The out of plane behaviour of masonry infilled frames

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Abstract. The great interest about out of plane behavior of masonry infill walls has recently increased since it is a key point in the seismic modelling of framed structures. Their contribute to the whole seismic resistance of a framed building cannot be skipped. After a review of the literature on the subject, this paper presents a trilinear constitutive model for the out of plane behavior of masonry infills based on the tensile strength of the constituents. Comparisons with literature model are provided and the identification of the model is based on experimental tests.

1. Introduction

The behaviour out-of-plane loading of masonry is a key-point in the seismic assessment of masonry building, especially in the cases in which partial collapses can be the main cause of damage due to seismic events [1,2]. Since the first laboratory tests by Fattal [3], several experimental studies have been performed during the last thirty years, to provide information about the seismic out of plane response behaviour of masonry infill [4].

The first analytical studies focused on developing equivalent static or linear models for a one way span are those provided by Priestley, using the "equal energy" approach [5], for a simply connected wall. A comprehensive review is provided in [6]. Recent papers deal with the force-displacement relationships on which is based the idealization of rocking behaviour of unreinforced masonry walls [7].

Simplified out-of-plane collapse mechanisms, taking into account connections with surrounding frame [8] and transversal walls, are considered to evaluate the behaviour of masonry walls subjected to out of plane forces [9,10]. In general cantilever walls and walls supported only at the top and bottom edges can be represented as equivalent SDOF system, in order to evaluate by simple static analysis the limit horizontal force at the threshold of rocking, assuming that the wall has cracked and hence the tensile strength of the mortar can be neglected [11].

Similarly, the displacement at the threshold of overturning can be obtained from that simple kinematic model [12]. The real behaviour of masonry infills is in fact strongly nonlinear [13,14]. The bilinear relations based on simple static do not take into account the real behaviour of the wall, due both to wall deformation and degradation and to real support boundary conditions [15]. The same considerations apply to the case of retrofit of a masonry building subjected to out of plane actions, even in case of simplified analyses [16–19]. The need of more accurate constitutive models, together with the

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exigence of relations with simple and representative structure, to be implemented in professional numerical codes, has enhanced the development of a huge set of models.

Several models have been recently proposed to take into account the real behaviour of the wall, considering that the value of the collapse load and the consequent load-displacement behaviour is strongly related to the way of computing the displacements and to the way of cracking [20,21].

The tri-linear model proposed by Doherty and others [6,22] to take into account the real behaviour of masonry, based on qualitative observation of laboratory test results, seem to be an useful tool to model real behaviour of masonry walls out of plane loaded.

Bilinear models obtained from rigid body behavior cannot capture the initial stiffness and actual strength capacity of the walls [7,23,24]. Simplified trilinear force-displacement models have a limited number of parameters which makes them very flexible. This is a great advantage in case of numerical analyses of complex structures [25]. The deformability of the walls is an important factor, together with the slenderness ratio and the boundary and load conditions of the wall [7,24,26,27].

In [28] is considered a damaged wall, so the force-displacement response of the wall takes into account the variable crack height, the finished compressive strength of the masonry and a flexible diaphragm support. The results are compared with those obtained from Doherty's similar model [6]. The comparison shows that the latter model overestimated the instability displacement of the wall and the lateral resistance of the wall for low compressive strength values of the mortar.

In [27] a mechanical model is developed for the out-of-plane response of URM masonry walls, with the analytical expression of the static pushover curve. In [29] a trilinear model is derived from the expression of the pushover curve, with new analytical formulations for the force and displacement parameters of the model itself. Compared to existing trilinear models, this model requires only one additional input parameter, namely the elastic masonry modulus and allows to cover a wide range of wall configurations.

In [30], a trilinear model for walls is developed, using a database of 38 experiments available in literature. The analytical expressions for the maximum lateral force and buckling displacement are derived using the kinematic approach. However, the force-displacement parameters for obtaining the bidirectional dorsal bending curve in the post-cracking phase show a large dispersion indicating that the available test results are not adequate for developing an empirically calibrated model. This is a general problem for masonry walls, even for the in-plane behaviour modelling [31,32].

This paper presents a tri-linear model in which the identification parameters are based on the mechanical characteristics of masonry materials. The need to make reference to both the constituent of the masonry, blocks and mortar, arises from the particular characteristics of a masonry type widely diffused in all Southern Italy: the tuff masonry, characterized by the low strength properties of the masonry block and high-performance mortars [33,34].

