Engineering Structures 83 (2015) 140–153

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A simplified four-branch model for the analytical study of the out-of-plane performance of regular stone URM walls

Tiago Miguel Ferreira [a,*], Alexandre A. Costa [b], Romeu Vicente [a], Humberto Varum [c]

[a] Department of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[b] Polytechnic of Porto, School of Engineering, R. Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal
[c] Department of Civil Engineering – Structural Division, Faculty of Engineering of the University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 3 March 2014
Revised 28 October 2014
Accepted 29 October 2014
Available online 22 November 2014

Keywords:
Regular stone URM
Seismic response
Out-of-plane
Single-degree-of-freedom
Four-branch model

ABSTRACT

During the last years, several studies have been made aiming to assess the out-of-plane seismic response of unreinforced stone masonry structures. This fact led to the development of a wide variety of models and approaches, ranging from simple kinematic based analytical models up to complex numerical simulations. Nevertheless, for the sake of simplicity, the out-of-plane seismic response of a masonry wall pier may be obtained by means of a simple single-degree-of-freedom system while still providing good results. In fact, despite the assumptions associated with such a simple formulation, it is also true that the epistemic uncertainty inherent with the selection of appropriate input parameters in more complex models may render them truly ineffective. In this framework, this paper focuses on the study of the out-of-plane bending of unreinforced stone masonry walls (cantilevers) by proposing a simplified analytical approach based on the construction of a linearized four-branch model, which is used to characterize the linear and nonlinear response of such structural elements through an overturning moment-rotation relationship. The formulation of the four-branch model is presented and described in detail and the meaningful parameters used for its construction are obtained from a set of experimental laboratory tests performed on six full-scale unreinforced regular *sacco* stone masonry specimens. Moreover, a parametric analysis aiming to evaluate the effect of these parameters' variation on the final configuration of the model is presented and critically discussed. Finally, the results obtained from the application of the developed four-branch model on real unreinforced regular *sacco* stone masonry walls are thoroughly analysed and the main conclusions obtained from its application are summarized.

1. Introduction and motivation

As mentioned by several authors, stone masonry is one of the oldest and most worldwide building technique still in use. If on the one hand, it is true that unreinforced stone masonry can be considered as one of the simplest type of structural systems concerning its assemblage, on the other hand, it is simultaneously one of the most complex construction systems in terms of performance assessment, particularly concerning its out-of-plane seismic response. In fact, among all the vulnerability issues associated with the seismic response of traditional unreinforced masonry walls, the out-of-plane wall response is undoubtedly the most important and complex. Such fact is recognized amongst the scientific community dedicated to the study of this type of structures and has been convincingly demonstrated by recent earthquakes [1]. Thus, it is clear that existing unreinforced masonry walls may be vulnerable to future earthquakes and therefore should be studied for their out-of-plane seismic resistance.

During the last years, several studies have been presented aiming to assess the out-of-plane seismic response of unreinforced stone masonry structures. This fact led to the development and the use of a wide variety of approaches, ranging from simple kinematic based analytical models up to complex numerical simulations [1]. Nevertheless, for the sake of simplicity, the out-of-plane seismic response of a masonry wall pier can be obtained by means of a simple single-degree-of-freedom system while still providing good results (see for example [2,3]). In fact, despite the assumptions associated with such a simple formulation (nonlinearities associated with material and construction practices, for example), it is also true that the epistemic uncertainty inherent with the selection of appropriate input parameters in more complex models may render them ineffective and unreliable. In addition, the simplicity and the low computational effort associated with single-degree-of-freedom formulations make them very interesting both for structural stability verification and assessment purposes.

* Corresponding author.
E-mail addresses: tmferreira@ua.pt (T.M. Ferreira), alc@isep.ipp.pt (A.A. Costa), romvic@ua.pt (R. Vicente), hvarum@fe.up.pt (H. Varum).

http://dx.doi.org/10.1016/j.engstruct.2014.10.048
0141-0296/

Bearing in mind the above reported framework, a simplified four-branch model based on a single-degree-of-freedom idealization of the out-of-plane response of unreinforced stone masonry walls is presented and thoroughly described in this paper. The model, based on an overturning moment-rotation relationship, is conditioned by two meaningful parameters which are related to the physical and mechanical features of the masonry walls. A parametric analysis aiming to evaluate the effect of these parameters on the final configuration of the model is discussed and an experimentally calibrated range for such parameters is proposed for unreinforced regular *sacco* stone masonry. Finally, an application of the developed four-branch model on real unreinforced regular *sacco* stone masonry walls is presented and a comparison between the results obtained and some displacement limits available in the literature is further provided and discussed.

2. The use of single-degree-of-freedom approaches for the analysis of the out-of-plane response of walls

Despite the already noted fact that several works have been presented regarding the assessment of the out-of-plane behaviour of unreinforced stone masonry structures, the truth is that limited attention has been given in the past to the dynamic response of out-of-plane mechanisms in the overall structural behaviour of unreinforced masonry buildings. In fact, this issue has been usually treated only based on the capacity of the structure to resist to lateral static forces [4]. However, different studies have demonstrated that unreinforced masonry walls subjected to dynamic loads can resist accelerations higher than their static strength (for example [5] or [6]) and that they tend to respond as rigid bodies subjected to rocking, the reason why these elements are more sensitive to displacement and velocity rather than acceleration.

