International Journal of Solids and Structures 80 (2016) 193–211

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Nonlinear micro-mechanical analysis of masonry periodic unit cells

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ARTICLE INFO

Article history:
Received 22 June 2015
Revised 3 November 2015
Available online 14 November 2015

Keywords:
Micro-modeling
Numerical modeling
Masonry
Compressive strength
Tensile strength

ABSTRACT

A model for the analysis of masonry periodic unit cells of several wall and pillar geometrical typologies is proposed. It is based on a micro-mechanical analysis of the masonry cell, which has been divided into cuboids, and coupled with constitutive laws modeling the behavior of the materials in tension and multiaxial compression.

The model may be used for the determination of the tensile and compressive strength of masonry composites, in addition to its elastic properties. The results obtained from its application to case studies from the literature are compared in terms of accuracy and computational cost to finite element analyses of the same structures with a favorable outcome.

Based on the micro-mechanical model formulations, and taking advantage of their low computational cost, a comprehensive parametric investigation is performed, covering the effects of several material parameters on the compressive strength of masonry. Finally, a closed-form expression for the determination of the compressive strength of masonry based on the properties of the units and the mortar is proposed.

1. Introduction

1.1. State of the art

Over the last few decades, the interest in the nonlinear behavior of masonry structures has seen a significant increase. The mechanical properties of the materials of which masonry members are comprised, coupled with the mechanical actions to which they are subjected in the composite, make the study of the behavior of masonry beyond the elastic limit a necessity. The numerical study of the nonlinear behavior of masonry composites becomes even more relevant considering the difficulty in acquiring masonry samples from existing buildings on which meaningful mechanical tests can be performed.

Micro-modeling techniques for the derivation of the mechanical properties of masonry composites are a powerful tool. They are capable of providing the orthotropic elastic properties of masonry under normal and shear loads as well as its strength domain under uniaxial or complex loading. The information obtained in terms of strength values, the evolution and propagation of damage in each component and the influence of individual material parameters on the response are highly important for the computational study of masonry structures and can prove to be an incentive for guiding experimental studies towards the determination of the critically important mechanical properties of masonry materials. In this context, knowledge- and performance-based design stand to benefit greatly from micro-modeling techniques.

Being composed of (at least) two macroscopically distinguishable material phases with potentially very different mechanical properties, generally arranged in a repeating pattern, masonry structures composed of units bonded with mortar joints are a suitable candidate for analysis using periodic unit cells. The analysis of these cells may be performed using finite element computations (Massart et al., 2005, Berto et al., 2004) or analytical expressions (Zucchini and Lourenço, 2002, Briccoli Bati et al., 1999, Pande et al., 1994), in order to derive the distribution of stress and strain in the volume of the cell. While the former is capable of providing accurate results, its use is hindered by potentially high computational cost. The latter choice is attractive due to its very low computational cost, but the validity of the assumptions made in the formulation of the analytical expressions needs to be rigorously checked through conceptual reasoning, accurate calculations and comparison with existing experimental data. Comparison with a finite element benchmark may also be required for the determination of the accuracy of analytical models, as experimental data does not often include an exhaustive measurement of all elastic properties of the masonry composite.

It has been demonstrated that numerical modeling of masonry wall structures under in-plane-loading needs to take into account the out-of-plane stresses (Anthoine, 1997; Lourenço and Pina-Henriques, 2006). While this necessity is straightforward in the case of multi-leaf walls or of pillars composed of interlocking masonry units, where the accurate representation of the geometry of the structure demands its full three-dimensional modeling, it is essential in the analysis of

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http://dx.doi.org/10.1016/j.ijsolstr.2015.11.004
0020-7683/

Notation

Dimensions

l	length
h	height
t	thickness
A	area

Material properties

E	young's modulus
ν	Poisson's ratio
G	shear modulus
f_t	compressive strength
f_c	tensile strength
c_0	initial cohesion
φ_0	initial friction angle
φ_r	residual friction angle
${G_f}^c$	compressive fracture energy
${G_f}^I$	tensile fracture energy
${G_f}^{II}$	shear fracture energy
h	characteristic length

