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An explicit finite element modelling method for masonry walls under out-of-plane loading

Sarkar Noor-E-Khuda, Manicka Dhanasekar *, David P. Thambiratnam

Queensland University of Technology (QUT), Brisbane, Australia

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A B S T R A C T

An explicit finite element modelling method is formulated using a layered shell element to examine the behaviour of masonry walls subject to out-of-plane loading. Masonry is modelled as a homogenised material with distinct directional properties that are calibrated from datasets of a "C" shaped wall tested under pressure loading applied to its web. The predictions of the layered shell model have been validated using several out-of-plane experimental datasets reported in the literature. Profound influence of support conditions, aspect ratio, pre-compression and opening to the strength and ductility of masonry walls is exhibited from the sensitivity analyses performed using the model.

1. Introduction

Masonry is vastly used in the construction of structural and non-structural walls. In cyclonic and seismic events masonry buildings experience a combination of in-plane and out-of-plane loading. Past researches [1–4] primarily focused on the in-plane shear behaviour of masonry walls, being the prime load path in the lateral load transfer mechanism. On the contrary the out-of-plane loading requires sufficient out-of-plane capacity to avoid partial or full failure of the walls, which leads to un-reparable damages to buildings and in many cases causalities due to falling debris. Recent studies [5,6] identified the out-of-plane collapse as one of the common failure mechanisms of masonry walls. Most studies on the out-of-plane behaviour of masonry walls are limited to experimental methods, which are expensive and time consuming. With the advent of high power computers, finite element methods offer economic and elegant alternate approach to the experimental counterpart. This paper presents an explicit finite element (EFE) modelling method, which provides highly stable solutions even after a series of adjacent elements fail and lose their stiffness provided the kinetic energy remains significantly lower than the internal energy in the static problems such as the one attended to in this paper. Although this paper predominantly deals with the static pressure loading normal to the plane of walls, the explicit modelling method formulated herein can be extended to the vehicular impacts and blast loadings on masonry facades that have become a source of concerns in recent times as demonstrated in [7] using experimental and EFE modelling using LS-DYNA. In this paper the formulated EFE modelling is incorporated into ABAQUS/EXPLICIT.

The accuracy of the EFE analysis largely depends on the time step definition of proper material properties and the discretisation of the continuum. Masonry comprises of a series of blocks/units connected through binder materials along its bed and head joints. Therefore, masonry displays distinct orthotropic tensile and compressive strengths, stiffness and post-peak softening features, which depend on its constitutive materials including the mode of construction.

To date most FE modelling techniques have considered masonry as a two-dimensional plane stress continuum [1,2,8] suitable for the prediction of the in-plane shear and compression responses. Out-of-plane flexural behaviour modelling requires definition of curvature (rotational) that can be obtained only in a three-dimensional space. Analytical models were developed [9–11] to predict the out-of-plane response of the unreinforced masonry (URM) walls. [10] proposed a simplified procedure to model the moment–curvature relationship of URM walls. Out-of-plane response requires investigation of full scale specimen of practicable dimensions to appropriately establish its moment–curvature

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* Corresponding author at: School of Civil Engineering and Built Environment, Queensland University of Technology, S-714, Gardens Point Campus, Brisbane, QLD 4001, Australia. Tel.: +61 7 3138 6666; fax: +61 7 3138 1170.

E-mail address: m.dhanasekar@qut.edu.au (M. Dhanasekar).

