THERMO-STRUCTURAL MODELING OF CLAY UNITS MASONRY WALLS UNDER FIRE CONDITIONS

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Abstract. *The study of structural masonry under fire conditions is still incipient in the scientific field. This is due to the small number of experimental and numerical studies in this area, which reflects in the low knowledge about the variation of the thermal and mechanical properties of these elements as a function of the temperature. Therefore, a thermo-structural numerical analysis of masonry walls of clay units was developed, through the calibration of existing experimental results. Complementarily, a parametric study was performed by varying the level of load applied to the wall. The results showed that it was possible to develop a consistent thermo-structural model that successfully represents the experimental tests. Regarding the parametric analysis, it was found that the compressive load level directly affects the thermo-structural behavior of the masonry. The increase of the load factor applied at ambient temperature caused the decrease of the relative axial force value, for any given exposure time. When extrapolating the results, it was possible to infer that the load level will negatively affect the fire resistance of the wall.*

Keywords: *Numerical thermo-structural modelling, Parametrical analysis, Masonry walls.*

1 INTRODUCTION

Structural masonry is a construction system increasingly used due to its technical and economic advantages. The reduction of the final cost, the time necessary for construction, and the waste of materials are just some of the advantages pointed out by the builders.

Given the increase in the number of cases of structures under fire conditions, a consensus has emerged among designers and researchers that designing structures at normal temperatures is not sufficient to guarantee structural safety. In Brazil, unlike steel and concrete structures, structural masonry does not yet have a specific standard that prescribes guidelines for its performance under high temperatures.

This is a direct consequence of the high experimental cost. Combined with the heterogeneous and non-linear behavior of the masonry, it contributes to the scarcity of data, culminating in a poorer understanding about the topic. It is true that masonry is influenced by its various components, since it is a composite element. This influence is even more significant at high temperatures, when the different materials' coefficients of thermal expansion result in the increasing of internal stresses.

In addition, materials under high temperatures show degeneration on their mechanical properties, such as modulus of elasticity and mechanical strength. According to Russo (2013), clay blocks walls lose almost 40% of their stiffness when they reach temperatures around 500°C. The loss reaches almost 100% at temperatures close to 1000°C.

Recent research, such as that of Rosemann (2011), evaluated the fire resistance of walls of hollow clay blocks filled and externally coated. As expected, external coating and the filler material increased the masonry's fire resistance, more specifically about 280%, when compared to the uncoated and without filling masonry.

Another important contribution of particular interest to this work is the study carried out by Rigão (2012). This author verified both hot-gases-tightness and fissures in small walls, and identified the occurrence of vertical cracks along the cross section, which were predominant in the heated face.

Facing the limitation of experimental results, an alternative widely used in the technical literature consists in the creation of numerical models that, when calibrated and validated with experimental data, enables the accomplishment of parametric studies. Such studies are of fundamental importance to understand the behavior of both the masonry elements and the whole structure, when they are subjected to high temperatures.

This work is related to this context. From the experimental results obtained by Rigão (2012), it is intended to perform the calibration and validation of a finite elements numerical model. This model will be the basis for a parametric study, allowing a better understanding of the subject.

2 EXPERIMENTAL TESTS

The experimental results obtained by Rigão (2012) were used for calibration and validation of the numerical model. The author tested three uncoated small walls made of clay units, with dimensions of 89 cm width and 100 cm height, Fig. 1a. They were positioned in front of an electric oven and inside a reaction frame, which was later used to apply loads to the walls, Fig. 1b. The front opening of the oven had dimensions of 60 x 72 cm.

a) b)

Figure 1. a) Tested walls; b) Test scheme. Reprinted from Rigão (2012)

The test was performed according to the requirements of ABNT NBR 5628:2001, which deals with high temperature tests to determine the fire resistance of construction components. The test consisted of two steps. The first one was performed 90 days after the walls' construction. The masonry was positioned in the oven's front opening and a compressive load of 70 kN was applied through a steel plate at the top of the wall, at normal temperature. In the second step, the oven was activated, so that only one of the walls' faces was directly exposed to temperature increases.

It is worth remembering that the temperature increase in one side of the wall caused a thermal gradient in its cross section. This resulted in increased load on the wall, measured by the same hydraulic jack responsible for the load application. The numerical analysis used the experimental results of two walls.

3 GENERAL ASPECTS OF NUMERICAL MODELING

The numerical model was discretized through the Finite Element Method by the ABAQUS computational code. This software was chosen because it has provided good results in the reproduction of the behavior of structures under fire conditions.

A macromodeling strategy was adopted for the small walls. In this model, units and mortar joints are considered to be dispersed through a continuous medium. Then, the entire masonry is now represented as a single element with homogeneous properties, as shown in Fig. 2.