Due to its thermal insulation properties, the tuff masonry is diffused as infill in reinforced concrete buildings since the fifties. In this case, the out of plane behaviour of the masonry wall is strongly influenced by the block properties A good agreement is observed between the proposed model and the model and the tests proposed by Doherty.

2. The trilinear models

The behaviour of cantilever and simply supported masonry walls in out of plane flexure (Fig. 1) can be easily modelled as that of rigid blocks separated by fully cracked cross-sections [35]. The Single-Degree-Of-Freedom model equivalent to these walls can be obtained in a fashion similar to that of a multi-storey building based on the fundamental modal deflection.

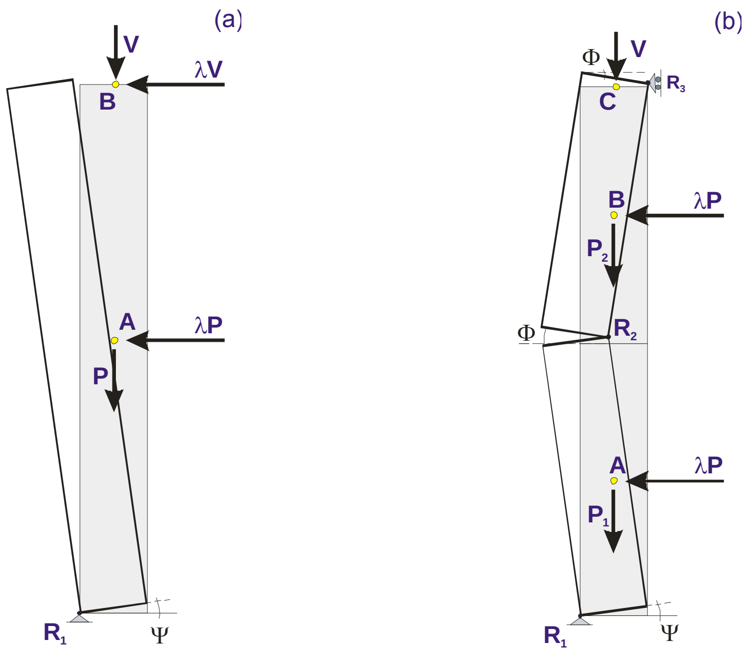

Figure 1. Unreinforced loadbearing masonry walls: cantilever wall (a), simply supported wall (b).

A bi-linear F-Δ relationship may be assumed provided that the wall behaves as a complex of rigid bodies in the cracked state (Figure 2 - red dotted line).

The real behaviour of the wall deviates significantly from this bilinear relationship so that several different relations have been proposed, taking into account the fact that little deviations have been observed from the bilinear behaviour in the range of large displacements (Figure 2 - blue curve).

In recent years, a trilinear relationship has been proposed by several Authors. This tri-linear F-Δ relationship is characterized by two displacement variables Δ1 and Δ2, both expressed as a percentage of the ultimate displacement Δu. The first take into account the initial stiffness reduction, the second controls the strength reduction.

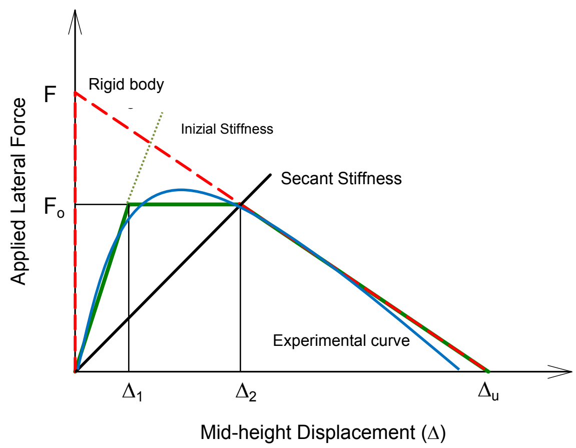

Figure 2. Rigid body, trilinear model and effective secant stiffness graphic.

In the model proposed by Doherty [6], the amount of the displacements Δ_1 and Δ_2, is derived by experimental dynamic tests in three different damage conditions of the wall: new, moderately degraded and severely degraded. The last two conditions are highly subjective, since the moderately degraded walls had effective bedjoints width essentially equal to their original ones, while severely degraded walls had cracked bedjoints with width 90% of the original one.

