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CURRENT METHODOLOGIES OF OUT-OF-PLANE SEISMIC ASSESSMENT OF UNREINFORCED MASONRY WALLS: EVALUATION THROUGH REFINED MODEL SIMULATIONS

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ABSTRACT

The assessment of the out-of-plane stability of unreinforced masonry walls is a key element in the seismic assessment of existing buildings. This paper investigates the validity and accuracy of a displacement-based approach for out-of-plane loaded unreinforced masonry walls against the results of numerical simulations. A discrete element model of a vertically-spanning masonry wall that is able to represent the peak strength, joint crack-initiation up to the complete joint detachment and rocking of the wall is first validated and next benchmarked against several configurations. Results from static pushover analyses are presented in view of the displacement-based assessment procedure. The displacement-based procedure is next tested against non-linear time-history dynamic analyses. Its applicability to different wall configurations is discussed.

KEYWORDS: *out-of-plane, unreinforced masonry, displacement-based approach, rocking, discrete elements, IDA*

INTRODUCTION

The assessment of the out-of-plane stability of walls is a key element in the seismic assessment of unreinforced masonry (URM) buildings. However, the set of rules and prescriptions provided by building codes in this field is still relatively narrow. Some codes (e.g. [1]) provide only geometric rules, by specifying limits on the thickness and the slenderness ratio of the wall. However, the out-of-plane failure of a wall depends upon a combination of geometry, boundary conditions and applied vertical loads that requires deeper consideration in view of a seismic assessment [2]–[4]. Other codes (e.g. [5], [6]) present analytical approaches that are complementary to the numerical tools and experimental methods that one can choose for the assessment [7]. Holding a prominent

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position among these are the displacement-based approaches, due to their ability in predicting not only the strength but also the out-of-plane displacement capacity of the wall [2], [3], [8].

In this paper, the validity and accuracy of the displacement-based approach contained in the Italian Code [5] is discussed against the results of numerical simulations. A discrete element model of vertically-spanning URM walls is first validated and a parametric study is then carried out on several static and dynamic wall configurations. The outcomes of this parametric study allows to test the displacement-based procedure contained in the Italian code [5], together with the geometric rule that this code recommends.

Assessment procedures contained in the Italian Code

The Italian Code [5] recommends the seismic assessment of URM walls or portions of URM walls undergoing out-plane collapse mechanisms and proposes a method applicable to existing buildings (see also [4]). The method is based on the non-linear kinematic analysis of the wall and allows one to compute λ_0, the load multiplier that triggers the mechanism, and Δ_0, the horizontal displacement attained by the wall at incipient collapse, measured on one section of the wall. In the case of a vertically-spanning URM wall, the wall follows the collapse mechanism depicted in Figure 1(a), where the position ζH of the third hinge can be determined by minimisation of the load multiplier (kinematic theorem of limit analysis). Based on the rigid body analysis, the pushover curve of the URM wall is idealised by a bi-linear curve of the form (Figure 1(b)):

$$\lambda = \lambda_0 \left(1 - \frac{\Delta}{\Delta_0}\right). \tag{1}$$

The capacity curve of the wall is obtained by computing the spectral displacement d_0:

$$d_0 = \Delta_0 \frac{\sum_n M_n \delta_n^{\,2}}{\delta_0 \sum_n M_n \delta_n}, \tag{2}$$

where δ_n denote the virtual displacements of the horizontal masses M_n of the portions of wall that are mobilised by the mechanism, and the spectral acceleration a_0:

$$a_0 = \frac{\lambda_0 g}{e}, \tag{3}$$

where e is the ratio of the total mobilised mass M^* over the total wall mass:

$$M^* = \frac{\left(\sum_n M_n \delta_n\right)^2}{g \sum_n M_n \delta_n^{\,2}}. \tag{4}$$

