Thermo-mechanical behavior of refractory masonry linings: An overview on numerical simulation

Pratik N. Gajjar[1], João M. Pereira[2], Paulo B. Lourenço[3]

Abstract: Refractories are unique materials used in linings of vessels to contain and process fluids at high temperatures. They can withstand complex combination of thermo-mechanical stresses and chemical wear generated by fluids and chemical agents during process. The main challenges for the usage of refractories are linked to the cost, availability of raw material and environmental regulations. This paper presents an overview of recent developments of numerical models using a multi-scale approach in order to identify the impacts of various parameters on the overall behavior of the masonry linings in industrial structure. The results presented in this paper provide, for specific boundary conditions and thermal loading, the evolution in time of the displacements, strains and temperature profiles on laboratory models. The overview of numerical models their results further help to validate models at industrial scale, reducing the burden of laboratory testing and ultimately, can be used for optimizing refractory linings, thus extending an economic and environ-mental benefits to the refractory industries.

Keywords: *Refractory, Thermo-mechanical Behavior, Numerical Modeling*

[1] PhD Student, University of Minho (ISISE), Department of Civil Engineering, pratik.gajjar@civil.uminho.pt
[2] Doctorate Researcher, University of Minho (ISISE), Department of Civil Engineering, jpereira@civil.uminho.pt
[3] Full Professor, University of Minho (ISISE), Department of Civil Engineering, pbl@civil.uminho.pt

INTRODUCTION

Masonry exhibits complex behavior when subjected to high temperature loadings. While for the general application of masonry, high temperature loadings are not considered, or they are considered for the specific case of fire according to the design codes. In case of the process involving the refractory masonry at high temperature, numerical or experimental analysis are necessary to evaluate the behavior, suitability and designing of the refractory materials used in the respective applications.

Refractory linings protect metallic structures from the hot products they contain, such as burning coal in coal fired plants or liquid steel in the steel making industry. Owing to the difference in thermal expansion coefficient between steel and refractory materials, significant stresses appear in the refractory that can lead to the failure of the linings. Thermo-mechanical finite element analyses of the global structure can assist the design and understanding of these complex structures. As the interest of this study is the behaviour of refractory masonry under high temperature, the governing time-dependent equations for conduction, the mode of heat transfer in solid (for transient heat transfer), is given in this section.

There are three modes of heat transfer: conduction, convection and radiation (Lewis et al., 2004). The amount of heat energy transferred in each heat transfer mode that can be calculated, is called flux. Radiation is the propagation of energy through electromagnetic wave emitted from the surface of a body. Radiation is emitted by all bodies at any temperature, and unlike how conductive and convective heat transfers through material molecules, radiation transfers heat even in vacuum. The radiative heat flux emitted by the surface of an object can be represented by equation 1 with Stefan-Boltzmann Law (Lewis et al., 2004):

$$q_s = \varepsilon_s \sigma T_s^4 \tag{1}$$

where q_s is the radiative flux emitted by the surface (W/m^2), ε_s is emissivity of the surface, σ is Stefan-Boltzmann constant (5.669 × 10^{-8} W/m^{2}K^4) and T_s is the temperature of the surface (K). As shown in Equation (1), the Stefan-Boltzmann Law states that heat energy emitted by the surface is proportional to the fourth power of the surface temperature. Emissivity is a property of a material that defines the effectiveness of surface's radiative energy emission; it ranges from 0 to 1, with 1 being most effective. (Lewis et al., 2004).

For the purpose of this research, the radiative flux of a wall surface subjected to fire is derived. In case of fire, the emitted radiative flux is represented as:

$$q_f = \varepsilon_f \sigma T_f^4 \tag{2}$$

where the subscript f stands for fire. Only a portion of fire flux is absorbed into the surface of the wall. The radiative flux of fire absorbed into the surface is

$$q_{abs} = \alpha_s q_f \tag{3}$$

where α_s is the absorptivity of the surface. According to Kirchhoff's identity, the absorptivity of a surface is equal to its emissivity. By using Kirchhoff's identity to replace absorptivity with emissivity, and substituting Equation (2) into (3), the absorbed radiative flux is rewritten as:

$$q_{abs} = \varepsilon_s \varepsilon_f \sigma T_f^4 \tag{4}$$

Lastly, considering the radiative flux emitted by the surface (q_s), the net radiative heat flux of the surface exposed to fire is derived as follows (adapted from Wickström, 2004):

$$q_{net,rad} = q_{abs} - q_s = \varepsilon_s \varepsilon_f \sigma T_f^4 - \varepsilon_s \sigma T_s^4 \quad (5)$$

The governing equation of conductive heat transfer can be derived by the energy conservation law; essentially, the body increases in temperature if the net flux is positive. Figure 1 represents a cubic volume with dimensions of Δx, Δy, and Δz (m) (Lewis et al., 2004).

