



HAL
open science

Modelling of joint effect in refractory structures

Eric Blond, Alain Gasser, Matthieu Landreau, Jean-Luc Daniel, Thi My Hanh
Nguyen

► **To cite this version:**

Eric Blond, Alain Gasser, Matthieu Landreau, Jean-Luc Daniel, Thi My Hanh Nguyen. Modelling of joint effect in refractory structures. 12th International Cermic Congress - CIMTEC 2010, Jun 2010, Montecatini, Italy. hal-00600484

HAL Id: hal-00600484

<https://hal.science/hal-00600484>

Submitted on 15 Jun 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Modelling of joint effect in refractory structures

BLOND Eric¹, GASSER Alain¹, LANDREAU Matthieu^{1,2}, DANIEL Jean-Luc¹,
and NGUYEN Thi my hanh¹

¹ Institut PRISME (EA 4229, University of Orléans), Polytech'Orléans, 8 rue L. de Vinci,
45072 Orléans, France

² CPM, Parc d'Activités Forbach Ouest 57612 FORBACH, FRANCE

¹surname.first name@univ-orleans.fr

Keywords: masonry modelling, homogenization, refractory, joints

Abstract. Some refractory linings of metallurgical vessels consist of masonry. To model these large-sized structures, it is convenient to use an equivalent material instead of a model that involves all bricks and joints. The properties of the equivalent material depend on geometrical and mechanical properties of the bricks, the joint states and the temperature. In this paper, several joint states which are the combinations of open/closed states of bed and head joints are considered. The equivalent material properties are determined thanks to periodic homogenization techniques. Results obtained with this approach are used to model different masonries walls, with or without mortar, subjected to bi-axial compression and bending. Finally, an application to a coke oven heating wall is presented.

Introduction

Masonry structures are researched extensively owing to their wide application in many fields such as civil engineering or cultural heritage restoration. To take into account joint effects in such large structures, two different approaches are possible [1]: the micro-modelling which describes each brick and joint with their own behaviour, the macro-modelling which pleads for replacing them with a homogeneous equivalent material. In micro-modelling approach, there are two subcategories: the simplified approach where only units and joints are represented and the detailed approach where units, joints and the unit/mortar interface are included.

The micro-modelling strategy is the most accurate but its computational cost is very onerous because of the necessity to model separately units and mortar. Then, to reduce the size of the numerical model, the mortar is classically reduced to an interface element (i.e. thickness of mortar close to zero and no real shearing in the sense of classical Cauchy media), as initiated by Page [2]. Despite of these assumptions this method will be a long-term task if the bricks which compose the structures don't have all the same shape, size, and architectural organization. Moreover, for mortarless walls, other factors should be additionally accounted for such as sliding between bricks, which cannot help the convergence for the computation by the classical Finite Element Method (FEM). Over the recent years, authors like Rafiee [3] manage to model large structures (for example: an arena and an aqueduct) using a Discrete Element Method (DEM) with stone blocks considered as rigid elements. It is really an interesting and promising numerical method. The actual recent developments focus on the coupling between DEM and the FEM to account for deformable parts, today limited to elastic behaviour. However, this method considers only bricks with simple shape and not a tongue-and-groove ones. Moreover, interaction between masonry and material with complex behaviour like a ramming-mix [4] is not actually possible in such computational codes.

In the macro-modelling alternative approach, all the masonry is represented by an equivalent continuum media. Thus, techniques of homogenization are becoming more and more popular among the masonry community. To account for many effects such as temperature dependence of the constitutive materials behaviour or complex 3D brick shape and architectural arrangement,

numerical approaches are better adapted than analytical ones. However, analytical expressions proposed by Cecchi [5,6] give a good estimation of the effective parameters for simple 2D shape and arrangement. From a numerical point of view, an alternative to the classical FEM approach, based on Cauchy's assumption, is to use enriched kinematics of the Cosserat continuum [7]. Unfortunately, the complexity of the Cosserat's kinematics is a great handicap for the development of new numerical codes. Then, it does not seem to be as promising as the DEM. Finally, the large majority of the literature focuses on the periodic homogenization of masonry by FEM as initially proposed by Anthoine [8]. The main difference between the numerous recent works concerns the definition of the joints behaviour. The dominant idea is that the non-linear behaviour of mortar (or contact for mortarless masonry) is the key point of the structure behaviour. However, in the work presented hereafter, the joint is purely elastic and can only be closed (perfect joint) or open (broken joint) without any other refinement. Then, the constitutive equation of equivalent material is linear elastic with different joint states and, as it was already demonstrated in the pioneering work of Luciano [9], it seems to be enough to reproduce the whole behaviour of the structure.