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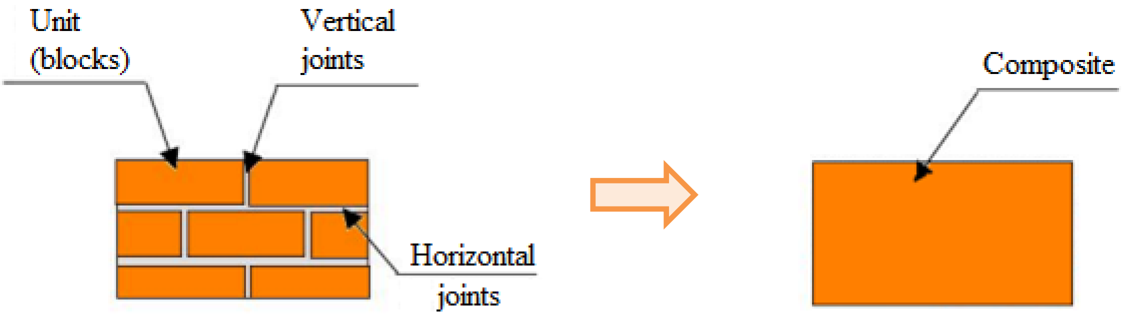

Figure 2. Modeling strategy: macromodeling. Adapted from Lourenço (1996)

3.1 Thermal Modeling

The distribution of temperature in the small walls was represented through three-dimensional modeling. A number of 17400 linear hexagonal DC3D8 type elements of the "heat transfer" family were used. The need for a large number of elements comes from the small dimensions of the blocks' hollow cores when compared to the total dimensions of the wall. The horizontal and vertical mortar joints were not represented, but the dimensions of the model were similar to the experimental ones.

The oven used in the experiment had an opening with dimensions of 60 x 72 cm. The fire was simulated in this area. Fig. 3 shows the oven position and the mesh used in the simulations.

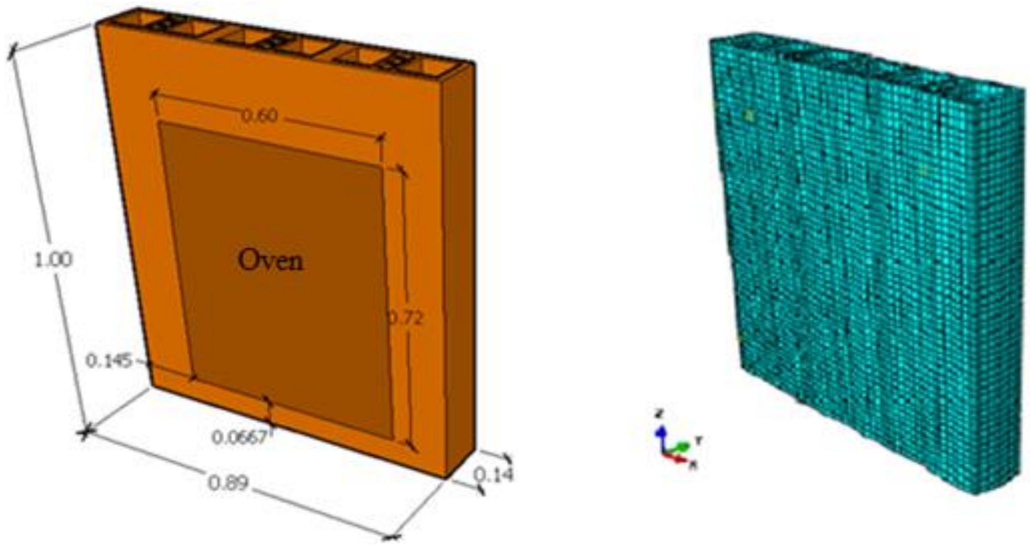

Figure 3. Oven position and mesh used in the simulations, dimensions in meters

The thermal properties were adjusted according to the experimental test carried out with the Wall 1. After that, it was verified that these properties were also suitable for Wall 3, since the materials used were the same, and the only changes were related to the ambient temperature and the oven temperature. The experimental results obtained for Wall 2 were disregarded because the elevation of the oven temperature presented discontinuity.

In the tests performed by Rigão (2012), the ambient temperature for Wall 1 was 20.5ºC and for Wall 3 was 22.0ºC. Through an initial step, these values were applied in the simulations and losses of heat by radiation and convection from the wall to the environment were considered over time. The experimental temperature elevations of the oven were inserted in the region exposed to fire. Temperature elevations of the air contained in the blocks' hollow cores was considered similar to the measurements made in the center of the wall. In the experiments, the region of the burned face outside the edges of the oven was isolated by sealing and protecting with rock wool. Therefore, heat flow was not considered in this region.

To validate the model, the temperatures obtained numerically and measured experimentally with four thermocouples were compared. The thermal conductivity and specific heat were changed until the best fit between the numerical and experimental temperature elevation curves was obtained. Fig. 4 shows the temperature measuring points, located in half-height of the model, and the properties used for convection and radiation on each face.