Table 1. Experimental evaluation of Δ_1 and Δ_2

Damage of the wall	Δ_1/Δ_u	Δ_2/Δ_u
New	6%	28%
Moderately degraded	13%	40%
Severely degraded	20%	50%

Doherty has shown that a reasonably effective secant stiffness for use with a substitute structure representation is that corresponding to a line through the point on the tri-linear force-displacement relation corresponding to $\Delta=\Delta_2$ (Fig. 2). The problem is that the evaluation of the displacement Δ_2 proposed by the author is only qualitative and involves experimental tests not simply performable. In fact, the 'substitute structure' selects an elastic SDOF with linear properties that characterize those of the real non-linear structure, based on the assumption that both the SDOF system and the real structure reach the same critical displacement under the same excitation. This approach needs a secant stiffness, in general, derived from the load-deflection relation in a quasi-static test. The effective secant stiffness for the semi-rigid wall in this manner obtained is expressed by:

$$K_s = K_0 \left(1 - \frac{1}{\Delta_2 / \Delta_1}\right) \tag{1}$$

where K_0 is the slope of the line corresponding to the softening range in the bilinear rigid body behaviour (Fig. 2). The effective undamped natural frequency for the SDOF system equivalent to the masonry wall is given in the following:

$$f_{s-eff} = \frac{\sqrt{K_s / M_e}}{2\pi} \tag{2}$$

In Godio and Beyer [29] and Derakhshan et al. [28] models, the values of Δ_1 have been considered as 2%, and 4%, respectively of Δ_{ins}, whereas, in [30] this value has been obtained using the wall geometry parameters, masonry properties, horizontal crack height, and axial load ratio.

In [31], a comparison between the models of Doherty et al. [7], Godio and Beyer [29] and Derakhshan et al. [28] is presented. The comparison shows that the models of Derakhshan et al. and Doherty et al. underestimate the idealized maximum force, F_o, compared to the peak force, F_{max} in the experimental force-displacement curve, the Godio and Beyer model, on the other hand, overestimates the lateral load for most walls.

Priestley [5] adopted a different approach to determine the load-deflection relationship for the unreinforced masonry wall during out of plane response. The load-deflection relation is obtained considering moments due to the shift of the resultant vertical forces toward the compressed edge of the wall and a linear relation between displacements and curvatures due to the distribution of compressive stresses. Null tensile strength is taken into account. The constitutive behaviour is elastic until the maximum moment produces the first cracking.

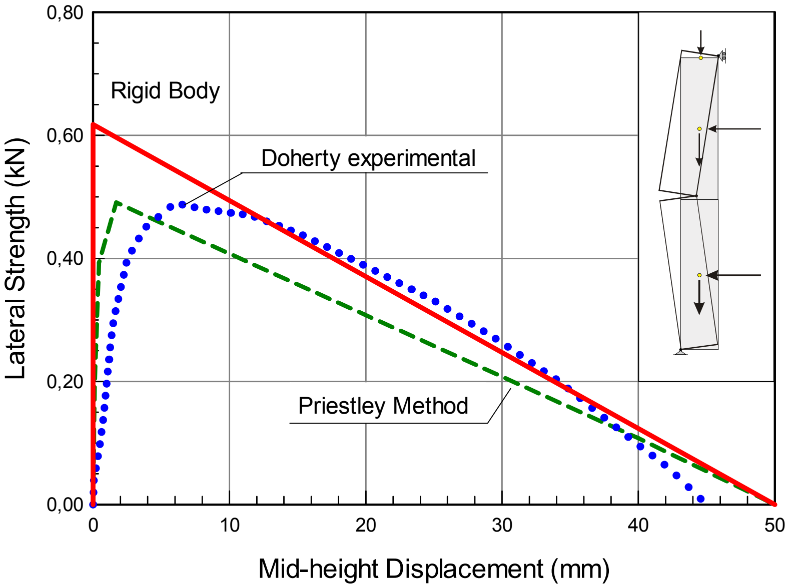

FIGURE 3. Rigid body model, Priestley method and comparison with experimental data for a simply supported masonry wall.

In the above figure, the Griffith-Doherty model is compared with experimental data performed at the University of Adelaide (Australia). The data from the Priestley method are also provided.