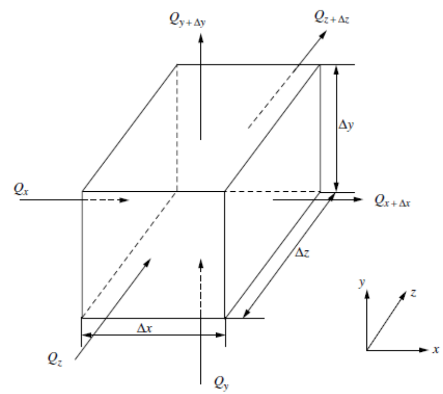


Figure 1 Representative Volume for Heat Conduction Analysis
(Lewis et al., 2004)

The strong form of conductive heat transfer is derived in equation (6),

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = \rho c \frac{\partial T}{\partial t} \quad (6)$$

The Galerkin weighted residual method can be applied to strong-form Equation (6) to conduct heat transfer FEA of a solid body (Lewis et al., 2004). Density (ρ), thermal conductivity (k), specific heat (c) are the properties of material that affect the heat transfer behavior in Equation (6). Higher density and specific heat require more heat energy for the cube to increase in temperature per unit time. On the other hand, higher thermal conductivity contributes to the necessity of less heat energy for the cube to increase the same amount of temperature per unit time (Lewis et al., 2004). This formation makes the basic of heat transfer in the FEA software used here.

REVIEW OF THERMOMECHANICAL FINITE ELEMENT MODELS

The research on finite element modeling of the thermomechanical behaviour of masonry wall subjected to fire or high temperature has begun in the 1990s (Salvatore Russo & Sciarretta, 2013). The purpose of modeling is to investigate the performance of masonry under high temperature and develop valid numerical modeling approaches. This section presents some of the earlier and recent works on finite element modeling of masonry.

One of the earliest finite element models for thermomechanical numerical modeling of masonry was created by Dhanasekar et al. (1994). The purpose of the study was to observe the bowing deformation of a masonry wall. The wall consisted of autoclaved concrete units and cement mortar, and their properties were obtained from previous experiments by other authors. The authors of this paper considered the temperature dependency of mechanical properties, including thermal expansion coefficient, tensile and compressive strength and elastic modulus.

In 2014, Nguyen and Meftah replicated the fire test of hollow clay brick masonry wall into three-dimensional thermomechanical finite element model. ISO 834 standard temperature fire curve was applied in the experiment. During the laboratory experiment, the walls were free to expand laterally, while the top of the wall was loaded through a steel beam. Only the right half of the wall was modeled due to the symmetry. The interface between the steel beam and the wall was modeled so that they are connected in compression only. The authors also implemented the spalling feature so that an element is removed during the analysis when its adjacent elements have failed in compression or tension. The analysis results showed similar spalling behaviour as the real experiment they conducted. However, the center deflection of the model was lower than the measured one. The authors stated that the discrepancy is possibly caused by the limitation of the material model to replicate the exact behaviour of hollow clay brick masonry (Nguyen & Meftah, 2014).

Russo and Sciarretta in 2014, conducted simulation of the masonry wall experiment they conducted previously, the experiment consisted of 51 cm by 51 cm by 25 cm brick wall samples tested inside a furnace at different high temperatures. Only one side of the wall sampled was fully exposed to the furnace temperature, while the other faces were insulated with fire-resistive rock wool cladding. Direct compressive tests or shear compressive tests were conducted on each sample after they were taken out from the furnace, and their crack patterns were studied. The experiment with the maximum furnace temperature was analysed using finite element method. The experiment procedure was replicated by applying fire load first, and them compression load at the top. The model was three-dimensional with units and joints modeled separately. The crack patterns of the real specimen and model were compared and were deemed to match well. The reduction in compressive strength of the wall after compressive test in the model was also in good agreement with the experimental results (Russo & Sciarretta, 2014).