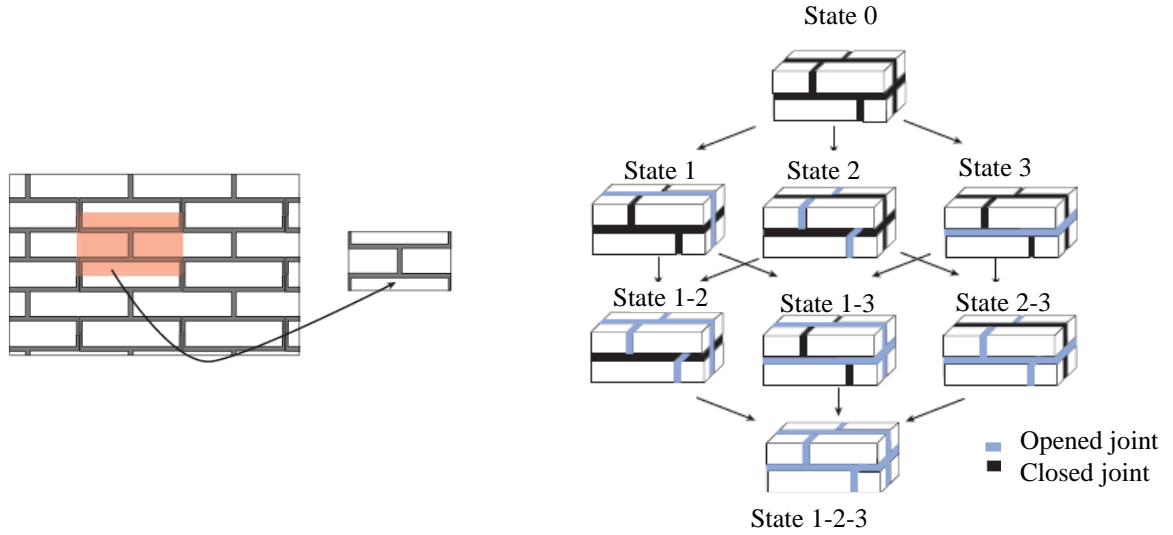
The presentation proposed here is a summary of the work initiated by Gasser and Boisse [10] on the modelling of refractory masonry by homogenisation. The objective is to derive a homogeneous material whose mechanical characteristics depend on the joint state, on the basis of the joint opening/closure mechanism. For each joint state, the equivalent mechanical properties are determined by homogenization using an energy approach and the finite element method. The transition criterion between joint states allows to make the difference between masonry with or without mortar. The unilateral contact conditions written in terms of macroscopic strain give the closure criterion for mortarless masonry while a local tensile cut-off combined with a local Mohr-Coulomb strength criterion defines the breakage / degradation (i.e., opening) of the mortar for "classical" masonry.

In the first part of the paper, the philosophy which drives the build of the different reference joint states is presented. In a second part, the necessary theoretical developments of periodical homogenization are quickly reminded. Then, the proposed method is used to simulate a bi-axial compression test of mortarless masonry and a bending test of masonry with mortar. Finally, an example of the simulation of an industrial refractory structure is presented: the case of a heating wall in coke oven battery.

Joint state definition

Whatever is the mechanical behaviour of bricks, joints are often the weak link of the masonry, mainly because of the low strength of the brick / mortar interface. Obviously, in service, a diffused damage in mortar, which results to its bulk breakage, is seldom observed. But, at the scale of the structure, it is not so different than an interface fracture because the mortar is thin regard to the brick size. Then, it is usually assumed (and often observed) that fractures develop only in the brick/mortar interface [9]. With this assumption, it becomes possible to simplify the representation of the joint damage by considering only two possibilities: the joint is closed until an ultimate strength is not reached and then the joint is open.

