude of -19.85, longitude of -43.9 and altitude of 785 m). Not considered were: the presence of people inside the building, turned-on lights, and equipment that might casually heat the area (sensibly or latently). For the air flux, the removal rate of 1 ren/h was considered according to recommendations from Brazilian standard NBR 15575 [2]. When the simulations were performed, they produced results for the temporal variations for the temperature and humidity of the interior ambient.

3.4 Calculating the reveberation time

Reverberation time (RT), is defined as the time necessary for the acoustic pressure level of an enclosure to fall to 60 dB by interrupting the source, and it is calculated in function of frequency by the acoustic model of the ESP-r software that applies the Sabine equation (Eq. 1), for a sound velocity in air of 343 m/s and temperature of 20 °C [4].

$$TR = 0{,}161\frac{V}{A_f^t} \quad \text{(s)} \tag{1}$$

in which, V if the volume of the enclosure (m³) and A_f^t is its total area (m²) for a frequency f (Hz).

The Sabine equation is a function of volume and absolute temperature of the enclosure, as well as the total closure area, taking into consideration the presence of furniture, occupants and air (Eq. 2) [4].

$$A_f^t = A_f^{fech} + A_f^{obj+pes} + A_f^{ar} \quad (\text{m}^2) \tag{2}$$

where, A_f^{fech} is the absorption area equivalent to the closure inside the enclosure (m²); $A_f^{obj+pes}$ is the absorption area equivalent to the objects and people inside the enclosure (m²); and A_f^{ar} is the absorption equivalent to the air inside the enclosure (m²).

Equation 3, also proposed by Sabine [4] is among the expressions proposed to calculate the absorption of the area equivalent to the closure of the inside of the enclosure (A_f^{fech}).

$$A_f^{fech} = S\overline{\alpha}_f^{Sab} = \sum_i^{fech}(S_i\alpha_{i,f}^{Sab}) \quad (\text{m}^2 \text{ Sabine}) \tag{3}$$

in which, S is the total inside area of the enclosure, $\overline{\alpha}_f^{Sab}$ is the average of the absorption coefficients at frequency f, S_i is the internal surface area i of enclosure (m²), and $\alpha_{i,f}^{Sab}$ is the absorption from Sabine of surface i at frequency f.

In an ample ambient, the distance covered by the sound waves crossing the air is long and the sound energy fraction that is absorbed cannot be neglected for frequencies above 1000 Hz [4]. This sound absorption depends on the temperature and air composition, as well as the particle concentration in the water vapor present and sound frequency. Besides this, there is an association with the classic energy losses (transformation of acoustic energy into equivalent thermal energy) and energy losses due to relaxation (distribution of internal energy that occurs during the collision of gas molecules). The sound absorption of the air present in the enclosure (A_f^{ar}) can be expressed by Equation 4 [12,4].

$$A_f^{ar} = 4mV \qquad (\text{m}^2) \tag{4}$$

where m is the sound absorption coefficient of air (m^{-1}) and V is the enclosure's volume (m^3).

In the computational simulations, the coefficient m can be expressed using the formulations presented in Equations 5 through 8 [4].

$$m = 3.68\times10^{-11} f^2\left(\frac{P}{P_0}\right)^{-1}\left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2}\left(\begin{array}{l} 0.1068e^{-3352.0/T}\dfrac{2f^2}{f_{rN}+\dfrac{f^2}{f_{rN}}} + \\ +\,0.0128e^{-2239.1/T}\dfrac{2f^2}{f_{r0}+\dfrac{f^2}{f_{r0}}} \end{array}\right) \qquad (\text{m}^{-1}) \tag{5}$$

$$f_{rN} = \frac{P}{P_0}\left(\frac{T}{T_0}\right)^{-1/2}\left(9 + 280h_a e^{-4.170\left[\left(\frac{T}{T_0}\right)^{-1/3}-1\right]}\right) \qquad (\text{Hz}) \tag{6}$$

$$f_{r0} = \frac{P}{P_0}\left(24 + 4.04\times10^4 h_a \frac{0.02 + h_a}{0.391 + h_a}\right) \qquad (\text{Hz}) \tag{7}$$

$$h_a = \frac{\phi\times10^{-6.8346\left(T_{0i}/T\right)^{1.261}+4.6151}}{\dfrac{P}{P_0}} \qquad (\%) \tag{8}$$

where f is the frequency (Hz), P is the air pressure (kPa), P_0 is the reference pressure for air (101.325 kPa), T is the air temperature (K), T_0 is the reference temperature for air (293.15 K), f_{rN} is the nitrogen relaxation frequency (Hz), f_{r0} is the oxygen relaxation frequency (Hz), h_a is the molar concentration of the water vapor (%), Φ is the relative humidity of the air (%) and T_{0i} is the triple point isothermal temperature (273.16 K).

