European Journal of Mechanics A/Solids 49 (2015) 67–81

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Experiments and nonlinear homogenization sustaining mean-field theories for refractory mortarless masonry: The classical secant procedure and its improved variants

Amna Rekik [a,*], Samir Allaoui [a], Alain Gasser [a], Eric Blond [a], Kirill Andreev [b], Sido Sinnema [b]

[a] Univ. Orléans, INSA-CVL, PRISME, EA4229, F45072 Orléans, France
[b] Ceramics Research Center, Tata Steel R&D, PO Box 10000, 1970CA Ijmuiden, The Netherlands

A R T I C L E I N F O

Article history:
Received 12 October 2012
Accepted 15 May 2014
Available online 23 June 2014

Keywords:
Mortarless joint
Digital Image Correlation
Nonlinear homogenization

A B S T R A C T

In order to support the optimization of mortarless brick linings of steel producing furnaces it is proposed in this paper to investigate only the compressibility of dry refractory joints. To this end, optical measurements based on the Digital Image Correlation method were carried out during compression of Magnesia-Carbon brick samples with dry joints. The second main objective is to assess the accuracy of the secant linearization schemes (the classical secant procedure and its modified extension) to reproduce the reference local and global behaviour of refractory mortarless linings accounting for the identified inelastic convex power-law behaviour of the Magnesia-Carbon dry joint. The reference nonlinear solution is obtained by means of finite elements method. Under normal compressive loading, unlike for usual (concave) power-law viscoplastic composites for which the secant schemes are known to provide too stiff results, it was found that the modified secant scheme leads to good overall predictions. The classical secant procedure underestimates the reference local and overall behaviour. To improve the latter result, an empirical improved secant formulation was proposed and implemented. It leads to better estimates at local and global levels.

1. Introduction

Many large-sized structures as civil engineering or historical buildings, monumental structures and refractory ceramic linings of metallurgical vessels are made of masonry material. Masonry is a composite material obtained by joining natural (clay, stone, etc) or artificial (ceramic) bricks by means of mortar layers as in refractory linings. For reasons of durability and resistances to harmful factors (fire, water, chemical products, etc.), the conventional bonded masonry is replaced by mortarless masonry systems such as interlocking mortarless hollow concrete block systems (Thanoon et al., 2008a), dry-stack mortarless sawn stone constructions (as the Egyptian pyramids and the Zimbabwe ruins for example) (Senthivel and Lourenço, 2009) and refractory linings of industrial furnaces including vessels of steel industry where the ceramic bricks are laid in direct contact with each other (Andreev et al., 2012; Gasser et al., 2004; Nguyen et al., 2009).

For conventional mortared masonry structures, several approaches and models have been developed and presented in the literature to investigate and predict their behaviours. For numerical purpose, two main approaches have been adopted for mortared masonry modelling: macro-modelling and micro-modelling. For the global structural behaviour, the macro-modelling approach (Di Pasquale, 1992; Lourenço, 1998; Marfia and Sacco, 2005) intentionally ignores the interaction between units and mortar but smears the effect of joint presence through the establishment of a relation between average strains and average stresses. It defines then a fictious homogeneous and continuous material equivalent to the studied masonry composite which is heterogeneous and discrete. Macro-approaches obviously require a preliminary mechanical characterization of the model based on experimental laboratory or in-situ tests on sufficiently large-sized masonry structures under homogeneous states of stress. The alternative micro-modelling approach adopted by many researchers (Giambanco et al., 2001; Lourenço, 1996; Lourenço and Rots, 1997, 1993; Pelissou and Lebon, 2009; Rekik and Lebon, 2010) is suitable for small structural elements with particular interest in strongly heterogeneous states of stress and strain. Its primary aim is to closely represent masonry from the knowledge of the properties of each constituent and the interface. The experimental data must be obtained from laboratory tests on masonry constituents and

* Corresponding author.
E-mail address: amna.rekik@univ-orleans.fr (A. Rekik).

http://dx.doi.org/10.1016/j.euromechsol.2014.05.006
0997-7538/

small masonry specimens. In studies based on micro analysis, two main approaches have been used: the simplified approach which is the more refined and the detailed micro-modelling approach. Simplified methods consist in modelling the bricks, mortar and interface separately by adopting suitable constitutive laws for each component. A simplified micro-model is an intermediate approach where the properties of the mortar and the mortar interface units are lumped into a common element, while expanded elements are used to model the brick units. Although this model reduces the computational cost of the analysis, some accuracy is obviously lost. Even it is proved that the micro-modelling approach gives highly accurate results especially at local level, such approach can hardly be used in practice for structural design since its model requires a separate discretization of bricks and joints, leads to intractable numerical difficulties as the size of the problem increases.