Masonry is a composite medium characterized by a periodic microstructure. Consequently, a repetitive cell, as presented in figure 1a, is employed to proceed to the evaluation of the effective parameters of the equivalent material (i.e. periodic homogenization). According to opening or closure of bed and head joints, different states for the elementary cell can be defined. Selecting a unit cell symmetrical with respect of three orthogonal planes passing through the origin, the problem can be reduced to an eighth of unit cell. Then, the number of possible states is reduced to symmetric joints opening/closure combination, as proposed on figure 1b. Of course, for each state, different effective parameters must be evaluated.



a) Choice of a periodic cell

b) Joint states definition at the cell scale

Figure 1: Periodic cell and associated joint state

Once different patterns were defined, a transition criterion is established to go from one state to another. Here, it is possible to adapt the criterion for the two different cases of masonry with or without mortar. For mortarless masonry, the bricks are laid in contact one another via soft interfaces (due to their asperities and shape defaults), then initially the joints are opened and the closure criterion should be linked to the local relative displacement of bricks. Conversely, in the case of masonry with mortar, joints are initially closed and the opening criterion should be linked to the local stress field. Thus, the difference between the two types of masonry is resumed to a change in the joint closure/opening criterion.

Homogenization of masonry

Because 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 with temperature dependent Young modulus, 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 (ABAQUS) and compared to the strain energy bulk density of the equivalent material submitted to the same load. Boundary conditions which must be applied on the cell are defined as regard to the expression of bulk density of strain energy. For example, in the case of a two dimensional problem, the shearing modulus G_{12} of the equivalent material is given by:

$$G_{12} = \frac{2W}{E_{12}^2} \quad (1)$$

Where W is the bulk density of strain energy in the heterogeneous cell computed by F.E.M. and E_{12} the homogeneous macroscopic shearing strain field. Then the strain tensor can be written:

$$E = (e_1 \otimes e_2 + e_2 \otimes e_1)E_{12} \quad (2)$$

Where e_i are the base vectors and E_{12} the shearing component of the strain tensor. The local displacement U is the sum of an average field, equal to the macroscopic one, and a local perturbation which must respect the periodicity of the problem. Then, the local displacement can be written as:

$$U(y) = E \cdot y + U^{per}(y) \quad (3)$$

Where y is the position vector and U^{per} the local periodic fluctuation vector. Let us note u_i^{per} the component of the vector of the periodic fluctuation, then:

$$U = \begin{pmatrix} E_{12}y_2 + u_1^{per} \\ E_{12}y_1 + u_2^{per} \\ u_3^{per} \end{pmatrix} \quad (4)$$

Symmetry conditions with respect to the plane lead to:

$$\begin{cases} u_2^{per}(l, y_2, y_3) = 0 \\ u_3^{per}(l, y_2, y_3) = 0 \\ u_3^{per}(y_1, y_2, h) = 0 \\ u_1^{per}(y_1, L, y_3) = 0 \\ u_3^{per}(y_1, L, y_3) = 0 \end{cases} \quad (5)$$

Where l , h and L are the depth, the height and the length of the eighth of the cell. Substituting the

periodic fluctuation in equation $U = \begin{pmatrix} E_{12}y_2 + u_1^{per} \\ E_{12}y_1 + u_2^{per} \\ u_3^{per} \end{pmatrix}$ (4), gives the boundary conditions corresponding to a perfect shearing:

$$\begin{cases} u_2(0, y_2, y_3) = 0 \\ u_3(0, y_2, y_3) = 0 \\ u_3(y_1, y_2, 0) = 0 \\ u_1(y_1, 0, y_3) = 0 \\ u_3(y_1, 0, y_3) = 0 \end{cases} \text{ and } \begin{cases} u_2(l, y_2, y_3) = lE_{12} \\ u_3(l, y_2, y_3) = 0 \\ u_3(y_1, y_2, h) = 0 \\ u_1(y_1, L, y_3) = LE_{12} \\ u_3(y_1, L, y_3) = 0 \end{cases} \quad (6)$$

The reader interested in details on the definition of boundary conditions for different loads should report to [8] and [11]. To identify automatically the effective parameters for many different equivalent materials, corresponding to many different cells (i.e. different architectures and/or different joint states) at different temperatures, the F.E.M. Code ABAQUS has been coupled with a Fortran routine.

