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Two-dimensional fictitious truss method for estimation of out-of-plane strength of masonry walls

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HIGHLIGHTS

- A new truss model is proposed for analyzing out-of-plane strength of masonry walls.
- The evolution of crack patterns of masonry walls is identified numerically.
- The fictitious truss model was experimentally verified for various masonry walls.

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ABSTRACT

The truss method is rarely used to analyze a masonry wall, especially a masonry wall under a load in the out-of-plane direction. The present study proposes a model called the fictitious truss method (FTM) to determine the ability of masonry structures to withstand a lateral load within their elastic deformation capacities, and introduces a two-dimensional linear static model for masonry walls. The model represents the effect of flexural interaction by computing the stress and strain in the axial direction of the material and by considering uniaxial force effects on masonry elements. Pressure is applied to the surface area of the wall sequentially to predict the ultimate tension and compression cracking. FTM modeling is validated using previously obtained results for confined and unconfined masonry walls and for reinforced and unreinforced masonry walls. The FTM is a reliable method of assessing the out-of-plane strength of masonry structures owing to its conceptual accuracy, simplicity, and computational efficiency.

1. Introduction

The masonry wall is widely used for its low cost in low-rise construction in various countries. Additionally, a ring beam around a masonry structure (confined masonry) wall is recommended for the prevention of injuries and casualties that might occur in the unexpected collapse of a masonry wall. One form of masonry wall collapse is due to loading in the out-of-plane direction, which can occur, for example, in an earthquake or a flood. However, there is no indication that many masonry walls have collapsed under wind pressure after the completion of their construction [4], which can be considered evidence of the adequacy of their construction.

There is a connection between walls and reinforced concrete, given the different deformations of the two materials in response to loading. This is strongly dependent on the type of masonry used for infill. Masonry can be built using different kinds of units (e.g., solid or hollow), unit materials (e.g., clay or concrete), and mortar, depending on the region. The infill wall and the confinement are usually connected with mortar (unreinforced masonry) using an anchor and reinforcement (reinforced masonry).

Research on out-of-plane loading has included experiments and theoretical analysis using different analytical methods, but there has been far less research on out-of-plane loading of masonry walls than on in-plane loading of masonry walls. Some experimental studies have been performed on out-of-plane behavior of masonry reinforced walls [1–3], unreinforced masonry walls [4,5], infill masonry walls [6–8] and confined masonry walls [9–11]. Based on these studies the main variables that affect the out-of-plane behavior of masonry walls are the aspect ratio (height divided by length), wall support conditions, wall slenderness ratio (height divided by thickness), axial load, in-plane stiffness of surrounding elements, wall openings, and unit type. Moreover, the out-of-plane behavior of confined walls is different than that observed for unreinforced, reinforced, and infill walls. The difference is mainly asso-

