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NUMERICAL ANALYSIS ON THE BEHAVIOUR OF CONCRETE MASONRY WALLS SUBJECTED TO FIRE

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Summary. This paper presents a numerical study on the structural behaviour of concrete masonry at elevated temperatures. Based on an experimental research previously performed on half-scale walls in fire situations, numerical models were developed and validated. The heat transfer models led to thermal fields with good agreement with the temperatures measured by thermocouples installed in the wall, a bigger scatter of temperatures was found in the experimental research. The mechanical analysis led to vertical and out-of-plane displacements in good agreement with the displacements measured by LVDTs. The numerical model was validated and will be used in future researches to perform parametric studies.

1 INTRODUCTION

Concrete masonry has been used worldwide all over centuries in loadbearing and partition walls. In Europe, the Standard EN 1996-1-2 (2005)[1] states that masonry walls must meet one or more requirements when exposed to fire. These requirements are I for temperature insulation, E for integrity to avoid the flow of smoke and hot gases through the wall, R for load-bearing capacity and M for mechanical impact.

In fire situations masonry walls are usually subjected to heating on one face, which leads to a thermal gradient through the thickness of the wall. In unrestrained walls, differential thermal expansion results in thermal bowing towards the fire, a complex phenomenon that depends on the wall's material's properties which are temperature dependent[2]. The material properties degradation caused by high temperatures associated with the thermal displacements may leads to structural collapse of the wall[3]. In some cases, the structural stability (R) of masonry walls is required during the fire to prevent the global structural collapse, prevent fire spread, mitigate local structure collapse and guarantee the safe evacuation of building occupants[4].

Beside of the importance of concrete masonries for civil construction, there is a lack of knowledge on the behaviour of such structures in fire situation. Meagher and Bennetts (1991)[5] used a theoretical computer-based method for analysing concrete walls in fire situation. The model allowed material and geometrical non-linearity, using a method based on force equilibrium and strain compatibility. The authors evaluated the influence of effective height and effective restraint on walls resistance.

Dhanasekar (1994)[2] developed a method for thermo-structural coupled finite element analysis based on layered thin shell elements. The results of the structural analysis predicting thermal bowing of masonry walls were presented. The model was validated using the experimental results reported by Shield *et al.* (1988)[6].

Nadjai *et al.* (2003a)[3] developed a thermo-structural finite element model (MasSET) to represent the behaviour of masonry walls under fire conditions. The model was designed to simulate masonry walls in fire situation. MasSET was validated based on experimental researches and proved to be a reliable tool. However, it can only be used for masonry units with no cavities. Nadjai *et al.* (2003b)[4] used the finite element model MasSET to conduct a parametric study on the effects of slenderness ratio, load eccentricity and boundary conditions of compartment masonry walls in fire situation.

Nguyen and Meftah (2012b)[7] used the experimental results reported by Nguyen and Meftah (2012a)[8] to calibrate a numerical model and investigate numerically the behaviour and performance of fired-clay masonry.

Kumar and Kodur (2017)[9] proposed a model to predict the fire response of load bearing walls. The numerical results were compared to experimental test results in structural and thermal domains in order to validate the model. The authors concluded that the model was capable of predict the response of walls from initial loading to collapse stage under combined effects of mechanical and temperatures loads.

In the sequence of the previous research works, this paper presents a research on the structural behaviour of concrete masonry walls subjected to fire. Based on an experimental research previously performed on half-scale walls in fire situations, numerical models were developed and validated. Masonry walls were constituted by concrete blocks with calcareous aggregates and mortar M10. Numerical models were calibrated based on experimental studies performed by Haach (2009)[10] and Lopes (2017)[11] at ambient and high temperatures, respectively. The heat transfers and the mechanical analysis led to good agreement with the experimental values. The numerical models were validated and will be used in future researches to perform parametric studies.

2 EXPERIMENTAL RESEARCH

The experimental results presented by Lopes (2017)[11] were used for the validation and calibration of the numerical models used in this study. The experimental program comprised six load-bearing masonry walls built according to EN 1365-1 (2012)[12] and EN 1363-1 (1999)[13]. The specimens were composed by seven units in length and ten courses in height with 7 mm of horizontal mortar joint. The total size of specimens was 1.40 x 1.0 m².

