6º CILASCI – Congresso Ibero-Latino-Americano sobre Segurança contra Incêndio
Belo Horizonte, Brasil, 27 a 29 de outubro, 2021

NUMERICAL SIMULATIONS ON REFRACTORY LININGS FOR STEEL CASTING VESSELS

Rafael G. Oliveira*	João Paulo C. Rodrigues	João Miguel Pereira
PhD Fellow	Professor	PhD Researcher
University of Coimbra, Portugal	University of Coimbra, Portugal and Federal University of Minas Gerais, Brazil	University of Minho, Portugal

Keywords: refractory linings, creep, thermomechanical simulation, high temperatures

1. INTRODUCTION

The manufacturing of several materials adopted in industry, civil construction and our daily life has processes performed at high temperatures, such as melting and heat treatments. Thus, these production processes require products that resist to high temperatures, maintaining their physical and chemical properties in service. Refractory ceramics, due to their properties, have been used for this purpose, having crucial importance in high temperature processes. Refractory linings (composed of refractory ceramics) are used in industrial vessels to produce steel, iron, cement, non-ferrous metals, glass, metallic alloys, in melting process, in petrochemical industry, in incinerators, in mineral processing, in power plants and many other applications. The service temperature of these vessels is around 1650ºC for the steel ladles and 1450ºC for the cement kilns, however, some processes may reach 2000ºC (Poirier and Rigaud, 2017; Khlifi, 2019).

The refractory linings used in industrial furnaces and vessels perform different functions (Poirier and Rigaud, 2017):

- Barrier function: the refractory layers must guarantee personnel safety and protect the steel shell and the adjacent industrial facilities when operating at high temperatures.
- Container function: the lining shall confine solid, liquid or gaseous substances in the containers without altering their chemical composition.
- Thermal insulation function: the refractory linings shall contain the heat within the vessels and limit heat losses, contributing to the thermal efficiency of the industrial processes.

This paper presents the results of a large numerical simulations used to represent the thermomechanical behaviour of steel vessels. Different modelling techniques were used and the results detailed and discussed.

---

* Corresponding author: Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra. Rua Luís Reis Santos. Polo II da Universidade. 3030-788 Coimbra. PORTUGAL. e-mail: rafael.oliveira@uc.pt

Xia and Ahokainen (2001) developed a numerical model to analyse the transient heat transfer of a steel ladle in the course of the holding period. The refractory layers (working, safety and insulation) and the steel shell were bi-dimensionally modelled. The heat losses in the steel shell, in the molten steel and in the exposed faces of the refractory layers was considered. The numerical predictions were validated against experimental results measured in a pilot ladle. The study was focused only in the heat transfer analysis; the mechanical behaviour of the steel ladle was not considered.

Glaser et al (2011) carried out a study similar to the one performed by (Xia and Ahokainen, 2001) to analyse the fluid flow and the heat transfer in a steel ladle. The authors also have used a two dimensional model to predict the temperature fields in the molten steel and in the components of the steel ladle. The model was validated against industrial measurements using infrared cameras. The authors highlighted that the insulation layer plays the major role limiting the heat losses. Only the thermal fields were being analysed in this study, the mechanical behaviour of the steel ladle components was not analysed.

Although innovative results were presented by (Xia and Ahokainen, 2001; Glaser et al, 2011), the mechanical simulation of the vessel was not performed. In service, the refractory linings are prone to creep, corrosion, abrasion and fracture. The restrained elongation results in elevated compression stresses in the linings and tensile stresses in the steel shell. The accurate prediction of the strain and stresses are crucial for the correct design of the equipment.

Yilmaz (2013) extended the previous studies (Xia and Ahokainen, 2001; Glaser et al, 2011) incorporating the analysis of the mechanical fields on the numerical models. The authors have used a two-dimensional axisymmetric model. The simulation was carried-out using a sequentially coupled heat transfer-structural analysis. The geometry of the steel ladle was composed by a wear lining with different thickness at the barrel and at the slag line, one safety lining, one insulating lining and one steel shell. The mechanical boundary condition considered the ladle lifted by a crane, as usual in the steelmaking process. Temperature-dependent mechanical and thermal properties were considered for the materials. The displacement fields were calculated; the author have identified the biggest displacement in the bottom of the steel ladle, caused by the weight of the molten steel and the refractory lining.

