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A unified model for the seismic analysis of brick masonry structures

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HIGHLIGHTS

- A unified model governed by ten parameters is proposed for modeling masonry walls.
- The identification procedure for each parameter of the proposed model is presented.
- Four wall specimens are cyclically loaded to validate the proposed approach.
- A half-scale building structure is tested to verify the effectiveness of the model.

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ABSTRACT

A significant portion of the building stock in seismic regions all over the world is constituted by brick masonry structures that are well known to be prone to damage under seismic excitations. For evaluating the dynamic performance of masonry buildings, efficient numerical models are required. In this paper, considering the typical hysteretic behavior of brick masonry walls, a unified model for the static and dynamic analysis of masonry structures governed by ten key parameters is proposed. The model is able to simulate different kinds of walls such as unconfined unperforated and perforated walls, as well as confined unperforated and perforated walls subjected to horizontal reverse cyclic loadings and vertical compression. The identification procedure of each key parameter, that includes, among the others, lateral strength, loading and unloading stiffness, accumulated damage factor, shrinkage factor, as well as slipping factor, is presented by analyzing over one hundred results collected from literature. In order to validate the proposed approach, four different types of wall specimens were tested under cyclic loads. Furthermore, a two-storey half-scale structure was tested to verify the effectiveness of the presented model in reproducing the deformation response and global hysteretic behavior of the structure.

1. Introduction

Masonry buildings represent a great portion of constructions all over the world, and several studies have been devoted to exploring the seismic performance of such buildings owing to their vulnerability emerged in earthquake disasters [1,2]. At present, many numerical approaches for masonry buildings have been proposed and applied, which can approximately be classified into three categories that include micro-scale, meso-scale and macro-scale models [3]. In the micro-scale approaches, the anisotropic and heterogeneous properties of masonry walls are taken into account by modelling brick units and mortar joints separately, to accurately simulate masonry in-plane and out-of-plane behavior. Mostly, the micro-scale models are realized employing FEM and DEM approaches [4]. However, the use of such models is not feasible at the structural level due to the extremely high computational cost. The meso-scale approaches deal with the masonry wall as a homogenous panel, and the response essentially depends on the assumed nonlinear material relationships and damage criteria [5–8]. However, meso-scale models with respect to micro-scale ones have no evident advantages considering both the computational accuracy and burden.

According to the macro-scale strategy, masonry walls are simplified as macro-elements characterized by homogenized properties. Simplified models have been proposed as well, such as the storey mechanism where concentrated mass elements are connected with shear springs [9] (Fig. 1a), the limit analysis and the equivalent strut model [10] (Fig. 1b) as well as the macro-element proposed in [11] (Fig. 1c).

Additionally, equivalent frame models have been also developed. They can be implemented by means of available software packages, since, due to their convenience and efficiency, they have been required or recommended in standards of different countries