2.1 Experimental setup

The experimental setup used by Lopes (2017)[11] is presented in Figure 1. It was composed by a reaction frame built of HEB 300 steel profiles within a hydraulic jack of 933 kN capacity. The hydraulic jack was controlled by a Walter + Bai NSPA 700 / DIG 2000 servo-controlled central unit. The test data was recorded by a TML TDS-350 data logger.

The temperature was applied by a modular electrical furnace, monitored and controlled to follow the standard fire curve ISO 834-1:1999[14]. The specimens were built in a steel frame and bolted to the reaction slab. To distribute the in-plane load one RHS 350x150 and one HEB 240 steel profiles, bolted to each other, were used on the top of the wall, as shown in Figure 1 (b).

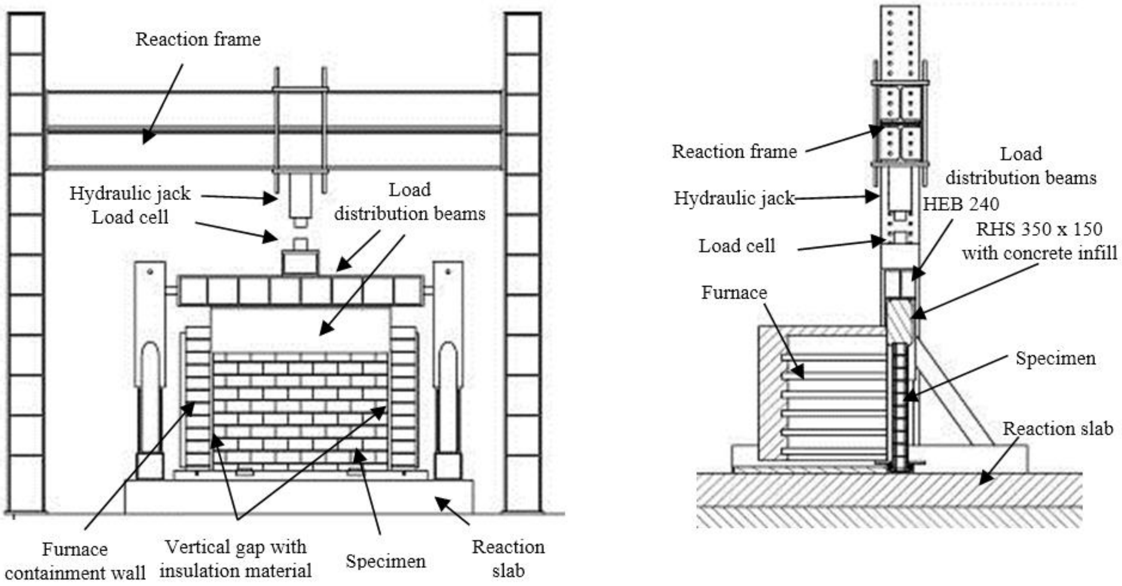


Figure 1 - Experimental setup: (a) Front view; (b) Longitudinal cut view (Lopes, 2017)[11]

2.2 Specimens

The walls were made of three-cell masonry units, like the ones used by Haach (2009)[10] on his research at ambient temperature. The masonry units had a scale of 1:2 due to limitations of the load application system of the laboratory for applying loads at levels of real scale walls. The dimensions of the concrete units presented in Figure 2 are given in

Table 1. According to the classification proposed in EN 1996-1.1 (2005)[15] these concrete units belong to group 2, due to the percentage of voids, size and orientation of holes. The mortar used on the horizontal joints was the commercial M10 mortar, manufactured according to EN 998-2 (2010)[16].

The vertical and out-of-plane displacements and the temperatures were measured according to EN 1365-1 (2012)[12] using linear variable displacement transducers (LVDT), as shown in Figure 3.

