Construction and Building Materials 109 (2016) 128–138

Contents lists available at ScienceDirect

Construction and Building Materials

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

Prediction of masonry compressive behaviour using a damage mechanics inspired modelling method

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HIGHLIGHTS

- Analytical model requires only constituents properties as input.
- Time and cost effective computational model to predict the masonry strength.
- Prediction of strength close to experimental data conservatively.
- Good comparison with National Masonry Standards (AS3700-2011 and Eurocode 6).
- Sensitive to unit strength, mortar strength and mortar joint thickness.

ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form 16 December 2015
Accepted 28 January 2016
Available online 6 February 2016

Keywords:
Damage
Limiting surfaces
Masonry compressive strength
Progressive stiffening characteristics
Analytical modelling

ABSTRACT

Masonry under compression is affected by the properties of its constituents and their interfaces. In spite of extensive investigations of the behaviour of masonry under compression, the information in the literature cannot be regarded as comprehensive due to ongoing inventions of new generation products – for example, polymer modified thin layer mortared masonry and drystack masonry. As comprehensive experimental studies are very expensive, an analytical model inspired by damage mechanics is developed and applied to the prediction of the compressive behaviour of masonry in this paper. The model incorporates a parabolic progressively softening stress–strain curve for the units and a progressively stiffening stress–strain curve until a threshold strain for the combined mortar and the unit-mortar interfaces is reached. The model simulates the mutual constraints imposed by each of these constituents through their respective tensile and compressive behaviour and volumetric changes. The advantage of the model is that it requires only the properties of the constituents and considers masonry as a continuum and computes the average properties of the composite masonry prisms/wallettes; it does not require discretisation of prism or wallette similar to the finite element methods. The capability of the model in capturing the phenomenological behaviour of masonry with appropriate elastic response, stiffness degradation and post peak softening is presented through numerical examples. The fitting of the experimental data to the model parameters is demonstrated through calibration of some selected test data on units and mortar from the literature; the calibrated model is shown to predict the responses of the experimentally determined masonry built using the corresponding units and mortar quite well. Through a series of sensitivity studies, the model is also shown to predict the masonry strength appropriately for changes to the properties of the units and mortar, the mortar joint thickness and the ratio of the height of unit to mortar joint thickness. The unit strength is shown to affect the masonry strength significantly. Although the mortar strength has only a marginal effect, reduction in mortar joint thickness is shown to have a profound effect on the masonry strength. The results obtained from the model are compared with the various provisions in the Australian Masonry Structures Standard AS3700 (2011) and Eurocode 6.

1. Introduction

Masonry is a non-homogeneous inelastic and anisotropic composite material, which is commonly built using stiffer units (blocks or bricks) and relatively soft mortar layers. When masonry is subjected to compression, the bond between the mortar layers and the units induces a stress state in which the units experience biaxial lateral tension–compression whilst the sandwiched mortared layers are under triaxial compression [1,2] as shown schematically in Fig. 1.

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http://dx.doi.org/10.1016/j.conbuildmat.2016.01.048

List of notations

b	mapping parameter	f'_{uc}	characteristic compressive strength of units
C_1	stress scale factor	H_u	height of units
C_2	power for shoulder prominence in sponge model	L	length of units
C_3	densification strain of sponge	R_i	energy release rate
$\tilde{C}$	effective compliance matrix	$(R_iR_i)^{1/2}$	resultant energy release rate
C_v	coefficient of variation	R_o	energy release rate at damage initiation
E	elastic Modulus	R_c	critical energy release rate
E_m	elastic modulus of masonry	T	width of units
E_{mo}	initial elastic modulus of mortar	t_j	thickness of mortar joints
f	loading function surface	α	damage parameter for tension
f_o	damage threshold surface	β	damage parameter for compression
F	bounding (rupture) surface	γ	damage parameter for volumetric change
f_b	normalised compressive strength of units as per EC06	ε	strain
f_k	characteristic compressive strength of masonry as per EC06	σ	stress
f_{mc}	mean compressive strength of mortar	ν	Poisson's ratio
f'_{mc}	characteristic compressive strength of mortar	$\rho\Lambda$	complementary energy of damaged material
f_m	mean compressive strength of masonry	ω_i	damage component along i axis
f'_m	characteristic compressive strength of masonry	ω_{hi}	damage healing component along i axis
f_{uc}	mean compressive strength of units	$\omega_{h,max}$	initial prescribed value of damage in mortar–interface

