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Comparison of Different Designs of Bottom Linings with Dry Joints

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Abstract

Many bottom linings of refractory structures used in steel making industry are made of masonries with or without mortar. Several designs are possible: parallel, fish bone or radial. To compare the influence of these designs on the maximum stresses in the steel shell, the masonry with dry joints was modelled by a homogeneous equivalent material that takes into account the possibility of joint closure. The thermo-mechanical properties of this equivalent material were determined using a periodic homogenization method. They depend on the joint states (open or closed in the two directions). The use of this equivalent material for the bottom lining of a steel ladle has shown that the design that minimizes the stresses in the steel shell is the radial design.

1. Introduction

In steel making industry, many bottom linings of refractory structures are made of masonries with or without mortar. Several designs can be used: parallel, fish bone or radial. To compare the influence of these designs on the maximum stresses in the steel shell, it is necessary to be able to build a finite element model of an industrial vessel submitted to thermo-mechanical loads. This model must take into account the presence of joints because they allow the decrease of stresses in the different parts of the vessel, in particular in the outside steel shell. To do this, two different approaches are possible[1)]: the micro-modelling which leads to modelling of each brick and joint with their own behaviour, and the macro-modelling that replaces them by a homogeneous equivalent material.

The micro-modelling strategy[2),3)] is the most accurate but its computational cost is very onerous as it requires to model separately bricks and mortar. In the macro-modelling alternative approach[4),5)], the whole masonry is represented by an equivalent continuum media. The large majority of the literature focuses on the periodic homogenization of masonries by Finite Element Method as proposed by Anthoine[6)].

In this study, the joint is assumed purely elastic and can only be closed or open. Then, the constitutive equation of equivalent material is linear elastic with different joint states like in the work of Luciano[7)]. The macro-modelling used herein is extensively presented in Nguyen *et al.*[8)] and briefly recalled hereafter.

2. Method

2.1 Homogeneous equivalent material

In this work, two types of joint are distinguished by their orientation (bed joints and head joints) and consequently four joint states can be identified in 2D as following:

- Joints are open in the two directions: the structure is totally discrete (state 1, **Fig. 1a**)
- Head joints are closed and bed joints are open: the structure is an array of separated bands (state 2, **Fig. 1b**)
- Head joints are open and bed joints are closed: the structure is a media containing distributed cracks (state 3, **Fig. 1c**)
- Joints are closed in the two directions: the structure is fully homogenous (state 4, **Fig. 1d**).

To each state above corresponds a different periodical masonry structure and thus corresponds a different equivalent behaviour.

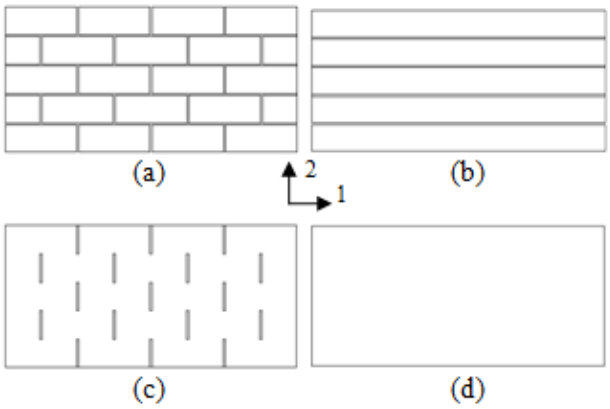


Figure 1 Periodical Representative Elementary Volumes corresponding to the four joint states: (a) state 1, (b) state 2, (c) state 3, (d) state 4.

Since the distribution of joints is different in the three directions, the equivalent material is assumed orthotropic. The behaviour of joints and bricks is assumed elastic, and so the equivalent material too. Since masonry arrangement is periodical, a periodical homogenization combined with an energy approach is well adapted. In order to evaluate the effective parameters, the strain energy bulk density is computed for the heterogeneous cell through finite element software and compared to the strain energy bulk density of the equivalent material submitted to the same load. Boundary conditions that must be applied on the cell are defined in regard to the expression of the bulk density of strain energy[8]. The homogenization is performed in the plane of the masonry, and the equivalent parameters

in the third direction are assumed to be equal to those of bricks. Conductivity and thermal expansion coefficients are also assumed to be equal to those of bricks.

2.2 Joint closure criteria

In mortarless masonries, there are two main reasons responsible for joint closure: first the deformation of bricks and second their sliding.

