Effect of Creep on Refractory Masonry Wall Subjected to Cyclic Temperature Loading

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Abstract

Refractory masonry in its application is usually exposed to chemical, thermal and mechanical loads in service. Mechanical loads develop from the thermal expansion of the refractories which is confined either by the regions of different temperature within the structure or by the boundary conditions. The aim of this work is to investigate, using numerical simulation, the influence of creep on the thermomechanical behavior of the refractory masonry. Different modeling approaches are used in order to produce thorough parametric and sensitivity studies. The investigation is specially focused on the adverse effect of creep on the stability of the masonry wall. The comparison is carried for different loading cycles by taking consideration of creep effect and without creep effect. The results presented in this paper provide, for specific boundary conditions and thermal loading, the evolution of out-of-plane displacement of the masonry wall while considering the effect of material specific primary creep at different high temperatures. For this specific case, it was found that the reduction in out-of-plane displacement due to creep is considerable and cannot be overlooked.

1. Introduction

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.

During the operational conditions, refractory materials are often exposed to the high thermomechanical loads resulting from the combined effects of thermal shocks, mechanical and thermal constraints Jin et al. (2011). Under such service conditions, refractories may exhibit elastic or inelastic behavior which depends on the duration and magnitudes of the thermal and mechanical loads as well as the behavior of the material itself. Inelastic behavior of refractories can be attributed to plastic behavior and creep effects at higher temperatures that are responsible for the irreversible deformation of the material and consequently to the overall behavior of the structure ,Andreev et al. (2003). The effects of creep on the thermomechanical behavior of refractory materials are widely researched both experimentally and numerically. However, the literature on the effect of creep on the overall behavior of a refractory masonry wall panels is scarcely available. This article is an effort towards overserving, numerically, the effect of creep on such masonry wall panels arising from cyclic high-temperature loadings.

2. Thermo-mechanical analysis of refractory masonry wall

With the aim of preparing for the experimental campaigns on the thermo-mechanical behavior of refractory masonry panels subjected to cyclic temperature loadings, some preliminary numerical analyses were carried out. These numerical simulations are essential to predict the range of acquisition equipment to be used during the experimental campaign as well as the critical locations of such acquisition points. The refractory material under the scope of this study is magnesia-chromite bricks with dry joints. The aim of these simulations is to observe the effect of primary creep on the behavior of a masonry panel under both mechanical and thermal loads
(**Figure 1**).

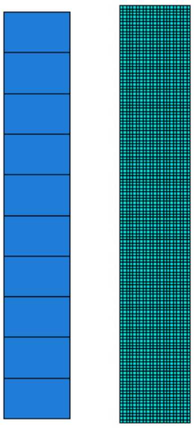

(a) (b)

Figure 1 – Refractory wall: a) 2D model; b) FE mesh

As can be seen in Figure 1(a), the units and the joints were modeled as 2D plane stress. The masonry wall has an overall height of 760mm and thickness of 124mm, composed of brick units with 124mm width and 76mm height.

2.1 Thermal and mechanical material properties

Magnesia-chromite refractory bricks, which can be used in furnace, kiln and steel linings were chosen as the unit material. Magnesia-chromite bricks exhibit 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. These properties are presented in **Table 1** and were obtained from Prietl (2006).

Dry joints between the brick units were modeled by considering the non-linear elasticity to represent the joint closing behavior of dry joints. Here overall initial joint opening of 0.12mm was considered and the normal pressure at which the joints closes was taken as 2 MPa, this joint closing behavior was reproduced from the experimental tests performed in Prietl (2006). However, this mechanism of joint closing was reproduced from the tests performed at room temperature and only the values of normal pressures obtained from that test are used in these simulations at high temperatures as well.

Table 1 - Input material properties [*temperature dependent]

Property	Parameter
Young's modulus	6.3 - 25.5 Gpa*
Poisson number	0.2
Density	3250 kg/m^3
Thermal expansion	1 - 1.7 10^{-5} K^{-1}*
Conductivity	3.26 - 3.48 W/mK*
Specific heat capacity	1 - 1.2 kJ/kgK*

In these numerical simulations, the primary creep behavior of magnesia-chromite brick is also considered. The Norton-Bailey creep law is used for this purpose. According to this law in strain hardening/softening formulation, the creep strain rate is a function of temperature, stress and creep strain.

$$\dot{\varepsilon}_{cr} = K(T) \cdot \sigma^{n} \cdot \varepsilon_{cr}^{a} \tag{1}$$

Here K is a temperature function, n the stress and a is the creep strain exponent. These parameters at different high temperatures for the refractory material used here were referred from Jin et al. (2014) and are shown in **Table 2**.

These parameters were further transformed into power law parameters as it is used in the Abaqus software package.