Bi-axial compression of a mortarless masonry

Figure 2 presents a typical result of compression of two bricks of same material laid in direct contact with each others. The load displacement curve is non-linear but could be reasonably approximated by two straight lines. The first, in blue, corresponds to the crushing of the shape default and roughness. The second, in red, corresponds to the brick behaviour. The joint will be called ‘‘opened’’ until the global rigidity be lower than the brick’s one. Then, the intersection of the two lines allows to define the initial size of the open joint.

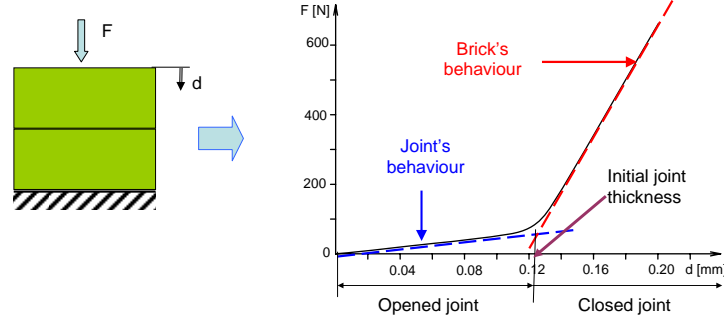


Figure 2: Typical result of compression test of two bricks laid in direct contact

In mortarless masonry, there are two main reasons responsible of joint closures, first the deformation of the brick and second their sliding. Then, the first criterion for the joint closure is based on the initial joint thickness g_n between the surfaces which are potentially in contact:

$$(\underline{u}^{(1)} - \underline{u}^{(2)}) \cdot \underline{n} = g_n \quad (7)$$

where $\underline{u}^{(1)}$ and $\underline{u}^{(2)}$ are the displacements of the nearest points of the two surfaces and \underline{n} is the normal vector to the two surfaces. This local criterion, to use in the homogeneous equivalent material, must be written in function of global strain. Then, accounting that the effective behaviour of the equivalent continuous media is piece-wise linear, it is possible to write [11]:

$$\sum_{k=1}^z [{}^k m_{njp}^{1-2} \Delta E_{jp}^k - {}^k \theta_n^{1-2} \Delta T^k] = g_n \quad (8)$$

Where z is the number of joint states 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 . The parameters ${}^k m_{njp}^{1-2}$ and ${}^k \theta_{njp}^{1-2}$ are the components of the tensor which link the global strain and temperature change to the local one in state k . The superscript (1-2) denotes the solids which are concerned. Moreover, the Einstein convention is used for summation when twice subscripts are repeated .

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

$$\left| \int_S \left[\sum_{k=1}^z ({}^k C_{ijpq} \Delta E_{pq} + {}^k P_{ij} \Delta T) \right] dS \right| \leq f_s \left| \int_S \left[\sum_{k=1}^z ({}^k C_{iipq} \Delta E_{pq} + {}^k P_{ii} \Delta T) \right] dS \right| \quad (9)$$

Where ${}^k C$ and ${}^k P$ are the tensors which link the macroscopic strain increment and temperature increment to the local stress increment and S is the surface contact. Finally, to take into account the possibility of the re-opening of joints during unloading, a criterion based on the impossibility to transfer tensile stress (i.e., cap in local tension) is added:

$$\sum_{k=1}^z ({}^k C_{iipq} \Delta E_{pq} + {}^k P_{ii} \Delta T) \geq 0 \quad (10)$$

This re-opening criterion does not need any more parameters than those previously defined.