The first criterion for joint closure is based on the initial joint thickness g_n between the surfaces that are potentially in contact:

$$\left(\underline{u}^{(1)} - \underline{u}^{(2)}\right).\underline{n} = g_n \qquad (1)$$

Where $\underline{u}^{(1)}$ and $\underline{u}^{(2)}$ are the displacements of the middle points of the two surfaces and $\underline{n}$ is the normal vector to the two surfaces. This local criterion, to be used in the homogeneous equivalent material, must be expressed in function of global strains. Then, accounting that the effective behaviour of the equivalent continuous media is piece-wise linear, it is possible to write[8]:

$$\sum_{k=1}^{z}\left[{}^{k}m_{njp}^{1-2}\Delta E_{jp}^{k} - {}^{k}\theta_{n}^{1-2}\Delta T^{k}\right] = g_n \qquad (2)$$

Where z is the number of joint state changes in the cell and ΔE^k and ΔT^k are respectively the change of global strain tensor and the change of temperature during state number k. Parameters ${}^{k}m_{njp}^{1-2}$ and ${}^{k}\theta_{njp}^{1-2}$ are the components of the tensor which links the global strain and the temperature change to the local strain in state k. The superscript (1-2) denotes the solids which are concerned. Moreover, the Einstein convention for summation with twice repeated subscripts is used.

The second criterion, accounting for brick sliding possibilities, is based on the Coulomb friction law. In the same manner than for the displacement, the local inequality between the ratio of tangential to normal loads and the friction coefficient is expressed in term of global strains[8]:

$$\left|\int_S\left[\sum_{k=1}^{z}\left({}^{k}C_{ijpq}\,{}^{k}\Delta E_{pq} + {}^{k}P_{ij}\,{}^{k}\Delta T\right)\right]dS\right| \leq f_s\left|\int_S\left[\sum_{k=1}^{z}\left({}^{k}C_{iipq}\,{}^{k}\Delta E_{pq} + {}^{k}P_{ii}\,{}^{k}\Delta T\right)\right]dS\right| \qquad (3)$$

Where ${}^{k}C$ and ${}^{k}P$ are the tensors which link the macroscopic strain increment and the temperature increment to the local stress increments and S is the contact surface. This sliding criterion is only used in state 3 because no sliding occurs in the other states.

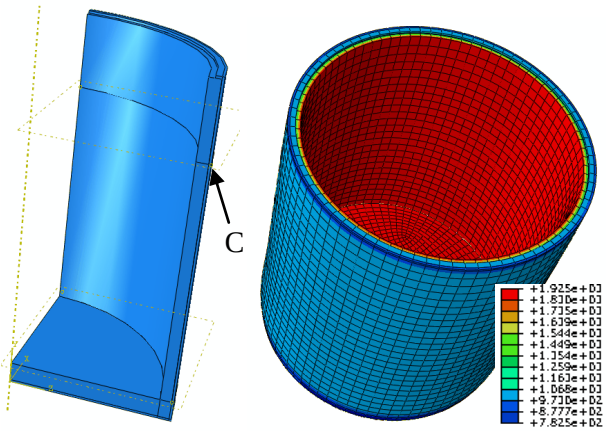
The parameters of these two criteria are determined using the same cell simulations that those used for the mechanical characteristic identification.

3. Model description

3.1 Steel ladle finite element model

A simplified steel ladle (**Fig. 2**) is taken as an example of vessel submitted to thermo-mechanical loading. It is made of:

- Steel shell: thickness 30mm
- Masonry wall made of refractory bricks without mortar: thickness 150mm, interior diameter 4m, height 4.5m
- Masonry bottom made of refractory bricks without mortar: thickness 250mm, diameter 4m.



(a) (b)

Fig. 2 (a) One quarter of the ladle model, (b) mesh and temperature field (°K) of the ladle.

In a first step, the temperature field is computed. A temperature of 1650°C is prescribed on surface edges of refractory linings. Convection ($h=5Wm^{-2}K^{-1}$) and radiation (e=0.7) are defined between the steel shell and the outside air (T=25°C). A perfect heat transfer is assumed between parts. The obtained temperature field is shown in **Fig. 2b**.

In a second step, a mechanical simulation is performed. The ladle is assumed to be suspended by his two trunnions. So, the vertical displacement at point C (see **Fig. 2a**) and his symmetric point is null. Contacts are defined between shell and wall lining, shell and bottom lining, wall and bottom lining with friction coefficient of 0.2. Gravity and computed temperature field are applied.

3.2 Materials

The shell is made of steel, while the wall and the bottom are made of refractory bricks of “material I” or “material II”. For simplification, their behaviours are assumed isotropic elastic linear, and only their thermo-mechanical properties at room temperature (**Table 1**) are used (to be more accurate, it is possible to determine an equivalent material depending on temperature[9]).