3. The proposed model

As it can be seen, the Priestley method involves an initial tangent stiffness very similar to that of the rigid body behaviour, due to the small entities of the elastic displacements, so that a more reasonable and simple model is the one provided by Doherty, with the limits expressed above. To avoid the problems linked to the complex experimental determination of the displacements involved in the Doherty tri-linear model, in this paper the values of the displacements are determined by a "plateau force", taking into account the tensile stress of the masonry materials. In other words, the three lines describing the semi-rigid behaviour of the wall are obtained considering (Figure 4):

- an initial linear elastic behaviour of the masonry wall, like that proposed in the Priestley method. It must be noted that the real behaviour is well represented by the theoretical elastic behaviour;
- a displacement interval at a constant force, corresponding to the attainment of tensile strength in the maximum moment section;
- a final slope of the tri-linear model governed by the rigid block behaviour.

In Figure 4, the proposed model is compared with the Priestley model too. The secant stiffness corresponding to the proposed model is almost coincident with that obtainable in the experimental case of moderately degraded walls, as reported in Table 1 [6].

The model has been applied to tuff masonry walls, taking into account the experimental values reported in Table 2 [36]. The results are reported in Figures 4 and 5 for simply supported and cantilever tuff masonry walls, respectively. As expected, the secant stiffness of the simply supported wall is higher than that of the cantilever wall. The Priestley method is also reported in the same figures.

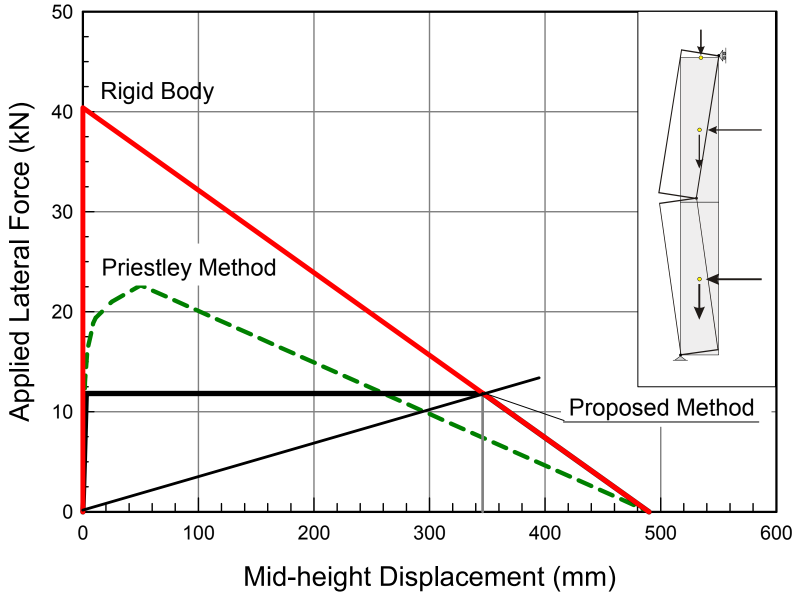

FIGURE 4. Rigid body, Priestley model and proposed trilinear model for tuff masonry simply supported wall.

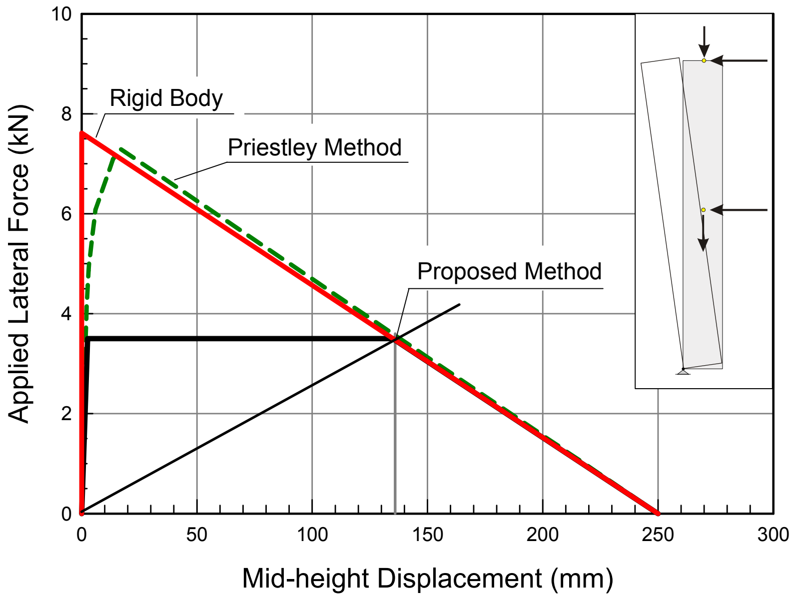

FIGURE 5. Rigid body, Priestley model and proposed trilinear model for tuff masonry cantilever wall.