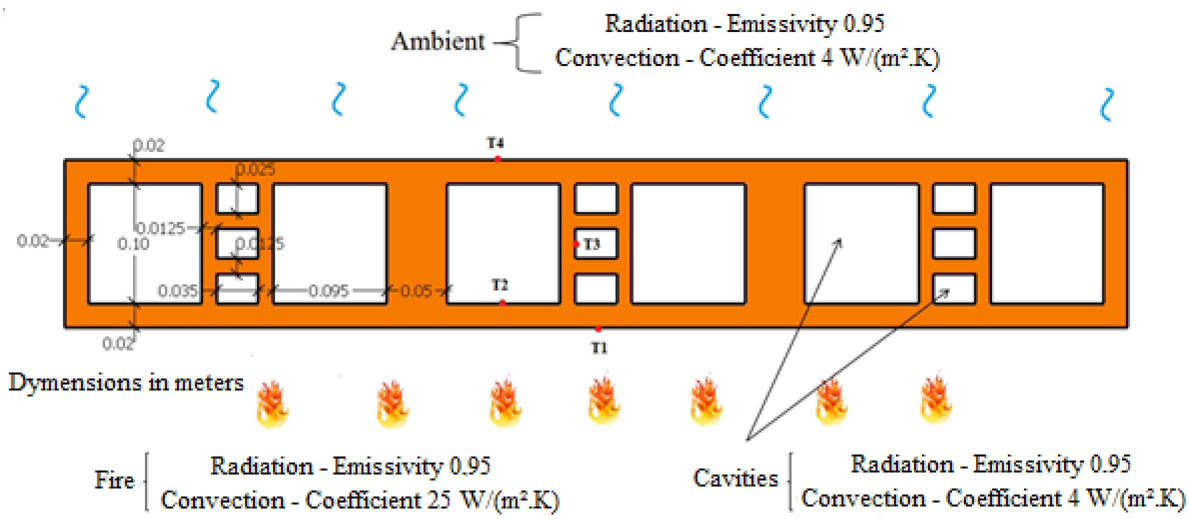

Figure 4. Temperature measuring points and convection and radiation properties

Table 1 shows the specific gravity, conductivity and specific heat values used in the numerical model.

Table 1. Thermal properties of the small walls

Temp.	Specific gravity	Conductivity	Specific heat
ºC	kg/m³	W/(m.K)	J/(kg.K)
0	1750	0.4	2100
20	1750	0.4	2100
50	1750	0.4	2100
70	1750	0.4	2100
85	1750	0.4	2100
99	1750	0.4	4000
101	1750	0.4	3700
200	1750	0.4	3650
300	1750	0.4	3500
400	1750	0.4	3400
500	1750	0.41	3300
1000	1750	0.41	3300
1500	1750	0.41	3300

3.2 Structural modeling

To determine the mechanical properties of the wall, the association between the mean of the prisms' experimental results obtained by Rigão (2012) and the relationship between prism and wall strength suggested by ABNT NBR 15812-1 (2010) was adopted. This same procedure was done for the modulus of elasticity. Thus, the compressive strength of the wall determined was 4.35 MPa, related to the gross area. The modulus of elasticity was around 3.56 GPa, also related to the gross area. Note that these properties were attributed to the two walls in which the difference between them corresponds only to the heating curves.

In ABAQUS, the constitutive model used to describe the material was the *Concrete Damaged Plasticity* (CDP), which can represent the mechanical behavior of brittle materials such as masonry. The input parameters, such as *dilation angle*, *viscoplasticity parameter*, *eccentricity*, and the tension and compression curves adopted in the calibration of the structural model were the same as those used by Santos *et al.* (2016). As in the reference experimental test there was no wall, tested at ambient temperature, with configuration similar to those used in the thermo-structural model, it was not possible to validate the numerical curve by comparing it to the experimental curve. The numerical curve at 20ºC will be presented along with the high temperature curves, in section 3.3.1.3.

3.3 Thermo-structural Modeling

The thermo-structural model consisted of the association of the temperature field obtained in the thermal analysis with the deformation field obtained from the loading of the structure at ambient temperature. Therefore, the steps were initially performed in a dissociated manner. Subsequently, they were joined in order to construct the thermo-structural model.

Fig. 5 shows the representation of the numerical model. It is constituted by the small wall associated with reference nodes (RP). The RP-1 and RP-2 nodes receive the degrees of freedom of the structural element ends and are useful for defining the boundary conditions. The RP-3 node has the function of working with the RP-2 node, giving rise to a spring. The goal was to simulate the stiffness provided to the wall by the steel plate and hydraulic jack during the experimental test.

