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# Thermomechanical Modelling of Refractory Mortarless Masonry Wall Subjected to Biaxial Compression

Mahmoud Ali \*, Thomas Sayet, Alain Gasser, Eric Blond

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## Abstract

Mortarless refractory masonry is widely used in the steel industry for the linings of high-temperature components such as steel ladles and furnaces. Successful design of these large-sized structures requires a proper understanding of the interaction between material discontinuity introduced by the presence of mortarless joints, joints closure and reopening due to loading/unloading, and their effect on the thermomechanical response of the structure. In the present study, 3D thermomechanical models have been developed to analyze the effects of joints reopening on the thermomechanical behavior of mortarless masonry walls. Four joint patterns, with their corresponding equivalent elastic properties, have been defined based on the state of head and bed joints (open or closed). The effective elastic properties of each joint pattern have been calculated with the help of the finite element method and the strain energy-based homogenization technique. The joints reopening and closure criteria have been defined as a function of macroscopic stresses and strains. The developed material model has been implemented in a commercial finite element software and then used to analyze the thermomechanical behavior of refractory masonry walls. The numerical model has been validated by comparing the numerical results with experimental data (biaxial compression test of a flat wall). Both results are in good agreement.

## 1. Introduction

Refractory masonry is widely used in the steel industry for the linings of large-sized high-temperature components such as steel ladles and furnaces. In order to design and optimize these components, suitable numerical models are required. In previous research works, two modeling approaches of masonry with mortar joints have been developed: micro modeling and macro modeling <sup>1)</sup>, <sup>2)</sup>. Micro-modeling approach is based on modeling the bricks and the joints separately, using different behavior laws. The mechanical properties for each constituent are usually obtained from experimental tests. The main drawback of this approach is that it

requires large computation time and high cost and, therefore, it is suitable for small sized structures.

Regarding the second approach (macro modeling), the masonry structure (brick, mortar and brick-mortar interface) is considered as a homogeneous medium. The mechanical properties are determined from experimental tests. A macro model is very effective from the computation time point of view. However, it is often not suitable to describe the micromechanics occurring at the local scale.

In case of mortarless masonry structures, very few numerical and/or analytical studies exist. Most of them are based on detailed micro modeling approach. However, previous numerical models are not suitable for modeling the linings of large-sized structures such as steel ladle and furnaces due to high computation time and cost. For example, Thanoon et al. <sup>3)</sup> developed a micro numerical model to investigate the effects of dry joints imperfections and progressive contact on the mechanical behavior of a hollow mortarless concrete masonry block. Similarly, Ngapeya et al. <sup>4)</sup> developed a 3D micro numerical model to study the effects of height imperfection on the load-bearing capacity of a mortarless stack masonry wall.

The present work is a continuity of previous works carried out by Gasser et al. <sup>5)</sup> and Nguyen et al. <sup>6)</sup> on mechanical homogenization and modeling of masonry systems with dry joints. The main objective is to develop an equivalent material model whose mechanical properties depend on the state of bed and head joints and to define suitable joint closure and reopening criteria. The developed material model has been implemented in Abaqus software and used to simulate a masonry wall under biaxial compression.

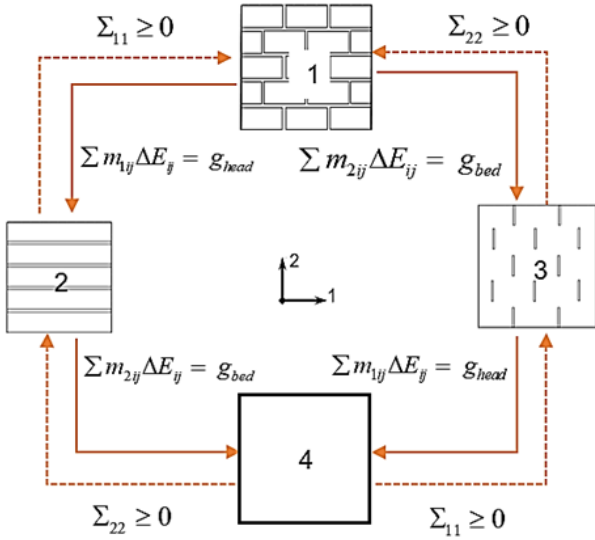
## 2. Methodology

### 2.1 Effective elastic properties

In order to determine the effective elastic properties, four possible joint patterns (also called joint states) are defined based on the status of bed and head joints as follows (see Fig.1): Pattern 1: bed and head joints are open. Pattern 2: bed joints are open and head joints are closed. Pattern 3: bed joints are

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**Fig. 1 Possible joint patterns and joint closure/reopening criteria.**

closed and head joints are open. Pattern 4: bed and head joints are closed.