Stress and strain

σ	stress
σ_{eff}	effective stress
ε	strain
$\varepsilon_{c/3}$	limit of proportionality
ε_c	peak strain
ε_u	ultimate strain

Integrity variables

T	tensile integrity variable
C	compressive integrity variable
S	shear integrity variable

Closed-form expressions

sb1	ratio of lateral to vertical stress in mortar
su1	ratio of lateral to vertical stress in unit
$f_{c,UC}$	unit compression mode strength
$f_{c,UCT}$	unit tension mode strength
$f_{c,MC}$	mortar compression mode strength

Material subscripts

u	unit
m	mortar
i	infill
if	interface
c	masonry composite

Cuboid subscripts

u	unit (general)
d	header unit
s	stretcher unit
b	bed joint
c	cross joint
h	head joint
t	transversal joint
i	infill

single leaf structures as well, since three-dimensional effects are a governing factor in the behavior of mortar joints in masonry under compression. While plane stress and plane strain finite element models may present significant computational cost advantages over full three-dimensional models, they tend to under- or overestimate the confinement effect on mortar in the joints respectively.

Several models based on computationally inexpensive analytical expressions have been proposed for various types of masonry. These include early models of stack bond pillars (Haller, 1959) and numerous works on stack and running bond walls (Zucchini and Lourenço, 2002; Pande et al., 1994; Taliercio, 2014). Other types of masonry, such as Flemish bond walls, three-leaf walls with infill and English bond pillars have not been the subject of much investigation. An attractive method of analytically dealing with masonry periodic unit cells is the micro-mechanical approach introduced by Aboudi (1991) for the analysis of periodically reinforced composites. The masonry cell is suitable for analysis using this method when seen as a regular arrangement of square or cubic sub-cells with varying mechanical properties and interlocking patterns.

Detailed micro-modeling requires extensive characterization of the mechanical properties of the masonry units, mortar, infill and interfaces. Due to the large number of parameters involved, coupled with inherent difficulties in determining these parameters from samples extracted from existing structures and with the high scatter that often characterizes them, several of these parameters are routinely given standard values. The study of the sensitivity of the compressive strength of masonry to some of these parameters is an interesting subject for investigation, as local or diffuse variation in a material property may be detrimental to the load bearing capacity of a structural member.

Closed-form expressions for the determination of the compressive strength of masonry have been proposed based on various analytical formulations (Ohler, 1986; Hilsdorf, 1969; Francis et al., 1971; Hendry, 1990) and are in use in modern design codes (CEN, 2005). Many of these expressions have a strong empirical dimension concerning the influence of the material properties of the constituent materials of masonry. Furthermore, several models have restrictions on their range of application as defined by the spectrum of elastic properties in which they provide reliable results. A relatively simple closed-form model based on the principles of detailed micro-modeling which overcomes as much as possible empirical assumptions and result instability of other closed-form models could be proposed.

1.2. Objectives

A number of objectives is attempted to be tackled through this investigation. A model for the computational modeling of masonry wall and pillar structures based on micro-mechanical modeling techniques and performed through the analysis of periodic unit cells is proposed. The analysis of the masonry cells is carried out using simple analytical expressions based on stress equilibrium, strain conformity and rational assumptions concerning the behavior of masonry geometrical components. By coupling with nonlinear constitutive laws, these models are intended to be used for the calculation of the nonlinear properties of masonry structures.

Several typologies of masonry walls and pillars are treated in this paper. A number of them, such as stack bond pillars, stack bond walls and running bond walls, have garnered the almost complete attention of researchers so far. The present investigation includes analyses on Flemish bond and three-leaf walls, as well as English bond pillars, which have not received the research attention that their abundance in the built environment would warrant.

The models have been employed in the study of the response of masonry under applied normal stress. Special emphasis is placed on compression, which exhibits a rather more complex dependence on material properties due to the effect of triaxial confinement of the mortar in masonry under compression.

In addition, a closed-form expression for the determination of the compressive strength of masonry is proposed based on the micro-mechanical models developed here. A further simplification of this expression is proposed based on empirical data. A number of experimental case studies on the compressive strength of masonry