While the works mentioned above mainly dealt with the masonry walls under the fire conditions, the main purpose of these works were to study the mechanical performance of regular masonry under high temperature in terms of the failure pattern, insulation for fire and residual mechanical strength of the masonry walls. Regarding refractory masonry, which is used for high temperature applications, it seems that the mechanical loads applied are rather small, when compared with the thermal loads.

Gruber and Harmuth in 2008, performed a numerical simulation on a unit-cell model to study the mechanical performance of the refractory brick in steel ladle linings. In steel ladles, the mechanical loads develop from the thermal expansion of the refractories which is confined either by the steel constructions on the outer side or by the regions of different temperatures within the refractory material. The main purpose of this study was the investigation of factors influencing the mechanical durability of refractory linings and the clarification of failure mechanisms. Especially irreversible strains at the hot face of the working lining caused by compressive stresses induce an opening of joints at the hot face. The investigations showed the relations between irreversible compressive strains at the hot face, opening of joints and the stability of the working lining. The controlled expansion seems to be a possible countermeasure to reduce the opening of joints and decrease the sensibility to tensile stresses. However, it was also observed that the necessary controlled expansion decreases with preheating of the ladle (Gruber & Harmuth, 2008).

Gasser et al in 2004, proposed a solution for the homogenization of masonry by studying the joint effects on the refractory lining. For the purpose of this study, the thermomechanical loads were simulated on an elementary cell using a model developed at the scale of bricks and joints, where joints were represented as contacts. The parameters for the homogenized materials were obtained for two dimensions where the material behaviour was orthotopic, elastic and non-linear depending on joint opening and closure. The parameters were determined by an inverse identification process and the developed model was validated by a thermomechanical test on an experimental structure (Gasser et al., 2004).

Nguyen et al in 2009, conducted a study with a goal to propose an equivalent material which has the same behaviour as masonry. The proposed equivalent material has four different behaviours depending on the local joint state, where each behaviour has been determined by homogenization techniques. The developed model was validated with a biaxial compression test on a masonry unit, and it was found to be in good agreement. It was also observed that the non-linear behaviour of the masonry was mainly due to the existence of different joint states in the whole lining rather than to the non-linear crushing of contact surfaces of bricks (Nguyen et al., 2009).

Andreev et al in 2012, performed laboratory scale tests and finite element modeling to study the compressive behaviour of dry joints in refractory ceramic masonry. Experimental joint closure was obtained for samples of two types of refractory bricks in wide temperature range. To study the influence of the joint geometry and the material stiffness, a finite element model of the joint was built. The experiments show that the observed exponential form of joint closure curve results from gradual closure of initially non-parallel surfaces. The stress needed to close the joint was found to be proportional to the material stiffness. It was also found that temperature influences the joint closure by changing the stiffness of material and by reducing the initial joint gap due to thermal expansion. The similar procedure and further development of homogenization theories was carried out by Rekik et al. (2015)

In some of the experiments and computational models, standard time-temperature fire curves from ISO 843 or national codes were applied, while for the special case of refractories the time-temperature load (recorded in service conditions) was applied according to its specific application as adopted by Gruber & Harmuth (2014) and other authors.

Based on the modeling decisions made in the previously presented studies, there are particular considerations to be made for preparing a finite element model for masonry. As for the geometry, a 2D or 3D model could be developed, depending on the boundary conditions of the structure. Units and joints can be modeled separately or homogenized into one composite material (Nguyen et al., 2009). However, homogenization might lead to a reduction of accuracy of the model (Russo & Sciarretta, 2014). Regarding the material behaviour in both compression and tension, all the previous authors use a linear behaviour in the pre-peak regime, while the post peak behaviour is either brittle or linear softening (in tension) and brittle or non-linear softening (in compression).

One of the difficulties of modeling masonry at elevated temperature is limited data the temperature-dependent thermal and mechanical properties of unit and mortar. In the previously discussed works, authors used temperature-dependent material properties by obtaining experimental data from units and mortars of the wall specimen on previous experimental campaigns, or by retrieving values of next closest material types from available literature, such as Eurocode. Most of the authors also have kept the same tensile and compression model curves and only changed the maximum strengths and strain values for elevated temperature. However, there is a possibility that the tensile and compressive behaviours may alter significantly at elevated temperature.