3.5 Thermal and acoustic performance

The minimum criteria for thermal performance during summer is that the maximum daily temperature of the air inside the enclosure, excluding the presence of internal heat sources (occupants, turned-on lights, other equipment), be less or equal to the daily maximum outdoor temperature [2].

For the acoustic performance, the reverberation time should be accordance with the usage of the enclosure, and should be one of the principal parameters for good noise control, since inadequate values could impede the hearing or comprehension of dialogues. The larger the enclosure volume containing inadequate sound absorption material is, the greater the reverberation duration. If reverberation persists in an ambient for a long time, it can overlap syllables and/or musical notes, making them disappear either temporarily or totally, whereby some types of sound sources may not be perceived [8].

Thus, enclosures destined for the spoken work (classrooms, conference areas and theaters) require short reverberation times so that the reflected sound falls as soon as possible and does not interfere with the direct sound. For a small room, a reverberation time of 0.5 s is adequate. In concert halls, this time should be much longer, since reverberation is necessary up to a certain point in order to have orchestral music acoustic quality [13,9].

The Brazilian standard NBR 12179 [14] presents a graph with ideal values for reverberation times in function of enclosure volume for a 500 HZ frequency, according to usage of the enclosure. These values are utilized to project or adjust the sound response of the ambient. Bistafa [9], presents a graph that permits obtention of the reverberation times recommended for other frequencies as a percentage of reverberation time in 500 HZ. For the auditorium analyzed, the RT reference is close to 1.0 s.

4 RESULTS

Figures 4, 6 and 8 display the internal temperature results (Ti) obtained in the thermal simulations. Figures 5, 7 and 9 show the reverberation time (RT) results obtained in the simulations performed in the ESP-r acoustic model at the time of 2:30 p.m.