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Nomenclature

A	area
A_0	initial area of reference surface
a	current area after loading
B	strain deformation transformation matrix
b	damping coefficient
c_d	current dilatational wave speed
Cs	curvilinear component of transverse shear stiffness
c_α, c_β	element distortion coefficients
E_n	Young's Modulus of masonry normal to bed joints
E_p	Young's Modulus of masonry parallel to bed joints
E_z	Young's Modulus of masonry along thickness direction
f	body force vector
f_{cn}	compressive strength normal to bed joint
f_{cp}	compressive strength parallel to bed joints
f_{cy}	compressive strength of masonry
f_{tn}	tensile strength normal to bed joints
f_{tp}	tensile strength parallel to bed joints
F_u	ultimate force
$\overline{f}_{zz}$	thickness increase factor used to identify integration points through element thickness
G	shear modulus of masonry
G_{fcn}	energy for compression failure normal to bed joints
G_{fcp}	energy for compression failure parallel to bed joints
G_{ftn}	fracture energy for tension failure normal to bed joints
G_{ftp}	fracture energy for tension failure parallel to bed joints
G_{xz}, G_{yx}	shear moduli in the out-of-plane direction
H	height of wall
h	changed thickness of element (mm) under loading
h_o	initial thickness of element (mm)
K_0	Initial stiffness of wall
$K_{xx}^{ts}, K_{yy}^{ts}, \overline{K}_{xy}$	actual section shear stiffness along x and y direction and xy plane
K_{xy}^{ts}	actual section shear stiffness along xy plane
L	length of wall
$L_c(mm)$	characteristic length of critical elements
l_x, l_y	change of length of element along x- and y-direction
l_x^o, l_y^o	initial length of element along x- and y-direction
M	mass matrix
$\overline{M}$	moment
m	bulk viscosity pressure
$\widetilde{m}$	normalised moment
N	shape function
Q	resultant transverse shear force
Q^x, Q^y	components of transverse shear forces
q^x, q^y	true transverse shear force components in shell orthonormal coordinate system
R	rotary inertia scaling
r	parameter that defines shape of $(\overline{M} - \varphi)$ curve
S	surface of finite body
S_z	coordinate in thickness direction
t	external traction
U	internal energy
u^n	displacement of body
$\dot{u}^n$	velocity
$\ddot{u}^n$	acceleration
u_x, u_y, u_z	displacement along local x, y, z direction, respectively
V	volume of element
V_o	initial volume of element
W	external work done
α	shear stress contribution factor to the tension failure
α_g	mathematical variable for plastic flow of masonry
β	biaxial compressive strength factor
γ	shear stress contribution factor to compression failure
$\overline{\gamma}^{ts}$	transverse shear strain
$\overline{\gamma}_0^{ts}$	transverse shear strain at centre of element
$\overline{\gamma}_x^{ts}, \overline{\gamma}_y^{ts}$	components of transverse shear strain
$\gamma_x^E, \gamma_x^F, \gamma_y^G, \gamma_y^H$	covariant transverse shear strains evaluated at the mid points E, F, G, H respectively of the element boundary
γ_{bf}	strain associated with butterfly deformation pattern
γ_{cc}	strain associated with crop circle pattern
γ_{hg}	hourglass transverse shear strain vector
λ', μ'	effective Lame's constant
Δ_u	ultimate displacement
Δ_y	yield displacement
$\Delta\varepsilon$	strain increment
$\Delta\varepsilon_{vol}$	volumetric strain rate
$\Delta\varepsilon_{xx}, \Delta\varepsilon_{xy}, \Delta\varepsilon_{yy}$	strain increment
$\Delta\overline{\varepsilon}_{xx}, \Delta\overline{\varepsilon}_{xy}, \Delta\overline{\varepsilon}_{yy}$	reference surface strain increment
$\Delta\kappa$	curvature increment
$\Delta\kappa_{xx}, \Delta\kappa_{yy}, \Delta\kappa_{xy}$	curvature increment along local x- and y-direction and xy plane
Δt	time step size
$\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy}$	strain components along local x- and y-direction and xy plane
$\overline{\varepsilon}_{xx}, \overline{\varepsilon}_{yy}, \overline{\varepsilon}_{xy}$	reference surface strain components
ε_z	strain component along thickness direction
κ_c	scalar control hardening and softening under compression
κ_t	scalar control tension softening
$\overline{\kappa}_{xy}$	reference surface curvature
μ	displacement ductility
v_n	Poisson's ratio of masonry normal to bed joints
v_p	Poisson's ratio of masonry parallel to bed joints
v_z	Poisson's ratio of masonry along thickness
ρ	mass density
ρ_{bv}	linear bulk viscosity pressure
ρ_{io}	ith element reference density
$\tau_{u,c}$	pure shear strength
$\tau_{pn}, \tau_{po}, \tau_{no}$	shear stress components
σ	stress
$\overline{\sigma}_{cn}, \overline{\sigma}_{cp}$	exponential compressive softening parameter along the normal and the parallel to bed joint directions, respectively
σ_n	normal stress component normal to masonry bed joint
σ_p	normal stress component parallel to masonry bed joint
σ_t	equivalent stress to define the softening behaviour
$\overline{\sigma}_{tn}, \overline{\sigma}_{tp}$	exponential tensile softening parameter along the normal and the parallel to bed joint directions, respectively
σ_v	vertical pre-compression
σ_z	stress component perpendicular to mid-plane
θ_x, θ_y	rotation about x and y direction
θ_z	rotation about shell normal
φ	curvature
$\widetilde{\varphi}$	normalised curvature
$\widetilde{\varphi}_o$	normalised curvature at maximum moment