2.1. Flexural-based approaches

Priestley was one of the first authors exploring this type of formulation by means of an extension of the ultimate strength methods of design analysis which replaced the traditional methods based on working stress calculations (excessively conservative) [7]. By introducing the concept of ductility within an energy framework, Priestley demonstrated that the level of seismic loading required to cause failure tends to greatly exceed the predictions obtained by simple ultimate strength calculations, especially in the case of face-loaded walls. Such theoretical formulation was experimentally validated through an extensive experimental programme on shaking table face loaded walls. Having validated this initial theoretical formulation, a novel procedure for ultimate load estimation incorporating energy considerations based on the computed load-deflection (or acceleration-displacement) curve was further proposed by the author. The main disadvantages of this approach lie in the fact that the energy demand calculation is very sensitive to the selection of the elastic natural frequency and it is relevant solely for a narrow band of frequencies. It is worth noting that this topic was later addressed by Doherty in [6], who, in 2002, presented a new simplified linearised displacement-based procedure wherein a trilinear relationship is used to characterise the out-of-plane response of unreinforced masonry walls by a nonlinear force-displacement relationship.

This procedure, later used and improved by [3,8,9], is based on the reserve capacity of rocking unreinforced masonry walls to displace out-of-plane without overturning, arising as the wall's post cracking response is governed by stability mechanisms. That is to say, the wall's geometric instability will only occur when the displacement exceeds its stability limit. Therefore, a cracked unreinforced masonry wall rocking with large horizontal displacements may be modelled as a rigid body on simple one-way bending (cantilevers or simply supported walls spanning vertically between supports). It is, however, important to note that the assumption of rigid body behaviour is realistic only for low values of axial force, being that, in the case of high compressive forces, the individual deformation of the blocks can lead to a non-negligible decrease of the maximum displacement motivated by the lateral deformability of the wall prior to incipient rocking. As here depicted in Fig. 1, the "semi-rigid" force-displacement relationship deviates from the bilinear idealization behaviour assuming a curvilinear profile with the maximum force lower than the rigid threshold resistance, F_0 [10]. Thus, this behaviour can be idealized by a trilinear relationship defined by three displacement parameters Δ_1, Δ_2 and Δ_f and the already mentioned force parameter F_0, where Δ_1 and Δ_2 control respectively the initial stiffness reduction and the strength reduction and Δ_f represents the maximum stable displacement.

According to this formulation the lateral static strength and the ultimate displacement of an unreinforced masonry wall subjected to out-of-plane loads are therefore only conditioned by three parameters: (i) geometry, (ii) boundary conditions and (iii) applied vertical forces (including self-weight). This way the uncertainties in the mechanical properties of the material (especially the elastic modulus and the compressive strength of masonry) do not affect significantly the results since the effective stiffness of the wall is the key parameter of the procedure. From an elastic displacement spectrum, the wall displacement demand is predicted independently of its natural period, i.e., knowing the effective mass and the effective stiffness, M_e and K_e respectively, the fundamental period of rocking is determined given the boundary conditions, state of degradation and level of pre-compression. The principal disadvantage of this formulation relies on the fact that parameters Δ_1, Δ_2 and Δ_f are quantified and calibrated purely on the basis of experimental tests (i.e. not mechanically based). A new improved formulation of this model was very recently proposed by [11].

2.2. Rigid body-based approaches

In 1963, Housner [12] presented one of the first studies on the dynamic response of a slender rigid block supported on a base undergoing horizontal accelerations. The author examined the free and forced vibration responses to rectangular and half-sine pulse excitations through the use of an energy approach which enabled an approximate analysis of the dynamics of a rigid block subjected to a white-noise excitation. In this study Housner has shown that the rocking frequency of the wall decreases with the increase of its initial rotation amplitude, presenting also the so-called "scale effects" which are based on the observation that the larger of two geometrically similar blocks could survive the excitation while the smaller block topples. Following Housner's work, Priestley et al. [13] presented a study wherein the possibility of foundation rocking of shear wall structures is investigated and where the author compared Housner's theory for free rocking of rigid blocks with experimental results obtained from a simple structural model with a number of different foundation conditions. In addition, a simple design method for assessing maximum rocking displacement, resorting to equivalent elastic characteristics and a response spectrum, was also presented and validated. It is worth mentioning that this methodology was later adopted by the FEMA 356 document [14]. These two works were indeed pioneers in a field where a large number of studies have been developed over the last decades ([15–21] are just some examples of those which were published between 1980 and 2007).

More recently, Sorrentino et al. [22] took a step forward on the application of the rigid-based principles with the study of the rocking response of unreinforced masonry façade walls. In this work, the façades are assumed to undergo one-sided rocking due to the