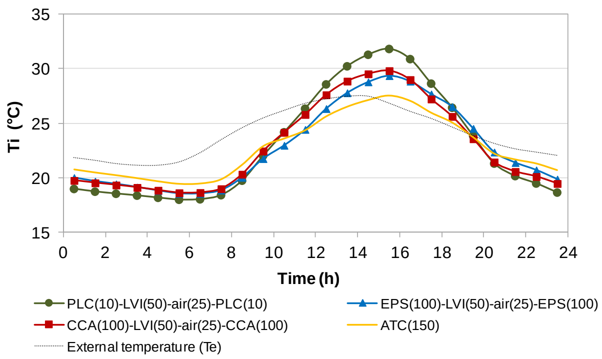

Figure 4: Ti using closings of PLC, EPS and CCA, with LVI, and ATC, to V1

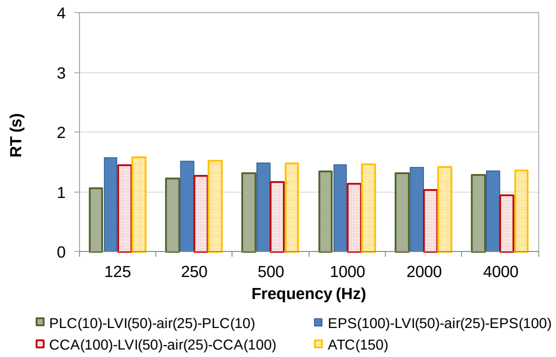

Figure 5: RT using closings of PLC, EPS and CCA with LVI, and ATC, to V1

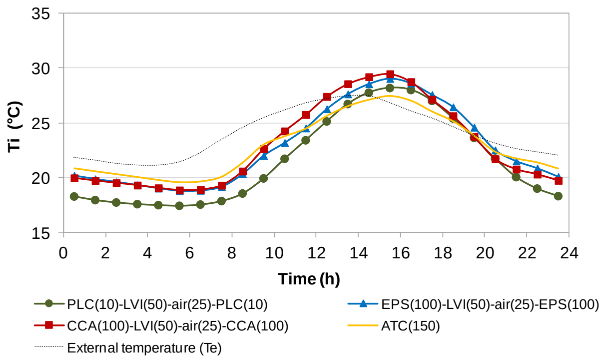

Figure 6: Ti using closings of PLC, EPS and CCA, with LVI, and ATC, to V2

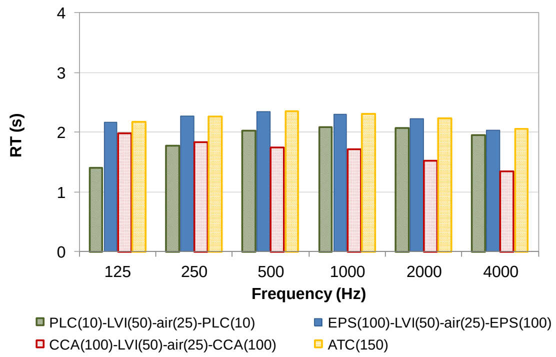

Figure 7: RT using closings of PLC, EPS and CCA with LVI, and ATC, to V2

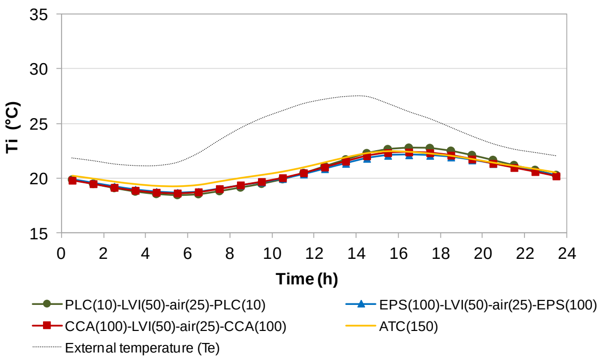

Figure 8: Ti using closings of PLC, EPS and CCA, with LVI, and ATC, to V3

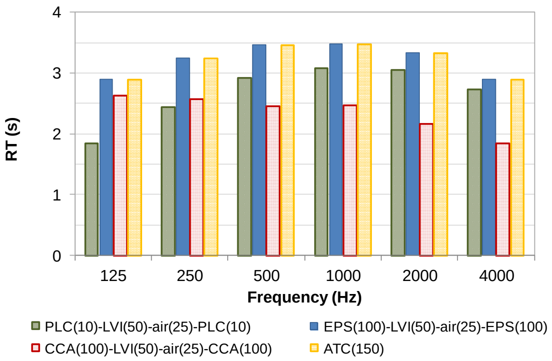

Figure 9: RT using closings of PLC, EPS and CCA with LVI, and ATC, to V3

In analysis of the thermal and acoustic response of the auditorium to volumes V1, V2 and V3, it can be observed that when the ambient volume is increased under the same climatic, physical, and thermal conditions, the temperatures tend to lower and the reverberation time tends to increase, due to the elevation in relative humidity. The closure systems are more efficient in an ambient of greater volume, in terms of thermal performance. The minimum criterion for thermal performance ($T_{i,máx} \leq T_{e,máx}$) required by NBR 15575 [2] is fulfilled by the analyzed closures with greater volume (V3) (Fig. 4 to 9).

In terms of acoustic performance, measured by the reverberation time, the closure systems showed to be more efficient in a smaller volume ambient, proportioning the RT values close to the reference value of 1.0 s. In an ambient of greater volume, the reverberation is higher, which can hinder the understanding of speech in the auditorium in volumes V2 and V3.

In volume V2, the closure consists of aerated autoclaved concrete exposed to high internal temperatures and shows smaller reverberation times. The closures consisting of cimentious slab proportioned satisfactory thermal and acoustic performances, being able to compete with the closure of the ceramic brick and mortar closure and still have the advantages of being lighter and thinner.

Figure 10 displays the value for the reverberation times proportioned by the closures analyzed at 1000 Hz, which is an important speech frequency. Figure 11 demonstrates the values of the sound absorption coefficients due to the air, for the frequencies of 500, 1000 and 2000 Hz, and for volumes V1, V2 and V3.

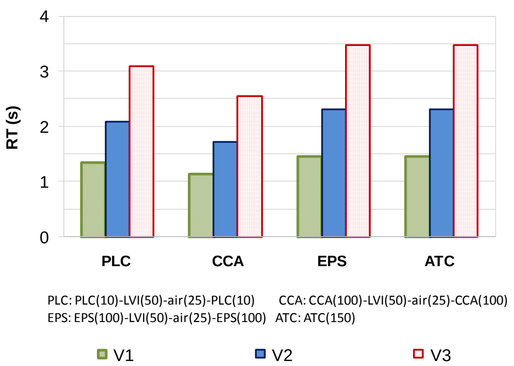

Figure 11: RT using closings at 1000 Hz frequency to V1, V2 and V3

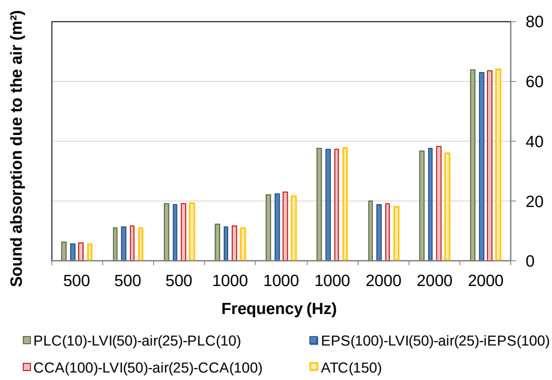

Figure 12: Sound absorption on due the air at 500, 1000 and 2000 Hz, and V1, V2 and V3

For a frequency of 1000 Hz, the closure consisted of aerated autoclaved concrete proportioned a smaller reverberation time for the three volumes, while the closures consisting of polystyrene expanded and the mortared ceramic brick proportioned higher reverberation time values. The cimentatious slab closure presented intermediate reverberation time values (Fig. 10).

