The influence of local mechanisms on large scale seismic vulnerability estimation of masonry building aggregates

Antonio Formisano[a], Nicola Chieffo[b], Bartolomeo Milo[c], Francesco Fabbrocino[d]

[a,c]University of Naples "Federico II", [b,d] Pegaso Telematics University

Abstract. The current paper deals with the seismic vulnerability evaluation of masonry constructions grouped in aggregates through an "ad hoc" quick vulnerability form based on new assessment parameters considering local collapse mechanisms. First, a parametric kinematic analysis on masonry walls with different height (*h*) / thickness (*t*) ratios has been developed with the purpose of identifying the collapse load multiplier for activation of the main four first-order failure mechanisms. Subsequently, a form initially conceived for building aggregates suffering second-mode collapse mechanisms, has been expanded on the basis of the achieved results. Tre proposed quick vulnerability technique has been applied to one case study within the territory of Arsita (Teramo, Italy) and, finally, it has been also validated by the comparison of results with those deriving from application of the well-known FaMIVE procedure.

Keywords: Seismic vulnerability, masonry aggregates, out-of-plane mechanisms, kinematic analysis, quick assessment form

Out-of-plane collapse mechanisms

The identification of the most significant failure mechanisms for masonry buildings is primarily connected to disconnections among walls usually caused by seismic actions, which identify macro-elements susceptible at collapse for instability. The analysis of the most recurrent out-of-plane failure mechanisms is done on the basis of the Principle of Virtual Works, which provides the collapse load multiplier activating those mechanisms. In the case under study, the above theory is applied to several masonry walls with different slenderness (height/thickness ratio) aiming at identifying the multiplier factor of the main four local collapse mechanisms (overturning, horizontal arch effect, vertical arch effect and corner overturning) (Fig. 1) detected under earthquake. Therefore, the achieved results, summarised under form of design charts, have led towards new seismic parameters for a new building aggregate evaluation form, which has been applied to a case study in Arsita, a little town damaged by the 2009 Italian earthquake. Finally, the effectiveness of the these parameters in foreseeing the building vulnerability has been proved by comparing the case study results with the ones deriving from the FaMIVE procedure.

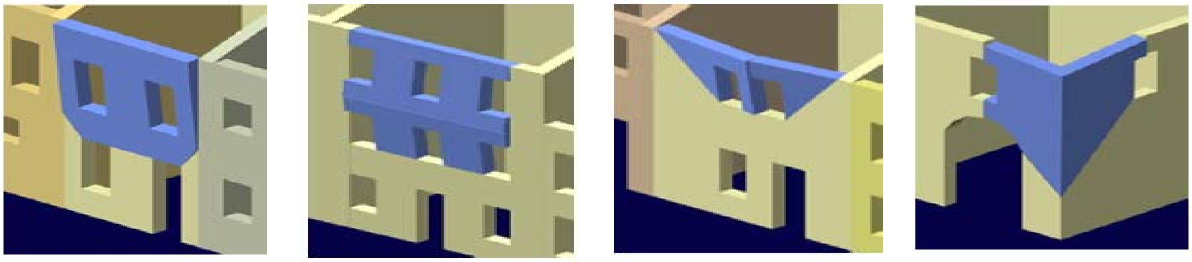

FIGURE 1. The main out-of-plane mechanisms of masonry buildings.

[a]antoform@unina.it; [b] nicola.chieffo@unipegaso.it; [c]bartolomilo@libero.it; [d]francesco.fabbrocino@unipegaso.it.

Parametric analysis on case studies

The examined structures have plan dimensions of 7x7 m developed on levels variable from 1 to 3 and having different height (3, 4 and 5 m). Walls have thickness changing from 30 cm to 80 cm and openings with variable geometrical dimensions. They are made of three different masonries (specific weight γ of 11, 16 and 22 kN/m^3). It is considered that the generic wall, depicted in Fig. 2 for the case studies examined, is not well constrained to other walls and floors. Barrel vaulted, r.c., steel and timber floors have been considered as roof and intermediate horizontal structures. It is supposed that vaults and other floor beams have 25 cm and 15 cm support length on the walls, respectively. In particular, when vaults are of concern, the presence of steel tie-beams has been taken into account with the purpose to eliminate their thrusting actions.

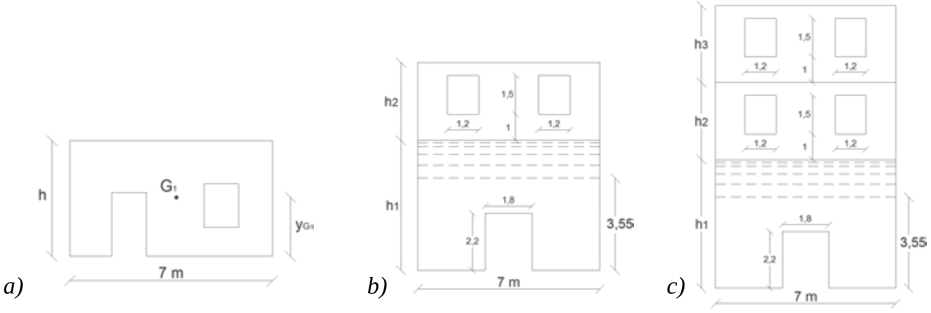

FIGURE 2. Geometric dimensions and properties of the wall case studies: a) 1 level; b) 2 levels; c) 3 levels.