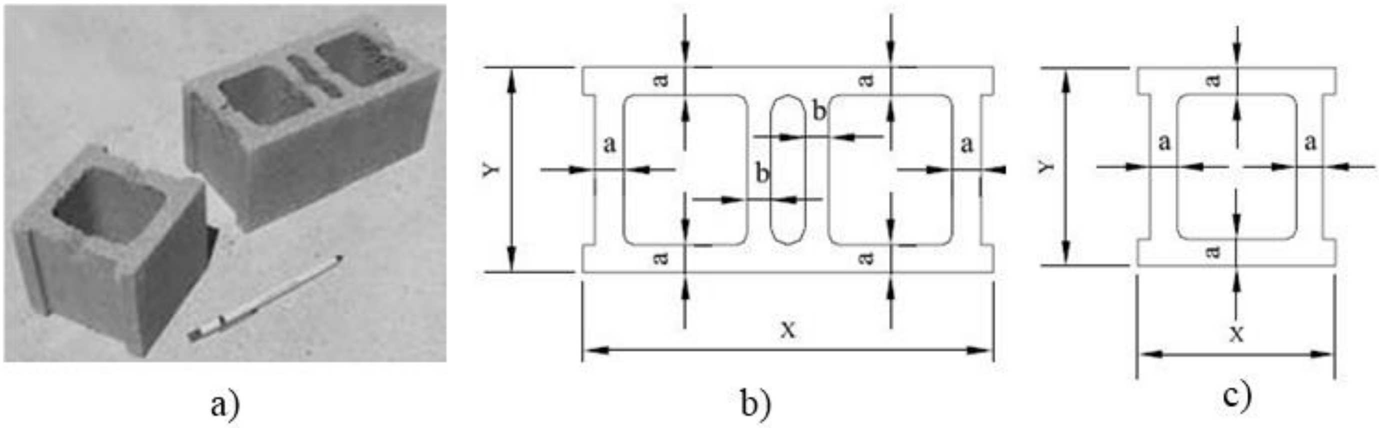


Figure 2 - Masonry Units: a) Reduced scale blocks; b) Block; c) Half block (Haach, 2009) [10]

Table 1 – Dimensions of units (Haach, 2009) [10]

	X (mm)	Y (mm)	Z (mm)	a (mm)	b (mm)	Net area of blocks (cm^2)	Area of Voids (cm^2)	Percentage of Voids (%)
Block	201	100	93	16	14	110.14	93.92	46
Half-Block	101	100	93	16	-	57.20	46.10	45

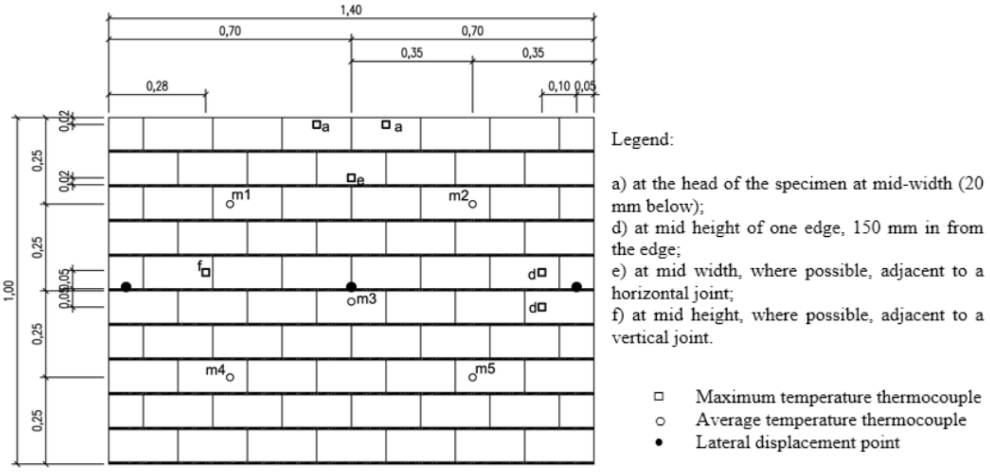


Figure 3 - Specimen dimensions and positioning of thermocouples and lateral displacement transducers (Lopes, 2017) [11]

2.3 Test procedure

The experimental campaign conducted by Lopes (2017)[11] comprised three different loading procedures. Specimens 1 and 2 were subjected to a 208 kN load, which represents 30% of the $f_{ak\perp}$ (characteristic value of the compressive strength normal to bed joints at ambient temperature) as proposed by Haach (2009)[10] for this type of masonry walls. The load was applied at the rate of 0.5 kN/s and then exposed to a fire load according to ISO 834-1[14] fire curve until collapse. The in-plane load was kept constant during the fire load exposure. Specimens 3 and 4 were subjected to the same experimental procedure, but subjected to a 319 kN load, which represents of 46% of the $f_{ak\perp}$.