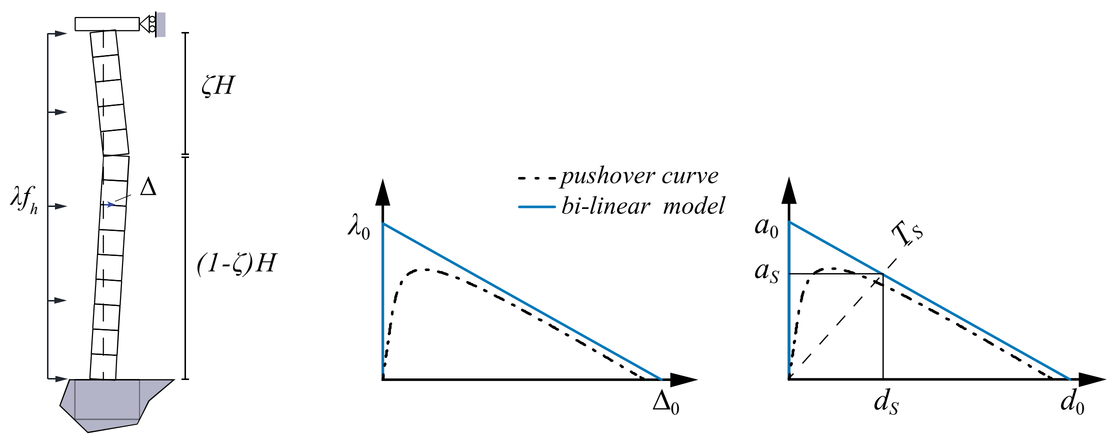
The Italian Code suggests a force-based procedure and a displacement-based procedure for determining the capacity of the wall in terms of peak ground acceleration that the wall can sustain. The force-based procedure is applicable to the Damage Limit State and, for walls situated at the ground floor, it consists in the following check:

$$a_0 > a_g S\,. \tag{5}$$

The displacement-based procedure is applicable to the Life-Safety Limit State and consists in the check:

$$d_0 > S_{De}(T_S)\,, \tag{6}$$

with $T_S = 2\pi\sqrt{(d_S/a_S)}$, $d_S = 0.4d_0$ (Figure 1(c)) and S_{De} the spectral acceleration of the record.



(a) Rigid body analysis (b) Bi-linear curve (c) Capacity curve

Figure 1: Illustration of the assessment method proposed by the Italian Code [5].

Geometric requirements contained in the Italian Code

The Italian Code [5] provides limitations to the thickness and the slenderness ratio of URM walls or portions of wall (Table 1). The slenderness ratio is computed as *H/t*, where *H* is the effective height and *t* is the effective thickness of the wall.

Table 1: Slenderness limitations for URM walls recommended by the Italian Code [5].

Masonry units	*H/t*	t_{min}
regular stone units	10	300 mm
regular stone units, Zone 3 and 4*	12	240 mm
artificial units	12	240 mm
artificial units with void ratio of 15% - 45%, Zone 4	20	200 mm
artificial units with void ratio < 15%, Zone 4	20	150 mm

**To Zone 3 it corresponds $a_g S < 0.15g$. To Zone 4, $a_g S < 0.075g$*

DISCRETE ELEMENT MODELS FOR URM WALLS

Discrete element models of vertically-spanning URM walls are built by using the software UDEC 6.0 [9]. Deformability of the masonry blocks and mortar layers is lumped at the joint level, that is included in the constitutive law used for contact. Moreover, blocks are assumed to have infinite stiffness and strength and an effective size $h \times t$ (Figure 3(a)). This modelling approach is referred to as meso-modelling [10] and it allows detailed numerical modelling of many existing structures [11]–[13]. Contact must be sufficiently discretised across the wall thickness in order to obtain a realistic representation of the out-of-plane response of masonry [14]–[16].

