Thermomechanical Modelling of a Steel Ladle Using Periodical Homogenisation for the Refractory Masonries

A. Gasser, E. Blond, N. Yahmi, L. B. Teixeira, S. Sinnema

In the steelmaking industry and in many others that involve the processing of molten metal, the metallurgical vessels can be lined with refractory bricks, with or without mortar. These refractory masonries can have different designs (for example parallel or radial for a bottom lining) with different joint thicknesses. The design of these linings poses a complex problem, since the bricks/joints subsystem imposes considerable computational problems due to the large amount of interfaces between them. To compare the influence of these designs on the maximum stresses in the structure, the masonry with dry joints was modelled by a homogeneous equivalent material that takes into account the possibility of joint closure. The thermomechanical properties of this equivalent material were determined using a periodic homogenization method. They are temperature depending and depend in the same time of the joint states (open or closed in the two directions). This masonry model was used to simulate the problem of a complete steel ladle with the finite element method, considering the insulating, safety and working (masonry) linings. It demonstrates the influence of the following parameters: (a) presence or not of joints, (b) thickness of joints, and (c) masonry design. This study brings a help for the design of refractory masonry linings and provides a better estimation of the applicability of a given lining to the thermomechanical loads imposed by operational conditions.

1 Introduction

In steel making industry, many metallurgical vessels are lined using refractory masonries with or without mortar. It is well known that the expansion allowance provided by joints is necessary to obtain stress levels that can be securely sustained by the materials, which usually have low mechanical resistance. In this context, the engineering calculations should, when possible, take into account this stress reducing effect, otherwise the calculation's accuracy is reduced, which can lead to misunderstandings of the product operational cycle.

To determine the influence of different masonry designs on the stresses in the structure, it is necessary to be able to build a finite element model of an industrial vessel subjected to thermomechanical loads. This model must take into account the presence of joints. For these considerations, two different approaches are possible: the micro-modelling which leads to model each brick and joint with their own behaviour, and the macro-modelling that simulates them by a homogeneous equivalent material.

The micro-modelling strategy [1] 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 [2, 3], the whole masonry is represented by an equivalent continuum media. The large majority of the literature focuses on the periodic homogenisation of masonries by Finite Element Method as proposed by Anthoine [4] for example. In this study, joints and bricks are assumed purely elastic. A periodic homogenisation allows the computation of the equivalent behaviour of the masonry. In the case of mortarless joints (also called dry joints), these joints can only be closed or open. Then, the constitutive equation of equivalent material is linear elastic with different

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joint states like in the work of Luciano and Sacco [5]. The macro-modelling used herein is extensively presented in Nguyen et al. [6] and briefly recalled hereafter.

This model is then used to simulate the behaviour of a complete steel ladle subjected to high temperatures. Different initial dry joint thicknesses were simulated for the wall and bottom linings, comparing the stresses obtained in the refractories and in the steel shell in each configuration.

2 Homogeneous equivalent material

2.1 Masonry joint state

Here, two types of joint are distinguished by their orientation (bed joints and head joints) and consequently four joint states can be identified in a 2D plane as following (no joints are considered in the third direction):

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

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

2.2 Homogeneous equivalent masonry behaviour

Since the distribution of joints is different in the three directions, the homogeneous equivalent material of the masonry is assumed orthotropic. The behaviour of joints and bricks is assumed elastic, and so the equivalent material too with 9 elastic parameters for each joint state: three Young's modulus (E_1, E_2, E_3), three Poisson's ratios (ν_{12}, ν_{13}, ν_{23}) and three shear modulus (G_{12}, G_{13}, G_{23}). For three joint states, these parameters are easy to determine (Tab. 1):

- State 1: all joints are open, there is no stiffness in the plane 12,
- State 4: all joints are closed, it is the behaviour of the bricks,
- State 2: head joints are closed and bed joints are open, there is no stiffness in direction 2, and the stiffness in direction 1 is the stiffness of the bricks (see Fig. 1 b).

So, only state 3 needs the use of a homogenisation technique.

