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Parametric analysis on first mode failure mechanisms of masonry building compounds: application to case studies

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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 multipliers 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.

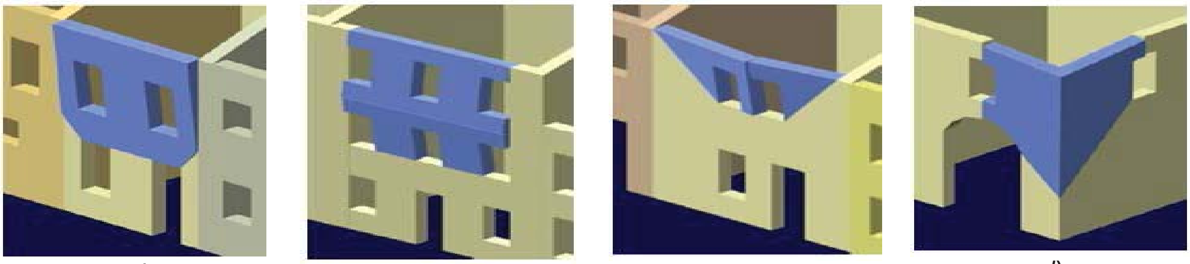
Keywords: Seismic vulnerability, masonry aggregates, out-of-plane mechanisms, kinematic analysis, quick assessment form

1. 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 out-of-plane failure mechanisms is done on the basis of linear kinematic analysis, where the kinematic approach is based, after the identification of the collapse mechanism, on the evaluation of the horizontal action activating that mechanism. The collapse load multiplier α_0 is obtained by applying the Principle of Virtual Work by equalling the total work performed by the external forces to the work of internal forces through the following relationship:

$$\alpha_0 \left[\sum_{i=1}^{n} P_i \delta_{ix} + \sum_{j=n+1}^{n+m} P_j \delta_{jx} \right] - \sum_{i=1}^{n} P_i \delta_{iy} - \sum_{h=1}^{o} F_h \delta_h = L_{fi} \qquad (1)$$

In the case study, the above theory is applied to several masonry walls with different slenderness *h/t*, where *h* and *t* are the wall height and thickness, respectively, 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 for masonry buildings 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 application of the FaMIVE procedure, a very suitable calculation tool to evaluate the vulnerability and risk of in-plan and out-of-plane mechanisms of masonry walls.

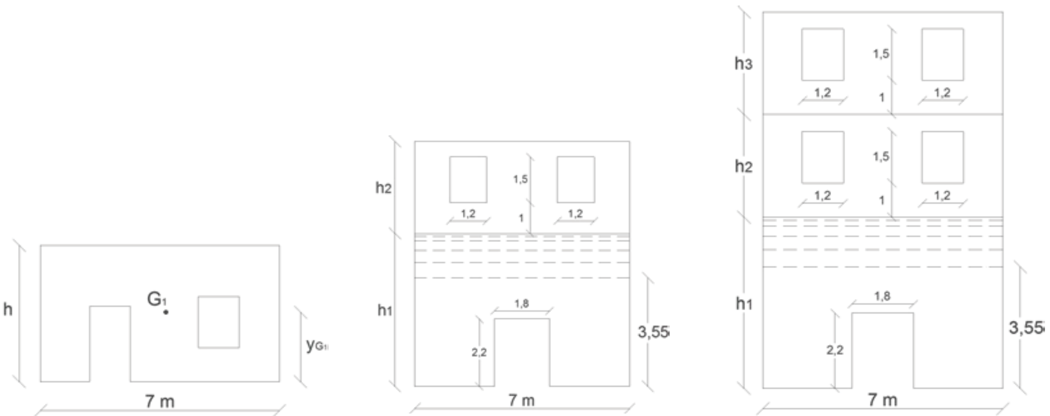


a) b) c) d)

Fig.1: The main out-of-plane mechanisms of masonry buildings: a) overturning; b) vertical arch effect; c) horizontal arch effect; d) corner overturning.

2. Parametric analysis on case studies

The examined structures have plan dimensions of 7x7 m and develop on levels variable from 1 to 3 with different heights (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 masonry types (specific gravity γ of 11, 16 and 22 kN/m^3). As usually detected into existing buildings, it is hypothesised that the generic walls belonging to the case studies examined are not well constrained to other walls and floors. Barrel vaulted, as well as r.c., mixed steel-tie and timber floors, have been considered as intermediate horizontal structures. Roofs are made of the above mentioned horizontal plane structures. It is supposed that vaults and other floor beams have 25 cm and 15 cm support lengths 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.
In Figure 2 some representative masonry walls of the investigated buildings are depicted.



a) b) c)

Fig. 2: Geometric dimensions of some wall case studies: a) 1 level; b) 2 levels; c) 3 levels.