THERMO-MECHANICAL ANALYSIS OF REFRACTORY MASONRY WALL

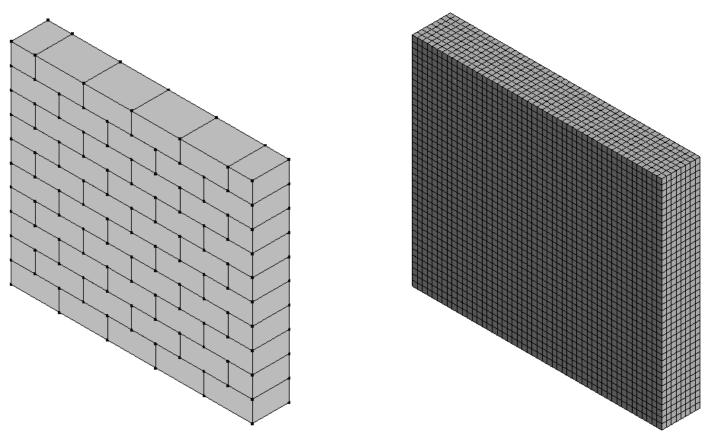
With the objective of preparing experimental campaigns on the thermo-mechanical behavior of refractory masonry panels, some preliminary numerical analyses were performed. These numerical analyses are essential to predict the range of acquisition equipment to be used during the experimental tests. The refractory material under the scope of this study is magnesia-chromite bricks with dry joints. The aim of these simulations is to predict the behavior of a masonry panel under both mechanical and thermal loads (Figure 2a).

As can be seen in Figure 2a, the units and the interface were modeled in a 3D model. The masonry wall has overall dimensions of 550 (L) x 84 (B) x 480 (H) mm, composed of brick units with 110 x 84 x 48 mm (full brick) and 55 x 84 x 48mm (half brick). The FEM model used in this work were built using 3D solid elements. The created FE mesh is composed of 16000 eight node isoparametric solid linear elements HX24L for the units and 5040 Q24IF plane quadrilateral elements for the interfaces. The final finite element mesh can be seen in Figure 2b.

Thermal and Mechanical Boundary conditions

An initial temperature of 25 °C was prescribed to the entire model. The standard time-temperature fire from EN 1991-1-2 (CEN, 2002) was applied as the thermal loading on the front side of the wall, and its convective and radiative fluxes were calculated using equations from EN 1991-1-2 (CEN, 2002). The duration of the fire exposure was set to 4 hours. This duration was deemed sufficiently long as the tabulated data of EN 1991-1-2 (CEN, 2002) only include up to 4 hours of fire resistance periods.

The back side of the wall is exposed to the constant external room temperature of 25 °C throughout the fire duration. The top and the bottom of the wall were assigned adiabatic boundary conditions. As per EN 1991-1-2 (CEN, 2002b), the emissivity of the units, ε, is taken as 0.8, and the coefficient of heat transfer, α, as 5 W/m^2K for the exposed face and 9 $W/m^2 K$ for convection on the unexposed face.



a) b)

Figure 2 - Refractory wall: a) 3D model; b) FE mesh.

As for the mechanical boundary conditions, the bottom of the wall is fixed in the all directions, assuming rigid and strong support. No support was assigned to the sides of the wall. While the top of the wall was subjected to a constant pre-compression load of 2.5 MPa (10% of the compressive strength at room temperature) throughout the entire simulation.

Thermal and Mechanical Material Properties

Magnesia-chromite refractory bricks, which can be used in furnace, kiln and steel ladle linings were chosen as the unit material. Magnesia-chromite bricks exhibits the lower wear rates and good corrosion resistance with low infiltration depth which makes these types of refractory suitable for application as the lining in Slag zone in steel ladles. The refractory bricks have temperature-dependent thermal and mechanical properties (Figure 3). These properties are presented in Table 1 and were obtained from Prietl (2006).

