FIRE-RESISTANCE MODELLING AND NUMERICAL SIMULATION OF MASONRY PARTITION WALL BEHAVIOUR

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SUMMARY

The present study is devoted to the evaluation of the fire response in the case of partition walls made with hollow terra cotta bricks and traditional mortar as joints. A thermo-hydro-mechanical model is proposed and is implemented in finite element method for illustrative purposes. The three heat transfer modes, i.e. conduction, radiation and convection as well as the water effect are considered in order to derive the temperature field within the structure. The mechanical behaviour is considered as non linear since the mechanical properties (Young's modulus, thermal expansion coefficient) are considered as temperature dependent. The behaviour of the masonry walls during the fire might then be easily analysed. Therefore, parametrical studies are considered in order to estimate the influence of the material properties.

The paper focuses on the case of masonry walls made with hollow bricks (horizontals alveolus). The insulation, the thermo-mechanical stresses as well as the lateral displacements are investigated.

INTRODUCTION

The knowledge of the structural behaviour during an accidental fire resistance is nowadays widely required. Actually, three main criteria (insulation, integrity and the load-bearing capacity) are investigated [Eurocode 6, Iso 834]. However, the experimental tests are cost and time consuming. Furthermore, many tests are required due to the various geometrical forms and materials properties that may exist [Kornmann-2005].

It is then expected that theoretical models are developed for simulation purposes. However, due to the wide range of geometrical forms and physical properties of the existing bricks, sophisticated theoretical approaches might be very complex. Furthermore, the material and structural characteristics vary with the temperature.

In the present study, a theoretical model is developed in order to simulate and predict the behaviour of masonry walls when subjected to fire. Their fire resistance is also investigated. In a first approach, the study focuses on the case of masonry walls made of hollow bricks (horizontal alveolus). A sensitivity analysis is performed in order to investigate the effect of

the constitutive material and geometrical parameters on the thermal behaviour, i.e. insulation property. Vertical loads are not considered in this paper.

ABOUT THE CONSTITUTIVE MATERIALS PROPERTIES

Masonry walls are considered as composite structures made with clay bricks with mortar as joints. Their chemical, physical, thermal and mechanical properties vary with the temperature. Actually, the increasing temperature generates chemical processes and phase changes within the material. They might be either endothermic or exothermic, resulting in thermal characteristics changes and influence the mechanical properties.

Let us consider the case of mortar and terra cotta. The evolution of their thermal and mechanical properties depends on several parameters. As an important governing parameter, the water has an important role. Actually, for the both mortar and terra cotta, the main variation of thermal conductivity λ and heat capacity C_p correspond to free water evaporation [Eurocode 6].

For instance, the evolution of heat capacity C_p of terra cotta can be derived from the evaporation energy ΔC_p^{peak} [Alnajim-2004]:

$$\Delta C_p^{peak} = \frac{\omega L}{2\Delta T} \tag{1}$$

where: ω is the water content of the sample obtained by a GTA[1] test, $L = 2260\, kJ.kg^{-1}$ is the latent heat of vaporization, ΔT is the half of evaporation temperature interval. Considering that the water evaporates between 95°C and 105°C, $\Delta T = 5°C$. ΔC_p^{peak} is then added to C_p^{ambi} (heat capacity value at ambient temperature) in order to obtain the evolution of heat capacity (Figure 1).

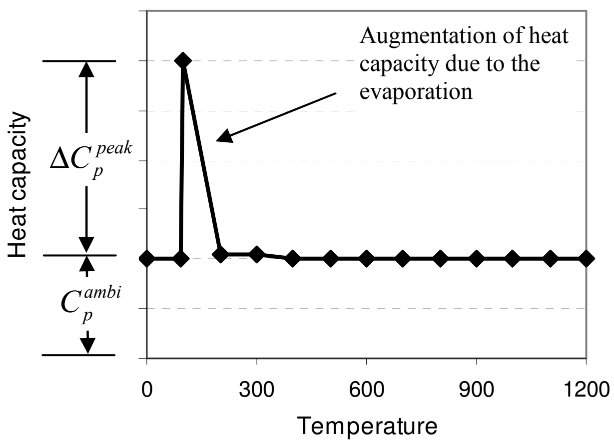


Figure 1. Interpolation of the heat capacity evolution according to [Eurocode 6]

Concerning thermal conductivity of terra cotta, the variation is due to the phase changes and the radiation inside the pores network within the material, at high temperature: in some cases,