For mortarless masonry, there have been limited analytical and numerical studies which depend mainly on the type of blocks used to assemble the walls. Among these studies, a finite element model was proposed by Oh (1994) to simulate the behaviour of interlocking mortarless block developed in Drexel University. Such a procedure is useful to simulate the contact behaviour of mortarless joint including geometric imperfection of the mortarless joint but is suitable only for modelling small masonry assemblies. Material nonlinearity is not considered to account for the behaviour of the masonry near the ultimate load and to predict failure mechanism. Alpa and Monetto (1998) suggested a macro-model based on homogenization techniques to model the joint and the block as a homogenous material. That model focuses on the joint movement mechanism assuming perfect joint. This model ignores significant issues such as material nonlinearity, joint imperfection and progressive material failure. Recently, Thanoon et al. (2008a, 2008b) proposed a finite element model and developed an incremental-iterative program to predict the behaviour and failure mechanism of the system under compression. The nonlinear progressive contact behaviour of mortarless joint that takes into account the geometric imperfection of the block bed interfaces is included based on experimental testing. The developed contact relations for dry joint within specified bounds can be used for any mortarless masonry system efficiently with less computational effort. As a continuity of the work of Gasser et al. (2004), Nguyen et al. (2009) proposed a model based on linear homogenization technique performed with finite element method. It derived four equivalent homogeneous materials for which mechanical properties depend on the joint state, on the basis of the joint opening/closure mechanism. The transition criteria between these joint states are based on the unilateral contact conditions written in terms of macroscopic strain. Similar studies (Brulin et al., 2011; Gasser et al., 2011) based on the same idea of four equivalent homogeneous materials for which mechanical properties depend on the joint state were carried on masonry refractory structures. On the other hand, Senthivel and Lourenço (2009) developed a nonlinear finite element analysis based on experimental data to model deformation characteristics such as load-displacement envelope diagrams and failure modes of dry stack masonry shear walls subjected to combined axial compression and lateral shear loading. This analysis is based on a multi-surface interface model where bricks and joints are assumed elastic and inelastic, respectively. More recently, Andreev et al. (2012) investigate the compressive closure of dry joints in two classes of refractory bricks: Magnesia-Carbon and Magnesia-Chromite bricks. The general aim of the investigation was to obtain data on the compressive joint closure behaviour to get a better insight into the masonry stress state and the joint condition during the service cycle of the furnace. To this end, the process of joint closure was measured indirectly by compressing samples with and without joints in wide temperature range. At room temperature, also direct optical measurements were performed. FEM computer analysis was used to interpret the measurement results.

Either for conventional mortared or mortarless masonry structures, a continuum model based on micromechanical considerations seems more preferable. Indeed, recently, especially in the case of regular masonry, efficient and reliable models based on periodic homogenization have been made to allow nonlinear analysis of large scale structures at a low numerical cost. The present work is closely connected with the latter kind of analysis. Its relevance is based on its dependence on nonlinear homogenization methods sustaining mean-field theories classically applied to nonlinear composites. In this paper, it is then proposed to assess the accuracy of predictive schemes belonging to the class of secant methods (the classical (Berveiller and Zaoui, 1979; Hutchinson, 1976) and its modified approach (Ponte Castañeda, 1991; Suquet, 1995, 2001)) to the particular case of refractory mortarless masonry. At room temperature, the nonlinear behaviour of the mortarless ceramic joint was identified experimentally based on Digital Image Correlation (DIC) method. The behaviour of the brick unit was assumed to be linear elastic. Linearization procedures defining a linear comparison composite (LCC) were then applied only for the head and bed dry joint behaviours. The linear homogenization of the LCC's behaviour was performed using finite element method (FEM). Therefore, the approximations on the macroscopic level are related to the sole linearization procedure. Results of nonlinear homogenization sustaining mean-field theories are compared at global and local scales to the results of the nonlinear reference solution. Furthermore, it is proposed to improve the results of the classical secant scheme in order to better estimate local and global behaviours of mortarless masonry. Note that the methodology proposed in this paper can be enlarged to the more general case of mortared masonry or eventually for masonry at high temperatures.

2. Experimental characterization of mortarless joint behaviour

In many furnaces, e.g. converters of steel industry, Magnesia-Carbon (MaC) bricks are laid on dry joint, without usage of mortar. The quantitative knowledge of the compressive behaviour of dry joints is an essential design parameter. As an example one can regard the superposition of the stress reducing effect of the joint. For these reasons and in order to support optimization of refractory masonry structures only the compressibility of dry joint will be investigated. Compressive tests on a stack of two Magnesia-Carbon (MaC) bricks (without mortar) were carried out. Commercially available MaC bricks were used. Their composition is shown in Table 1. Because of their high resistance against chemical and mechanical wear the bricks are used in the insulating linings of steel making vessels. The morphology of the brick is bigger grains of

Table 1
Chemical composition and physical properties of MaC bricks (Andreev et al., 2012).

Material type	MaC
Density, g/cm^3	2.93
Open porosity, %	10
MgO, %	98
Cr_2O_3, %	–
CaO, %	1
Fe_2O_3, %	0.5
Al_2O_3, %	–
SiO_2, %	0.5
Total C, %	14