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Finite element analysis of the in-plane shear behaviour of masonry panels confined with reinforced grouted cores

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HIGHLIGHTS

- Masonry confined with reinforced grouted cores have been examined.
- Explicit FE modelling of URM and confined masonry presented.
- Diagonal test datasets used to validate the FE model.
- Reinforcement in confining core is shown to remain elastic.
- FE predictions compared with four major national masonry design standards.

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ABSTRACT

A combined experimental and numerical program was conducted to study the in-plane shear behaviour of hollow concrete masonry panels containing reinforced grout cores. This paper is focused on the numerical program. A two dimensional macromodelling strategy was used to simulate the behaviour of the confined masonry (CM) shear panels. Both the unreinforced masonry and the confining element were modelled using macromasonry properties and the steel reinforcement was modelled as an embedded truss element located within the grout using perfectly bonded constraint. The FE model reproduced key behaviours observed in the experiments, including the shear strength, the deformation and the crack patterns of the unconfined and confined masonry panels. The predictions of the validated model were used to evaluate the existing in-plane shear expressions available in the national masonry standards and research publications.

1. Introduction

Earthquake and severe tropical cyclones (typhoons) are the major natural disasters, facing the mankind; designing buildings to withstand to these natural disasters requires careful attention to the potential for higher demand of in-plane shear load and brittle shear failure. Where the demand exceeds the capacity of the shear walls, the entire building may be destroyed allowing less time to dwellers to evacuate. The in-plane shear analysis usually considers the slabs as rigid diaphragms to distribute the lateral forces to shear walls.

Masonry is perhaps the least understood oldest major construction material as far as its structural in-plane behaviour is concerned. Unreinforced Masonry (URM) buildings are designed mainly for gravity loads and their capacity to in-plane load is generally inadequate. To overcome this inadequacy, a grid of horizontal and vertical reinforced grout elements that break a large masonry wall into smaller panels can be introduced; these elements can effectively confine URM panels. This type of masonry wall construction, known as confined masonry, is shown to outperform other types of masonry constructions in seismic zones [1,2]. In this type of construction the unreinforced masonry panels with specific recesses for placing reinforcement is constructed first followed by pouring concrete into these recesses. This type of construction has similarity to partially grouted (or wide spaced reinforced) masonry shear walls adopted in Australia and most parts of North America [3,4]. The load resisting capacity of the confined masonry is maintained until the masonry panels experience severe cracking. Significant lateral deformation and ductility can thus be attained before the collapse.

The in-plane shear capacity of the walls can be determined using cost-effective numerical tools because such tools can be

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Nomenclature

A_g	gross sectional area (mm^2)
A_n	net area (mm^2)
A_s	area of reinforcement (mm^2)
A_{sh}	area of horizontal reinforcement (mm^2)
A_{sv}	area of vertical reinforcement (mm^2)
b	width of the block/wall (mm)
b_w	effective width of the wall (mm)
d	distance from extreme compression fibre to centre of longitudinal tension reinforcement or 0.8 L for walls (mm)
d_v	effective depth for shear calculations should be greater than 0.8 L (m)
$f_{hmc\perp}/f_m$	mean compressive strength of hollow masonry perpendicular to bed joint (MPa)
f'_m	characteristic compressive strength of masonry (MPa)
f_{yh}	yield strength of horizontal reinforcement (MPa)
f_{yv}	yield strength of vertical reinforcement (MPa)
H_e	effective wall height (m)
H	wall height (m)
k_p	coefficient of the effect of flexural reinforcement
k_u	reduction factor
L	wall length (m)
$M_f/V_f d_v$	aspect ratio
n	number of horizontal grouts
P	pre compression load (kN)
s_h	spacing of horizontal shear reinforcement
v_{bm}	basic shear strength provided by masonry (MPa)
V_n	in-plane shear capacity of the wall (kN)
λ	aspect ratio
γ	factor concerning the type of grouting
δ	factor concerning the loading method

useful to model walls with differing parameters that can be evaluated through standard testing on masonry sub-assemblages (as against full scale structural walls).