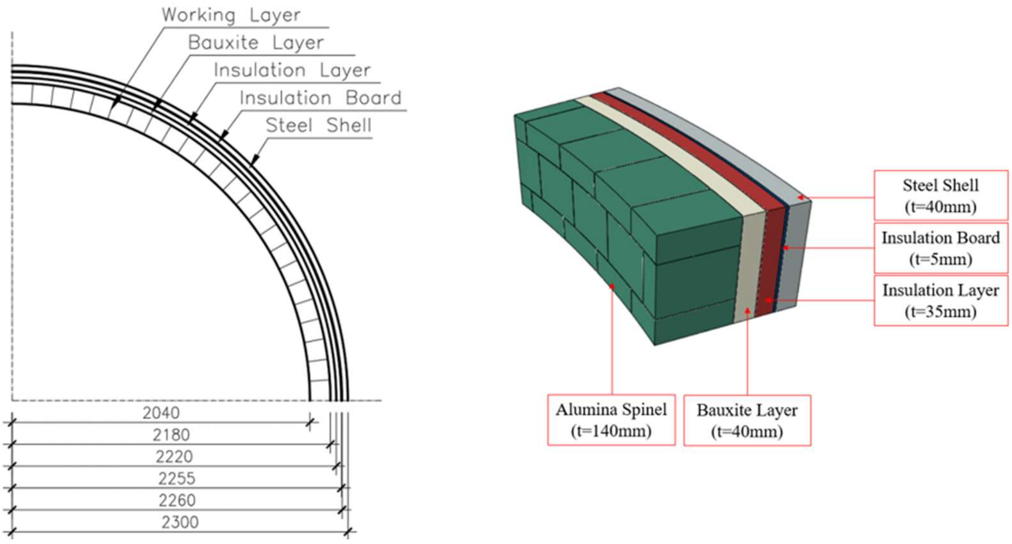
The model presented by the author was innovative, nevertheless, it did not take into account the transient heat flow of the process, as a steady-state analysis was performed to identify the temperature fields. Additionally, the author did not consider the viscoplastic strains in the refractory linings caused by relaxation.

Gasser et al (2013) used the homogenization techniques to evaluate the influence of different masonry designs of the bottom of the linings. The homogenizing techniques reduced significantly the computational effort required to run the simulations, thus, it was possible to use more detailed three-dimensional models in the numerical simulations. Different masonry designs could be used in the bottom of the steel ladle, the most used are the parallel, fish bone and radial. The authors aimed to benchmark the performance of these designs in terms of stress level and displacement in the steel shell. Therefore, homogenized models of steel ladles with different bottom designs were developed. The thermomechanical properties of the materials were taken as temperature dependent. The authors have also evaluated the influence of the presence of the joints and the influence of the joint thickness. It was observed that the presence

of joints reduced significantly the stresses generated in the steel shell, moreover, it was noticed that the radial design led to the smallest stress amplitudes in the steel shell.
Ali et al (2020) have used the homogenizing technique to simulate the thermomechanical behaviour of steel vessels. The developed constitutive model was validated against experimental results, and good agreement was observed. The homogenizing technique developed was used to simulate the transient thermomechanical behaviour of a steel ladle. Three operational cycles were simulated. The authors have performed a parametric study to analyse the impact of the joint presences and joint thickness in the overall behaviour of the ladle. An isotropic model (without joints) and models with different joint thickness (0.1 mm, 0.3 mm and 0.5 mm) were studied. The numerical predictions shown an orthotropic and nonlinear thermomechanical behaviour. The stresses originated from the restrained thermal elongation of the refractory lining decreased with the increasing in the joint thickness.