The design loads adopted in the parametric analysis are shown in Table 1.

Table 1: Loads deriving from different types of floors considered.

	rc floors	timber floors	steel floors	vaults
G_1 (kN/m^2)	3	1	2	5
G_2 (kN/m^2)	2	2	2	2
Q (kN/m^2)	2	2	2	2

3. 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 floors), the collapse load multipliers α_0 related to the main local out-of-plane mechanisms mentioned in Section 2 have been evaluated. For the sake of example, in Figure 3 these multipliers related to the building with two storeys have been plotted as a function of the wall slenderness (*h/t*) considering the variability of the floor types.

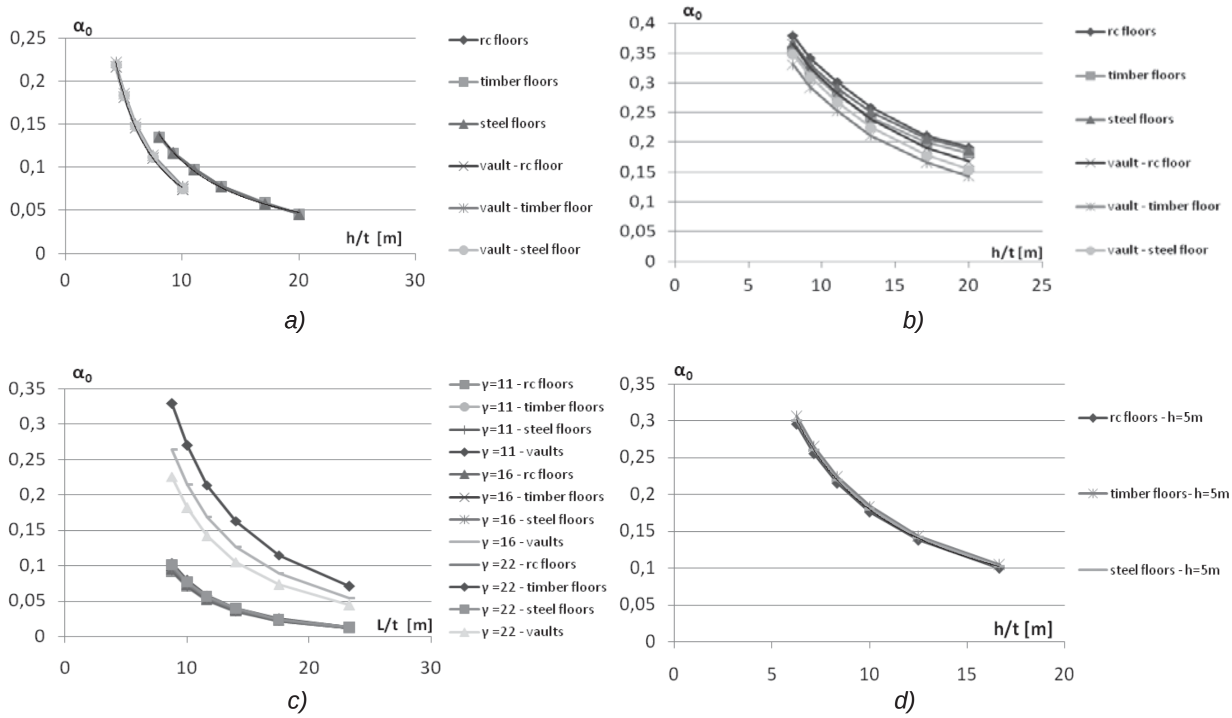


Fig. 3: Design charts: a) overturning; b) vertical arch effect; c) horizontal arch effect; d) corner overturning.

From the Figure 3 it is apparent that, for all mechanisms, the collapse load multiplier decreases as the wall slenderness augments. In the case of overturning, the α_0 factors for buildings with vaults are lesser than those detected for buildings with plane floors. The same results occur also when the vertical arch effect is of concern. In this case the maximum α_0 factors are achieved with rc floors. For the horizontal arch mechanism, the different types of horizontal floors do not modify the collapse multiplier value. The highest values of α_0 are attained with vaults: in particular, these factors increase with the reduction of the masonry specific gravity. Finally, for the corner overturning mechanism, the influence of the typologies of floors on this local mechanism is basically negligible.

4. 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 by the first Author [1, 2, 3] (Table 2).

This form is based on fifteen parameters taking into account the global in-plane interactions among aggregate units. The effectiveness of such a speedy seismic evaluation method has been already given by the comparison with an other trustworthy methodology [4].

To 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, aiming at being framed within a given class. The conditions of belonging to the four classes are defined in Table 3.