In case of joint pattern 1, 2 and 4, it is possible to define the mechanical properties directly from those of the brick. However, in case of joint pattern 3, the mechanical properties have been determined thanks to the homogenization technique and the Finite Element Method 'FEM'.

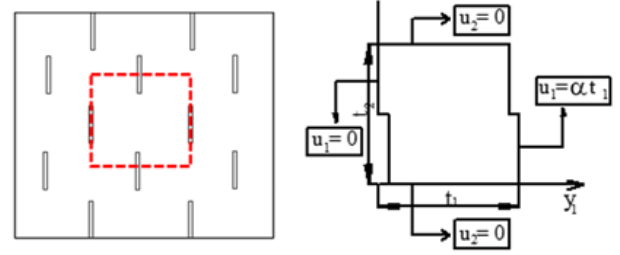
In order to determine the mechanical constants of joint pattern 3, a Representative Elementary Volume (REV) is chosen (see Fig. 2), then symmetric and periodic boundary conditions are applied. For the considered homogenization problem, in the linear elastic range, the macroscopic stress ( $\bar{\Sigma}$ ), strain ( $\bar{E}$ ) and constitutive law can be written as follows:

$$\bar{\Sigma} = \langle \bar{\sigma} \rangle = \frac{1}{V} \int_V \bar{\sigma} dV \quad (1)$$

$$\bar{E} = \langle \bar{\varepsilon} \rangle = \frac{1}{V} \int_V \bar{\varepsilon} dV \quad (2)$$

$$\bar{\Sigma} = \bar{A} \bar{E} \quad (3)$$

Where  $\bar{\sigma}, \bar{\varepsilon}, V, \langle * \rangle, \bar{A}$  are the local stress, local strain, volume of the representative element, the average operator, and macroscopic elasticity tensor, respectively. The number of bars above the symbol denotes the rank of the tensor. The local stress and strain in the REV with volume ( $V$ ) and subjected to macroscopic strain ( $\bar{E}$ ) can be obtained by solving the following equations <sup>7)</sup>:



**Fig. 2 Periodic structure and one quarter of the periodic cell.**

$$\begin{cases} u(x) = \bar{E} \cdot x + u^*(x), & \forall x \in V \\ \varepsilon(u(x)) = \frac{1}{2} (\nabla u(x) + {}^t \nabla u(x)) \\ = \bar{E} \cdot x + \varepsilon(u^*(x)), & \forall x \in V \\ \text{div}(\sigma) = 0, & \forall x \in V \\ \sigma(x) = a(y)\varepsilon, & \forall x \in V \end{cases} \quad (4)$$

A finite element software (Abaqus) has been used to solve the homogenization problem given by Eq. (4) and to obtain the mechanical constants. Table 1 summarizes the mechanical properties of the equivalent homogeneous material.

**Table 1 mechanical properties of equivalent homogeneous material <sup>1</sup>.**

Patte rn	$E_1$	$E_2$	$E_3$	$\nu_{12}$	$\nu_{13}$	$\nu_{23}$	$G_{12}$	$G_{13}$	$G_{23}$
1	0	0	$E_b$	0	0	0	0	$G_b$	$G_b$
2	$E_b$	0	$E_b$	0	$\nu_b$	0	0	$G_b$	$G_b$
3	$E_h$	$E_b$	$E_b$	$\nu_h$	$\nu_h$	$\nu_b$	$G_h$	$G_h$	$G_b$
4	$E_b$	$E_b$	$E_b$	$\nu_b$	$\nu_b$	$\nu_b$	$G_b$	$G_b$	$G_b$