2. STEEL VESSELS MODELLING

This section presents a numerical simulation of a steel ladle under a full operational cycle. The geometry of the steel ladle is shown in Figure 1. The vessel is composed by a 140 mm thick working lining (alumina spinel), a 40 mm safety lining (bauxite layer), a 35 mm thick insulation lining (fire clay), a 5 mm insulation board (medium density) and a 40 mm thick steel shell. Aiming to reduce the computational time, the ladle was modelled as 15 degrees slice with axisymmetric boundary conditions.



a) b)

Figure 1 – Details of the steel ladle: a) Dimensions of the ladle, b) Details of the model

The steel ladle was submitted to a thermal cycle composed by: *i*) pre-heating from 40ºC to 600 ºC in one hour; ii) pre-heating from 600ºC to 1050ºC in 13 hours; *iii*) dwell time of 2 hours at 1050ºC; *iv*) steel pouring and treatment for 2.5 hours, in this period the temperature of the molten steel decreases from 1650ºC to 1550ºC; *v*) waiting time at 400ºC for 2 hours. The thermal cycle is detailed in Figure 2. The emissivity of the alumina spinel and the steel shell were taken as 0.70 (EN 1996-1.2, 2005; EN 1993-1-2, 2005). The convection coefficient was taken as 8 W/m^{2}ºC, as usually defined for natural convection.

The density and thermal elongation coefficient of the used materials were taken as non-temperature dependent and are presented in Table 1. The specific heat and the thermal conductivity are given in Figure 3. The Young's moduli are detailed in Figure 4 (Ali *et al*, 2021; Ali et al, 2020; Vitiello, 2021; Vitiello et al, 2019).

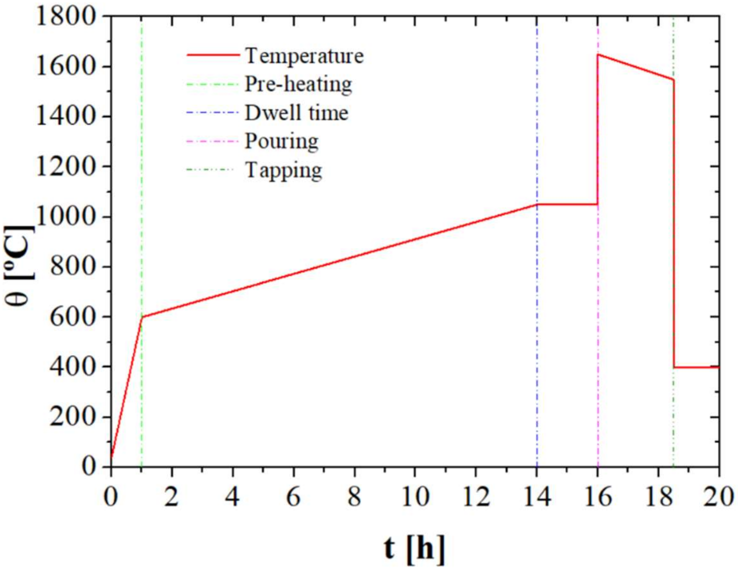
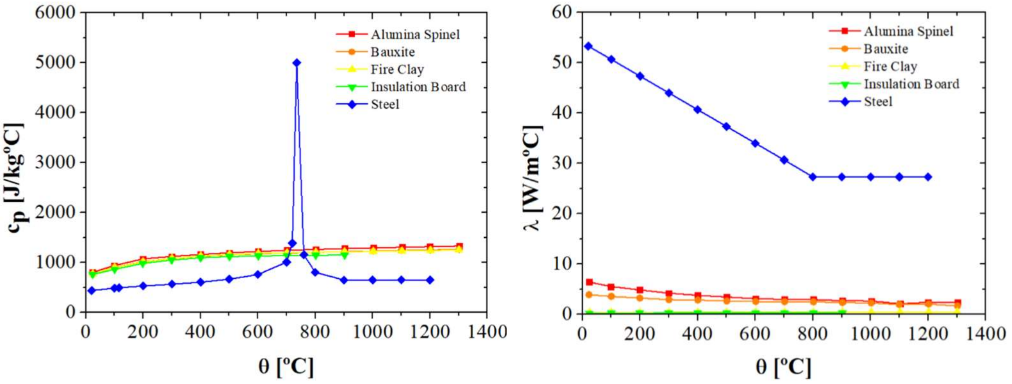


Figure 2 – Thermal cycle of the steel ladle

Table 1 – Materials' properties

Properties	Alumina Spinel	Bauxite	Fire Clay	Insulation Board	Steel
Density [kg/m^3]	3130	2680	857	998	7850
Thermal elongation coefficient [/ºC]	7.4×10^{-6}	7.8×10^{-6}	6.4×10^{-6}	9.3×10^{-6}	1.33×10^{-5}



a) b)