Table 2 - Norton-Bailey creep law parameters corresponding to different temperatures

Temperature (°C)	K (MPa^{-n}s^{-1})	n	a
1100	1.18×10^{-16}	2.86	-1.80
1200	2.77×10^{-16}		
1300	2.33×10^{-15}		
1400	1.24×10^{-11}		

2.2 Thermal and Mechanical boundary conditions

An initial temperature of 20 °C was prescribed to the entire model. The time-temperature profile as shown in **Figure 2**, was applied as the thermal loading on the front side of the wall, and heat transfer coefficient of 900 W/m^2/K was considered as to reproduce the forced convection on the high temperature exposed the face. The total duration for the analysis was 39 hours;

- Heating in 20 hours to 1200 °C.
- Dwelling for an hour at 1200 °C.
- Five heating and cooling cycles from 1200 °C to 1400 °C as shown in **Figure 2**.

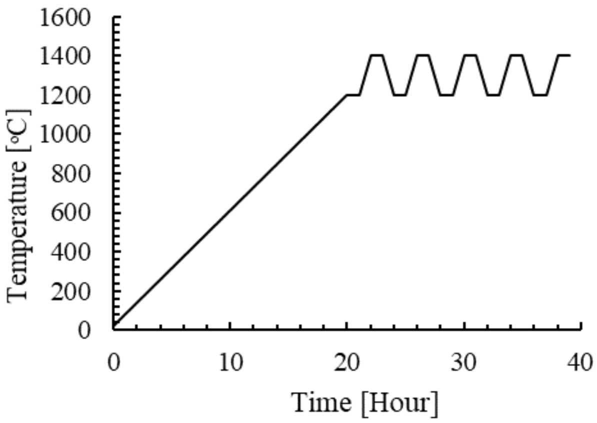


Figure 2 – Time-temperature profile

The back side of the wall is exposed to the constant external room temperature of 20 °C throughout the simulation. The top and the bottom of the wall were assigned adiabatic boundary conditions. The heat transfer coefficient at the back side was taken as 50 W/m^2/K as to reproduce the forced cooling at room temperature by external fans. While the radiation to ambient temperature was also considered at the back side of the wall with an emissivity of the units as 0.8.

As for the mechanical boundary conditions, the bottom of the wall is restrained for vertical and out-of-plane movements. While the top of the wall was subjected to a constant pre-compression load of 8.5MPa (10% of the compressive strength at room temperature) throughout the simulation.

2.2 Analysis procedure

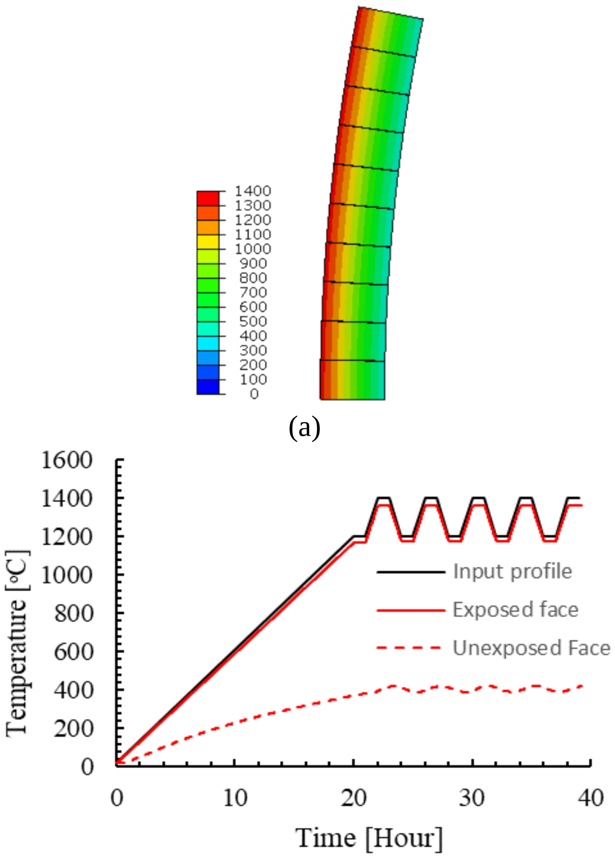
Analysis of these masonry wall panels was performed in Abaqus software. For the purpose of these simulations, a 2D plane stress representation of the 3D geometry was assumed. The created finite element mesh is composed of 2730 linear quadrilateral elements of type CPS4T which considers the coupled bilinear displacement and temperature.

The analyses were performed by using coupled transient temperature-displacement procedure available in the software.

3. Results and discussion

3.1 Temperature distribution

In coupled temperature-displacement analysis procedure, heat transfer analysis is performed simultaneously with the mechanical analysis. From heat transfer analysis, it is possible to obtain the temperature distributions in the refractory masonry wall during the entire simulation. **Figure 3** presents the results of this analysis in terms of both: temperature fields (**Figure 3a**) and temperature curves (**Figure 3b**). The same results in terms of temperature distributions were obtained for all the simulations.