Since masonry arrangement is periodic (Fig. 2), a Periodical Linear Homogenisation (PLH) combined with an energy approach is well adapted for state 3. In order to evaluate the effective parameters, the strain en-

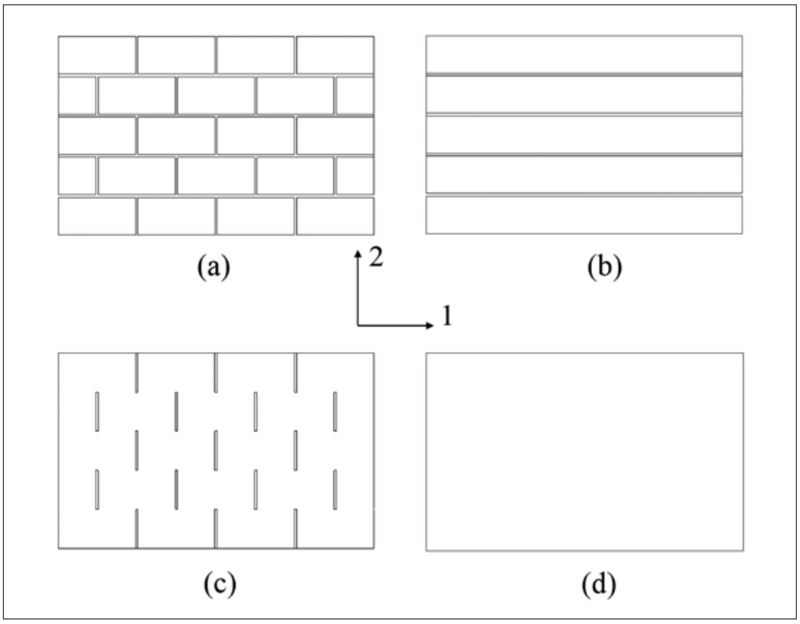

Fig. 1 a–d Joint states: (a) state 1, (b) state 2, (c) state 3, and (d) state 4

Tab. 1 Elastic orthotropic parameters of the homogeneous equivalent material (E_b, ν_b, G_b are the brick elastic isotropic properties, with $G_b = \frac{E_b}{2(1+\nu_b)}$)

	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
State 1	0	0	E_b	0	0	0	0	G_b	G_b
State 2	E_b	0	E_b	0	ν_b	0	0	G_b	G_b
State 4	E_b	E_b	E_b	ν_b	ν_b	ν_b	G_b	G_b	G_b

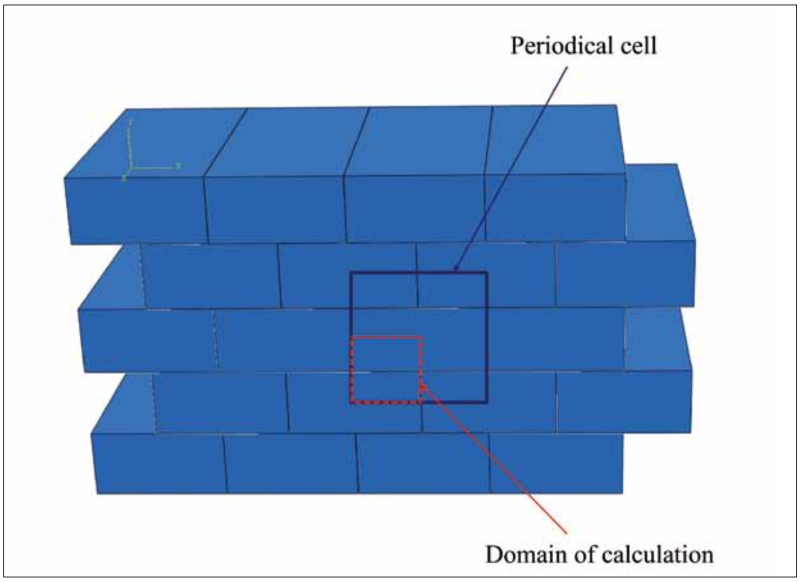

Fig. 2 Flat masonry, periodical cell (solid line), and domain of calculation (dashed line)

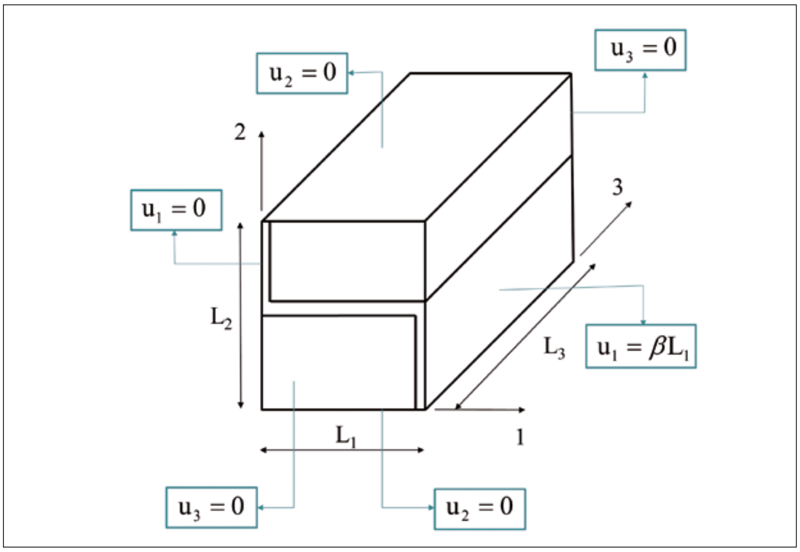

Fig. 3 Domain of calculation submitted to tension load in direction 1, and boundary conditions