## 2.2 Joints closure and reopening criteria

When the masonry structure is subjected to mechanical or thermal loading, it will change from one joint pattern to another. For instance, when joint pattern 1 is subjected to compression load in direction 1, the thickness of head joints will decrease gradually until reaching zero. Then, the structure will change to pattern 2 (see Fig. 1). The corresponding joint is considered to be closed when <sup>6)</sup>:

$$\sum m_{ij} \Delta E_{ij}^T = g \quad (5)$$

Where  $m_{ij}$  is a proportional coefficient,  $E_{ij}^T$  is the macroscopic total strain and  $g$  is the initial joint

<sup>1</sup> E Youngs modulus,  $\nu$  Poisson's ratio and G shear modulus. The subscript b refers to brick and h refers to computed by homogenization technique.

thickness. In the linear elastic range, the macroscopic total strain can be expressed as:

$$E^T = E^e + E^{th}. \quad (6)$$

Where  $E^e$  and  $E^{th}$  are the macroscopic elastic and thermal strains. After joints closure and during thermal or mechanical unloading joints can reopen if the normal stress to the joint surface is higher than zero. Head joints can reopen if  $\sum_{11} \geq 0$  and bed joints can reopen if  $\sum_{22} \geq 0$ .  $\sum_{11}$  and  $\sum_{22}$  can be written as:

$$\begin{cases} \sum_{11} = A_{1111}E_{11}^e + A_{1122}E_{22}^e + A_{1133}E_{33}^e \\ \sum_{22} = A_{1122}E_{11}^e + A_{2222}E_{22}^e + A_{2233}E_{33}^e \end{cases} \quad (7)$$

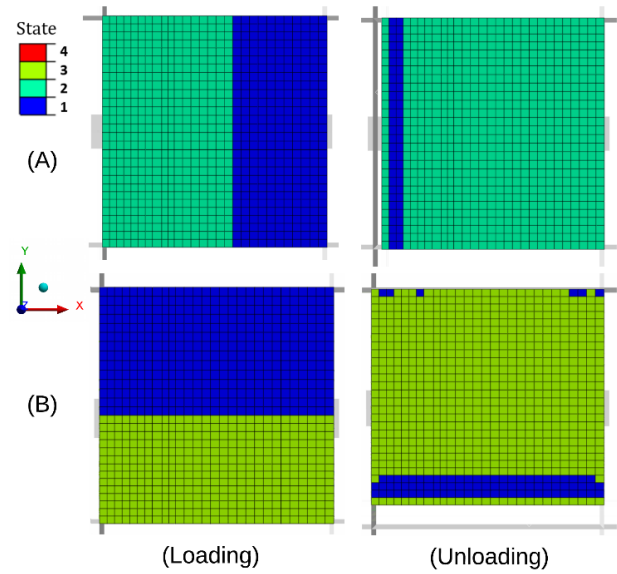
Where  $A_{ijkl}$  are the macroscopic elastic constants determined by the homogenization technique. The above-described material model has been implemented in a commercial finite element software by means of UMAT subroutine and then used to analyze the thermomechanical behavior of refractory masonry walls.

### 3. Results and Discussions

Figure 3 presents the numerical results of a masonry wall subjected to axial loading and unloading. In the beginning, bed and head joints are open and the masonry structure is in state 1. During loading, joints thickness will decrease gradually till reaching zero and masonry will change to either state 2 (X-loading) or state 3 (Y-loading). During unloading, some joints will reopen and change back to state 1. After reopening the final joint thickness is usually less than the initial one.

Figure 4 shows the biaxial compression test setup at RHI Magnesita technology center (Leoben, Austria). The test device is composed of four ceramic plates, masonry test field and four linear variable differential transformers (LVDTs). Two of the ceramic plates are fixed and the others are moving thanks to two hydraulic pistons. The pistons can either provide a constant increase in displacement or in force. Four LVDTs have been used to measure the displacement in two directions (horizontal and vertical).

A commercial finite element code (Abaqus) has been used to simulate the experimental test. Figure 5 depicts the solution domain of the experimental test. The four ceramic plates, as well as the support device, have been modeled as rigid plates. Two of them are fixed while displacement boundary conditions have been applied to the other two. The friction between the bricks and the rigid plates and between the bricks and the support device have been considered. During the first few millimeters, the LVDTs will not predict any displacement. So, a



**Fig. 3 Joints closure and reopening due to X (A) and Y (B) loading and unloading.**

preload, in the two directions, has been applied till the sensors detect a displacement. Then, loads have been applied in both directions.