Model parameters

In UDEC, discrete elements have rounded corners. The rounding length, which in what follows is denoted with r, influences the out-of-plane behaviour of the wall as it reduces the effective thickness from t to $t' = t - 2r$. Some model parameters need therefore to be adjusted. In particular, the normal (n) and tangential (t) joints stiffness become [13], [17]:

$$k_n = \frac{E_m}{b}\frac{t}{t'} \qquad k_t = \frac{G_m}{b}\frac{t}{t'}, \tag{7}$$

where E_m is the modulus of elasticity of the masonry considered as a whole and $G_m = E_m / 2(1+v)$ with $v = 0.2$. Cohesion is also modified in order to take into account the reduction of the net cross section [13].

When modelling slender vertically-spanning masonry walls, cracking and opening of the joints control the out-plane response. Using relatively high values of cohesion and friction angle avoid unexpected slip failure mechanisms. In the walls modelled here, joints are characterised by zero dilatancy, friction angle $\phi = 35°$, cohesion $c = 2$ MPa and zero tensile strength. The damping used in UDEC is of a Rayleigh model [9]. A stiffness-proportional damping is used herein. It is centered on the rocking frequency of a single discrete element. It is computed according to [13], [17] and modified in order to take into account the refined contact discretisation level herein adopted:

$$\omega_n = \sqrt{\frac{E_m t^2}{\rho h^2 (t^2 + h^2)}}. \tag{8}$$

The damping ratio is $\zeta = 0.4$. In the static analyses, a local damping is used [9].

Model validation

The discrete element model is validated against a number of static pushover tests carried out by Doherty et al. [8], [18] on URM walls. In these tests, the URM walls were subjected to a varying concentrated out-of-plane force F applied at the wall mid-height. Figure 2 compares the pushover curves obtained from the tests with those given by the discrete element model. The force F is plotted in versus the mid-height displacement Δ_{mid}, which was controlled during the tests. In the UDEC model, the magnitude of the force is controlled throughout the simulation, in order to limit the amount of kinetic energy that may arise upon load application. This allows one to apply the load in quasi-static condition and to plot the descending branch of the curve, as in a displacement-controlled simulation. In the simulations, E_m is chosen in order to fit the initial branch of the experimental curves with the model. The rounding length is $r = 0.5\%\ t$ for all specimens, except for Specimen 11, for which it is fixed to $r = 4\%\ t$ to capture the effect of mortar drop out observed by Doherty [18].