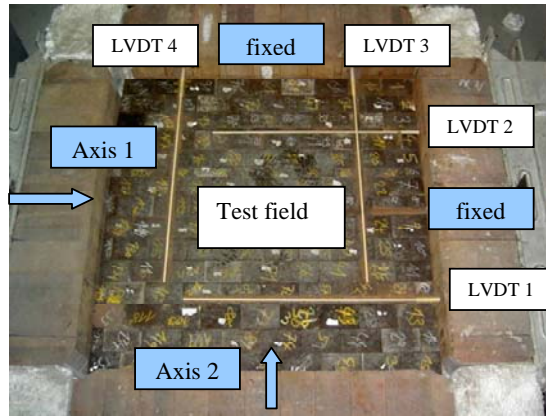


Figure 3: Installed test lining segment

To validate the proposed model, results of the simulation of a biaxial compression of the equivalent material was compared with those issued from a biaxial compression test on a real mortarless masonry performed by the center of research of RHI (Leoben). The wall laid on the ground and is bi-axially loaded by two pistons via ceramic layers. Displacements at four points, corresponding to the positions of the sensors, are recorded (Fig. 3). The wall has a square form with each side of 1100 mm and thickness of 185 mm. All details of the experimental set up are presented in [12]. The test was realized at constant room temperature. The results of the first comparisons show the excellent ability of the model to reproduce the results obtained during the loading stage if the initial joint thickness is well known [11, 13]. In a second time, assuming an average initial joint thickness of 0.1 mm and using the same effective parameters than in [11], the cyclic loading and unloading have been simulated. Figure 4 presents the comparison between the computation results and the experimental data from the cyclic biaxial compression test performed at RHI.

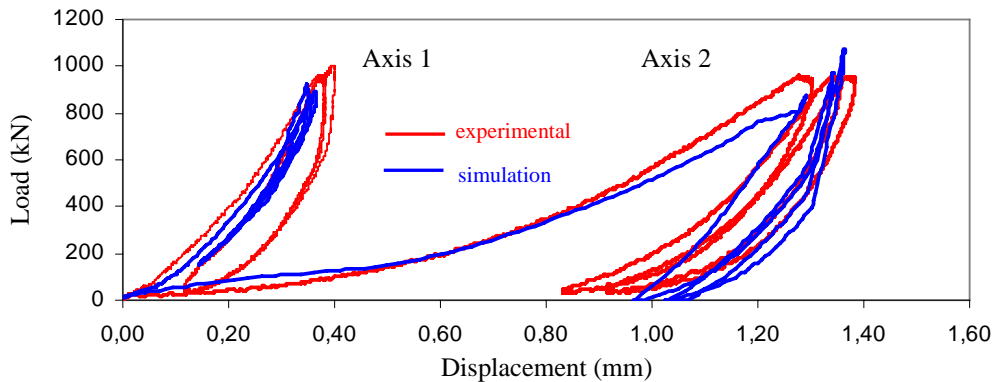


Figure 4 : Cyclic biaxial compression, comparison between simulation and test

Figure 4 shows that the model well reproduces the high anisotropy of the behaviour of the masonry. Moreover, the shapes of the first load are close for the model and the test. For the first unloading, the model captures the global shape but follows not exactly the experimental curve. Despite this discrepancy, the model seems able to reproduce the hysteresis of the cyclic loading curve and the evolution of the maximum displacement along axis 2 with each consecutive load. In conclusion, the proposed model reproduces well the whole behaviour of mortarless masonry but could be improved to better reproduce the reopening of joints during unloading stage.

Bending of masonry with mortar

In this study and as presented previously, it is assumed that fractures might develop only in the brick/mortar interface due to the small thickness of the mortar [1, 9]. The damage or breaking of mortar interface is due to local shearing or tensile strength, so the criterion for joint opening is the combination of a cut-off criterion for tension and a modified Mohr-Coulomb for shear:

$$\left\{ \begin{array}{l} \sigma_{ii} > f_{tension} \\ or \\ \sqrt{\sigma_{ji}^2 + \sigma_{ki}^2} > f_{shear} \end{array} \right. \quad (11)$$

Where f_{shear} and $f_{tension}$ are the tensile and shear strength of brick-mortar interface. A modification in Mohr-Coulomb criterion allows taking into account hardening of shear limit strength only in compression:

$$f_{shear} = c - \frac{1}{2} \tan \Phi (1 - \text{sign}(\sigma_{ii})) \sigma_{ii} \quad (12)$$