ergy bulk density is computed for the heterogeneous cell through a finite element software for 9 different loads (three tension, three biaxial tension and three shear loads). The obtained strain energies are compared to the strain energy bulk density of the equivalent material submitted to the same load to obtain the nine parameters of the orthotropic equivalent material. Boundary conditions that must be applied on the domain of calculation (one quarter of the periodical cell, due to the two symmetries, Fig. 2) are defined to respect the symmetry and periodic conditions [6]. One example is given Fig. 3 for a tension load in direction 1. The mechanical properties of the equivalent material are computed for each temperature.

Conductivity and thermal expansion coefficients are assumed to be equal to those of bricks.

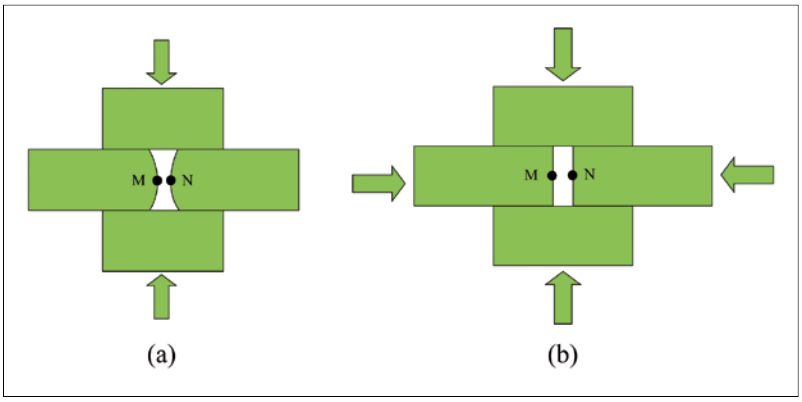

Fig. 4 a–b Origins of joint closure: (a) transverse brick deformation (Poisson's strain effect), and (b) normal brick deformation, and brick sliding

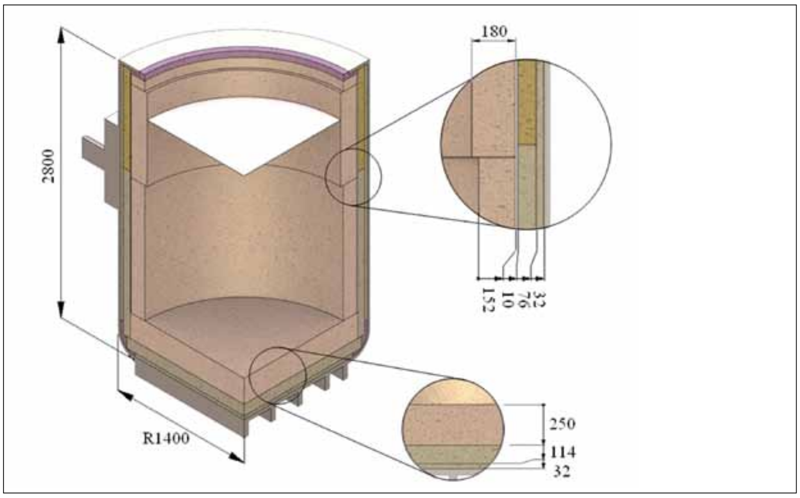

Fig. 5 Steel ladle model

2.3 Joint closure criteria

To each joint state corresponds a different periodical masonry structure and thus corresponds a different equivalent behaviour. To determine in which state the mortarless masonry is, it is necessary to have a joint closure criterion. There are two main reasons responsible for joint closure: first the deformation of bricks and second their sliding (Fig. 4).

The first criterion for joint closure is based on the initial joint thickness between the surfaces that are potentially in contact. This local criterion, to be used in the homogeneous equivalent material, must be expressed in function of global strains [6].

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 [6].

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

This sliding criterion is only used in state 3 because no sliding occurs in the other states.