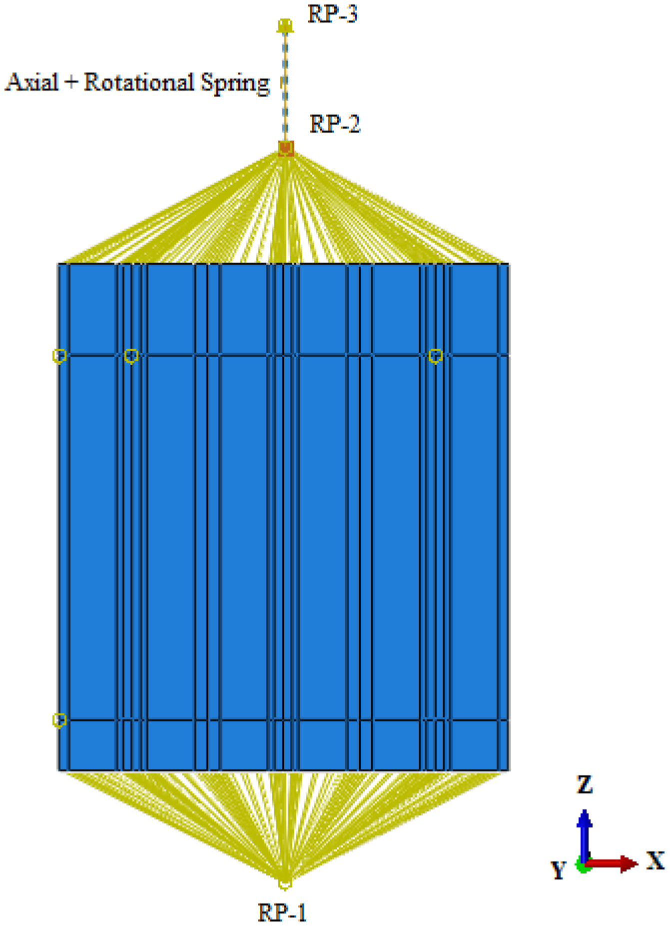

Figure 5. Representation of the numerical model of the small wall

The thermo-structural model was developed in two steps, following one of the thermo-structural modeling options in ABAQUS. The first step consisted in applying an axial load of 70 kN on the wall, at ambient temperature, through the RP-2 node. In this step, this node is free to move only in the z-direction. Then, the wall was supposed to be fixed to its lower base. In fact, the RP-1 node is fixed, and the RP-2 node can only translate in the z-direction. It is also important to say that RP-3 did not present any nodal restraint in the first step. The second step consisted in the union between the previously defined temperature field and the stress-strain data obtained from the load applied in the first step. As the second step concerns the wall heating, it was necessary to restrain, during the simulation, thermal deformations due to the presence of the experiment's load application equipment. Thus, a spring with infinite stiffness was assumed to bind the nodes RP-2 and RP-3, in addition to the z-direction displacement restraint imposed on them.

3.3.1 Materials properties

To carry out a thermo-structural model and obtain satisfactory results, it is necessary to provide the numerical model with specific properties of clay blocks under high temperatures, such as their thermal expansion coefficient and constitutive model.

In Brazil, there is no standard dealing with the design of structural masonry under fire conditions. Therefore, this work considered the European standard Eurocode 6 Part 1-2 (2005), which addresses this topic, in addition to the studies previously cited. It is worth noting that, although dealing with the theme, this norm presents limitations regarding the thermo-structural behavior of the walls, such as the variation of strength and stiffness with the increase of the temperature. Thus, it was necessary to apply some considerations based on other works. The considerations made will be discussed below.

3.3.1.1 Modulus of elasticity and compressive strength

With respect to the mechanical properties of clay units, the European standard presents parameterized stress-strain diagrams for temperatures up to 750ºC (Fig. 6), allowing the obtaining of reduction factors for both modulus of elasticity and compressive strength, shown in Table 2.

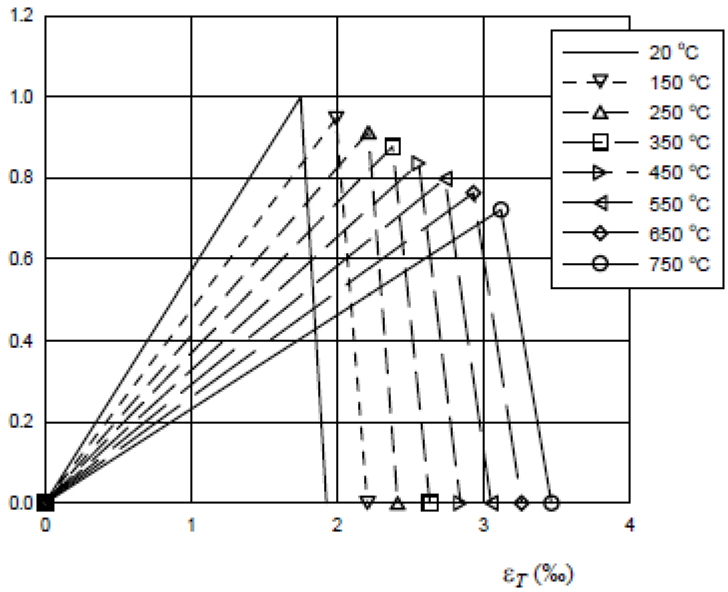

Figure 6. Parameterized stress-strain curves of clay units for high temperatures. Reprinted from Eurocode 6 Part 1-2 (2005)