Figure 3 – Thermal properties of the materials: a) Specific heat; b) Thermal conductivity

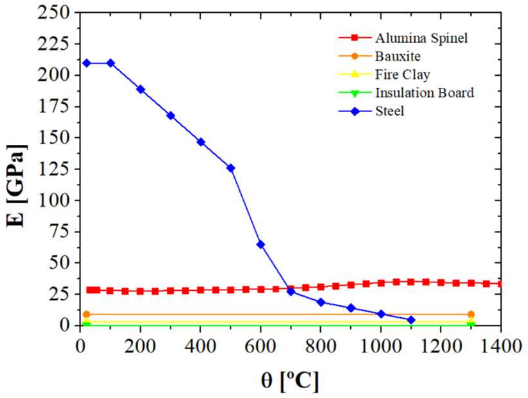


Figure 4 – Materials Young's moduli

3. NUMERICAL MODEL

A micro-modelling approach was chosen to represent the steel ladle. The bricks of the working lining were modelled separately and surface-to-surface contact interactions were used to represent their interactions. The masonry layers of the safety lining (bauxite) and insulation lining (fireclay) were built with thin-layer mortar, and they were assumed and modelled as a homogeneous material and their Young's moduli were calculated according to EN 1996-1-1 (2005). The general arrangement of the model is presented in Figure 5a. A sequentially coupled analysis was done. The DC3D8 elements were used for the heat transfer and the elements C3D8R for the mechanical analysis. A mesh study was performed and led to the element dimensions of approximately 20 mm. The adopted mesh is given in Figure 5b.

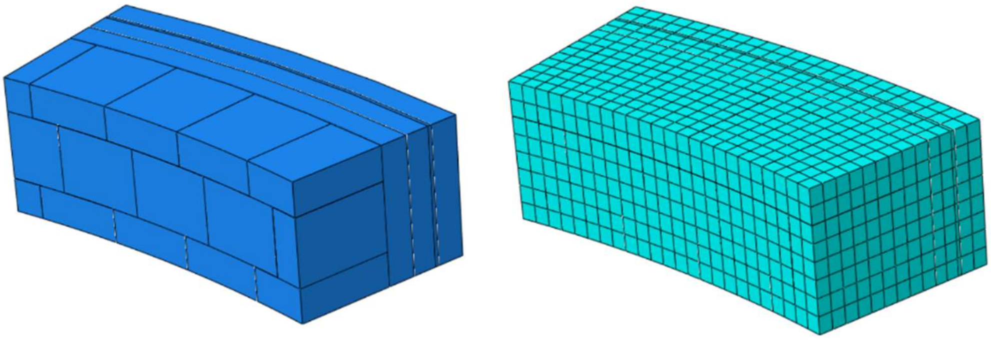

a) b)

Figure 5 – Details of the model: a) General arrangement, b) Mesh

The numerical simulations aimed to evaluate the influence of the modelling strategy in the thermomechanical behaviour of the linings, the following comparisons were done:

- Material modelling approach: elastic and visco-plastic;
- Joints modelling: hard contact and pressure-overclosure
- Young's modulus characterization: obtained by ultrasonic measurements and by compressive tests

Table 2 summarizes the performed simulations.

Table 2 – Materials properties

Model	Material Modelling	Joints	Young modulus
MAE.NJ.EUS	Elastic	Hard contact	Ultrasonic measurements
MAE.WJ.EUS	Elastic	Pressure-overclosure	Ultrasonic measurements
MAV.WJ.EUS	Visco-plastic	Pressure-overclosure	Ultrasonic measurements
MAV.WJ.ECT	Visco-plastic	Pressure-overclosure	Compressive tests