With c the unit-interface cohesion, and Φ the internal friction angle. Using the same way and the same notation than for mortarless masonry, the criterion is written in term of macroscopic strain:

$$\left\{ \begin{array}{l} \sum_{k=1}^n {}^k C_{iilm} {}^k \Delta E_{lm} > f_t \\ or \\ \sqrt{\left(\sum_{k=1}^n {}^k C_{jilm} {}^k \Delta E_{lm} \right)^2 + \left(\sum_{k=1}^n {}^k C_{hilim} {}^k \Delta E_{lm} \right)^2} > f_{shear} \end{array} \right. \quad (13)$$

And the modified Mohr-Coulomb limits can be written:

$$f_{cis} = c - \frac{1}{2} \tan \phi \left(1 - \text{sgn} \left(\sum_{k=1}^n {}^k C_{iilm} {}^k \Delta E_{lm} \right) \right) \sum_{k=1}^n {}^k C_{iilm} {}^k \Delta E_{lm} \quad (14)$$

In [14] this model was used to compute a shearing wall test. The comparisons between test and simulation is in good agreement. Hereafter, the ‘‘deep beam test’’ test of [2] is considered. The beam is $757 \times 457 \text{ mm}^2$ wide. As represented on figure 5a, it is supported at each side over a support length equal to 188 mm. The top load P is applied through a stiff steel beam. Although the brick size is not the same than for the shearing test, the effective parameters used herein are the same than in [14] because the mortar / brick ratio is similar. Figure 5b presents the stress deduced from strain gauges pasted on the bricks (see fig. 5a) and stress calculated from the model. Results are in fairly good agreement.

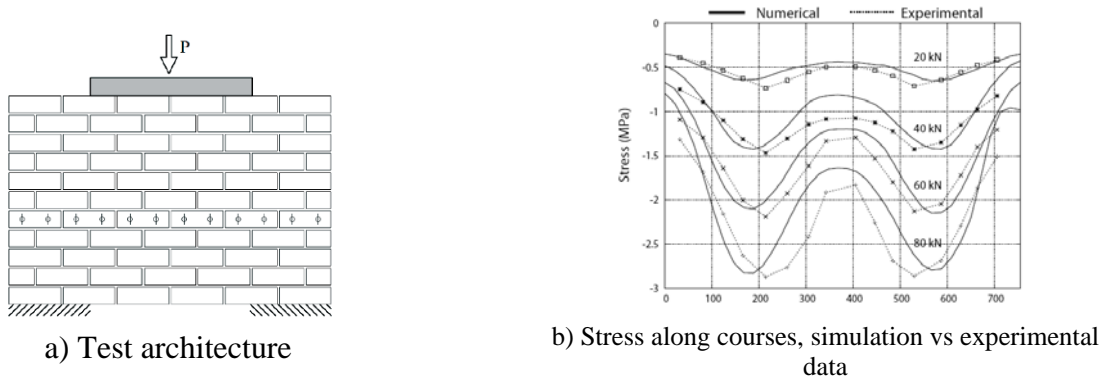


Figure 5: Deep beam test, simulation vs. experiment [2]

These results show that replacing the masonry by a homogeneous effective media with effective elastic parameters depending on the local cell joint states allows to predict reasonably the behaviour

of masonry structures. Then, it becomes possible to use such approach to study the design of refractory structures.

Coke oven heating wall modelling

Several studies summed up in [15, 16], were already performed on heating walls. Analytical works were very simplified since the heating wall was modelled as a beam. An improvement was brought by numerical methods. Nevertheless, all existing models present some simplifications: masonry joints are not taken into account; the heating wall is represented by an orthotropic shell or in 2D. Thus complete models, which take into account all phenomena, do not exist until now. To build this model, all parameters have been taken into account:

- Complexity of the structure (figure 6a): heating walls include flues and are made of masonries with various types of bricks (with various shapes and materials).
- Brick and joint material behaviours: refractory thermo-mechanical behaviour is temperature dependent
- Knowledge of thermo-mechanical loading: temperature field, weight of walls, roof and larry car, pre-stresses (anchoring system), lateral pressure due to coal pushing