Design charts

Considering the variability of the input data (mechanical properties of the masonry, wall thickness, number of floors, storey height, geometry of openings, type of slabs), the collapse load multipliers α_0 related to the main local out-of-plane mechanisms have been evaluated. For the sake of example, these multipliers related to the building with two storeys have been plotted as a function of the wall slenderness (*h/t*) and length (*L*) in Figure 3.

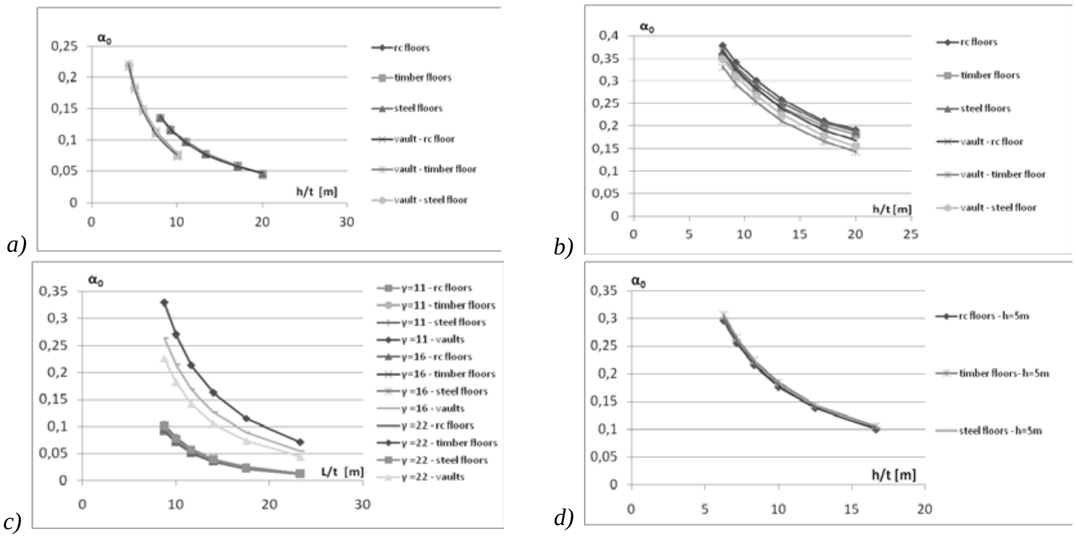

FIGURE 3. Design charts: a) overturning; b) vertical arch effect; c) horizontal arch effect; d) corner overturning.

Expansion of the vulnerability form for historical aggregates

The results achieved from the previous parametric analysis allows to add some parameters related to out-of-plane mechanisms to the quick survey form for historical aggregates implemented in Formisano, et al. (2010b; 2011; 2015). This form is based on fifteen parameters taking into account the global in-plane interaction among aggregate units. The effectiveness of such a speedy seismic evaluation method has been already attested by the comparison with an other trustworthy methodology (Maio et al., 2015). For each of the new parameters related to local mechanisms, four vulnerability classes, ranging from A (the best) to D (the worst), with owns scores and a weight, the latter representative of the more or less importance of the parameter with respect to others, are assigned. The four vulnerability classes are defined on the basis of the value assumed by the collapse load multiplier α_0 which represents an acceleration value. Therefore, this factor can be compared to the spectral accelerations related to the investigated site, to the building reference life and to the limit state considered to be framed within a given class. The conditions of belonging to the four classes are defined in Table i).

TABLE i). Vulnerability classes and scores for local mechanism parameters

Vulnerability class (score)	
A (0)	$\alpha_0 > a_g(SLV)$
B (15)	$a_g\ (SLD) < \alpha_0 < a_g\ (SLV)$
C (30)	$a_g\ (SLO) < \alpha_0 < a_g\ (SLD)$
D (45)	$\alpha_0 < a_g\ (SLO)$

Due to the dangerousness of the out-of-plane mechanisms, a weight equal to 1.5 has been assigned to each new form parameter. For each of the 19 parameters a vulnerability class among the available four is assigned by the user with a sufficient degree of objectivity. Subsequently, in order to obtain a numerical vulnerability index, the selected score of a given parameter is multiplied by the respective weight (w_i) and the sum of these multiplications extended to all parameters is done.

This quick investigation method has been applied to a case study (aggregate n. 7 in Fig. 4) in the city of Arsita, which was damaged by the 2009 L'Aquila event (Formisano et al., 2010a; Indirli et al., 2013) (Fig. 4). This aggregate is made of five different Structural Units (S.U.), which develop averagely on two levels and are mainly characterized by hewn stone masonry blocks and timber roofs.