Specimens 5 and 6 were subjected to 208 kN load, (30% of the $f_{ak\perp}$) then exposed to a fire load according to ISO 834-1[14] fire curve. After 90 minutes of fire exposure, the vertical load was increased at a constant rate of 0.05 kN/s until the collapse of the wall.

3 NUMERICAL MODEL

To better understand the behaviour of concrete masonry walls they were simulated numerically using the finite element software Abaqus[17]. This software can predict the behaviour of structures at high temperatures, under diversified boundary conditions and load cases.

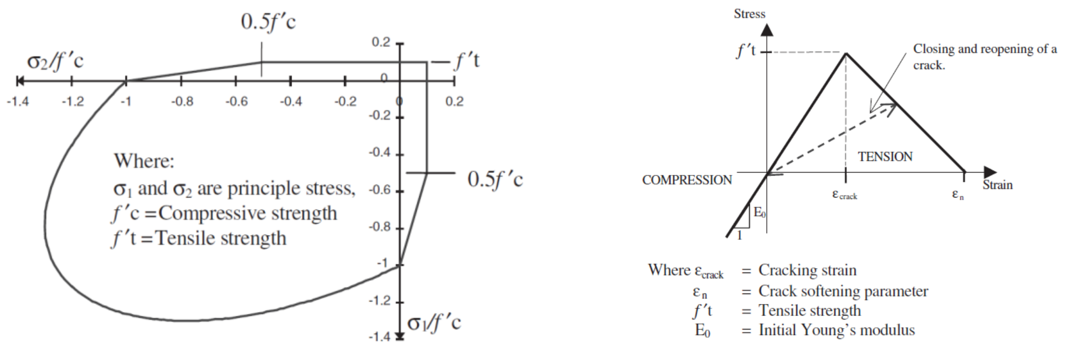
3.1 Analysis procedure

The sequential non-couple analysis was performed in four steps. First a buckling analysis is done to generate the deformed shape of the initial imperfections. Then, a heat transfer analysis is performed to determine the temperature fields along the test. Then a static mechanical analysis is performed, in this step the geometrical initial imperfections are inputted and the mechanical load is applied. Finally, the temperatures fields are applied to the model.

3.2 Material properties

The temperature dependent parabolic stress-strain relation presented on EN 1992-1-2 (2004)[18] was used with linear strain-softening branch. The behaviour of concrete under biaxial stresses was represented by a well-established biaxial failure, as shown in Figure 4 (a).

The brittle tensile nature of masonry units and mortar was accounted in the model using a Concrete Damaged Plasticity Model, which can be used as general capability for the analysis of concrete structures under different load conditions. The material cracking model adopted with crack closing and reopening features is presented in Figure 4 (b).



(a) (b)

Figure 4 - (a) Biaxial failure surface for plane stress concrete material; (b) The material cracking model adopted with crack closing and reopening features (Nadjai *et al.*, 2003)

The compressive stress-strain curves for the masonry are presented in Figure 5 for different temperature levels. The dilation angle in the p-q plane was taken as 30º. The flow potential eccentricity was taken as 0.10, the ratio of initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress was taken as 1.16. The ratio of the second stress invariant on the tensile meridian to that on the compressive meridian was taken as 2/3.

The simulation of masonry walls in fire situation has a well-recognized geometric non-linearity. Changes in geometry due heating and mechanical loads significantly influence the structure thermomechanical behaviour. The global non-linear effects are included in the model.