3 Steel ladle modelling

In this study a complete steel ladle was simulated. The refractory lining of this ladle contains a working layer, a backfill, and two safety layers. A ramming mix with approximated material properties was considered to fill the empty spaces between the safety layers and the bottom plate, and also between the working layer and the border plate. All the refractories of the working line (masonries with joints without mortar) were homogenized using the PLH technique, and the other linings were considered to be monolithic blocks. The brick size for the working layers is 160 mm × 100 mm in the hot face, varying only in the thickness dimension. The general ladle dimensions and layer's thicknesses are represented in Fig. 5, in millimetres. This figure also shows the height of the slag in the model.

The ladle was considered to be hold by the trunnions. To reduce the computational time, only one quarter of the ladle was modelled (due to two plane symmetries) and the steel shell was modelled using shell elements. The wall plate was considered to have a thickness of 25 mm and the bottom plate a thickness of 30 mm. The refractories and the trunnion were modelled using solid elements. For simplicity, since the homogenization induces a considerable non linearity in the model, nonlinear contacts were used only between the working line of the bottom and of the wall, with friction coefficient of 0,2.

A steady-state temperature load was applied at the ladle, as shown in Fig. 6. To calculate the temperature's field an internal temperature of 1600 °C was applied, and in the steel shell a temperature varying convection coefficient and a radiation to ambient (ε = 0,85, ambient temperature = 35 °C) were considered. It is important to notice that during operation a real steel ladle may not achieve the steady-state, so the joints closing may vary according to the time from operation beginning.

As explained above, the orthotropic material's properties in the linear homogenization case are defined for each joint state, and updated according to the changing of state due to loading. For the present case, the cylindrical lining domain of calculation (DOC) was approximated by a flat DOC.

Four different configurations were modelled: without joints, dry joints of 0,1 mm, 0,3 mm and 0,5 mm. These joints can appear due to imperfections in the bricks surfaces in a way that, even if they are in initial contact during the assemblage of the lining, some thermal expansion can occur without meaningful stress generation.

All refractory materials were considered to have a Poisson's ratio of 0,2. The evolution of Young's modulus with temperature for each material is shown in Fig. 7. As can be observed, the material used in the safety lining of the slag zone is much stiffer than the others, and the Young's modulus is not available for all materials at the entire range of temperatures.

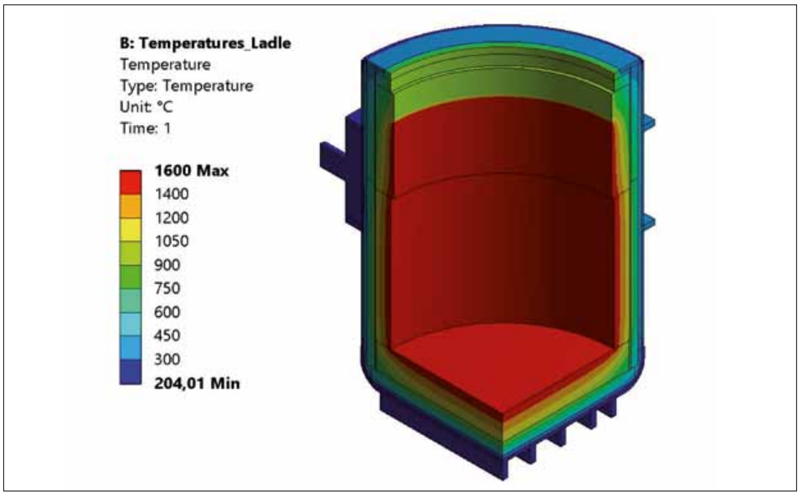

Fig. 6 Temperature distribution in the steel ladle

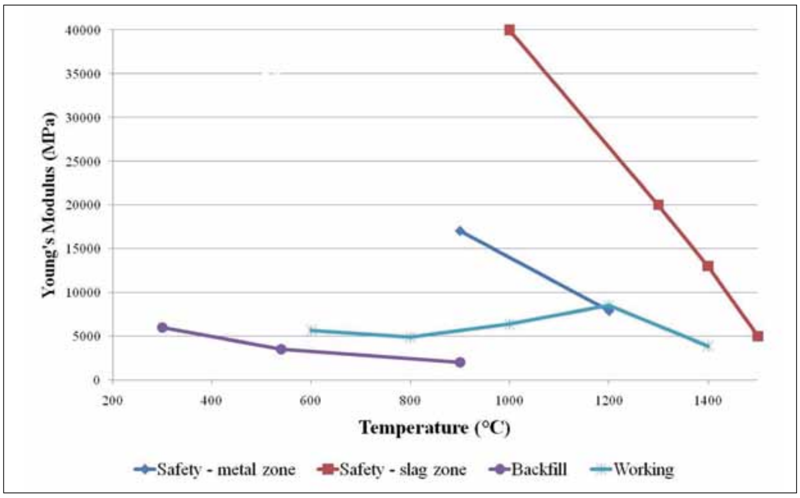

Fig. 7 Young's modulus evolution versus temperature for the different materials of the steel ladle