Table 2. Reduction factors of clay unit's mechanical properties

Temperature	$k_{E,\theta}$*	$k_{fy,\theta}$**
20	1.00	1.00
150	0.94	0.83
250	0.91	0.72
350	0.87	0.64
450	0.83	0.57
550	0.80	0.51
650	0.77	0.46
750	0.72	0.40

*Reduction factor for the modulus of elasticity ** Reduction factor for the yield strength

The reduction factors include temperatures up to 750°C. However, some points of the tested walls reached temperatures higher than 900 °C. Faced with this limitation, the analysis was extended to the maximum temperature verified experimentally, through a simple linear regression from the data of Table 2.

3.3.1.2 Thermal expansion

For this property, a constant coefficient of linear expansion of 8.4 x 10^{-6}/ºC was used for any temperature range, as described by Andreini *et al.* (2015).

3.3.1.3 Constitutive model

Section 3.1 brought discussions about the constitutive model adopted to perform the numerical analysis at ambient temperature. At high temperatures, the model was maintained, but the reduction of the mechanical properties values was considered, through the reduction factors described in Table 2. Fig. 7 and Fig. 8 show the compression and tension stress-strain curves of the wall, respectively, for the temperature ranges studied at this paper.

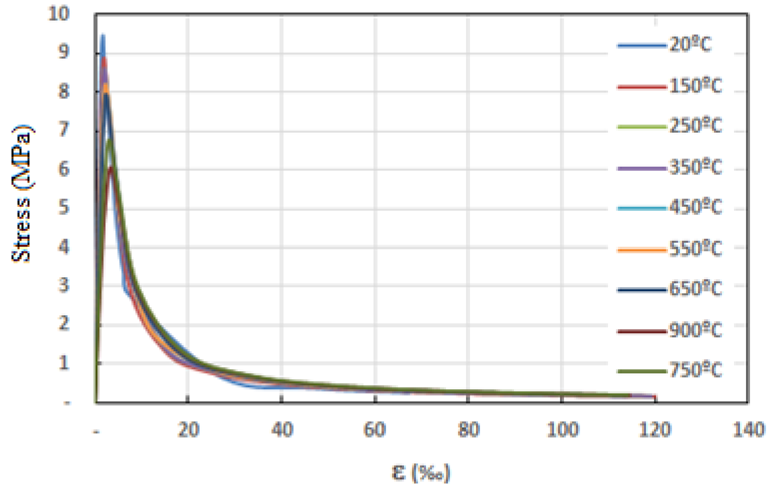

Figure 7. Constitutive model for the compression of the wall, under various temperature ranges

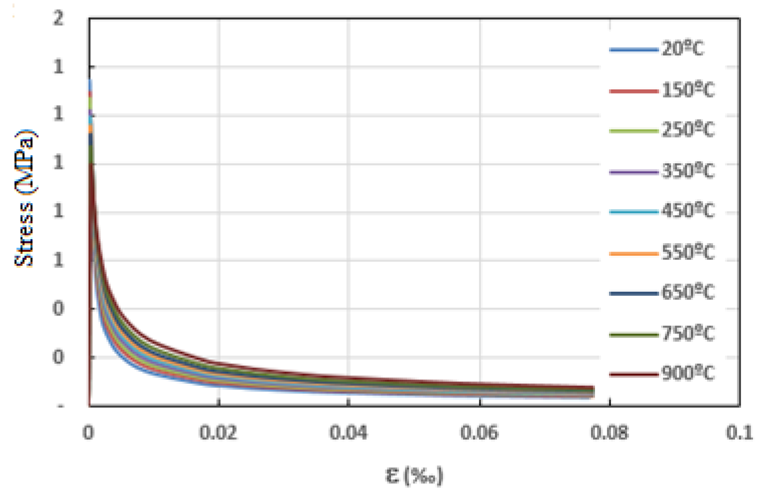

Figure 8. Constitutive model for the tension of the wall, under various temperature ranges

4 VALIDATION OF THE NUMERICAL MODEL

Considering the modeling strategy presented in section 3, the thermal and thermo-structural model for the walls were validated through the tests described by Rigão (2012) already detailed in section 2.

4.1 Thermal model

The thermal model was validated through comparisons between the experimental and numerical results of temperature elevation in four different points of the wall, as shown in Fig. 9.