Table 1 Thermo-mechanical properties of materials.

	Material I	Material II	Steel
Young's modulus (GPa)	7.9	17	210
Poisson's ratio	0.2	0.2	0.3
Conductivity ($Wm^{-1}K^{-1}$) [1)]	10	10	46
Thermal expansion (10^{-6} °C^{-1})	11.3	9	12

3.3 Refractory lining modelling

Three designs of bottom linings are considered (**Fig. 3**): parallel, fish bone and radial. The same equivalent material is used for these three designs, but its orthotropic directions are different:

- Parallel: the whole part has the same orthotropic directions
- Fish bone: the part is divided in four quarters, and the orthotropic directions are rotated of an angle of 90° from one quarter to its neighbour
- Radial: orthotropic directions are the cylindrical axes. The use of the identified equivalent material in this case is an approximation because bricks are not parallelograms and the radius of curvature is lower near the centre of the part than on its edge. But it is a reasonable assumption as shown by Brulin *et al*[10].

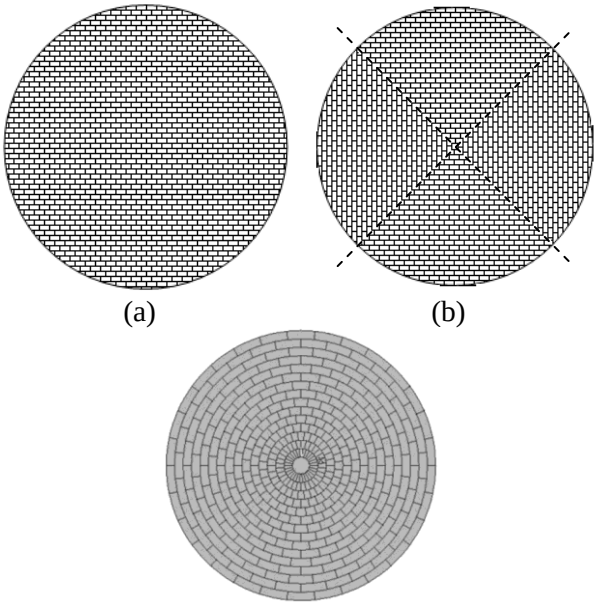


Fig. 3 Bottom lining designs: parallel (a), fish bone (b) and radial (c).

The brick size for bottom linings is: 250x160x100mm^3. To evaluate the influence of the joint thickness, two thicknesses are used: 0.1mm and 0.25mm.

In the aim to win computation time, the joints are not taken into account in the wall: the thermo-mechanical properties of the wall are those of bricks.

4. Results and discussion

The orthotropic mechanical properties of the equivalent material obtained for the four joint states by periodical homogenization are given in **Table 2**. When introduced in the ladle finite element model, it is possible to observe the progressive closure of bed and head joints in the bottom lining with increasing temperature (see for example **Fig. 4** for fish bone design).

Table 2 Orthotropic properties of equivalent material corresponding to material I.

	State 1	State 2	State 3	State 4
E_1 (GPa)	0	7.9	3.02	7.9
E_2 (GPa)	0	0	7.9	7.9
E_3 (GPa)	7.9	7.9	7.9	7.9
ν_{12}	0	0	0.076	0.2
ν_{13}	0	0.2	0.2	0.2
ν_{23}	0	0	0.2	0.2
G_{12} (GPa)	0	0	2.38	3.29
G_{13} (GPa)	3.29	3.29	3.29	3.29
G_{23} (GPa)	3.29	3.29	3.29	3.29

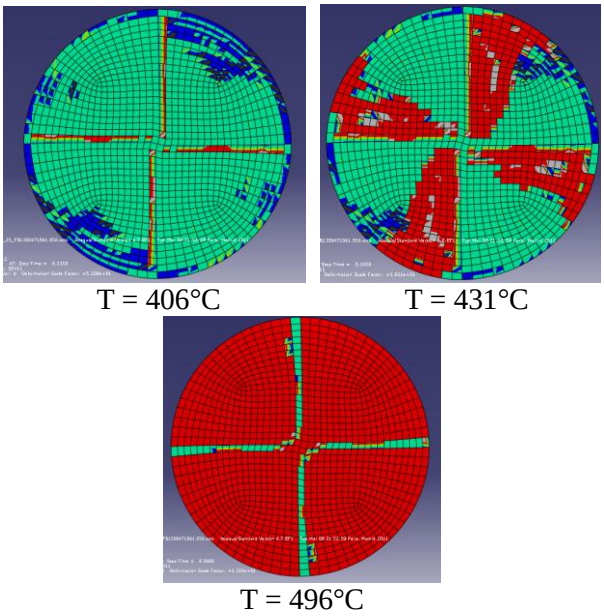


Fig. 4 Progressive joint closure with temperature increase at the top of a fish bone bottom lining: state 1 (blue), state 2 (cyan), state 3 (green) and state 4 (red) (See Fig. 1 for state description).