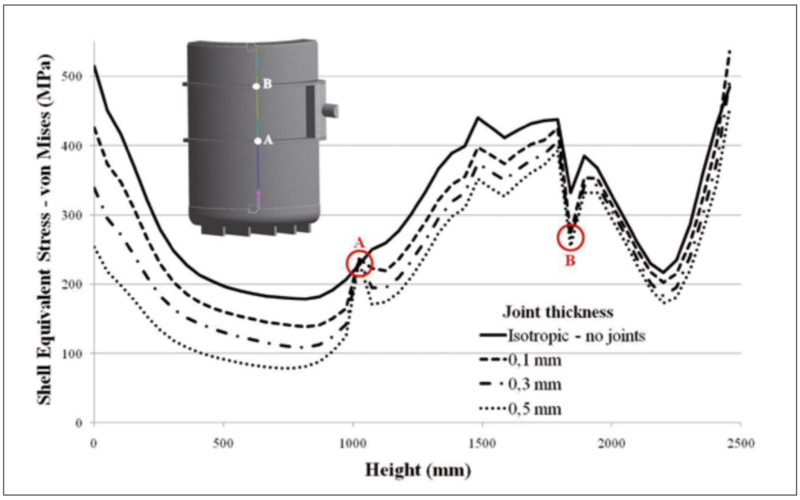

Fig. 8 von Mises equivalent stress in a vertical line of the steel shell

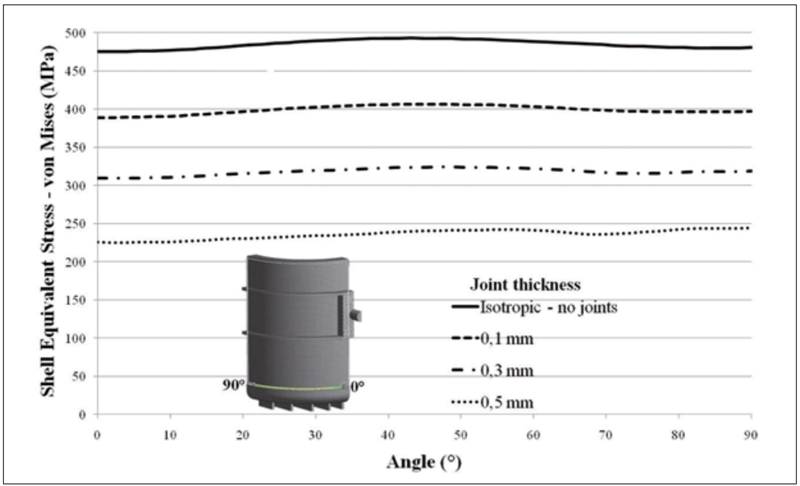

Fig. 9 von Mises equivalent stress in a circumferential line of the steel shell (at the mid-height of the bottom lining)

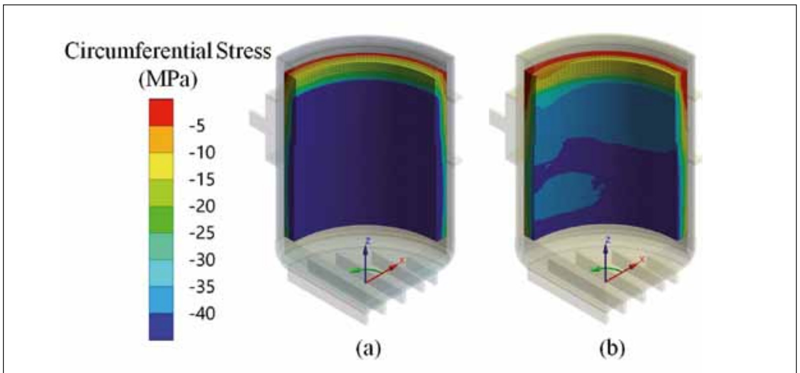

Fig. 10 Circumferential stresses in the refractory wall: (a) 0,1 mm joints, and (b) 0,5 mm joints