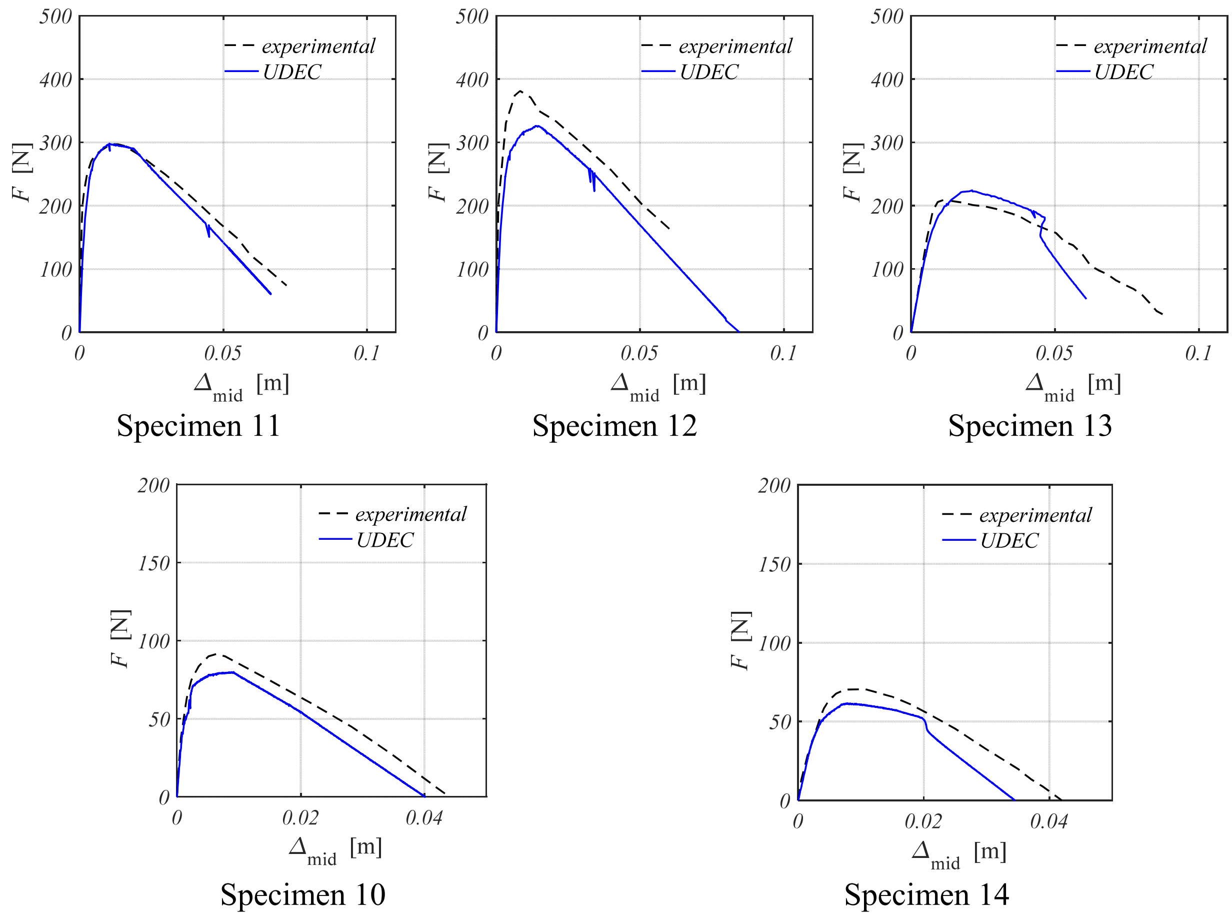


Figure 2: Simulation of the quasi-static push tests carried out by Doherty et al. [8], [18]**.**

PARAMETRIC STUDY

The parametric study investigates the static and dynamic behaviour of URM walls of length L = 1000 mm and height H = 2800 mm (Figure 3(a)). The walls consist of 14 vertically-stacked rigid discrete elements, which lay on a rigid 600×300 mm² support at the base and are in contact with a 600×100 mm² block at the top. This configuration is representative of vertically-spanning inter-story load-bearing URM walls, in contact with reinforced-concrete (RC) floor slabs placed at their ends [2].

Table 2: Properties of the walls tested in the parametric study.

(a) Elastic modulus	(b) Wall thickness	(c) Block rounding	(d) Axial load ratio
C1: 125 MPa	C5: 100 mm	C9: 0.5 %	C13: 1 %
C2: 250 MPa	C6*: 200 mm	C10: 1 %	C14: 1.5 %
C3: 1000 MPa	C7: 250 mm	C11: 1.5 %	C15: 3 %
C4: 2000 MPa	C8: 300 mm	C12: 3 %	C16: 4.5 %