[1] Gravimetric Thermal Analysis

the porosity rises up to 40% . The evolution of λ can be obtained directly by experience or by indirect method. A simple example is proposed herein in order to determine the evolution of λ. Consider the structure presented in the Figure 2. At static state of transfer, the heat flux transferred from the hot side to cold side q_{heat} can be supposed constant in the horizontal direction and equal the value at each partition:

$$q_{heat} = -\lambda\left(T_i^{av}\right)\frac{T_i^{ue} - T_i^{ex}}{e_i} = const \qquad (2)$$

where: $T_i^{av} = \frac{\left(T_i^{ex} - T_i^{ue}\right)}{2}$ is the average temperature at the partition i; T_i^{ex} and T_i^{ue} are its temperatures indicated by the thermocouples at exposed and unexposed faces respectively; $\lambda(T)$ is the thermal conductivity at temperature T. The Equation 2 permits to establish the relations between the thermal conductivities corresponding with temperature T_i^{av}.

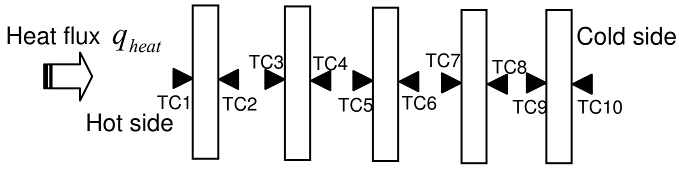
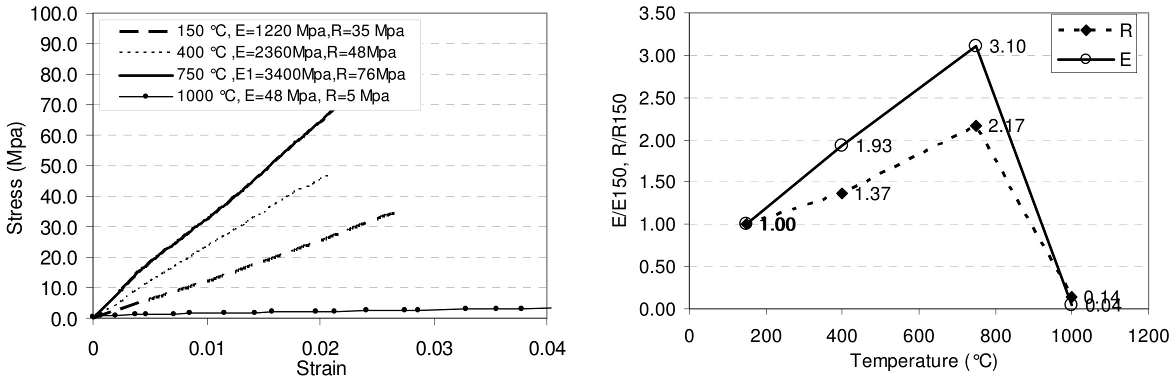


Figure 2. The vertical partitions of a hollow brick and the positions of the thermocouples.

At ambient temperature, the mortar presents a quasi-fragile behaviour in tension and a ductile behaviour in compression, [Gabor-2002]. At high temperature, the compressive strength and Young modulus decrease with the temperature increase, [Cerny-2003, Culfik-2002, Nechnech-2000]. The Young modulus decreases quasi linearly and more quickly than the resistance: almost 90% of loss at 600°C, and complete loss at almost 900°C.

For the terra cotta, at ambient temperature, the behaviour is brittle, linear and elastic for both compression and tention [Kornmann-2005]. At high temperature, the tests performed on samples extracted from the hollow bricks [Ctmnc-2006] show that the behaviours remain brittle, linear and elastic until T= $550°C$. Beyond that, the linear elastic phase corresponds to a stress value reaching 1/5 to 1/3 of the ultimate strength. Afterwards, a nonlinear phase appears resulting in rigidity decrease. At very high temperature (more than $800°C$), the fired



a) b)

Figure 3. a) Stress-strain relationships of the terra-cotta sample at different temperatures. b) Variation of the Young modulus and the compressive strength of the terra cotta sample. [Ctmnc-2006].

clay becomes very ductile but suffers an important loss of its bearing capacity (Figure 3a). The evolutions of the compressive resistance and the Young modulus present similar trends (Figure 3b). An increase is observed from $20°C$ up to $550°C$, followed by a decrease due to the change of quartz form (α to β) and the decarbonation in the material.

