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Simulating masonry wall behaviour using a simplified micro-model approach

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ABSTRACT

In this paper, a simplified micro-model approach utilising a combination of plasticity-based constitutive models and the extended finite element method (XFEM) is proposed. The approach is shown to be an efficient means of simulating the three-dimensional non-linear behaviour of masonry under monotonic in-plane, out of plane and cyclic loads. The constitutive models include surface-based cohesive behaviour to capture the elastic and plastic behaviour of masonry joints and a Drucker Prager (DP) plasticity model to simulate crushing of masonry under compression. The novel use of XFEM in simulating crack propagation within masonry units without initial definition of crack location is detailed. Analysis is conducted using standard finite element software (Abaqus 6.13) following a Newton Raphson algorithm solution without employing user-defined subroutines. The capability of the model in terms of capturing non-linear behaviour and failure modes of masonry under vertical and horizontal loads is demonstrated via comparison with a number of published experimental studies.

1. Introduction

Masonry is one of the oldest and most widespread structural materials; it has been and is still used for various construction purposes. Masonry consists of units and mortar, these constituents have their own mechanical properties and their geometry and arrangement can vary forming different masonry assemblages. Thus masonry is classified as a heterogeneous anisotropic material, and analysis, understanding and capture of the structural behaviour of masonry is therefore complex. For design of non-standard masonry structures or assessment of existing structures, recourse to numerical modelling is often required to understand the structural behaviour under various loading conditions.

Nowadays, numerical models offer a viable alternative to physical experiments. Different numerical methods such as the finite element method (FEM), discrete element method (DEM), limit analysis [1,2] and the applied element method (AEM) [3] have been employed to conduct numerical analysis and simulate linear and non-linear behaviour of masonry. The finite element method (FEM) is the focus of this paper. FEM for masonry is based on two main modelling approaches, namely, Micro-modelling and Macro-modelling, the choice depending on the level of accuracy and detail required.

In the Micro-model approach, the simulation can be detailed; the units and mortar are modelled as continuum elements and unit-mortar interfaces are modelled as discontinuum elements. The detailed Micro-model Fig. 1(a) can provide accurate results, but it is computationally intensive and thus limited to simulating relatively small masonry elements. Alternatively, a simplified Micro-modelling approach Fig. 1(b) can be adopted to address the disadvantages of the detailed micro approach. In the simplified approach, the units are expanded by adding the mortar thickness, the expanded units are modelled as a series of continuum elements and the interaction between the expanded units is modelled as series of discontinuum elements.

In the Macro-model approach, Fig. 1(c), the masonry is considered as a homogenous material with no distinction between units and mortar, the material properties are obtained from average properties of masonry constituents and the masonry is modelled as a series of continuum elements [4]. This approach is adopted where relatively larger and more complex masonry structures are modelled and the global behaviour is of interest, but it cannot capture detailed failure modes.

Over the past four decades, finite element techniques have continuously evolved to capture the complex structural behaviour of masonry walls and associated structures. Arya and Hegemier [5]