**standard configuration*

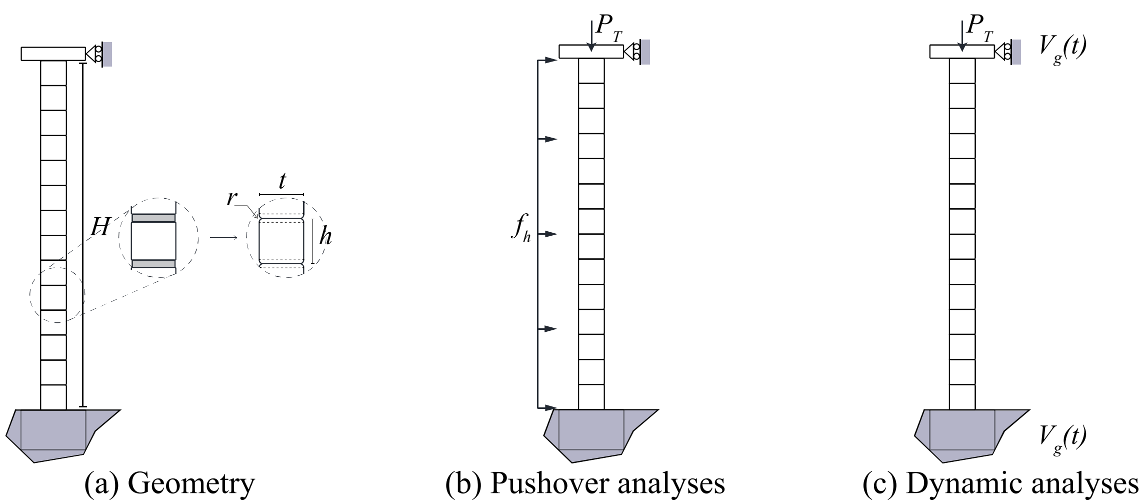


Figure 3: Configuration used for parametric study and evaluation of the seismic assessment procedure. Geometry (a) and boundary conditions for pushover (b) and dynamic analyses (c).

The parameters considered in this study are: (a) the wall thickness t, (b) the block rounding length r, (c) the masonry elastic modulus E_m and (d) the axial load ratio, indicated as *ALR*. Starting from a standard configuration, each parameter is varied separately and takes four different values. This results in 16 different configurations (Table 2). In its standard configuration, the masonry has the following properties: E_m = 500 MPa, f_c = 6.50 MPa. The mass density is ρ_m = 1800 kg/m^3 and *ALR* = 2%.

Each of the 16 configurations undergoes a static pushover analysis. Every analysis starts with the application of the gravity load and of a concentrated axial load to the block representing the upper RC slab. This is followed by the application of a uniform horizontal load (Figure 3(b)), whose magnitude varies during the simulation. A uniform load is modelled in UDEC by forces applied at the centre of mass of each discrete element.

Results from pushover analyses

Figure 4 shows the pushover curves obtained from the parametric study. The curves are plotted in terms of normalised horizontal reaction force F, with M the total mass of the wall and g the gravity, and normalised displacement Δ_{mid}, measured at wall mid-height. Figure 4(a) shows that the lateral stiffness and peak strength of the wall increase with increasing elastic modulus. However, the ultimate displacement attained when reaching the collapse mechanisms is always the same. Figure

4(b) shows how increasing the wall thickness leads to an increase of its lateral stiffness and strength. The ultimate displacement is always fixed to about 0.6t, except when the wall is very slender (configuration C5). In that case, the third hinge of the collapse mechanism forms at a smaller height, because the influence of the self-weight over the applied axial load become less important than in the other cases. The effect of changing the block rounding has limited impact on the peak strength of the wall (Figure 4(c)). However, increasing the axial load ratio (Figure 4(d)) engenders an important increase both in its strength and in its ultimate displacement.