THERMO-MECHANICAL FORMULATION

For hollow bricks masonry, the three modes of transfer from the exposed to unexposed face of the wall are considered, i.e. convection and the radiation in the exposed and unexposed faces, conduction in the solid partitions (shells and webs) and radiation inside the cavities. The combination of theses transfer modes in transitory regime leads to [Crabol-1989, Hans-2006]:

$$\rho C_p(T)\frac{\partial T}{\partial t} = \lambda(T)\nabla^2 T + r(T,t) \tag{3}$$

where: $\lambda(T)$ is the thermal conductivity depending on the temperature, $r(T,t)$ is the density of heat source, containing the radiation term, ρ is the density.

The thermo-mechanical characteristics of the terra-cotta and mortar are collected from experimental tests. As they depend on the temperature, the behaviour is elastic and non-linear. Under the mechanical loads and the fire action, the stresses σ, strains ε are generated and satisfy the equilibrium, kinematical conditions (Equations 4a, 4b) and the behaviour laws (Equation 5) [Lemaître and Chaboche-1996]:

$$div\underline{\underline{\sigma}} + f = \rho\vec{\gamma} \tag{4a}$$

$$\underline{\underline{\varepsilon}} = \frac{1}{2}\left[grad\vec{u} + \left(grad\vec{u}\right)^T\right] \tag{4b}$$

$$\underline{\underline{\varepsilon}} = \frac{1+\nu}{E}\underline{\underline{\sigma}} - \frac{\nu}{E}Tr\left(\underline{\underline{\sigma}}\right)\underline{\underline{I}} + \alpha\Delta\theta\underline{\underline{I}} \quad \text{or} \quad \underline{\underline{\sigma}} = \lambda Tr\left(\underline{\underline{\varepsilon}}\right)\underline{\underline{I}} + 2\mu\underline{\underline{\varepsilon}} - (3\lambda + 2\mu)\alpha\Delta\theta\underline{\underline{I}} \tag{5}$$

where $\underline{\underline{\sigma}}$ is the stress tensor, $\underline{\underline{\varepsilon}}$ is the strain tensor, E, μ, λ are respectively the Young modulus, shear modulus, Lamé coefficient depending on the temperature and ν is the Poisson ratio. The term $\alpha\Delta\theta\underline{\underline{I}}$ is the strain tensor generated by the thermal effect, where α is the thermal expansion coefficient which depends on the temperature.

The finite elements method is used to solve the problem. Two distinct parts are considered: the first one consists in solving the heat transfer equations in order to evaluate the temperature inside the structure; then, as a second part, the temperature field is considered as the input data at each calculation step (Figure 4).

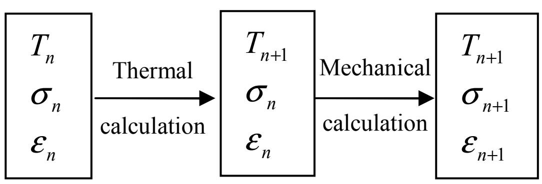


Figure 4. Schematic presentation of the decoupled problem (n is the index corresponding with the number of time step)

VALIDATION OF THE MODEL

Validation of the thermal model

As presented above, the three modes of transfer are considered for the heat transfer model in the hollow masonry structures. Introducing the evaporation energy in the heat capacity term expresses the water effect. To validate the simulation, an experience is performed on a hollow terra-cotta brick (Figure 5) having 3 rows and 4 columns of horizontals alveolus. The heat is applied on one side (exposed face), the opposed side (unexposed face) being at ambient temperature. Ten thermocouples are installed at both sides of five vertical partitions (Figure 2). The material characteristics are given in the Table 1. The simulation is run by the finite elements code Cast3M[2], developed by CEA[3]. The numerical results are compared with the measures (Figure 6).

Figure 5. The brick under study.

Table 1. Thermal characteristics of the terra cotta sample.

Physical parameter	Value
Thermal conductivity at ambient temperature $\left(W \cdot m^{-1} \cdot K^{-1}\right)$	1.27
Heat capacity at ambient temperature $\left(J \cdot kg^{-1} \cdot K^{-1}\right)$	870
Emissivity coefficient	0.9
Convection exchange coefficient $\left(W \cdot m^{-2} \cdot K^{-1}\right)$	8
Water content $(\%)$	1.6
Density $\left(kg \cdot m^{-3}\right)$	1836

The comparison shows a good accordance between the experimental and the numerical results. For instance, the insulation property **I** [Eurocode 6] is 78 min experimentally and 76 min by calculation. One may therefore consider that the model predicts correctly the thermal response of the wall. Therefore, this heat transfer model might be considered in order to study masonry structures response under fire and mechanical effects.