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Nomenclature

A_n	effective area n of element truss
A_c	pressure effective area
A_r	reinforcement effective area
AR	aspect ratio
A_t	tension effective area
a	depth of the equivalent stress block
α'	constants representing contribution of bricks compressive strengths on f_m
α	shape factor of compressive area
b_{eff}	width of unit load to be used
β'	constants representing contribution of mortar compressive strengths on f_m
β_1	function of strength class of materials
c	distance from center of thickness of masonry wall to the top
d_t	diagonal truss element
δ	displacement
E	Young's modulus
E_b	modulus of elasticity of bricks
E_m	modulus of elasticity of masonry
E_j	modulus of elasticity of mortar
ε'_m	peak strain in masonry, i.e., compressive strain corresponding to fm _
ε_m	compressive strain in masonry
ε	strain
E_c	modulus of elasticity of concrete
f_j	compressive strength of mortar
f'_m	compressive prism strength of masonry
f_m	compressive strength of mortar
f_b	compressive strength of brick
f_c	compressive strength of concrete
f'_{me}	compressive strength of member of truss
f_{tpe}	average out-of-plane flexural tensile strength perpendicular
f_p	compressive strength of unit masonry
FTM	fictitious truss method
FTMSD	fictitious truss method single diagonal
FTMDD	fictitious truss method double diagonal
H	height of masonry wall
h_t	horizontal truss element
I_{eq}	inertia unit equivalent of masonry element
I_n	inertia of element n equivalent of masonry element
I_{tot}	inertia unit of masonry element
θ_d	angle of diagonal truss
σu	ultimate stress
L	length of masonry wall
n	total number of data points
P	joint load
p	joint load
P_{eq}	joint load equivalent
PoE	percentage of error
Q	uniform load
t_{eff}	effective width of a cross section of truss model
v_t	vertical truss
t	thickness of masonry
t_w	thickness of masonry
$\gamma_{eq(u)}$	specific gravity equivalent of unit
$\gamma_{eq(m)}$	specific gravity equivalent of mortar
ξ	specific gravity factor
γ_u	specific gravity factor unit
γ_m	specific gravity factor mortar
γ_{eq}	specific gravity equivalent
t_w	total height of vertical truss elements
v_t	vertical truss element
W_e	strength of masonry by using experimental method
W_{ss}	strength of masonry by using spring–strut method
W_{yl}	strength of masonry by using yield-line method
W_{fl}	strength of masonry by using failure-line method
W_{cs}	strength of masonry by using compressive strut method
W_t	strength of masonry by using FTM in tension
W_c	strength of masonry by using FTM in compression
y	distance from center of effective width of a cross section of the masonry wall to center of element top truss area

ciated with construction procedures and wall reinforcement details. The differences between infill and confined walls are as follows. Firstly, confined walls consist of unreinforced panels surrounded by flexible reinforced concrete confining elements. The wall panels are constructed first, and later the confining elements are constructed. Infill walls consist of unreinforced or reinforced masonry walls surrounded by stiff concrete or structural steel frames [12]. The frames are constructed first, and later the masonry panels are constructed. This type of construction causes gaps between the frames and the masonry panels. Construction gaps delay the formation of arching action [6,13].

The aspect ratio and slenderness ratio [4,10,12,14] have been shown to affect the strength of unreinforced masonry (URM). Some researchers have used finite element (FE) theory and software to analyze masonry walls under out-of-plane loading. Drysdale et al. [4] used FE elastic plate analysis, Noor-E-Khuda et al. [1] used the explicit FE method and a layered shell model, and La-Mendola et al. [15] and Milani et al. [16] used commercial FE software. The FE method is very helpful, but it is complex and requires considerable cost.

On the other hand, numerical modeling of the out-of-plane response of infill frames was reviewed by Asteris et al. [17], whose in-depth literature review included some models of out-of-plane responses for infill frames. There are flexural-action-based models and arching-action-based models.

Cavalery et al. [18] investigated modeling of the out-of-plane behavior of masonry walls. They proposed analytical modeling of the moment curvature law and a numerical procedure to determine the flexural response of masonry cross sections, including nonlinearity owing to the σ–ε law in compression and the assumption of limit-tension material. This investigation simplifies the solution to a problem in which the bending moment increases because of increases in the eccentricity of the constant compressive axial load. This investigation used previous calcarenite and clay brick wall experimental data to validate the analytical model of the moment-curvature curve. This approach can be used for various classes of materials and structures, and is easy to apply means of the analytical moment-curvature law, allowing a fitted "exact" numerical result to be defined. In this investigation, the tensile strength was negligible."

Some researchers have also investigated near-surface-mount-reinforced masonry walls. [15,19–22]. They used fiber-reinforced polymer (FRP), carbon-fiber-reinforced polymer (CFRP) strips, and polymer-textile-reinforced mortar to reinforce a masonry wall. These materials are used to improve the out-of-plane performance of a URM wall. Near-surface-mount-reinforced masonry walls are