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Nomenclature

A_c	sum of cross-sectional area of concrete tie-columns
A_m	horizontal cross-sectional area of the masonry panel
A_y	cross-sectional area of the reinforcements in the tie-column
A_{sc}	total cross-sectional area of the reinforcements in the middle tie-column
A_t	total cross-sectional area of the CM wall that includes both masonry panel and concrete columns
b	shear stress distribution coefficient
b_c	tie-column width
C	accumulated damage factor
C_i	interaction coefficient equal to $2.5bL/H$
d_r	diameter of the reinforcing bar
d_y	displacement corresponding to the yield strength
d_m	displacement corresponding to the lateral strength
E_A	envelope area of one hysteretic loop
E_c, E_m	elastic modulus of concrete and masonry
$E_{h,eff}$	effective energy dissipated in one symmetrical loading loop with a vertex at the maximum deformation
f_a	axial compression stress due to gravity loads
f_c	compressive strength of concrete
f_m	compressive strength of masonry
f	design compressive strength of UCM walls
f_t	tensile strength of masonry
f_y	yield strength of the reinforcement in the tie-column
f_{v0}	shear strength without any vertical compression
f_{ct}	axial tensile strength of concrete
f_{vm}	shear strength of masonry
G_m	shear modulus of masonry
h	height of the brick unit
H	height of the wall
h_{eff}	height of the resultant of lateral force
I_j, A_j	inertia moment and area of cross-section of each pier segment
I_{eqj}, A_{eqj}	equivalent inertia moment and equivalent area of cross-section of each pier segment for perforated CM walls
I_{zeqj}, A_{zeqj}	equivalent inertia moment and equivalent area of cross-section of each pier segment for perforated UCM walls
K_0	initial stiffness
K_m	secant stiffness corresponding to V_m
K_u	unloading stiffness
K_j	equivalent initial stiffness of each pier segment
l	width of the brick unit
L	width or length of the wall
n_c	number of tie-columns
n	number of reinforcing bars in one tie-column
P_D	superimposed dead load at the top of the wall
Q_G	lower-bound axial compressive force due to gravity loads
r	tie-column longitudinal reinforcement ratio
T	thickness of the wall
V_y	yield strength
V_r	shear capacity due to rocking
V_{CL}	shear capacity due to shear sliding
V_{tc}	shear capacity due to toe-compression
V_m	peak strength, ultimate lateral strength
V'_m	reduced lateral strength
V_u	unloading strength
$\hat{V}_m$	lateral strength of masonry part in a CM wall
$\overline{V}$	mean of positive and negative peak values of shear capacity
α	ratio between V_m and V_y
α_k	unloading stiffness coefficient
α_n	coefficient accounting for shear stress not distributed on full cross-section
α_1	factor equal to 0.5 for fixed-free cantilever wall, equal to 1.0 for fixed-fixed wall pier
β	ratio between positive yield strength and negative yield strength
γ_E	adjusting coefficient for seismic design
γ_{RE}	capacity factor
γ	shrinkage factor
$\overline{\Delta}$	mean of positive and negative peak values of lateral displacement
ζ_c	participating coefficient of the middle tie-column
η_z	collaboration coefficient of tie-columns
η_c	confining coefficient
η_a	coefficient for allocating the vertical compression
ηK_0	hardening stiffness
$\eta_{soft}K_0$	softening stiffness
η_i	cross-sectional reduction coefficient
η_j	strength ratio of head-joint to bed-joint, equals to 0–0.3 depending on the mortar quality of head-joint
λ	revision coefficient accounting for the compression ratio and aspect ratio, governed by Eq. (13)
μ	friction coefficient
v_{tL}	lower-bound bed-joint shear strength
σ_0	average vertical compression stress
ψ	aspect ratio of the masonry panel
ω	slipping factor
ξ_{hyst}	equivalent viscous damping coefficient

and regions [12–14]. In the equivalent frame models, horizontal and vertical macro-elements connected by rigid joint regions are combined to describe the composition of piers and spandrels, resulting particularly profitable for representing regularly arranged perforated walls [15–19] (Fig. 1d). However, in the case of irregular arranged openings, the effect of the horizontal slabs is difficult to be taken into account. To the authors' knowledge, few equivalent frame models have been developed for representing confined masonry (CM) structures subjected to reverse cyclic loading. In fact, most of the available models deals with the nonlinear static analysis (pushover) of unconfined (UCM) structures under the equivalent seismic effect [20]. CM constructions consist of unreinforced masonry walls embraced by reinforced concrete columns and beams. This type of construction was first introduced in Italy starting from the beginning of 20th century, in order to create a masonry building resistant to earthquake actions with improved strength and ductility with respect to unreinforced masonry. This technique was then spread in all continents, in particular in regions of high seismic risk, where the use of this type of construction became very extensive [61]. In China, this technique has been very common since 1980s, after the 1976 earthquake in Tangshan that was considered the most severe earthquake of the 20th century in terms of number of deaths (more than 240,000). Now this technique is mandatory according to the Chinese seismic code for masonry buildings [34] in those areas with high seismic risk.

Within this context, in the present paper a unified macro-element that is able to model different kinds of walls, including UCM walls, CM walls, perforated UCM walls and perforated CM walls is introduced. In the proposed approach, the masonry wall is considered as an integral unit, rather than composed by independent piers and spandrels, whose mechanical behavior depends on a compound mechanism consisting of flexure, shear and friction [21]. According to the proposed strategy, the masonry wall is