For additional information, the relations between the insulation **I** and the material physical parameters are given in Figure 7. The individual role of each parameter on the fire resistance might then be evaluated. For instance, it is shown that, in natural condition, the variation of the exchange coefficient from 8 up to 25 $W \cdot m^{-2} K^{-1}$ does not cause major variation of the insulation property (environmental condition). However, the changes of thermal conductivity and heat capacity (nature of the material) have great influences. It is noted that the changes of

[2] http://www-cast3m.cea.fr/
[3] Commissariat d'Energie Atomique, France

the positions of the webs inside the brick do not induce the differences of the temperature at the unexposed face. However, the distributions of the temperature are different.

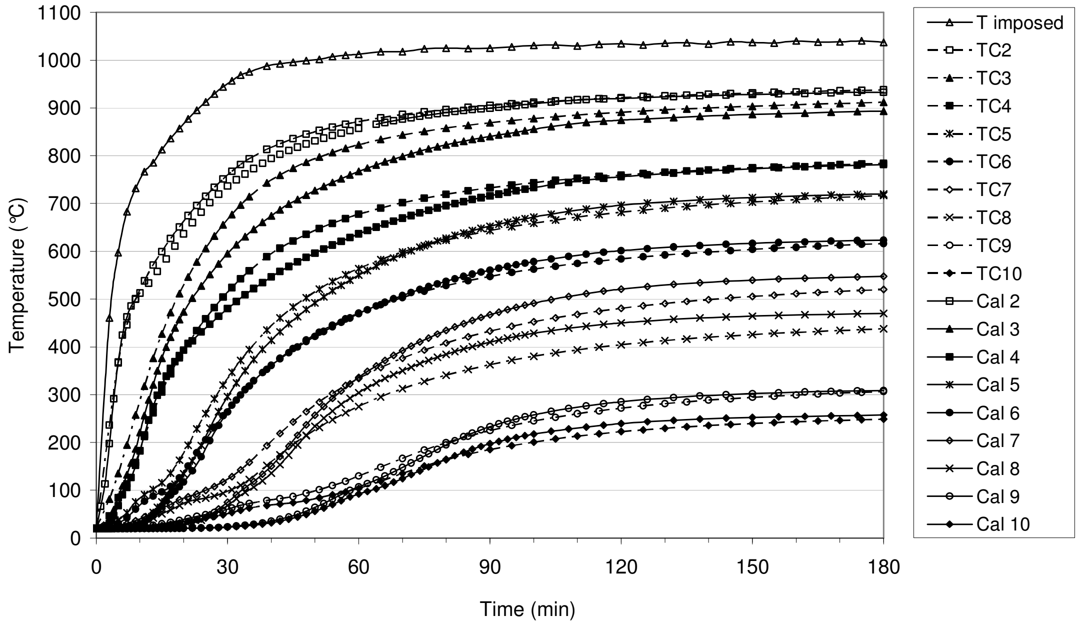
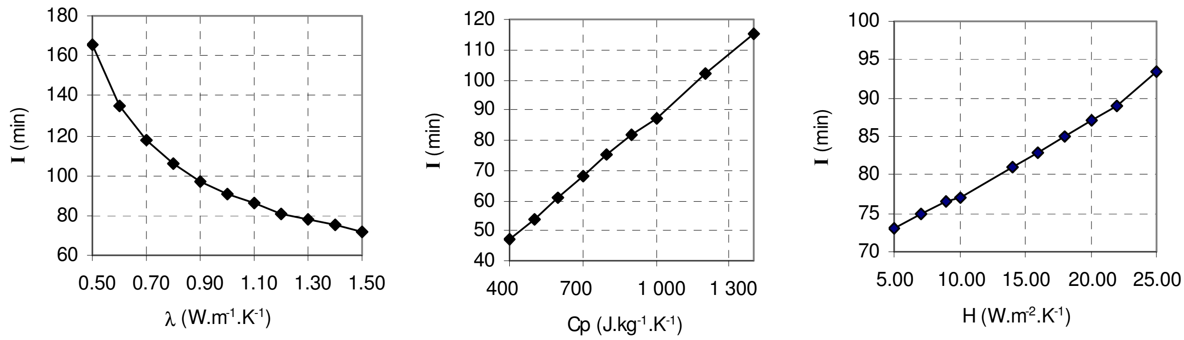


Figure 6. Evolution of the temperature inside the brick



a) b) c)

Figure 7. Relation between the insulation property and : a) thermal conductivity, b) heat capacity, c) convective exchange coefficient.