After applying the preload, the four joint patterns will be present in the masonry structure as follow (see Fig. 5): pattern 1, in all masonry far away from the moving plates, pattern 2 near the moving plate in direction 1, pattern 3 near the moving plate in direction 2, and pattern 4 near the intersection between the two moving plates.

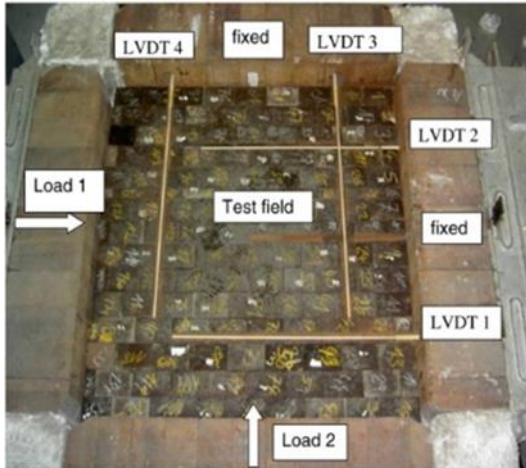
Figure 6 shows a comparison between experimental and numerical results. As can be seen from the figure, both numerical and experimental results are in good agreement. The overall behavior of the masonry is orthotropic and nonlinear due to the gradual closure/reopening of the joints and changing from one joint pattern to another. The reaction forces, in the two directions, increase with the increase of the applied displacement due to the gradual closure of the joints and the increase of material stiffness with joints closure. The displacement in direction 2 is higher than that in direction 1 as the number of joints in direction 2 is higher than in direction 1 (13 bed joints in direction 2 and 8 head joints in direction 1). After unloading, the masonry structure will not return back to the initial configuration and there is always a permanent deformation in both directions. This can be attributed to that the final joint thickness in both directions is less than the initial one.

### 4. Conclusion

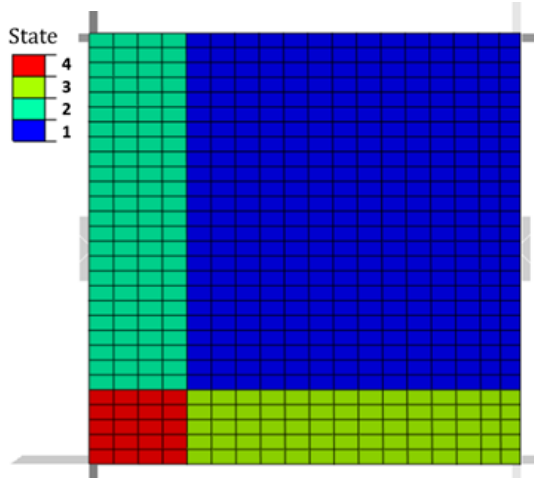
Three-dimensional thermomechanical models have been developed to analyze the effects of joints closure/reopening on the mechanical behavior of mortarlless masonry walls. Four joint patterns, with their corresponding equivalent elastic properties,

have been defined based on the state of head and bed joints.

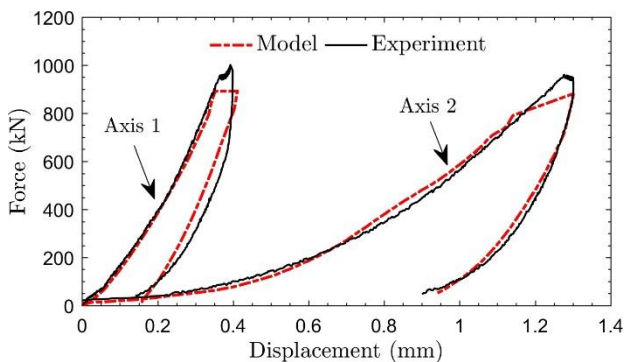
The overall behavior of the masonry is orthotropic and nonlinear due to the gradual closure of joints and changing from one joint pattern to another. After unloading the final joint thickness is usually lower than the initial one and there will be a permanent deformation in both directions.



**Fig. 4 Biaxial compression test setup** <sup>6)</sup>.



**Fig. 5 Joint states after the preload.**



**Fig. 6 Reaction forces versus displacement during loading and unloading obtained from experiment and simulation.**

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