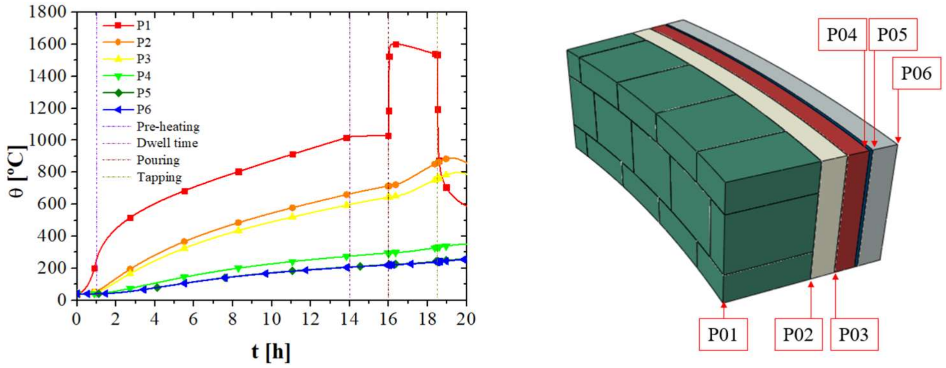
The numerical models were validated against the experimental results carried out by the authors and the results presented at Oliveira et al (2019) and Oliveira et al (2020).

4. RESULTS

The results of the analyses are presented and analysed in this section. The temperature fields are shown and analysed in detail. Lastly, the mechanical stresses developed in the refractory linings are presented and discussed.

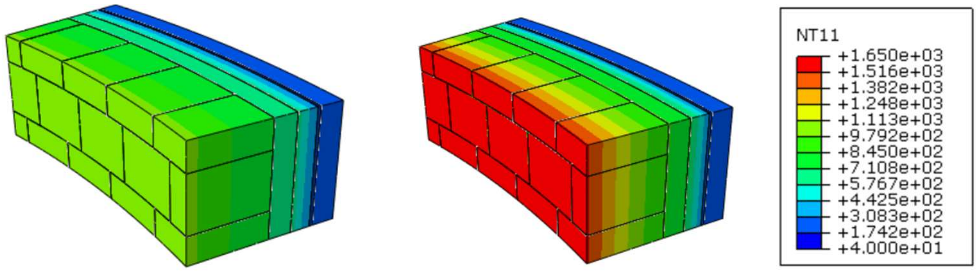
4.1 Temperature Fields

The temperature distribution obtained in the ladle is given in Figure 6. The maximum temperatures obtained in the working lining were 1603ºC at 16.3 h and 889ºC at 19.24 h, for the hot (P01) and cold (P02) face, respectively. The points P03 and P04 were submitted to temperatures up to 798ºC at 19.5 h and 351ºC at 20.1 h, respectively. The temperatures in the steel shell reached 260ºC by the end of the first cycle. The temperature gradient between P05 and P06 is negligible, due to the high thermal conductivity of the steel shell. Figure 7 presents the temperatures in the ladle immediately before the pouring and tapping.



a) b)

Figure 6 – Thermal response of the ladle: a) Temperatures, b) Location of the points

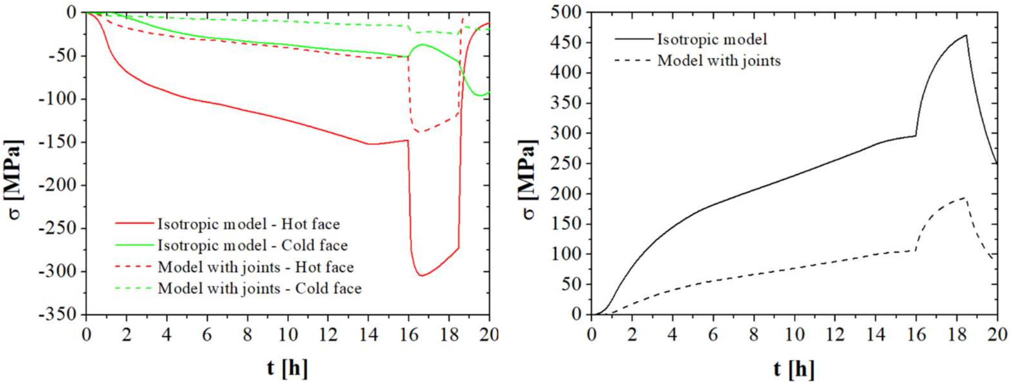


a) b) c)

Figure 7 – Temperatures in the ladle: a) Immediately before pouring, b) Immediately before tapping; c) Legend [in ºC]