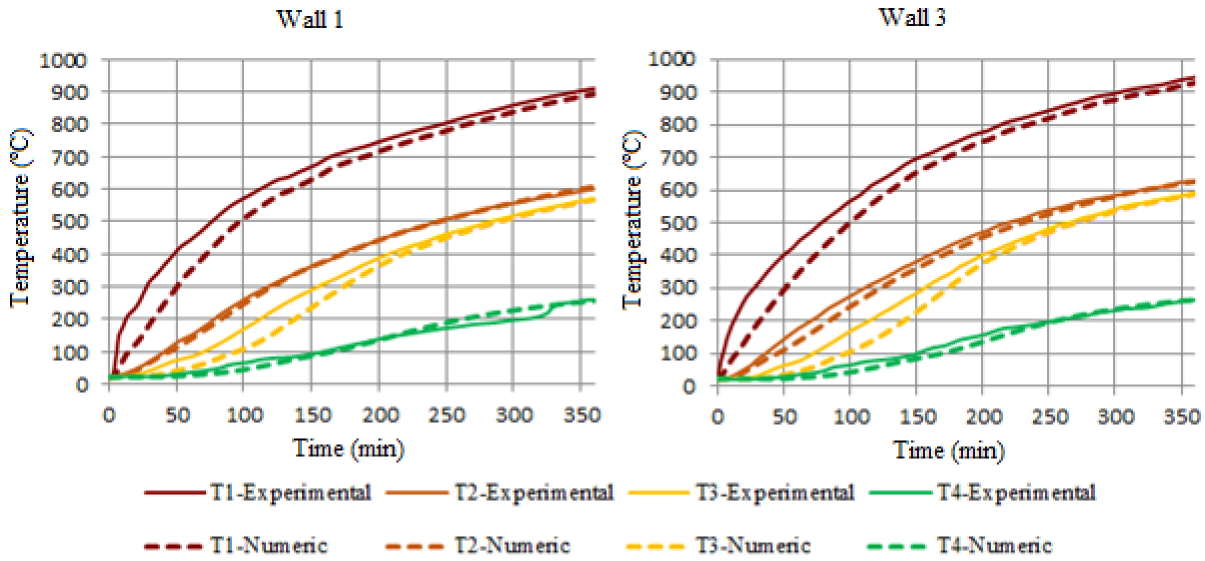

Figure 9. Temperature elevations in the walls 1 and 3

It is observed that the best adjustments occurred in the measurements made by the thermocouples 2 and 4. One of the criteria for evaluation of the structural masonry wall's fire resistance is the criterion of thermal insulation, which is satisfied when the mean temperature variation of the non-exposed surface does not exceed 140ºC and the temperature variation of any point of that surface does not exceed 180ºC, according to Eurocode 6 (2005).

According to Rigão (2012), Walls 1 and 3 reached the temperature limit of the thermal insulation criterion in 227 and 203 minutes, respectively. In the numerical simulations, the values of 223 and 220 minutes were obtained, corresponding to relative errors of 1.76% for Wall 1 and 8.37% for Wall 3. Thus, it was possible to obtain good adjustments between experimental and numerical temperature curves using the ABAQUS software.

4.2 Thermo-structural model

The thermo-structural model was validated through comparisons between the axial force evolution curves on the walls. Fig. 10 shows the growth curves of the compression force obtained in the numerical models and the experimental tests. As discussed in section 3.2, the thermo-structural model was validated for the two walls (P1 and P3).