(a)

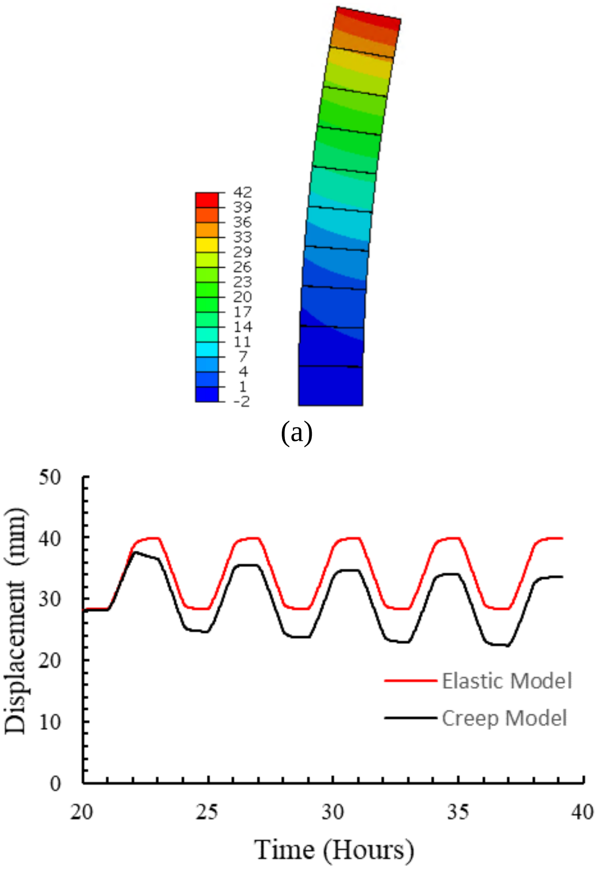
(b)

Figure 3 - a) temperature distribution at 39 hours; b) temperature profiles

3.2 Out-of-plane displacement

Figure 4 shows the results of the thermo-mechanical analysis, in terms of both: out-of-plane displacement field for the elastic model (**Figure 4a**) and out-of-plane displacement profiles at top of the wall at the exposed side, for both the model with elastic material properties and the model with creep parameters (Figure 4**b**).

From the displacement profile, it is possible to observe the effect of creep on the overall behavior of the masonry wall. The effect can be seen starting from the first cycle of the high thermal loading, where the effect of primary creep should be higher. However, from the results, it is also possible to notice that with each cycle, the decrease in displacement due to creep from the first cycle is getting lower. This can be attributed to the creep strain rate, which is more in the beginning.



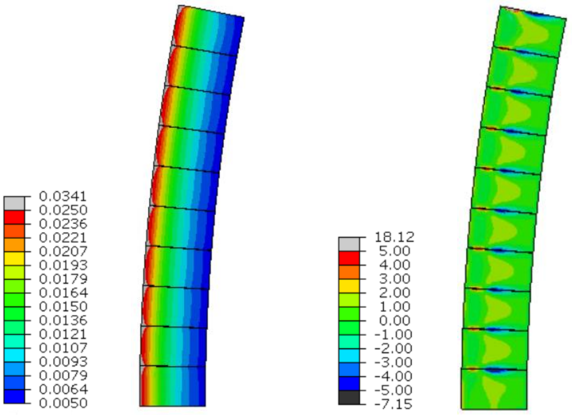
(a)

(b)

Figure 4 - a) out-of-plane displacement at 39 hours; b) displacement profiles for elastic model and creep model

3.2 Stress and strain distributions on model considering creep

Distributions of maximum principal stress and strain help in identifying the critical locations which might suffer damage under thermomechanical loadings. **Figure 5** shows the distribution of maximum principal stress (**Figure 5a**) and strain (**Figure 5b**).



(a) (b)

Figure 5 – a) Maximum principal total strain distribution; b) Maximum principal stress distribution

4 Conclusions

Numerical simulations of the refractory masonry wall panels show the considerable effect of creep on the behavior of the overall structure and materials under high cyclic temperature loadings. From these analyses considering the effects of creep, it is possible to observe the following.

(1) The reduction in out-of-plane displacement is mainly due to the primary compressive creep considered in the model.

(2) At the end of the analysis (i.e. 39th hour) the reduction in out-of-plane displacement is observed as 6.47 mm compared to the model with only elastic material properties.

(3) Out of this overall reductions, the major part can be observed in the first loading cycle which is 3.4 mm (52.55%).

(4) From consecutive loading cycles, the reductions are observed to be getting lower. In 2nd cycle 1.2mm (18.54%), 3rd cycle 0.76mm (11.74%), 4th cycle 0.6mm (9.27%) and at the end of 5th cycle 0.51 (7.9%).

From these simulations, it is possible to conclude that creep at high temperature plays an important role in the overall behavior of the masonry wall. However, it was found that the experimental and numerical tests on such masonry panels are scarcely available. Hence, additional efforts on the thermo-mechanical characterization of refractory masonry walls under high temperature are required for proper calibration of numerical models.

With available experimental data, it will be possible to calibrate the numerical models using the effects of creep on the overall behavior of the wall either using micro modeling approach (as presented in this article) and macro modeling approaches using a continuum medium.

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