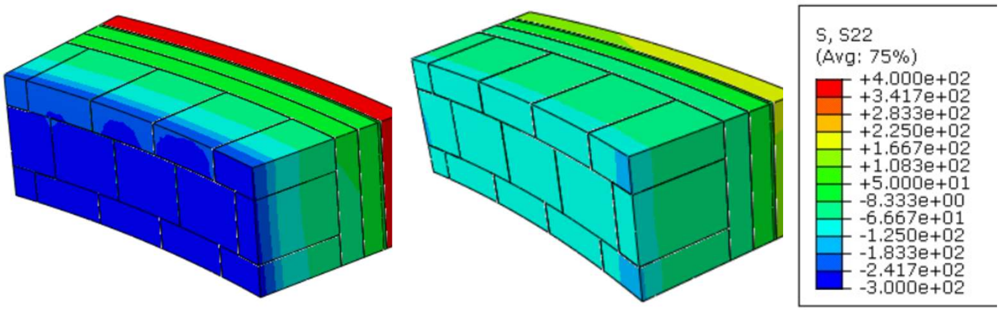
4.2 Stress Fields

The joints played an important role in dry-stacked refractory masonries reducing the stiffness of the linings and consequently reducing the compressive stresses developed in the working layer and the tensile stresses in the steel shell. The influence of the joints in a fully elastic model is being studied in this section. Figure 8 presents the stresses predicted by the numerical models of a isotropic ladle and a ladle with joints. A significant reduction of the stresses was observed in the model with the presence of the joints. When the joints are included in the analysis, the maximum compressive stress in the hot face of the working lining decreases from 304 MPa to 132 MPa, in the cold face the compressive stress decreases from 96 MPa to 24 MPa. The tensile stresses in the steel shell decreases from 463 MPa to 194 MPa. The stresses are plot in Figure 9 for both models.



a) b)

Figure 8 – Influence of the joints in the stresses developed in the ladle in a fully elastic model: a) Refractory lining; b) Steel Shell

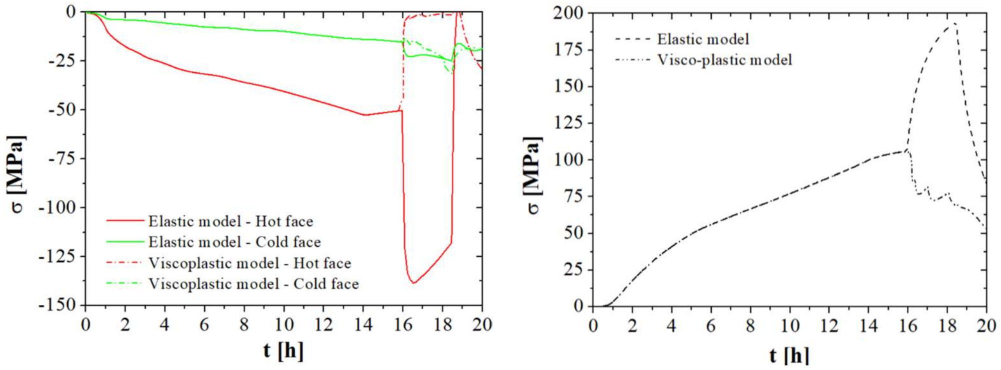


a) b) c)

Figure 9 – Tangential stresses in the ladle: a) Isotropic model; b) Model with joins; c) Legend [MPa]

In spite of the significant reduction, the stresses developed in the refractory lining are several times higher than the material's compressive strength. Additionally, the stresses developed in the steel shell would lead to the yielding of the material. To have a better idea of the behaviour of the steel ladle, it is necessary to include the visco-plastic effects caused by creep.

The influence of the creep strains in the stresses developed in the steel ladle are presented in Figure 10. The accounting of creep in the model results in a considerable stresses relief in the vessel. Due to the relaxation, the maximum compressive stress in the hot face of the working lining decreased from 132 MPa in the elastic model to 52 MPa in the visco-plastic model.