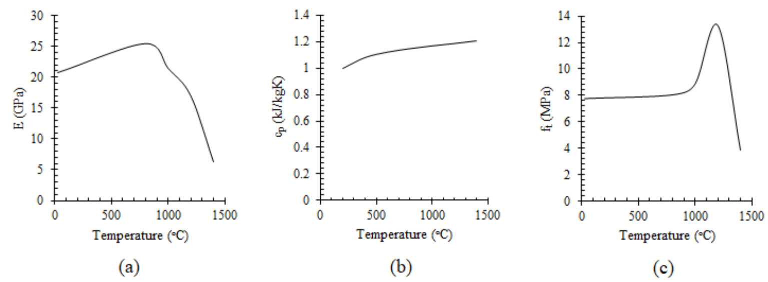


Figure 3 – (a) Young's Modulus-Temperature (b) Specific Heat-Temperature (c) Tensile Strength-Temperature plots

For the analysis, software DIANA was used, and total strain-based crack model was adopted as the constitutive material model for the analysis by using material parameters from Table 1 while assuming rotating crack behaviour. Parabolic and exponential stress-strain relations were used to describe the tensile and compressive behaviour respectively (Figure 4). The dry joints of the refractory masonry panel were modeled using Coulomb friction interface constitutive model from DIANA, for this model, the stiffness parameters were taken from Lourenço et al, 2005, while the values of cohesion, friction angle and Dilatancy angle were taken from the Landreau et al, 2011. The input properties are shown in Table 2.

Table 1 - Input material properties [*temperature dependent]

Property	Abbreviation	Parameter
Young's modulus	E	6.3 - 25.5 Gpa*
Poisson number	v	0.2
Density	ρ	3250 kg/m^3
Tensile Strength	f_t	3.88 - 13.26 Mpa*
Tensile fracture energy	G_f	0.131 - 0.766 N/mm*
Compressive strength	f_c	24.5 - 117.4 Mpa*
Compressive fracture energy	G_c	15.86 - 25.54 N/mm*
Thermal expansion	α	1 - 1.7 10^{-5} K^{-1*}
Conductivity	λ	3.26 - 3.48 W/mK*
Specific heat capacity	c_p	1 - 1.2 kJ/kgK*

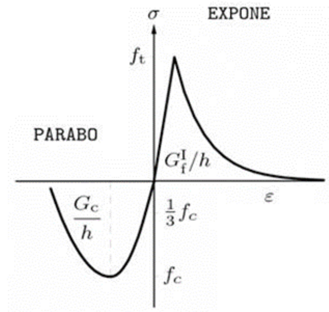


Figure 4 – Adopted behavior in compression and tension

Table 2 - Input interface properties for the simulation

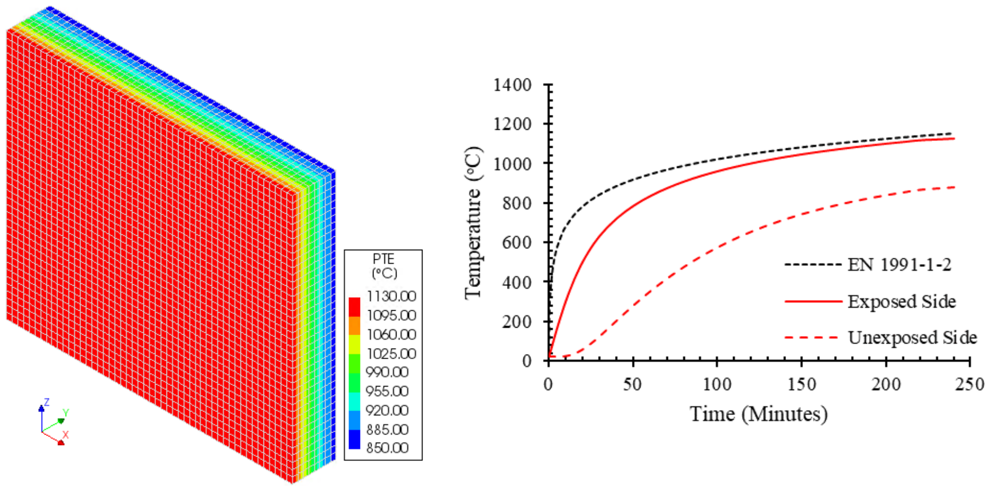
Property	Abbreviation	Parameter
Normal Stiffness-modulus	k_n	13 N/mm^3
Shear Stiffness-modulus	k_s	5 N/mm^3
Cohesion	c	0.48 N/mm^2
Friction angle	φ	42 degrees
Dilatancy angle	ψ	0 degrees