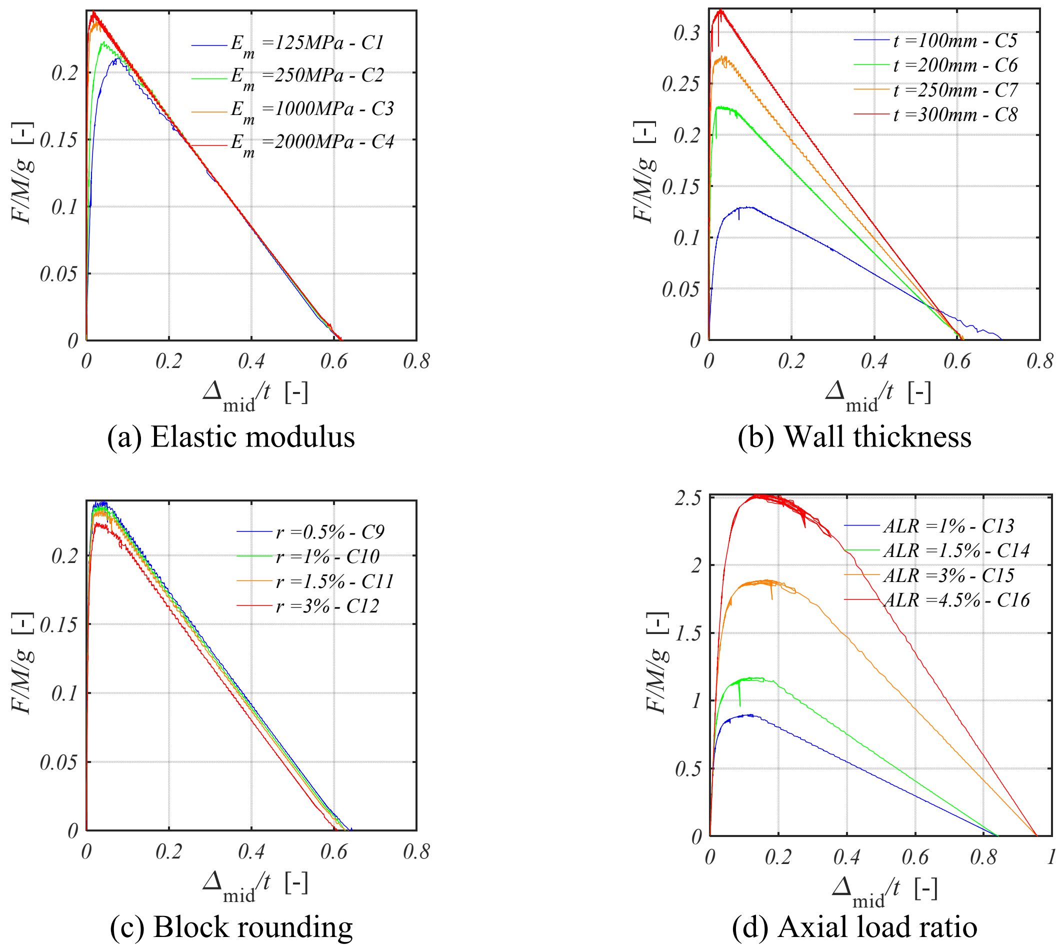


Figure 4: Pushover curves from the parametric study.

EVALUATION OF THE OUT-OF-PLANE SEISMIC ASSESSMENT PROCEDURE

The displacement-based procedure contained in the Italian Code [5] is applied and tested for each of the 16 configurations analysed in the parametric study. The procedure is applied as follows: first, the bi-linear curve of rigid body analysis is computed and compared to the pushover curve obtained from the discrete element simulations; the capacity curve is next retrieved and the 'limit' value of spectral acceleration S_{De} is determined by equating condition (6). The procedure is tested against a series of non-linear time-history analyses (THA) that are carried out on the discrete element models used for the static pushover analyses. Use is made of 10 records (Table 3) selected from a series of natural ground motions that cover a relatively wide range of PGA and PGV [19]. The records are first scaled to equal the S_{De} value given by condition (6). The velocity time history of the scaled records is then applied to the top and the bottom supports of the discrete element models (Figure 3(c)). Failure of the walls under the ground motions is finally verified. Failure occurs when the maximum out-plane deflection attained by the wall during the THA equals the wall thickness [2], [8].

Table 3: Ground motions used in the time-history analyses.