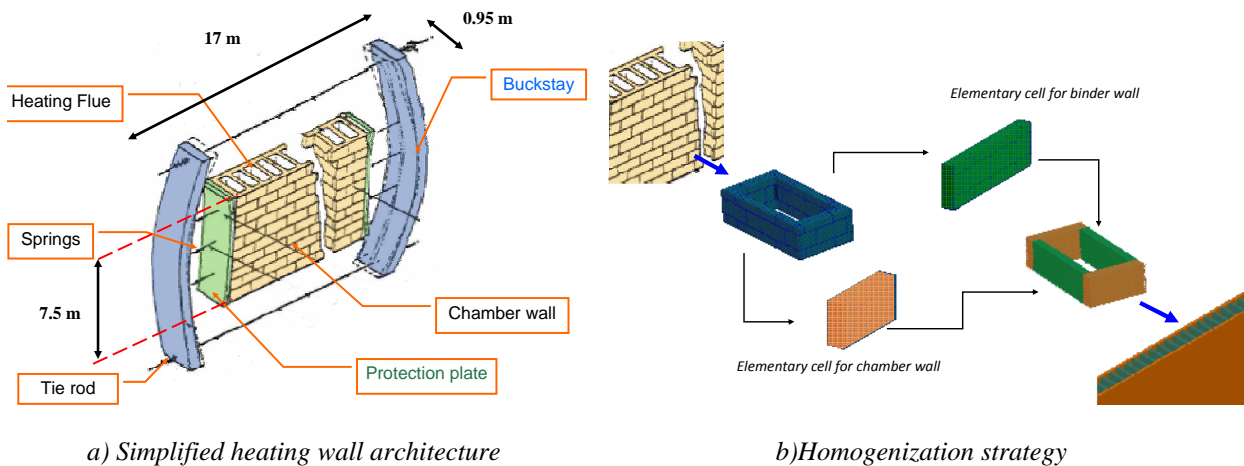


Figure 6: Heating wall architecture and elementary cells.

In order to keep the 3D effective properties of the equivalent material of heating wall, two elementary cells were chosen: the first one for the chamber wall and the second one for the binder wall as shown on figure 6b. To accurately identify the effective thermomechanical properties, mechanical and thermal tests were carried out on both silica brick and mortar samples [14, 17].

As presented before, unit cell mechanical behaviour is function of the joint states and, here, is also function of the temperature. Thus, equivalent behaviours were determined for each joint state at three temperatures: 800, 1080 and 1350°C. Some numerical values of effective mechanical parameters are presented in [14] and all are summarized in [17]. Equivalent thermal parameters were determined for different states too. The effective thermal conductivity was bounded by the Hashin-Shtrikman (HS) bounds [18]. The expansion coefficients were identified by the same method than mechanical parameters and the density and specific heat were estimated by an average per volume unit.

The calculation of this large structure was realised in two steps. The first one is the modelling of thermal loads in order to obtain the thermal field in the heating wall. All thermal exchanges have been taken into account: exchanges between the chamber wall and the coal and those between the protection plate and insulating bricks in the coke oven heads and the heating of flues. Results of the

thermal computation are presented in [14]. The temperature field was validated thanks to coke oven heating wall instrumentation. In fact different thermocouples were put at different positions in the structure and the temperature in flues were measured by the CPM with Pyrofil©.

In the second step, the previously obtained temperature field is used in the thermomechanical model as an imposed temperature field. In this mechanical step, all loads previously quoted (i.e., weights of roof and larry car, anchoring system, lateral pressure) are applied on the structure. Due to the discrete damage evolution (i.e., closed joint toward open one) an explicit integration scheme is used. Despite of the large reduction of the size of the model induced by the use of equivalent material, the computation is time consuming and requires important computers resource: around two weeks on 24 CPUs with 20 Gb of RAM. First results are presented on figure 7.