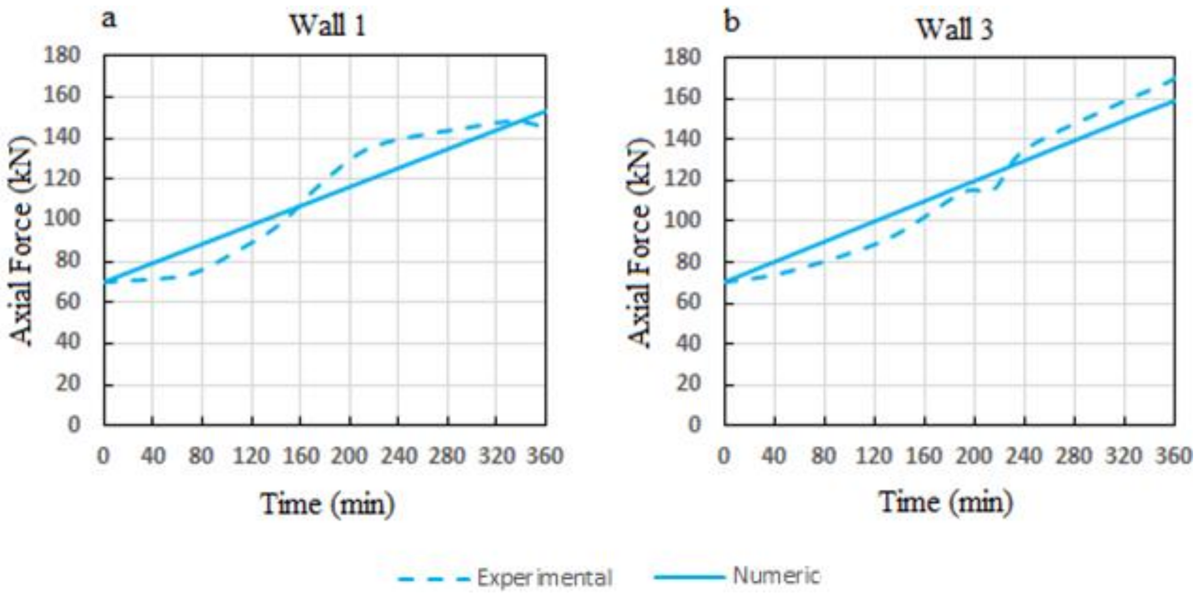

Figure 10. Comparison between numerical and experimental results for axial force evolution

Initially, it is noteworthy to mention that both the experimental test's walls were loaded axially with 70 kN and presented a very similar thermal field, as shown in section 4.1. Then, it was expected that the evolution of the compression forces would be similar. Nonetheless, Fig. 10 reveals that this did not occur.

According to the numerical results, although the axial forces grew linearly, they were able to represent Wall 3 satisfactorily. For this reason, it can be suggested that there were measurement or assembly errors in the Wall 1 test, which caused the different result.

The results show that the proposed numerical model is validated due to the proximity of experimental and numerical curves. In the numerical analysis, a rising line represented the axial force growth during the analyzed time. This behavior is very different from the sinuous behavior of the experimental test. However, it does not disqualify the validation of the model. From the results, two important conclusions that explain the obtained results are presented. The first one concerns the modeling strategy. In the macromodeling, there is no materials discretization (mortar and clay units), or geometric discretization (mortar joints between the units). Consequently, the model does not allow the relative displacement between the components, preventing the appearance of stresses due to the expulsion of the mortar when the temperature increases. Thus, the model is subjected to a state of stresses different from the real one, presenting, consequently, greater resistance to fire.

The second one refers to the load applied in the experimental test. The material is still in the elastic regime for the applied load, which is around only 13% of the wall's ultimate load. Therefore, the increased stress due to the fire was not able to cause the wall to reach its maximum load. It can be said that the wall would still withstand a longer exposure time than that of the experimental test.

From the validation of the numerical model, a parametric analysis will be performed in section 5.

5 PARAMETRIC ANALYSIS

From the numerical model validated for the structural masonry walls and the same modeling strategy, this study was expanded to other cases not addressed in the experimental program. In this section, a parametric analysis is performed by varying the axial load applied to the masonry element. Table 3 lists the values of the applied compressive load and the load factor, which corresponds to the ratio of the applied load to the wall's compressive strength, at ambient temperature, according to the design methods described by ABNT NBR 15.812-1: 2010.

Table 3. Description of the parametric analysis

Axial load	Load factor
70 kN	0.13
170 kN	0.31
270 kN	0.49
370 kN	0.68

Regarding the modeling aspects, only the wall's heating curve and the time of fire exposure were changed. For this analysis, the standard fire curve ISO 834:1999 was used, in order to address the recommendations defined by the current standards. The temperature rise in the blocks' hollow cores was proportionally estimated based on the experimental results. Fig. 11 shows the measured temperatures at the four points of the wall, generated with the standard fire curve ISO 834:1999.

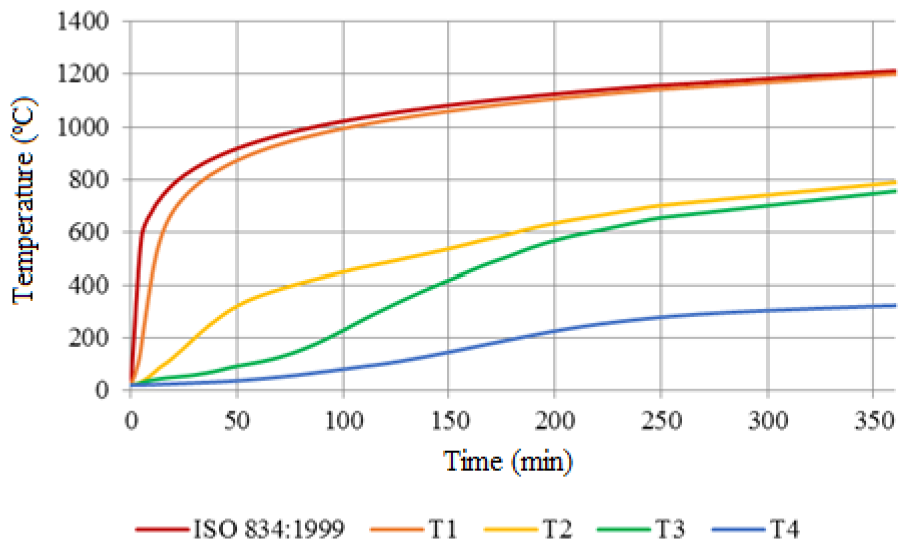

Figure 11. Wall temperatures generated with the standard fire curve ISO 834:1999.