For smaller frequencies and volumes, the sound absorption due to the air tends to become insignificant, and as the frequency increases by on octave for the same air volume, the air's sound absorption practically doubles, tending to diminish the reverberation time. Doubling the ambient volume, doubles the air volume, but the relationship between the sound absorption of the air and the total air equivalent to the absorption of the volume for another, does not accompany this proportion because the area of absorption is also increased equivalently to the closure system (Fig.11).

5 CONCLUSIONS

- The integrated evaluation of thermal and acoustic performance to be applied in industrialized closure systems consisting of multi-layers, is an adequate tool for a preliminary thermal and acoustic analysis of the closure, due to the great number of variable involved in the analysis.
- Some closure systems proportion good thermal performance, but the acoustic performance in terms of reverberation time was not satisfactory. This preliminary closure analysis thus becomes of great importance for solving thermal acoustic responses.
- The results show that the closure systems meet the minimum criterion for thermal performance adopted by NBR 15575 [3] and the value of RT is near the reference value, allowing one to evaluate how much a closure system is more efficient than the other in terms of thermal and acoustic comfort, and highlighting the relevant parameters when choosing such systems.

6 ACKNOWLEDGMENTS

The authors acknowledge the financial support from CNPq, FAPEMIG and UFOP.

7 REFERENCES

[1] Associação Brasileira de Normas Técnicas. *NBR 15220: Desempenho térmico de edificações*. Rio de Janeiro (2005). (in Portuguese)

[2] Associação Brasileira de Normas Técnicas. *NBR 15575: Edifícios habitacionais – Desempenho*. Rio de Janeiro (2013). (in Portuguese)

[3] Clarke, J.A. et al. *ESP-r: A program for building energy simulation*. Version 9 Series, ESRU Manual U93/1. Glasgow, Scotland (1993).

[4] Citherlet, S. *Towards the holistic Assessment of building performance based on an integrated simulation approach*. Thesis (Doctor ès Sciences). Swiss Federal Institute of Technology (EPFL), Lausanne, 2001.

[5] Ribas, R.A.J. *Método para avaliação do desempenho térmico e acústico de edificações aplicado em painéis de fechamento industrializados*. Tese (Doutorado em Engenharia Civil). Universidade Federal de Ouro Preto, Ouro Preto (2013). (in Portuguese)

[6] Sales, U.C. *Mapeamento dos problemas gerados na associação entre sistemas de vedação e estrutura metálica e caracterização acústica e vibratória de painéis de vedação*. Dissertação (Mestrado em Engenharia Civil). Universidade Federal de Ouro Preto, Ouro Preto (2001). (in Portuguese)

[7] Bies, D.A. and Hansen, C.H. *Engineering Noise Control: Theory and Practice*. 3ª ed. London and New York, Spon Press (2003).

[8] Maekawa, Z.; Rindel, J.H. and Lord, P. *Environmental and Architectural Acoustics*. 2ª ed. New York, Spon Press (2011).

[9] Bistafa, S.R. *Acústica Aplicada ao Controle de Ruído*. São Paulo, Edgard Blücher (2006). (in Portuguese)

[10] RILEM – International Union of Laboratories and Experts in Construction Materials, Systems and Structures. RILEM Technical Comittees 78-MCA and 51-ALC. *Autoclaved aerated concrete: properties, testing and design*. New York, Taylor & Francis (2005). ISBN 0 419 17960 7. In: <http://books.google.com.br/books?id=diiPFbTX-9EC&printsec=frontcover&hl=pt-BR&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false>. Accessed on April 5, 2012.

[11] Hassan, O.A.B. *Building Acoustics and Vibrations: Theory and Practice*. Singapore, World Scientific (2009).

[12] Knudsen, V.O. and Harris, C.M. *Acoustical Designing in Architecture*. The Acoustical Society of America ed. New York (1978).

[13] Mehta, M.; Johnson, J. and Rocafort, J. *Architectural Acoustics: Principles and Design*. New Jersey, Prentice Hall (1999).

[14] Associação Brasileira de Normas Técnicas. *NBR 12179: Tratamento acústico em recintos fechados – Procedimento*. Rio de Janeiro (1992). (in Portuguese)