The equilibrium solution of the equations in each step of the non-linear heat transfer analysis is obtained using a Modified Newton-Raphson iterative method. The convergence tolerance was implemented so that the norm of the incremental temperature field increment of the last iteration step is lower than 1×10^{-6} of the reference temperature increment. The smallest time step used for the heat transfer analysis is 1 second, which was implemented for the first three minutes; no larger time step could be used at this initial period because the fire-exposed face of the model heats up the fastest with a sharp increase of standard time-temperature fire curve. A time step of 2 seconds was used until 5 minute-mark, 5 seconds until 15 minute-mark, 10 seconds until the 30 minute-mark, 30 seconds until 130-minute mark, and 60 seconds from until the end (4-hour mark).

The equilibrium solution of the equations in each step of the non-linear mechanical analysis is obtained using a Modified Newton-Raphson iterative method. The same time step from the heat transfer analysis was used for the mechanical analysis because the mechanical analysis calculates thermal stress and strain using temperature data of elements at each time step. Before conducting thermo-mechanical analysis, the wall was loaded with the vertical load at top and self-weight. For thermomechanical analysis, creep, geometric non-linearity and P-Delta effects were not considered.

Results & Interpretation

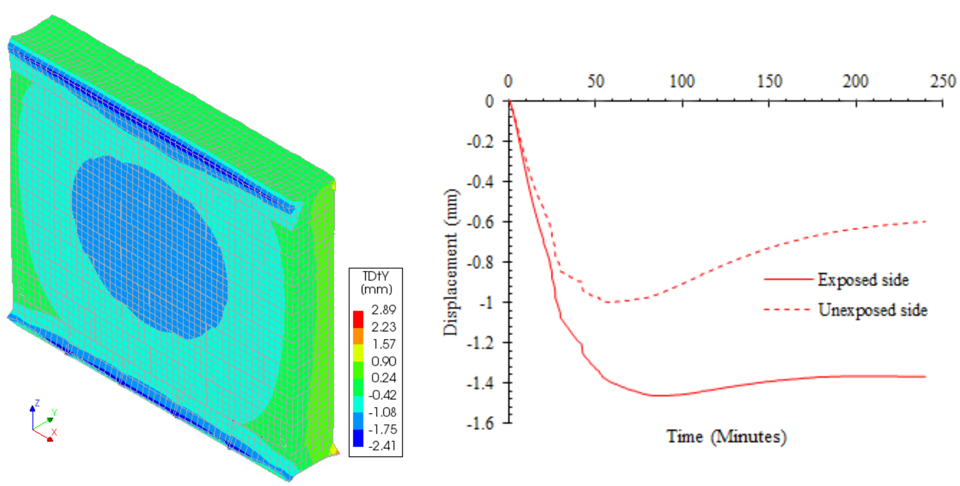
Firstly, as described previously, a heat transfer analysis was performed. From this analysis it is possible to obtain the temperature distributions in the refractory masonry wall during the entire simulation. Figure 5 presents the results of the heat transfer analysis, in terms of both: temperature fields (Figure 5a) and temperature curves (Figure 5b). From the obtained results it is possible to see that the difference of temperature between the faces and between the applied external temperature loadings can be observed to be directly proportional to the thermal conductivity and specific heat of the material.



a) b)

Figure 5 – Heat-tranfer analysis results: a) temperature distribution at 240-minutes; b) temperature profiles.

With the heat transfer analysis performed, a thermo-mechanical analysis was conducted using the temperature data obtained in the heat transfer analysis. Figure 6 shows the results of the thermo-mechanical analysis, in terms of both: out-of-plane displacement field (Figure 6a) and out-of-plane displacement profiles at the center point of each face. It is possible to see the buckling of wall towards the exposed side of masonry. From the temperature distribution on the wall and displacement, it can be noticed that this difference of displacement between both the faces are related to the thermal expansion of the material.



a) b)