4.1 Influence of bottom designs

Von Mises stresses in the vertical part of the

steel shell (at the mid height of the bottom part) are compared along its circumference for the three bottom designs (**Fig. 5**). The parallel design presents the most important difference between minimum and maximum stresses (variation of 9%). The stresses for radial design are almost constant (they should be constant, but the small variation is due to computational approximations). The fish bone design gives intermediate results between parallel and radial. So the radial design allows the minimization of the maximum stresses in the steel shell.

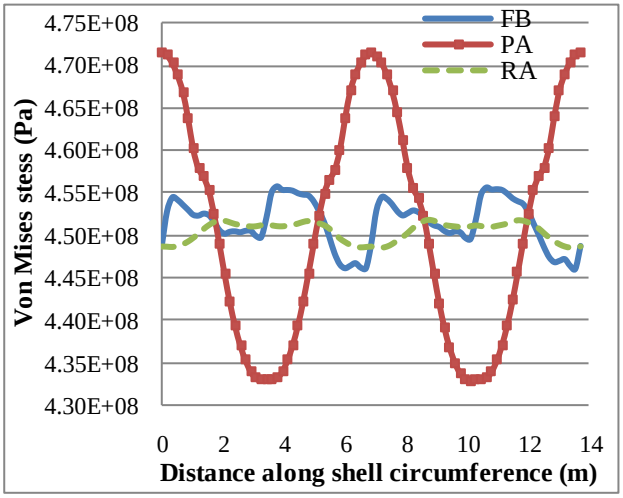


Figure 5 Von Mises stresses in the shell along its circumference for the three models (Material I, joint thickness of 0.25mm): parallel (PA), fish bone (FB) and radial (RA).

4.2 Influence of material and joint thickness

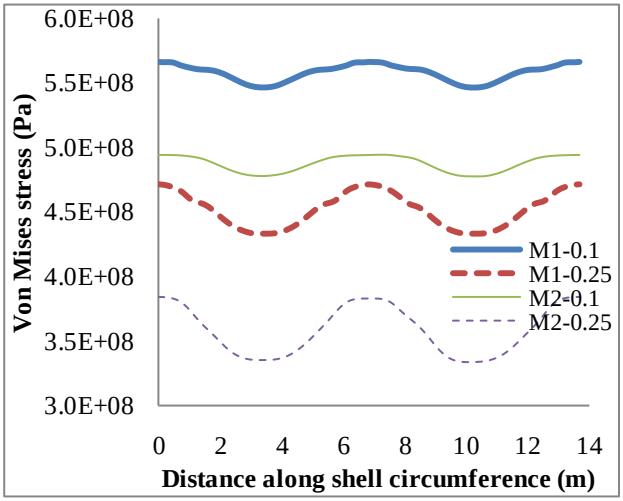


Figure 6 Comparison of Von Mises stresses along the shell circumference for material I (M1) and material II (M2) for joint thicknesses of 0.1mm and 0.25mm (parallel design).

Fig. 6 shows the influence of the material properties and the joint thickness on stresses in the shell. As expected, material I (with the highest thermal expansion coefficient) gives the highest stresses. It is also shown that higher the joint thickness is the lower the stresses are. Furthermore, the increase of the joint thickness causes the increase of the stress variation along the shell circumference because the number of joints is not the same in all directions (except for radial design).

5 Conclusions

The orthotropic behaviour of a material equivalent to a refractory masonry was determined for each joint state using a periodic homogenization method. A closure criterion allows the computation of the joint state. This equivalent material was used for the bottom lining of a steel ladle to determine stresses in the steel shell. The influence of the bottom design, the joint thickness and the material was studied. It was observed that to decrease the maximum stress value, a radial design with large joints and low material thermal expansion is the best solution.

The model will be improved taking into account the temperature effects on material properties: the elastic properties of the equivalent material can be determined for several temperatures, and the non linear refractory behaviour at high temperature will be introduced using a non linear homogenization technique.

Acknowledgements

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