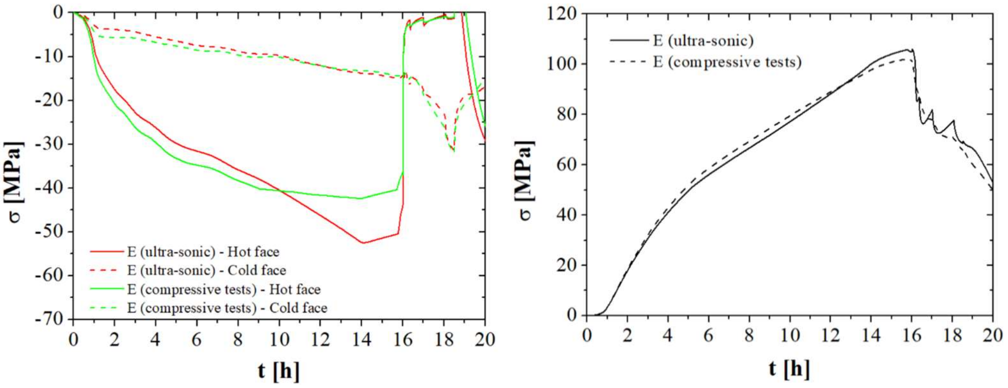


a) b)

Figure 10 – Influence of the creep in the stresses developed in the ladle with joints: a) Refractory lining; b) Steel Shell

The creep strains in the hot face resulted in a slightly increase of the stresses in the cold face. This phenomenon was also observed in the numerical simulation of the ladle, the visco-plastic strains resulted in an increasing of the compressive stresses in the cold face from 24 MPa to 31 MPa. The tensile stresses in the steel shell decreased from 194 MPa to 106 MPa.

The Young’s modulus of the refractory materials could be obtained by compressive tests or ultrasonic measurements. As stated by Andreev and Zinngrebe (2009), above 1200ºC it was possible to observe the weakening of the material in compressive tests, this weakening was not seen in the dynamic measurements of the Young’s modulus. The material was influenced by micro plastic events, which were responsible for the greater part of the deviations observed between both. Figure 11 shows the comparison of the stresses developed in the ladle for models accounting the Young’s modulus obtained by ultra-sonic technique and by compressive tests. It as possible to identify a slight reduction of the stresses in hot face from 52 MPa (ultra-sonic) to 42 MPa (compressive tests). The reduction of the stresses in the cold face and in the steel shell were not significant.



a) b)

Figure 11 – Influence of the Young's modulus in the stresses developed in the ladle: a) Refractory lining; b) Steel Shell

5. CONCLUSIONS

Based on the numerical simulations presented in this section, it was possible to draw the following conclusions:

- The account of the joint behaviour is really important for leading to reliable results of the stresses in the steel ladle. The model is sensible to the joint thickness curve used, therefore, it should be correctly determined based on compression tests in masonry wallets, as compressive tests in two stacked bricks may result in the underestimation of the joint closure curve.
- The visco-plastic strains developed in the working lining results in significant relief of the stresses (relaxation). Therefore, the creep properties of the material should be characterized under different temperatures, from 1000 ºC to 1500 ºC.
- The measurement of the Young's modulus by the ultrasonic technique resulted in values slightly higher than the ones obtained at the compressive tests, mostly for high temperatures. The ultrasonic technique does not account the effects of the micro plastic events that happen in the material's microstructure. Thus, the use of ultra-sonic measurements may result in the overestimation of the stresses in the ladle.
- The formulation recommended by Thanoon et al (2013) presents the evolution of the compressive stresses in the wall in terms of joint closure. The formulation was proven to be suitable to model the normal behaviour of dry joints presenting good results for the loading stage of the tests. However, this formulation may not be used to represent the residual strains on the unloading stage and, consequently, different models must be used to represent the loading and unloading of masonry.

- The use of the Norton-Bailey creep law led to good results in the numerical models. The models were validated against experimental results and a good agreement was observed between them. This creep law was able to represent the behaviour of refractory lining under uniaxial creep, biaxial creep and biaxial relaxation. Nevertheless, the development of asymmetric creep models is recommended (Teixeira et al, 2019; Teixeira et al, 2020).

REFERENCES

[1] Poirier J, Rigaud M. (2017) "*Corrosion of Refractories: The Fundamentals*". F.I.R.E Compendium Series; 450 p.