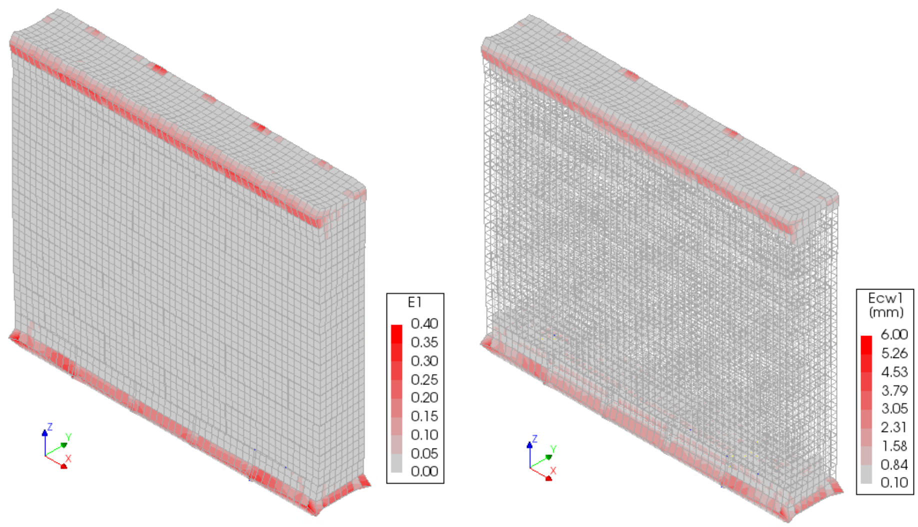
Figure 6 – Thermo-mechanical analysis results: a) out-of-plane displacement at 240-minutes; b) displacement profile at the center point of the wall.

Besides temperature and displacement fields, also the damage was studied. Figure 7 represents the damage of the masonry panel in terms of both: maximum principal strains (Figure 7a) and crack distribution (Figure

7b). It is possible to see that the strains at the 240-minutes are concentrated at the top and bottom part of the structure, similarly, crack distribution in the masonry wall can be noticed to be concentrated at top and bottom of the structure. This crack pattern has been similarly observed by other authors (Russo and Sciarretta, 2014). Although, from this analysis it was observed that the joint opening or sliding were not relevant, caution must be taken when analyzing these results, as the mechanical properties of the interface were considered non-temperature-dependent, and the values used in this model were not obtained for this particular material.

CONCLUSION

Numerical simulation of the refractory masonry wall panel shows the non-linear behavior of the structure and materials under high temperature. From this numerical analysis it is possible to observe the development of stresses and damage under the transient temperature loading conditions. Evolution of these stresses and damage were found to be in agreement with the experiments available in the literature performed on clay bricks. However, given the complexity and cost involved in testing at high temperatures, it was found that the tests are majorly performed on the brick units and tests on the refractory wall panels are scarcely available. Clearly, additional effort on the thermo-mechanical characterization of refractory masonry panels under high temperatures is required for proper calibration of the numerical models.



a) b)

Figure 7 – Thermo-mechanical analysis results: a) maximum principal strains distribution; b) crack distribution.

The results presented in this paper can be used to estimate the behaviour of a masonry wall under thermo-mechanical loading aiding the development of future thermo-mechanical experiments. With available experimental data it will be possible to properly calibrate numerical models using both micro modeling approaches (such as the models presented in this paper) and macro modeling approaches using a continuum medium with thermo-mechanical properties homogenized from the micro models and the experimental data.

ACKNOWLEDGMENT

This work was supported by the funding scheme of the European Commission, Marie Skłodowska-Curie Actions Innovative Training Networks in the framework of the project ATHOR - Advanced THermomechanical multiscale modelling of Refractory linings – 764987 Grant.

REFERENCES

Andreev, K, and H Harmuth. 2003. "FEM Simulation of the Thermo-Mechanical Behaviour and Failure of Refractories—a Case Study." *Journal of Materials Processing Technology* 143: 72–77.

Andreev, K, Sido Sinnema, A Rekik, Samir Allaoui, Eric Blond, and A Gasser. 2012. "Compressive Behaviour of Dry Joints in Refractory Ceramic Masonry." *Construction and Building Materials* 34: 402–8.

Damhof, F, W A M Brekelmans, and M G D Geers. 2011. "Predictive FEM Simulation of Thermal Shock Damage in the Refractory Lining of Steelmaking Installations." *Journal of Materials Processing Technology* 211 (12): 2091–2105.

Dhanasekar, M, VJGS Chandrasekaran, and S J Grubits. 1994. "A Numerical Model for the Thermal Bowing of Masonry Walls." In *Proceeding Tenth International Brick Masonry Conference*, 1093–1102.

DIANA-User's Maual Release 10.2. 2017. First edit. The Netherlands: DIANA FEA BV.