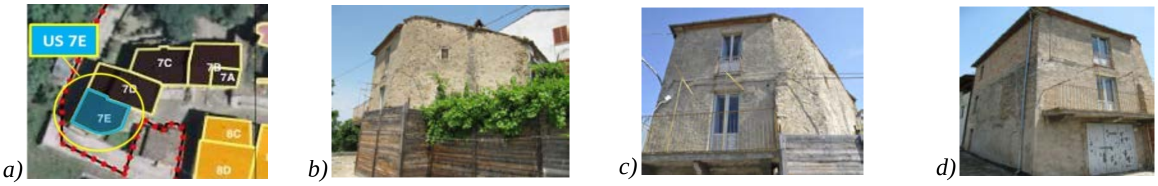

FIGURE 4. Aggregate n. 7 in Arsita: a) plan view, b) east view, c) south view and d) west view of the S.U. 7E.

For this aggregate, thanks to the knowledge of geometrical properties of constituent S.U., the collapse load multiplier related to the four examined out-of-plane mechanisms has been calculated on the basis of the wall slenderness according to the relationships reported in the previous section. In Table ii) the minimum factors α_0 for each possible collapse mechanisms are reported for all the S.U. constituting the investigated aggregate.

TABLE ii). Out-of-plane mechanisms occurring in the aggregate n.7

S.U.	**Type of mechanism (collapse load multiplier α_0)**			
A	Overturning (0.114g)	Corner overturning (0.220g)		
B	Overturning (0.078g)	Corner overturning (0.220g)		
C	Overturning (0.098g)	Corner overturning (0.264g)	Vertical arch effect (1.019g)	
D	Overturning (0.046g)	Corner overturning (0.207g)	Vertical arch effect (1.076g)	
E	Overturning (0.079g)	Corner overturning (0.207g)	Vertical arch effect (0.966g)	Horizontal arch effect (0.054g)

However, after all the α_0 factors have been calculated for each mechanism and for each S.U., they have been compared to the accelerations defined by the Italian code for the different limit states of the Arsita town, which are shown in Table iii). This allows to assign a vulnerability class to each out-of-plane collapse parameter of the form.

TABLE iii). Spectral acceleration for different reference limit states.

$\mathbf{a_g}(\mathbf{SLV})$	$\mathbf{a_g}(\mathbf{SLD})$	$\mathbf{a_g}(\mathbf{SLO})$
0.190g	0.078g	0.062g

Therefore, the vulnerability indexes of the S.U. related only to the inspected local mechanisms have been calculated and reported under form of histograms in Figure 5a, where such indexes are normalised in the range [0-1]. From the obtained results it appears that the vulnerability increases from unit A to unit E, with the latter having the highest vulnerability index I_v. This outcome is in agreement with the FaMIVE method (D'Ayala and Speranza, 2003) which, applied to the whole historic centre of Arsita, provides an out-of-plane vulnerability index for S.U. n. 7E (30-45%) greater than those of other units belonging to the same aggregate (0-30%) (Figure 5b). As a result, the reliability of the quick assessment method proposed for local failure mechanisms has been proved.

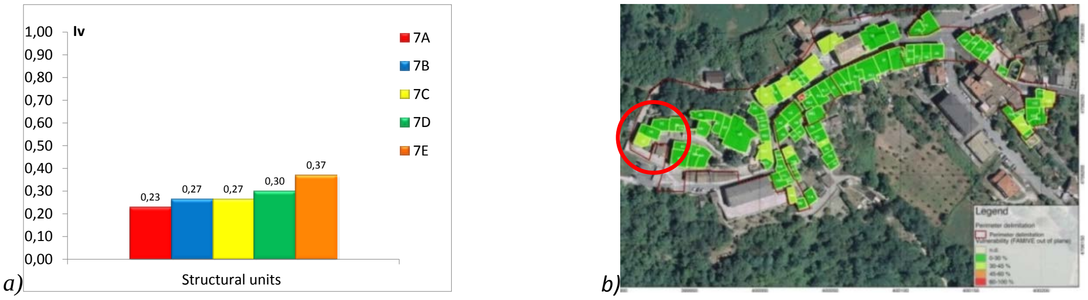

FIGURE 5. Out-of-plane vulnerability indexes of the aggregate n. 7: a) quick form; b) FaMIVE method.

CONCLUSIONS

The parametric study based on kinematic analysis performed on masonry buildings having different masonry types, wall slenderness and floor typologies has provided four additional parameters related to the main out-of-plane mechanisms for masonry walls able to extend a quick seismic vulnerability form already implemented for historical aggregates. The application of the methodology to a building aggregate in the historical built-up of Arsita has shown that the most vulnerable S.U. is the head one. This result is in agreement with the provisions of the FaMIVE method which, applied to the historic centre inspected, has confirmed the reliability of the large scale analysis method setup.

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