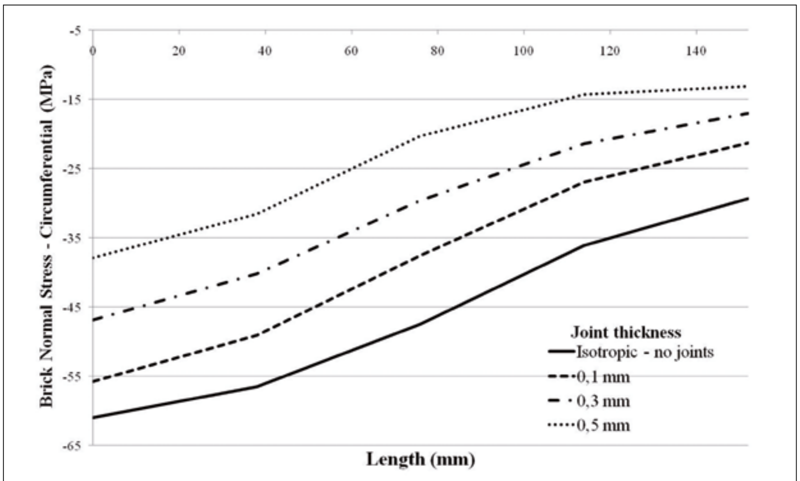

Fig. 11 Circumferential stress variation in the refractory wall thickness

4 Results and discussion

Fig. 8 shows the von Mises equivalent stresses in a vertical line of the steel shell, starting from the junction of the bottom plate with the wall plate. The configuration without joints presented the highest stress through all the height, achieving approximately 500 MPa in position zero. The stresses tend to lower until the region close to the trunnions bottom line, then increasing until the trunnions upper line. In the exact position of the reinforcement rings (A and B in Fig. 8), the stresses are the same for all configurations. The other simulated cases show the importance of the joints design in the shell equivalent stresses. In the case where the joints have 0,5 mm, the stress at position zero is approximately 250 MPa, a reduction of 50 %. Therefore, the refractories expansion allowance is an important parameter in the steel shell design.

At the bottom plate of the steel shell the same tendency of stress reduction with increase of joint thickness is observed, more influenced by the joints of the bottom lining. This can be observed in Fig. 9.

Fig. 10 shows a circumferential stress plot comparing the cases with joints of 0,1 mm and 0,5 mm thickness, where it is possible to see that in the first case the entire hot face in contact with molten steel (below slag line) has stresses above –40 MPa, while in the latter case several regions present stresses between –30 and –40 MPa.

To give a better idea on the stress reduction due to the increase of the joint thickness, Fig. 11 shows the circumferential stress variation in the refractory wall thickness, in a line going from the hot face to the working line cold face, in the region near the trunnions. In this situation, the stress at the hot face in the case without joints is –61 MPa, decreasing in modulus to –30 MPa at the cold face. When using joints of 0,5 mm, the stresses at the hot and cold faces are, respectively, –38 MPa and –13 MPa.

At the bottom lining, the normal stresses in direction y can vary from –52 MPa in the hot face of the case without joints to –26 MPa in the case with joints of 0,5 mm. Fig. 12 shows how the area affected by stresses above –35 MPa decrease significantly when increasing the joints and Fig. 13 shows the stresses distribution on the thickness of the bricks in the center of the bottom, from the hot face (0 mm) to the cold face (250 mm). Although there is an obvious and significant decrease in the stresses of the refractory and the shell when increasing the joints thickness, there is a limit for the maximum expansion allowance that can be used in a lining. Fig. 14 shows that for the case with joints of 0,5 mm not all the joints are closed even with 100 % of loading, i.e., in operation with the ladle at thermal steady-state. The designer must define a criterion saying how much of the joints should be closed through the lining thickness at each oper-