Validation of the thermo-mechanical couple model

As the heat transfer model provides accurate results, the study considers hereafter the coupling between thermal and mechanical effects. The mechanical behaviour of masonry structure might then be investigated. For this purpose, a compartment wall is considered: its dimensions are $3000mm \times 3000mm$, involving five columns and nine rows of hollow bricks with traditional mortar as joints; the bricks have two columns and seven rows of alveolus and have the dimensions $h_b \times l_b \times e_b = 300 \times 570 \times 100 mm^3$ (Figure 8). The wall fills a concrete frame. The inferior, superior and one vertical edge are connected to the frame by a layer of mortar having $10mm$ thickness, remaining free on the fourth edge. During the test, the

thermocouples are used to capture the temperature at the exposed face. The displacement sensor are for the capture of the lateral displacements of the wall.

The heat provided by the furnace at the exposed face follows the normative equation [Eurocode 6, Iso 834]:

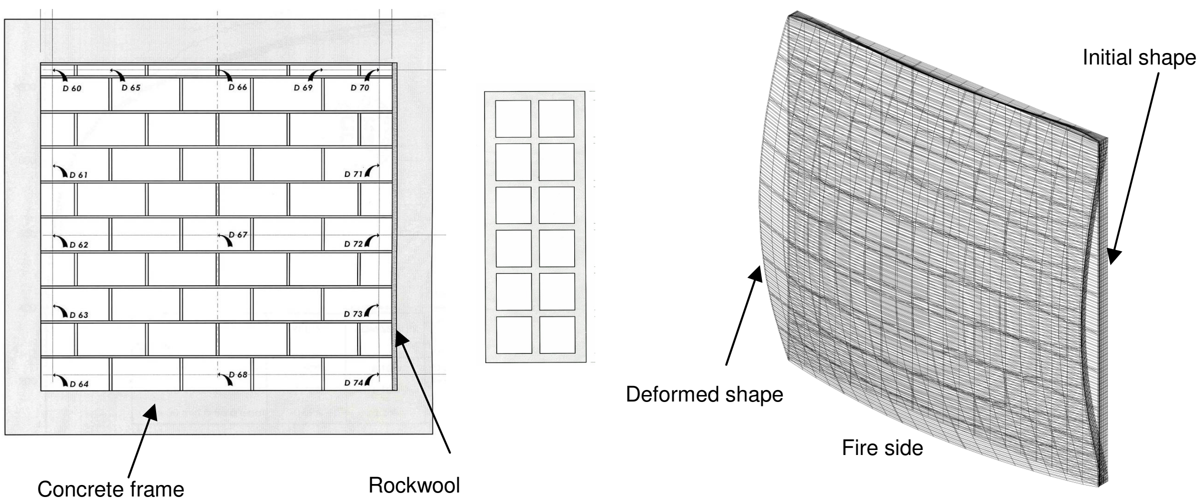
$$T = 345\log(8t+1) + 20 \tag{6}$$

where T is the temperature in $°C$ at any moment t (in minute). The thermo-mechanical characteristics of the terra-cotta and of mortar are presented in the Table 2.

Table 2. Thermo-mechanical characteristics of the constitutive materials.

Characteristic	Terra-cotta	Mortar
Density $(kg \cdot m^{-3})$	1836	1500
Thermal conductivity at 20°C $(W \cdot m^{-1} \cdot K^{-1})$	1.27	1.5
Heat capacity $(J \cdot kg^{-1} \cdot K^{-1})$	800	1170
Thermal expansion coefficient (K^{-1})	$7 \cdot 10^{-6}$	$1 \cdot 10^{-5}$
Young modulus at 20°C (MPa)	1220	15000
Poisson's coefficient	0.22	0.25