The value of tensile strength considered in the analysis is the minimum between that of blocks and that of mortar, in the case of brick walls, the lowest value is that of the mortar.

The walls of southern Italy, considered in this paper, are made of blocks in tuff and mortar [37], so the lowest tensile strength value is that of the blocks.

Table 2. Material properties

Material	number of specimens	$\square_0$ (N/mm^2)	E (N/mm^2)	σ_t (N/mm^2)	ν
Mortar	3+6	14.00	1,910.00	2.70	0.21
Tuff	3+3	2.20	1,250.00	0.39	0.08
Masonry	3	1.30	1,000.00	-	-

The mortar is almost always pozzolanic mortar, like that reported in table 2, composed of pozzolana and hydrated lime (1:3 is the weight ratio of the components) [34]. The result is a mortar with high compressive strength and high adhesion properties to tuff blocks.

The limited number of mechanical parameters required for the definition of the model, together with the simple structure of the experimental tests involved, allow the use of the model in the cases in which the out of plane tests are difficult to perform.

In the case of tuff masonry, due to the large dimensions of blocks, significant testing walls are not easy to handle. Besides, the experimental parameters proposed by Doherty seem to be affected only by qualitative observation of cracking on the tested wall, so that a quantitative evaluation is not possible.

In Table 3 the geometrical characteristics of the panel took into account in the present analysis are reported.

Table 3. Loads and geometrical characteristics of panels

Panel	Length (mm)	Width (mm)	Height (mm)	Applied Overburden (N)	Density (kN/m^3)
Tuff masonry	1000	600	6000	30000	17

In Figure 6 the proposed model is compared with the Doherty [6], Derakhshan et al. [28] and Godio and Beyer [29] models. The initial linear elastic behaviour of the masonry wall is very similar to the Godio and Beyer model, the "plateau force" is very similar to the Derakhshan et al. model, the final slope of the tri-linear model governed by the rigid block behaviour, as Doherty model [6].

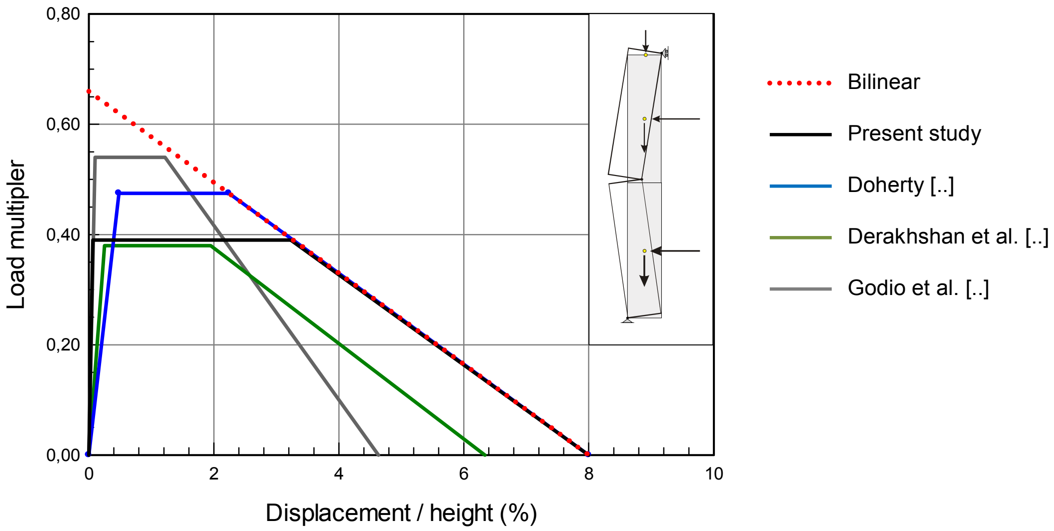

FIGURE 6. Comparison with existing trilinear models

4. Conclusions

A proposal for the determination of a trilinear constitutive model representing the out of plane behaviour of masonry infills has been presented in this paper. Comparisons with models and experimental tests in literature are provided for correct identification. The basic constitutive parameter is the minimum value between the tensile strength of mortar and blocks. The model can be particularly suitable for masonry infills where the tensile strength of the blocks is significantly lower compared to the mortar one, like in the case where the blocks are made by a soft rock like the tuff. Good agreement with literature data is observed.

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