The diagonal compression test is an elegant and adequate approach to evaluate the masonry properties [1,5,6]. It is also widely being used to evaluate the effectiveness of damaged/undamaged panels strengthened using different techniques [7–9]. The diagonal compression test results have also been used to validate the Finite Element (FE) models [8,10]. Generally the diagonal compression test panel failures are more brittle than those observed in shear wall tests; therefore, they can be considered as lower bound (conservative) testing method.

Numerical studies on masonry shear walls have been carried out in two different levels; (a) microlevel, and (b) macrolevel. The micromodelling is devoted to develop reliable interface deformation and failure mechanisms through the theories of plasticity or fracture mechanics. Using multi surface plasticity models Lourenço and Rots [11], Gambarota and Lagomarsino [12], and van Zijl [13] successfully predicted the inplane shear capacity of horizontally loaded walls.

Using the model developed by Lourenço and Rots [11], Petersen et al. [8] attempted to validate diagonally loaded URM panels (with and without FRP strengthening) in DIANA platform and succeeded in predicting the peak load but failed to predict post peak behaviour; they could not predict the brittle failure exhibited by the diagonally loaded URM panels in the experiment using their FE model, which reported ductile response unconservatively. Similar 2-D micromodelling attempt was made by Gabor et al. [10] for diagonally loaded URM panels that resulted in similar outcomes as that of Petersen et al. [8].

Sousa et al. [14] developed a 3-D approach using similar micromodelling concept for diagonal loaded URM panels; again their FE model exhibited higher ductile response than that of their experiment test results. Despite the prediction of peak load capacity of diagonally loaded wall panels, this micromodelling technique is quite laborious and require careful definition of contact interfaces; when considering hollow block grouted masonry, there are far too many interfaces and this approach becomes impractical if not impossible.

The macromodelling technique can be applied to large size masonry walls with ease. The downside is that it requires homogenised material properties. To date, no attempts were made to simulate the response of the diagonally loaded hollow concrete masonry panels using macromodelling technique. This paper contains the details of an adapted macromodelling approach for unconfined and confined masonry panels tested under diagonal compression, which successfully predicted the failure mode, shear strength and deformation characteristics.

Empirical formulae are provided in many national masonry standards [15–18] and research papers [19,20] for reinforced masonry shear capacity prediction. Most of these design expressions are formulated from small scale tests conducted in the laboratories and/or based on the experience of designers. The Australian Masonry standard (AS3700) [16] has attracted many criticisms from researchers as its predictions remain highly unconservative [4,21–23]. Relatively, the predictions made by MSJC-2008 [15], CSA:S304.1-2004 [17] and NZS4230-2004 [18] are less criticised, in few occasions their predictions are reported as reasonable for small experimental walls [24]. These criticisms may be attributed to the inherent variability in masonry and the large number of parameters that affect the behaviour of shear walls.

This paper describes calibration of a macromodelling method from the response of diagonally loaded unconfined and confined masonry panels determined from experiments and then using the FE model to predict the behaviour of horizontally loaded reinforced masonry shear panels. The predictions of the validated model were used to evaluate the existing in-plane shear expressions available in the national masonry standards and research publications.

2. Experimental program

A testing program was undertaken to calibrate the FE model. These testing programs contained 55 small scale test specimens to characterise the material properties of the masonry assemblages. Four diagonally loaded unconfined and confined masonry panels were tested to validate the FE model predictions. All these test specimens were constructed using half scale hollow blocks of dimensions 185 mm × 90 mm × 90.5 mm (length × height × width) manufactured in Canada and imported to Australia.

2.1. Characterisation of materials

All material tests were carried out on half scale specimens. All specimens were tested in 14 days except the grout cylinders (which were tested on the 28th day). First 7 days were cured under control environment then next seven days were allowed air curing. The mortar thickness was reduced to 5 mm and hence the fine aggregates used in the mortar were scaled down accordingly. In the grout, 10 mm aggregates were used with scaled down fine aggregates. Very high slump value of 260 mm was used in order to self-compact the poured grout into hollow masonry recesses. The compressive strength of the grout (f_c) was determined from 12 specimens tested in accordance with AS3600.