[2] Khlifi I. (2019) *"Optimisation of optical methods for strain field measurements dedicated to the characterisation of the fracture behaviour of refractories: application to magnesia based materials*". Material chemistry. PhD Thesis, University of Limoges, 182 p.

[3] Xia, Z.; Zhang, Y.; Ellyin, F. (2003) "*A unified periodical boundary conditions for representative volume elements of composites and applications*. Int. J. Solids Struct, 40, 1907–1921

[4] Glaser, B.; Görnerup, M.; Sichen, D. "*Fluid Flow and Heat Transfer in the Ladle during Teeming*". Steel Res.Int. 2011, 82, 827–835.

[5] Yilmaz, S. (2003) "*Thermomechanical Modelling for Refractory Lining of a Steel Ladle Lifted by Crane*". Steel Res. Int., 74, 485–490

[6] Gasser A, Genty F, Daniel JL, Chen L. "Influence of different masonry designs of bottom linings". In: 13th Unified International Technical Conference on Refractories (UNITECR); 2013. p. 775–80.

[7] Ali M, Sayet T, Gasser A, Blond E. (2020). "*Transient thermo-mechanical analysis of steel ladle refractory linings using mechanical homogenization approach*". Ceramics, 2:171–188.

[8] Ali M, Sayet T, Gasser A, Blond E. (2021). "*Computational Homogenization of Elastic-Viscoplastic Refractor Masonry with Dry Joints*". International Journal of Mechanical Sciences, 196:106275.

[9] European Committee for Standardisation. EN 1996-1.2 (2005), "Eurocode 6 – Design of masonry structures, Part 1.2: General rules Structural Fire Design", Brussels, Belgium.

[10] European Committee for Standardisation. EN 1993-1.2 (2005), "Eurocode 3 – EN 1993-1-2 (2005) (English): Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design", Brussels, Belgium.

[11] Vitiello, D., Smith, D., Nait-Ali, B., Doyen-Tessier, N., Tonessen, T. Laim, L., Rebouillat, L. (2019) "Thermal properties characterization of refractory materials used in the insulation layer of steel ladles". Unified Int Tech Conf Refractories, Yokohama, Japan:205–8.

[12] Vitiello, D. (2021) "*Thermo-physical properties of insulating refractory materials*". Material chemistry. PhD Thesis, University of Limoges, 136 p.

[13] European Committee for Standardisation. EN 1996-1.1 (2005), "*Eurocode 6 – Design of masonry structures, Part 1.1: General rules for reinforced and unreinforced masonry structures"*, Brussels, Belgium.

[14] Oliveira R, Rodrigues JP, Pereira JM. (2019) "*The characterization of joint behaviour in mortarless refractory masonry*". In: Proceedings of the Unified International Technical Conference of Refractories, Yokohama, Japan. p. 612–4.

[15] Oliveira R, Rodrigues, JP, Pereira, M, Lourenço, P, Marschall, H. (2021). "*Normal and tangential behaviour of dry joints in refractory masonry*" - Engineering Structures, vol. 243, 112600

[16] Oliveira R, Rodrigues, JP, Pereira, M, Lourenço, P, Marschall, H. (2021). "*Thermomechanical behaviour of refractory dry -stacked masonry walls under uniaxiall compression*" - Engineering Structures, Vol. 240, 112361

[17] Andreev K, Zinngreve, E. (2009). "*Compressive Behaviour of ACS torpedo bricks*". 11th Unified International Technical Conference on Refractories, UNITECR.

[18] Thanoon W, Alwathaf A, Noorzaei J, Jaafar M, Abdulkadir M. (2008) *"Finite element analysis of interlocking mortarless hollow block masonry prism*". Comput Struct; 86:520–8

[19] Teixeira L, Gillibert J, Blond E, Sayet T. (2019) *"Creep characterization of refractory materials at high temperatures using the Integrated Digital Image Correlation*". In: Unified International Technical Conference of Refractories, Yokohama, Japan: 899–902.

[20] Teixeira L, Samadi S, Gillibert J, Jin S, Sayet T, Gruber D, et al. (2020) *"Experimental investigation of the tension and compression creep behavior of alumina-spinel refractories at high temperatures*". Ceramics 2020;3(3):372–83.