According to EN 1996-1-1 (2015)[15] an initial eccentricity, e_{init}, shall be considered to take in account constructions imperfections. The initial eccentricity, e_{init}, was assumed to be $h_{ef}/450$, where h_{ef} is the effective height of the wall.

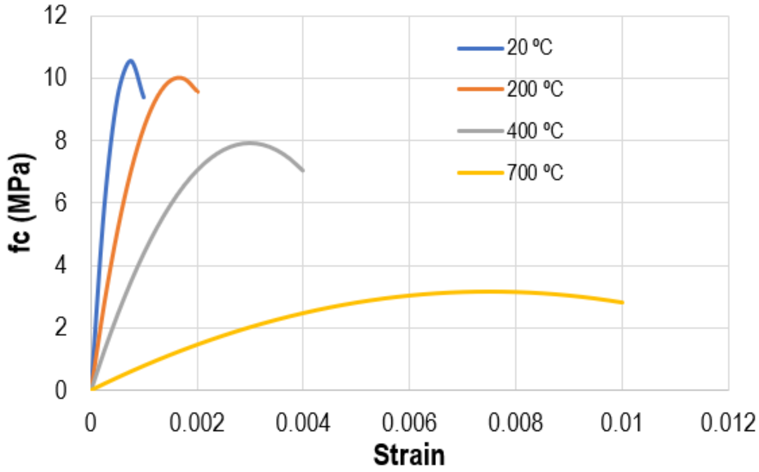


Figure 5 - Compressive stress-strain curves for different temperatures

3.3 Effects of temperature in material properties

The effects of elevated temperatures in the material properties were included in the model. The temperature distributions over the thickness of masonry walls are generally curvilinear, giving rise to a non-linear application of thermal strains[3]. The degradation of materials' properties due increase in temperature was incorporated in the model. The variation of mechanical properties was defined based on EN 1996-1-2:2005[1] and EN 1992-1-2:2004[18], as presented in Figure 6.

4 VALIDATION OF THE NUMERICAL MODEL

The developed finite element models were validated against the experimental results. In this section, the numerical predictions of sample #1 are compared with the experimental results in thermal and structural domains.

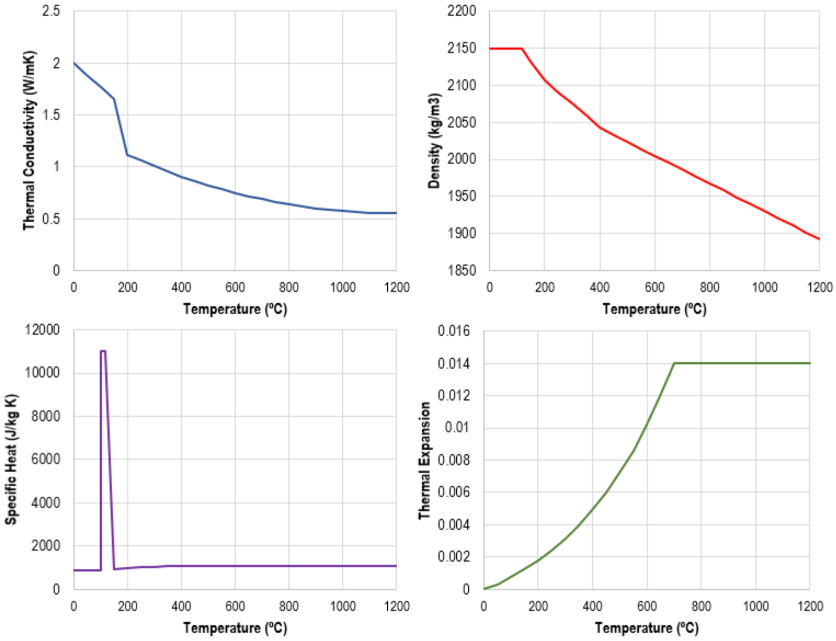
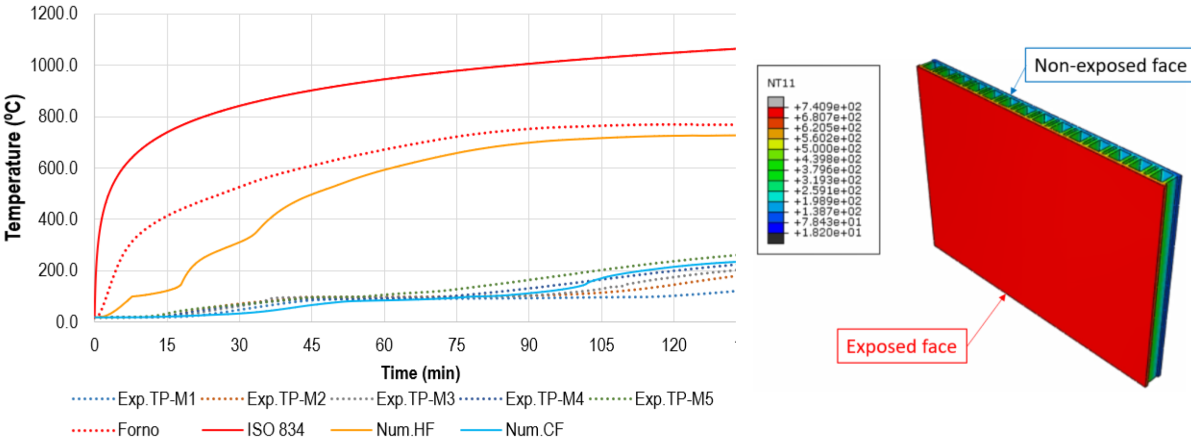