EN 1991-1-2 (2002) (English): Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire

Gasser, Alain, Kristin Terny-Rebeyrotte, and Philippe Boisse. 2004. "Modelling of Joint Effects on Refractory Lining Behaviour." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 218 (1): 19–28.

Gruber, D, K Andreev, and H Harmuth. 2004. "FEM Simulation of the Thermomechanical Behaviour of the Refractory Lining of a Blast Furnace." *Journal of Materials Processing Technology* 155: 1539–43.

Gruber, Dietmar, Kirill Andreev, and Harald Harmuth. 2004. "Optimisation of the Lining Design of a BOF Converter by Finite Element Simulations." *Steel Research International* 75 (7): 455–61.

Gruber, Dietmar, and Harald Harmuth. 2014. "Thermomechanical Behavior of Steel Ladle Linings and the Influence of Insulations." *Steel Research International* 85 (4): 512–18.

Gruber, Dietmar, and Harald Harmuth. 2008. "Durability of Brick Lined Steel Ladles from a Mechanical Point of View." *Steel Research International* 79 (12): 913–17.

Landreau, M, D Isler, A Gasser, E Blond, and J-L Daniel. 2011. "Modelling of a Coke Oven Heating Wall." In *6th European Coke and Ironmaking Congress 2011*, 20–25.

Lewis, Roland W, Perumal Nithiarasu, and Kankanhalli N Seetharamu. 2004. *Fundamentals of the Finite Element Method for Heat and Fluid Flow*. John Wiley & Sons.

Lourenço, Paulo B, Daniel V Oliveira, Pere Roca, and Agustin Orduña. 2005. "Dry Joint Stone Masonry Walls Subjected to In-Plane Combined Loading." *Journal of Structural Engineering* 131 (11): 1665–73.

Nguyen, T M H, E Blond, A Gasser, and T Prietl. 2009. "Mechanical Homogenisation of Masonry Wall without Mortar." *European Journal of Mechanics-A/Solids* 28 (3): 535–44.

Nguyen, Thê-Duong, and Fekri Meftah. 2014. "Behavior of Hollow Clay Brick Masonry Walls during Fire. Part 2: 3D Finite Element Modeling and Spalling Assessment." *Fire Safety Journal* 66: 35–45.

Nguyen, Thê-Duong, Fekri Meftah, Rabih Chammas, and Ahmed Mebarki. 2009. "The Behaviour of Masonry Walls Subjected to Fire: Modelling and Parametrical Studies in the Case of Hollow Burnt-Clay Bricks." *Fire Safety Journal* 44 (4): 629–41.

Prietl, Thomas. 2006. "Ermittlung Materialspezifischer Kennwerte von Feuerfesten Werkstoffen Und Zustellungen Unter Uni- Und Biaxialen Lastbedingungen Für Die Nichteisenmetallindustrie."

Rekik, Amna, Samir Allaoui, Alain Gasser, Eric Blond, Kirill Andreev, and Sido Sinnema. 2015. "Experiments and Nonlinear Homogenization Sustaining Mean-Field Theories for Refractory Mortarless Masonry: The Classical Secant Procedure and Its Improved Variants." *European Journal of Mechanics-A/Solids* 49: 67–81.

Russo, Salvatore, and Francesca Sciarretta. 2014. "Numerical Investigation on the Residual Behaviour of Masonry Walls Damaged by Fire Exposure." *Key Engineering Materials* 624.

Russo, Salvatore, and Francesca Sciarretta. 2013. "Masonry Exposed to High Temperatures: Mechanical Behaviour and Properties—an Overview." *Fire Safety Journal* 55: 69–86.

Santos, M F, M H Moreira, M G G Campos, PIBGB Pelissari, R A Angélico, E Y Sako, S Sinnema, and V C Pandolfelli. 2018. "Enhanced Numerical Tool to Evaluate Steel Ladle Thermal Losses." *Ceramics International* 44 (11): 12831–40.

Volkova, Olena, and Dieter Janke. 2003. "Modelling of Temperature Distribution in Refractory Ladle Lining for Steelmaking." *ISIJ International* 43 (8): 1185–90.

Wickström, Ulf. 2004. "Heat Transfer by Radiation and Convection in Fire Testing." *Fire and Materials* 28 (5): 411–15.