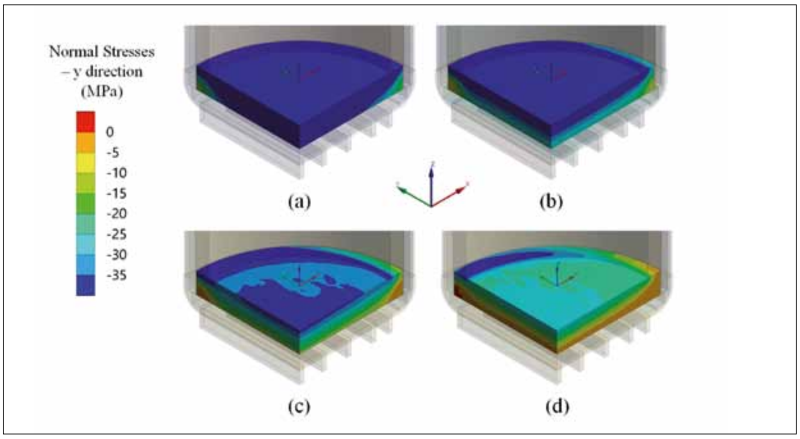

Fig. 12 a–d Normal stress variation in the y direction in the refractory bottom: (a) isotropic – no joints, (b) 0,1 mm joints, (c) 0,3 mm joints, and (d) 0,5 mm joints

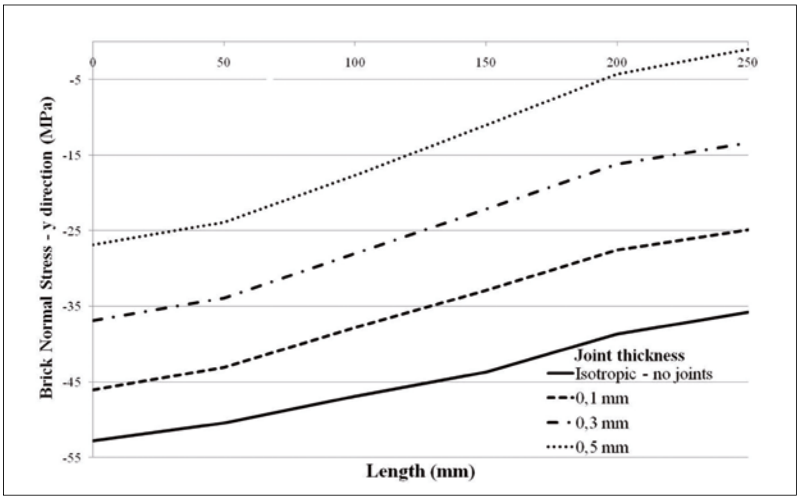

Fig. 13 Normal stress variation in the y direction in the center of refractory bottom

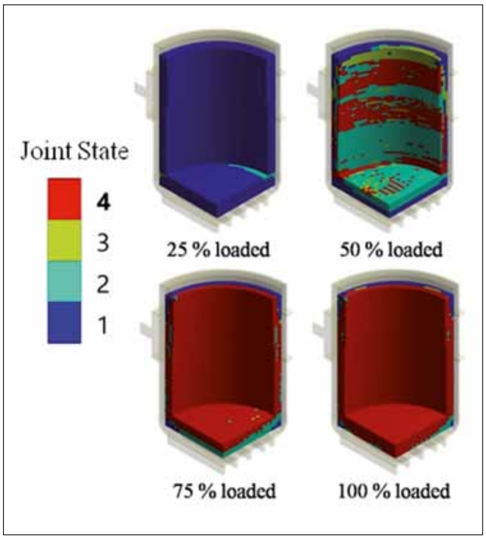

Fig. 14 Joint status in the steel ladle: joint thickness: 0,5 mm

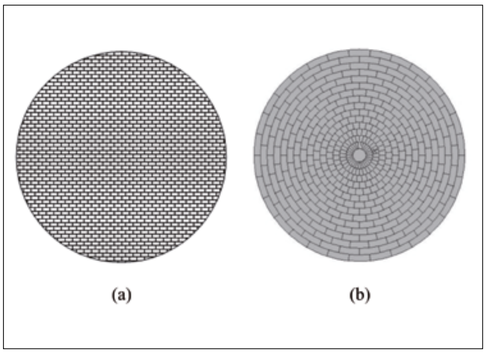

Fig. 15 a–b Bottom lining designs: parallel (a), and radial (b)

ational step and what the accepted stress values are, then performing the calculations using the PLH to dimension the joints.

To study the influence of the bottom lining design, two different designs are considered (Fig. 15): parallel and radial. The same equivalent material is used for these two designs, but its orthotropic directions are different:

- Parallel: the whole part has the same orthotropic directions
- 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. [7].