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Nomenclature

c	cohesion between the masonry joints interfaces (MPa)
D	damage evolution variable
d	material cohesion (MPa)
E_{adj}	adjusted elastic modulus (MPa)
E_m	elastic modulus of mortar (MPa)
E_u	elastic modulus of units (MPa)
f_{mt}	flexural tensile strength of masonry (MPa)
G_m	shear modulus of mortar (MPa)
G_u	shear modulus of units (MPa)
G_I	work done by the traction-separation in the normal direction (N/mm)
G_{II}	work done by the traction-separation in the first shear direction (N/mm)
G_{III}	work done by the traction-separation in the second shear direction (N/mm)
G_{TC}	critical mixed-mode energy dissipation at failure (N/mm)
G_{IC}	critical fracture energy in the normal direction, refers to as mode I fracture energy (N/mm)
G_{IIC}	critical fracture energy in the first and second shear directions, refers to as mode II and mode III fracture energies (N/mm)
H	height of masonry assemblage (mm)
h_m	thickness of mortar (mm)
h_u	height of masonry unit (mm)
$\mathbf{I}$	identity matrix
$\boldsymbol{K}$	elastic stiffness matrix
K_{nn}	stiffness of masonry joints in the normal direction (N/mm^3)
K_{ss}	stiffness of masonry joints in the first shear direction (N/mm^3)
K_{tt}	stiffness of masonry joints in the second shear direction (N/mm^3)
k_b	numerical factor
l_u	length of masonry units (mm)
$\mathrm{M_d}$	diagonal bending moment capacity of masonry (N mm/mm)
$\mathrm{M_h}$	horizontal bending moment capacity of masonry (N mm/mm)
n	number of courses in a masonry assemblage
R	ratio of the yield stress in triaxial tension to the yield stress in triaxial compression (flow stress ratio)
r	third invariant of deviatoric stress (MPa)
$\mathbf{S}$	stress deviator (MPa)
$\boldsymbol{t}$	nominal traction stress vector
t_u	thickness of masonry units (mm)
t^o_{eff}	effective traction stress at damage initiation under combinations of normal and shear tractions in the joints (MPa)
t_n	normal traction stress in masonry joints in the normal direction (MPa)
t_s	shear traction stress in masonry joints along the first shear direction (MPa)
t_t	shear traction stress in masonry joints along the second shear direction (MPa)
t_n^{max}	maximum allowable traction stress in masonry joints in the normal direction (Tensile strength of masonry joints) (MPa)
t_s^{max}	maximum allowable traction stress in masonry joints in the first shear direction (Shear strength of masonry joints) (MPa)
t_t^{max}	maximum allowable traction stress in masonry joints in the second shear direction (Shear strength of masonry joints) (MPa)
β	material friction angle (Degree)
δ	separation vector
δ_{eff}	effective separation (mm)
δ_n^o	separation of masonry joints at the initiation of damage in the normal direction (mm)
δ_s^o	separation of masonry joints at the initiation of damage in the first shear direction (mm)
δ_t^o	separation of masonry joints at the initiation of damage in the second shear direction (mm)
δ_n^f	separation of masonry joints at the complete failure in the normal direction (mm)
δ_s^f	separation of masonry joints at the complete failure in the first shear direction (mm)
δ_t^f	separation of masonry joints at complete failure in the second shear direction (mm)
η	exponent in the BK law associated with cohesive property i.e. brittle, ductile, etc.
μ	coefficient of friction between the masonry joints interfaces
ν	Poisson's ratio
$\boldsymbol{\sigma}$	stress tensor
σ_c	compressive yield stress of masonry assemblage (MPa)
σ_n	normal contact pressure stress in masonry joint interfaces (MPa)
$\boldsymbol{\tau}_{crit}$	critical shear stress in masonry joint interfaces at which interfaces fail (MPa)
$\boldsymbol{\tau}_{sliding}$	post-failure shear stress in masonry joint interfaces at which interfaces slide (MPa)
$\varnothing$	gle of diagonal crack line in masonry under out of plane loading (Degree)
ψ	dilation angle (Degree)

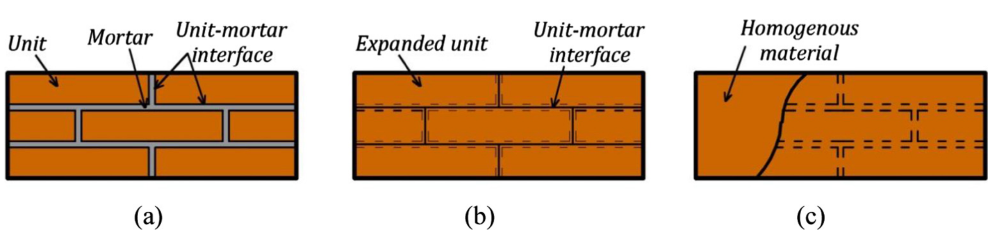

Fig. 1. Finite element modelling approaches: (a) detailed Micro-model; (b) simplified Micro-model; (c) Macro-model (based on [4]).