Compressive strength is an important factor used for the characterisation of masonry in structural designs. Most of the design standards suggest empirical formulations and/or a table of masonry strength based on the unit strength and type of mortar used as in Standards Australia (AS3700-2011 [3]); American Code (ACI 530-2005 [4]) and Eurocode (BS EN 1996-1-1:2005; BSI, 2005 [5]). The second accepted method in the standards is experimental testing of stack bonded prisms/stretcher bonded wallettes under uniaxial compression. To date the design standards do not incorporate any clauses for adoption of simplified theories for predicting the compressive strength of masonry. Many researchers have used plasticity theories based on Mohr–Coulomb criteria, and/or Rankine and Hill type criteria or by implementing their own proposed micro-models in a finite element framework using commercially available packages (for example, *ANSYS*®, *ABAQUS*®, *LUSAS*® and *DIANA*®) to model masonry prisms and wallettes subjected to compression [6–8]. Many reported models have been shown to predict compressive strengths higher than the experimental data (for example in [2,9]), which is non-conservative and hence could not be adopted in structural design with confidence.

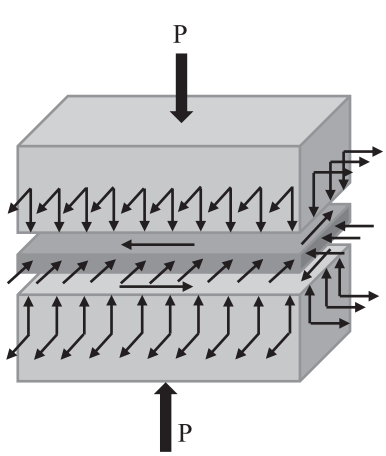

Fig. 1. States of stress of masonry units, mortar and interfaces under uniaxial compression.

Finite element modelling for determining basic masonry properties is time consuming and, hence, cannot be adopted in routine design; experiments, on the other hand, are expensive. Analytical modelling method is an attractive proposition in this context.

An analytical model based on the principles of the damage mechanics coupled with the limiting surfaces developed for homogeneous concrete can be seen in [10–12]. The simplicity of this model inspires its adoption to describe the response of hollow or solid concrete/clay/calcium silicate/stone units that exhibit a progressive softening stress–strain characteristic. A progressively stiffening model for sponge compressibility is proposed in [13]. This model inspires its adoption for a homogenised mortar and unit-mortar interface layer. The two models have been blended seamlessly in the formulation of damage constitutive model and the limiting surface relations to compute the average stress–strain behaviour of masonry prisms/wallettes subjected to uniaxial compression. The model predictions have been compared with a set of experimental data available in the literature. The predictions have been found quite representative and reasonably conservative (and hence reliable for adoption in design). The sensitivity of the model to the properties of the units, mortar and the thickness of mortar joints is demonstrated through a series of numerical examples. The efficiency ratio (the ratio of masonry strength to the unit strength) predicted from the model increase with the reduction in the thickness of mortar joints which is quite similar to the experimental datasets reported in the literature.

2. Behaviour of masonry constituents under compression

It is well known that when masonry is subjected to uniaxial compression, its constituents should be considered under triaxial stress states for effective modelling. More details on triaxial damage stress–strain model are presented in Section 3.

Masonry constituents (units and mortar) are quasi brittle materials. The compressive stress–strain curve of these materials is parabolic with a very small elastic range followed by an inelastic hardening range until peak stress is achieved followed by descending post-peak curve (Fig. 2). Mortar behaviour is affected by the bond at the unit-mortar interface. A nonlinear progressive stiffening response of mortar under compression until a threshold strain