Fig. 16 shows the shell equivalent stresses in both of the simulations. The model shows that near the trunnions region (0°) the stresses are lower when using the parallel design, and the maximum difference between the two designs at this region is of 8,5 MPa. Closer to the region at 90° from the trunnions, the radial design shows a lower value of stress, and the maximum difference between them is of 10,5 MPa. Despite this difference in the stresses, it can be noticed that it corresponds only to

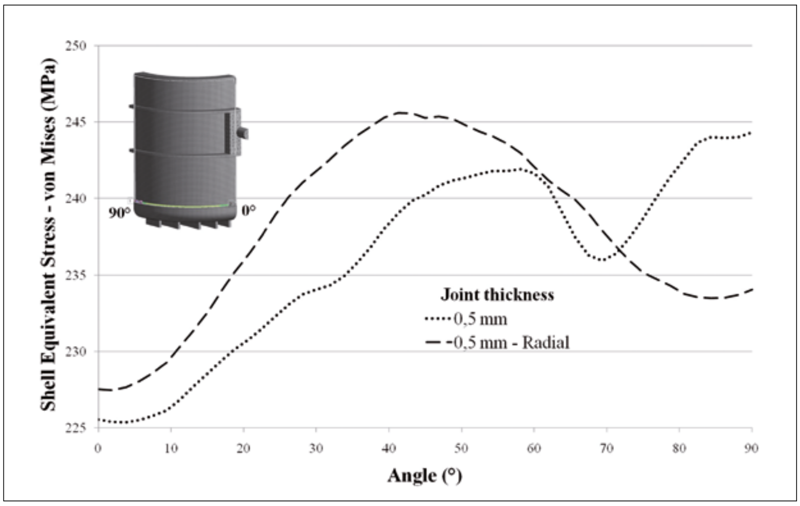

Fig. 16 Equivalent stresses at the shell – parallel and radial designs

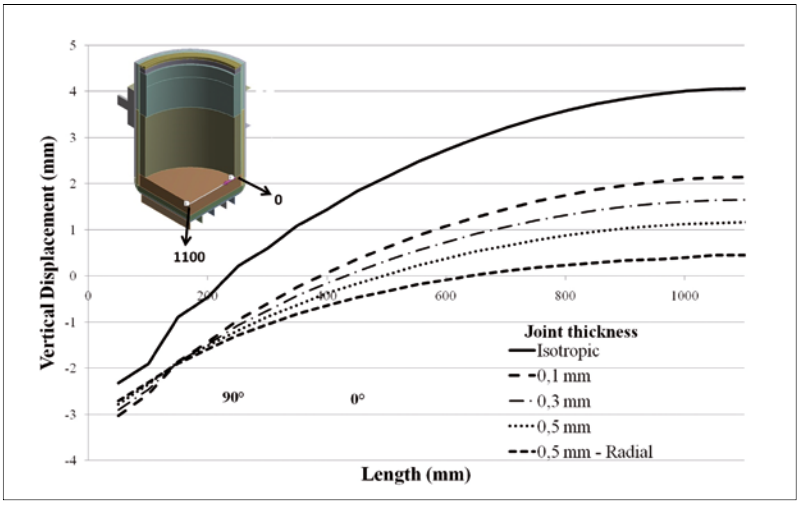

Fig. 17 Influence of joint thickness and bottom design (parallel or radial) on vertical bottom lining displacement along a diameter

4 % of the maximum stress obtained at the shell.

The joints at the bottom have also an influence on the vertical displacement of the bottom lining, as can be seen in Fig. 17. In the isotropic case (without considering the joints), the centre point of the bottom presents a vertical displacement of 6,38 mm with respect to the external border of the bottom, and with a joint of 0,5 mm (parallel design) this value is equal to 3,94 mm, what represents a decrease of 38 %. For the same joint thickness (0,5 mm), the radial design presents a relative displacement of 3,14 mm, i.e. a decrease of 51 % with respect to the isotropic case and 20 % with respect to the parallel design (with the same joint thickness of 0,5 mm).

5 Conclusion

The temperature depending orthotropic behaviour of a homogeneous material equivalent to a refractory masonry without mortar was determined using a periodic homogenization method. A closure criterion allows the computation of the joint state. This masonry equivalent material was used to simulate a complete steel ladle in thermal steady-state. The effect of increasing the joints thickness in the lining and the design of the bottom lining were studied.

The calculations showed that, when using the linear homogenization technique, it is possible to predict which joints will be closed and which ones will be open in consequence of the imposed loads, what significantly changes the magnitudes and the distributions of stresses in the lining. An important conclusion is that, although the increase of joints thickness has an obvious beneficial effect in the reduction of stresses in the refractory lining, it should be limited to guaranty that the joints will be closed when the ladle is loaded with melted steel.

The model will be improved taking into account the nonlinear refractory behaviour at high temperature. It will be introduced using a nonlinear homogenization technique.

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