Figure 6 - Thermal properties: (a) Conductivity; (b) Density; (c) Specific Heat; and (d) Thermal elongation

4.1 Heat transfer analysis

To validate thermal response of the developed finite element model, a temperature history predicted by the model was compared with the experimental results, as presented in Figure 7.



(a) (b)

Figure 7 - Test#1: (a) numerical vs experimental temperatures (b) temperature fields at 130 min

The temperature started to increase in an approximately constant rate up to the 90~100ºC interval was reached. In this stage the free water in the constitutive materials started to evaporate and a plateau could be seen in the temperature-time curve.

The highest temperature measurement thermocouples (a1 and a2) showed clearly the plateaus lasting for almost 30 minutes. The lowest temperature measurement points (d1 and d2) showed a plateau that lasted for 10 minutes. This is a result of a steam flow through the vertical holes of the blocks and steam accumulated at the top of the specimen, cooling the top of the specimen. This effect was not represented at the numerical model.

Based on the comparison of the numerical and experimental temperatures some aspects can be highlighted:

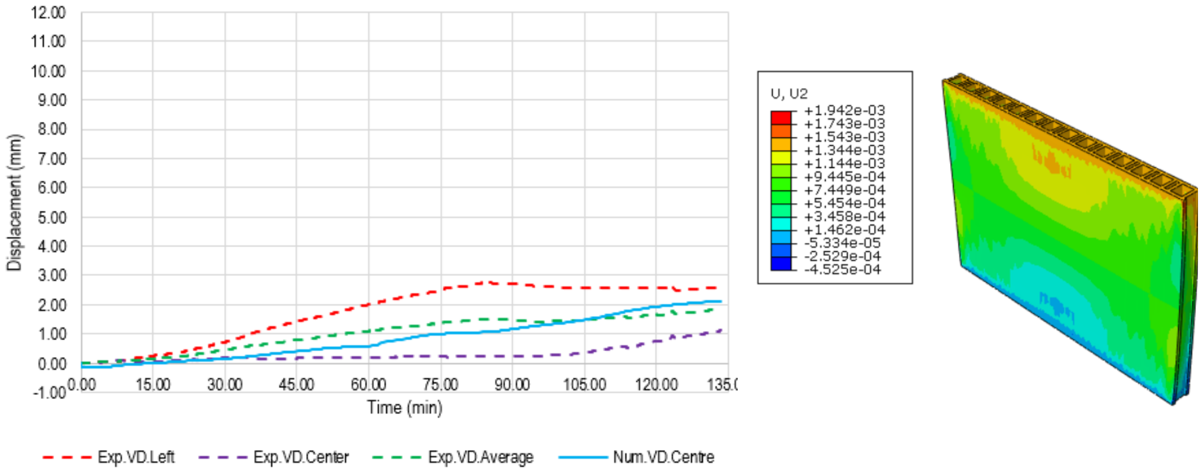
a) the dispersion of temperatures is smaller in the numerical than in the experimental results. The numerical model could not represent the steam flow through the internal holes of the blocks as well as the steam accumulation at the top of the specimen;