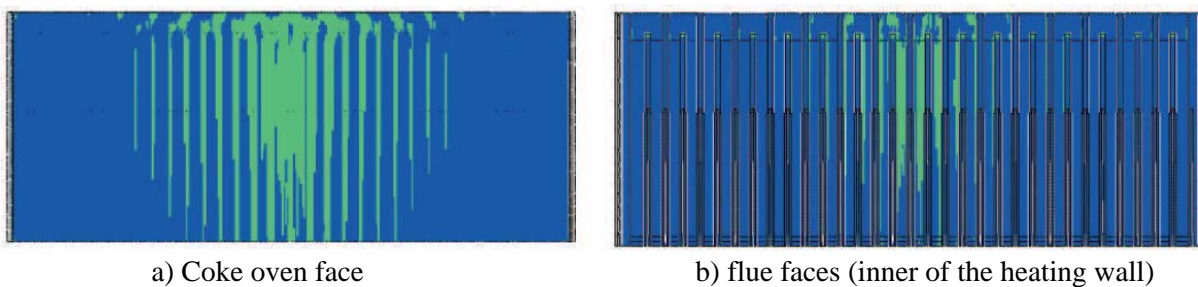


Figure 7: vertical joint opening on the liner (a) view from oven and (b) view from flue

Localization of vertical joints openings presented on figure 7 is in fairly good agreement with observations on site. Indeed, vertical fractures, localized near the binder, are often observed on the chamber wall of heating wall. Moreover, as assumed by previous models [15, 16], the centre of the heating wall is the most damaged zone. These results confirm that the replacement of the masonry by an equivalent homogeneous material allows to reproduce a realistic degradation of a complex industrial structures. This ongoing work focuses now on the estimation of the limit for coal pushing.

Conclusion

In this paper the philosophy of the masonry model developed by Gasser *et al.* has been presented and some theoretical aspects were briefly summarized. Then, to demonstrate the capability of this model to capture the behaviour of different type of masonries, two different tests were simulated: bi-axial compression of mortarless masonry and a bending of masonry with mortar. The simulation results are in good agreement with experimental data.

The proposed model is based on the simple hypothesis on the constituent material: elasticity for mortar and brick and discrete damage for mortar, joints are open or closed. This simplification reduces the number of parameters to be identified but is capable to capture the complex behaviour of industrial structures. Moreover, the results have shown that the main part of the non linearity of the masonry behaviour is well reproduced. Nevertheless the model could be refined to better reproduce some particular points like the opening of joints during unloading for example.

References

- [1] P. B. Lourenço, Ph. D. Thesis, Delft University of Technology, 1996
- [2] A.W. Page, Journal of structural division, n°104, pp. 1267-1285, 1978
- [3] A. Rafiee, M. Vinches, C. Bohatier. Engineering Structures, vol 30, n°12, pp 3457-3467, 2008

- [4] J. Brulin, L. Josserand, E. Blond, A. Rekik, A. Gasser, F. Roulet. UNited International TEchnical Congress on Refractory, Bahia, Brazil, October 2009
- [5] A. Cecchi, K. Sab. Eur. J. of Mech. – A / Solids, vol 21, n°2, pp249-268, 2002
- [6] A. Cecchi, K. Sab, Eur. J. of Mech. – A / Solids, vol 21, n°5, pp 715-746, 2002
- [7] Stefanou, I., Sulem, J., Vardoulakis, I. Acta Geotech. 3, 71–83., 2008
- [8] A. Anthoine. Int. J. Solid Structures, Vol 32, N°2, pp. 137-163, 1995
- [9] Luciano, R., Sacco, E. International Journal of Solids and Structures 34 (24), 3191–3208, 1997
- [10] Gasser, A., Terny-Rebeyrotte, K., Boisse, P. J. Mater.: Design Appl. (IMechE) 218, 19–28, 2004
- [11] T.M.H. Nguyen, E. Blond, A. Gasser, T. Prietl, European Journal of Mechanics A/Solids 28 (2009) 535–544
- [12] T. Prietl, O. Ach, H. Studnicka. Erzmetall – World of Metallurgy, vol. 59, pp. 127-132
- [13] T.M.H Nguyen, E. Blond, A. Gasser, T. Prietl. UNited International TEchnical Congress on Refractory, Dresden, Germany, 18-21 September 2007, pp1991-1996
- [14] M. Landreau, E. Blond, A. Gasser, D. Isler. UNited International TEchnical Congress on Refractory, Bahia, Brazil, October 2009
- [15] H. Dürselen, 1999, Cokemaking International, 1, 40-48.
- [16] J. F. McDermott, Iron and Steel Society. 1990
- [17] M. Landreau, Ph. D thesis, Université d’Orléans, France, 2009 (in French)
- [18] K. J Geography Res 1971; 76(5):1278-1308