It is observed that the temperature of 160ºC, the limit of the thermal insulation criterion, was reached in the non-exposed surface in approximately 160 minutes. If compared to the experimental tests, there is an anticipation of 67 and 43 minutes in relation to Walls 1 and 3, respectively. This result is consistent with the fact that in the experiments conducted by Rigão (2012), the heating rate was lower than that defined by ISO 834: 1999.

Although the limit temperature of the thermal insulation criterion was reached in approximately 160 minutes, it was decided to extend the simulations to a heating time of 10 hours, in order to achieve the failure of the structural element. Regarding the thermal and thermo-structural properties, the parameters described in item 3 were kept the same.

Fig. 12 shows the evolution curves of the relative axial force for all models. This parameter consists of the ratio between the force developed during the heating and that applied in the ambient temperature step.

A linear growth of the compression force was verified in all the cases. This suggests that the wall did not reach its maximum capacity until the end of the analysis. This is justified because of the differential heating to which the wall is subjected, since only one of its faces is exposed to fire. The structural element is subjected to an average temperature that does not degrade its mechanical properties sufficiently to cause its rupture.

In general, when the load applied before the heating is increased, the value reached by the relative axial force decreases, for a given exposure time. It means that the axial force acting on the wall can increase considerably until its load capacity is reached.

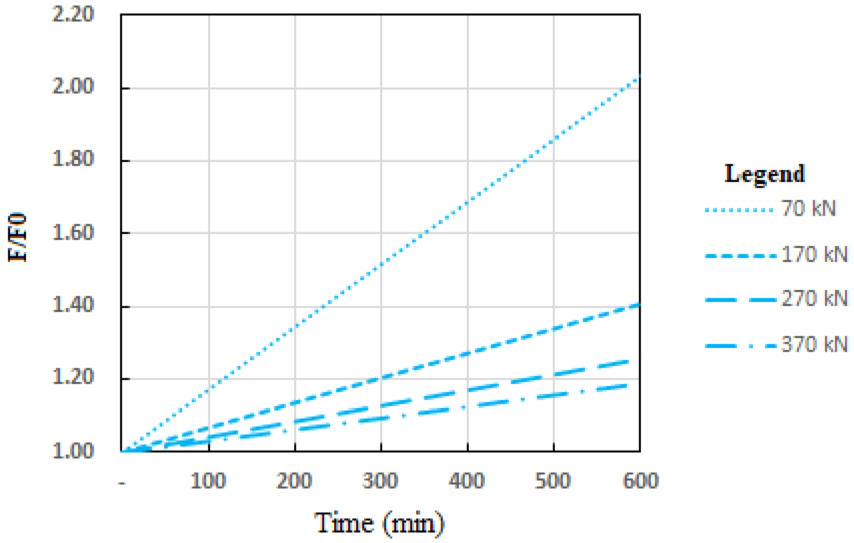

Figure 12. Results of the parametric analysis for variation of the applied axial load

As the wall rupture was not observed in any of the cases, no conclusion was obtained regarding the period of fire resistance by the mechanical resistance criterion, characterized as the time in which the structural element is able to withstand its designed load, according to Eurocode 6 (2005). When analyzing the curves trajectory, it can be inferred that walls that are submitted to higher loads at ambient temperature will have lower resistance to fire. The fire will induce increases of axial load, which are added to the load initially applied. Therefore, the ultimate load will be reached faster. In Fig. 12, the above is evidenced by the reduction of the axial force gain rate (the slope of the lines decreases) with the increase of the load factor.

6 CONCLUSION

Using the ABAQUS computational package, this paper developed numerical models of structural masonry walls under fire conditions. It can be concluded that the implemented numerical strategy was able to successfully represent the thermal and thermo-structural behavior of the walls of the reference experimental tests, even with the limitations of the current norms that deal with this subject. It also allowed the extension of the study to other cases not addressed in the experimental program, through a parametric analysis.

Based on the results obtained through the parametric analysis, it was possible to verify that the load level directly affects the thermo-structural behavior of the masonry. The increase of the load factor applied at ambient temperature causes the decrease of the relative axial force value, for any given exposure time. In the present analysis, it was not possible to load the wall until its maximum load capacity. However, when extrapolating the results, it was possible to infer that the load level will negatively affect the fire resistance. It is recommended for future work, the analysis of other factors in the parameterization, such as the cross section, wall's compressive strength, and type of block. It is also suggested to focus on the tightness criterion, which was not analyzed in the present study.

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