b) the numerical models presented good agreement with the experimental results, the predicted temperatures in the range defined by the average temperature given by the thermocouples (m1 to m5, presented in Figure 3);

c) even for thermal characterization, masonry is a very heterogeneous material. The temperature ranges for each specimen had specific and different results.

4.2 Mechanical analysis

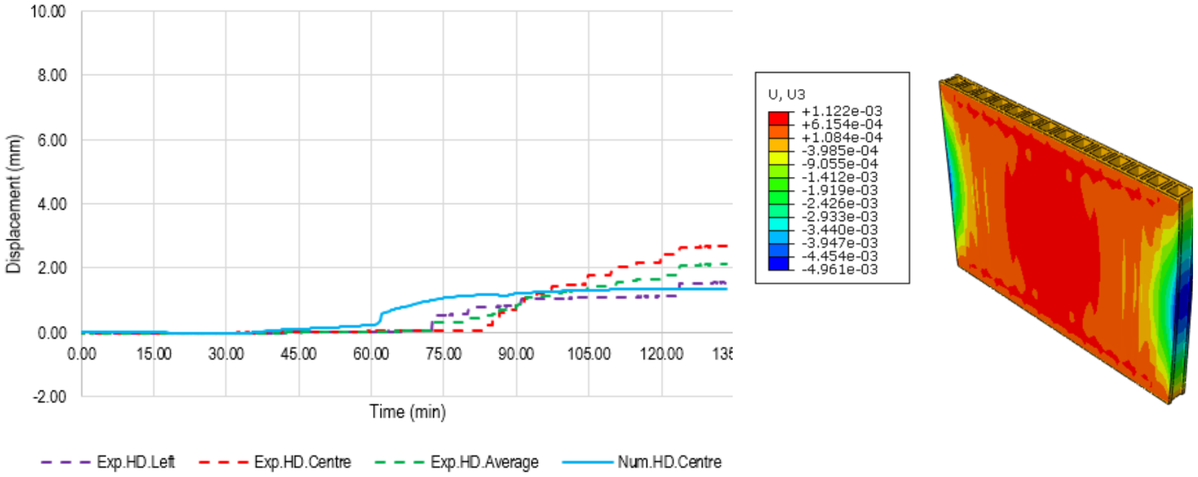
The mechanical analysis was validated based on the vertical and horizontal displacements of the wall. The comparison of the numerical and experimental results are presented in Figure 8 and Figure 9, for the vertical and out-of-plane displacements, respectively.



(a) (b)

Figure 8 - Test#1: (a) numerical vs experimental vertical displacements (b) vertical displacement fields at 130 min

The vertical displacements started to grow from the beginning of the test due to the thermal elongation of the wall. During test #1, the effects of thermal expansion were more important than the reduction of the stiffness of the wall, positive displacements were found during the whole test. The numerical results were in good agreement with the experimental ones.



(a) (b)

Figure 9 - Test#1: (a) Numerical vs experimental out-of-plane displacements (b) Out-of-plane displacement fields at 130 min

The out-of-plane displacement started to grow from the beginning of the fire on the numerical model due to the thermal bowing of the wall.

5 Conclusions

This paper presented a research on the structural behaviour of concrete masonry walls subjected to fire. Based on an experimental research previously performed on half-scale walls in fire situation, numerical models were developed and validated. The heat transfer models led to thermal fields that showed good agreement with the experimental temperatures measured in the walls. A significant scatter of temperatures was found in the experimental but not in the numerical results. The mechanical analysis led to vertical and out-of-plane displacements in good agreement with the displacements measured in the experimental tests. The numerical model was validated and will be used in future researches to perform parametric studies.

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