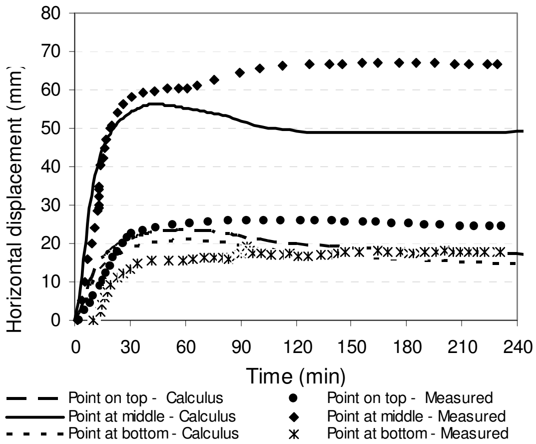
The numerical simulation provides the same deformed shape than the experimental result and the global behaviour of this thin wall is similar to homogeneous plate behaviour (Figure 8b). The displacement of the wall increases quickly at the beginning of the fire exposure due to the great horizontal gradient of temperature. When the temperature increases at the unexposed face, the horizontal temperature gradient decreases: the curvature of the wall decreases therefore, this phenomenon being due to temperature redistribution. Meantime, the Young modulus decreases at high temperature (Figure 3b).

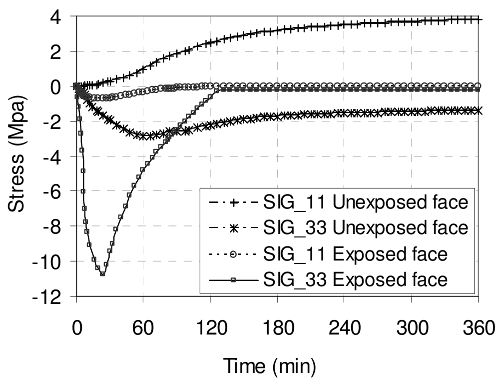


a) b)

Figure 8. a) Configuration of the tested wall and cross section of the brick.
b) Global deformation shape of the wall obtained by calculation.

The displacements at three points (top, bottom and centre of the wall) are presented in Figure 9a. One may notice the good adequacy between two families of curves at the beginning of the test. The differences are observed after 60 minutes of fire exposure: in fact, the displacement increases continuously while the calculation shows the inverse i.e. a displacement decrease. This difference may be caused by possible local mechanical damages of the mortar joint or the failure of the brick at very high temperature. These two possible phenomena are not yet taken into account by the presented model.





a) b)

Figures 9. a). Evolutions of the displacements of the wall.
b). Evolutions of stresses at the wall centre, in both exposed and unexposed sides (SIG_11 and SIG_33 being the principal stresses σ_{11} and σ_{33}).

In the case of compartment wall, external loads should not be applied since only thermal effects should be considered. The arising stresses depend on Young modulus values and its evolution with the temperature. It is shown that the compression stresses arising at the exposed side are more important than those at the unexposed side (Figure 9b). This phenomenon is due to the thermal deformation (extension) of the material but prevented by the boundaries conditions and the auto-stress phenomenon. This latter is caused by the temperature gradient within the thickness. The stresses at the exposed face are submitted to an increase followed by a quick decrease due to the rapid temperature increase and the simultaneous Young modulus decrease. But, the tension stresses at the unexposed side are submitted to continuous increase, resulting in cracks, as it has been observed during the test, and horizontal displacement increase.

Except the local enormous stresses at the four fixed points, i.e. at the wall corners, the maximal compressive stresses do not exceed the material strength. This may explain the fact that the wall has shown during the test a good stability though it has been damaged at the corners.

According to the fact that the model provides results in good accordance with the results, i.e. global lateral displacement, deformed shape, temperature field, it might be stated that the thermo-mechanical model presented in this study predicts correctly the behaviour of masonry walls with mortar as joints. However, local mechanical damages are not yet considered by the model.

CONCLUSIONS

In this work, a model is proposed for the thermal transfer and the mechanical behaviour of terra cotta bricks having mortar as joints. It is applied to evaluate the thermo-mechanical behaviour of masonry wall. It requires the experimental knowledge of five parameters: the water content ω, the heat capacity C_p, the thermal conductivity λ, the relationship $E(T)$ between Young modulus and the temperature T, and the thermal expansion coefficient $\alpha(T)$.

Under the mechanical loads and the fire action, the stresses σ and the strains ε satisfy the classical equilibrium and kinematical conditions where the Young modulus varies with the temperature. This elastic non linear model describes the thermo-mechanical behaviour of the terra cotta. For illustrative purposes, an experience is performed on masonry walls made with hollow terra-cotta brick and mortar as joints. This wall is cast within a reinforced concrete frame.

The numerical calculation, by finite element method, provides results that are in accordance with the results: temperature field, lateral displacements, deformed shape. However, local mechanical damages are not yet considered by the model.

It might then be stated that the non linear thermo-mechanical model presented in this study predicts correctly the behaviour of masonry walls with mortar as joints.

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