#	Earthquake	Date	Station	Magnitude	Duration	Label*
1	Kern County, USA	1952	Taft Lincoln School	7.36	20s	TAF111
2	San Fernando, USA	1971	Pacoima Dam (upp. left abut)	6.61	12s	PUL164
3	Friuli, Italy	1976	Tolmezzo	6.5	10s	TMZ000
4	Imperial Valley, USA	1979	Bonds Corner	6.53	15s	BCR230
5	Imperial Valley, USA	1979	El Centro (Array \#7)	6.53	15s	E07230
6	Nahanni, Canada	1985	Site 1	6.76	10s	S1280
7	Loma Prieta, USA	1989	Los Gatos (Lexington Dam)	6.93	10s	LEX000
8	Northridge, USA	1994	Rinaldi (Receiving Stat.)	6.69	10s	RRS228
9	Northridge, USA	1994	Sylmar (Olive View Med FF)	6.69	10s	SYL360
10	Kobe, Japan	1995	Takatori	6.9	15s	TAK000

**Source: PEER-NGA database.*

Figure 5 shows the percentage of walls that fail during the THA carried out at the 'limit' spectral acceleration S_{De} given by condition (6). A low value of the masonry elastic modulus E_m (configuration C1), which is typical in URM walls subjected to cyclic out-of-plane load, lead to an increase of seismic vulnerability of the wall. The effect of the E_m-modulus on the seismic capacity of the wall is, however, not taken into account neither in the displacement-based nor in the force-based approach proposed by the Italian Code. An increase of thickness (configurations C5-C8), and therefore a decrease of slenderness ratio of the wall, considerably diminishes the seismic vulnerability of the walls. For walls with slenderness ratio of 12 (configuration C7), which is the limit value suggested by [5] (Table 1), approximately the 50% of the walls fail under the acceleration imposed by the code. This value considerably decreases with increasing slenderness (configuration C8). Increasing the axial load ratio (configurations C13-C16), although increasing the force capacity of the walls (Figure 4(d)), largely increases wall vulnerability to seismic loading.

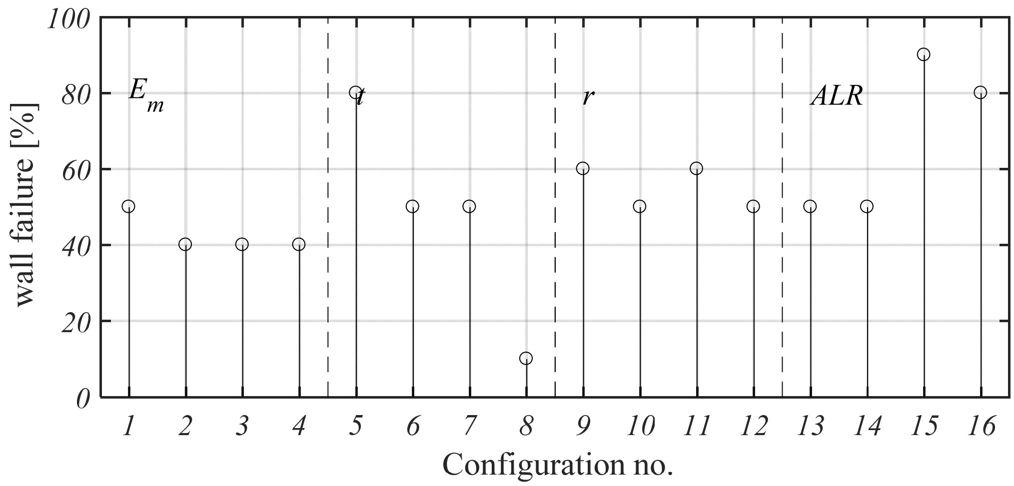


Figure 5: Percentage of walls failing when subjected to the ground motions of Table 3 scaled at the 'limit' value of S_{De} given by the Italian Code [20], Eq.(6).

CONCLUSIONS

In this paper, the applicability of the displacement-based assessment procedure suggested by the Italian Code is discussed based on the results from refined discrete element static and dynamic simulations carried out on a series of vertically-spanning URM walls. The walls have different modulus of elasticity of the masonry, wall thickness (or slenderness), block rounding and axial load ratio. In general, the displacement-based approach tends to estimate the actual capacity of the walls to resist natural ground motions in 50% of the cases. However, the detrimental effects of low modulus of elasticity and, especially, high axial load ratio are not well captured by the code.

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