Table 2: The vulnerability assessment form for building aggregates.

Parameter	Class score (*s*)				Weight *(w)*
	A	B	C	D	
Organization of vertical structures	0	5	20	45	1.00
Nature of vertical structures	0	5	25	45	0.25
Location of the building and type of foundation	0	5	25	45	0.75
Distribution of plan resisting elements	0	5	25	45	1.50
In-plane regularity	0	5	25	45	0.50
Vertical regularity	0	5	25	45	0.50 ÷ 1.00
Type of floor	0	5	15	45	0.75 ÷ 1.00
Roofing	0	15	25	45	0.75
Details	0	0	25	45	0.25
Physical conditions	0	5	25	45	1.00
Adjacent buildings with different height	-20	0	15	45	1.00
Position of the building in the aggregate	-45	-25	-15	0	1.50
Number of staggered floors	0	15	25	45	0.50
Structural or typological heterogeneity among S.U.	-15	-10	0	45	1.20
Percentage difference of opening areas among adjacent facades	-20	0	25	45	1.00

Table 3: 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 and the sum of these multiplications extended to all parameters is done. The vulnerability index is defined as the sum of the weight multiplied by the scores of each parameter.
This quick investigation method has been applied to a case study in the little municipality of Arsita, which was damaged by the 2009 L'Aquila event [4, 5] (Fig. 4).

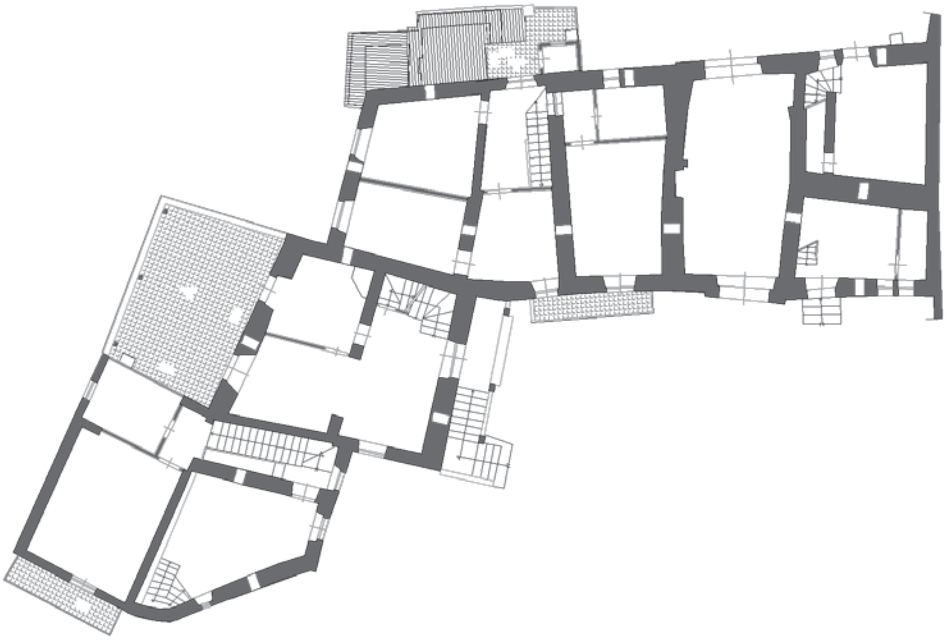


Fig. 4: First floor of the aggregate n. 7 in the municipality of Arsita (Teramo, Italy).

The case study is the aggregate of the town indicated with n.7, which is made of five different Structural Units (S.U.), developing averagely on two levels and mainly characterized by hewn stone masonry blocks and timber roofs. Thanks to the analysis of the geometric properties of the aggregate constituent masonry walls, it is possible to associate to each S.U. the value of the collapse load multiplier, which activates the main local out-of-plane mechanisms, on the basis of the wall slenderness according to the relationships reported in the previous section. Subsequently, the evaluation of the seismic vulnerability of the five S.U., by using the herein enlarged survey form, is made.
In Table 4 the minimum factors α_0 for each possible out-of-plane collapse mechanisms are reported for all the S.U. constituting the investigated aggregate.

Table 4: 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 possible α_0 factors have been calculated for each possible mechanisms 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 5. This allows to assign a vulnerability class to each out-of-plane collapse parameters of the form.

Table 5: Spectral accelerations of the municipality of Arsita for different limit states.

a_g (SLV)	a_g (SLD)	a_g (SLO)
0.190g	0.078g	0.062g

The compilation of the quick survey forms based on 19 parameters for all S.U. provides vulnerability indices within the range [-125 ÷ 785.25]. These indices are then transformed into vulnerability factors between zero and one, as shown in Figure 5.

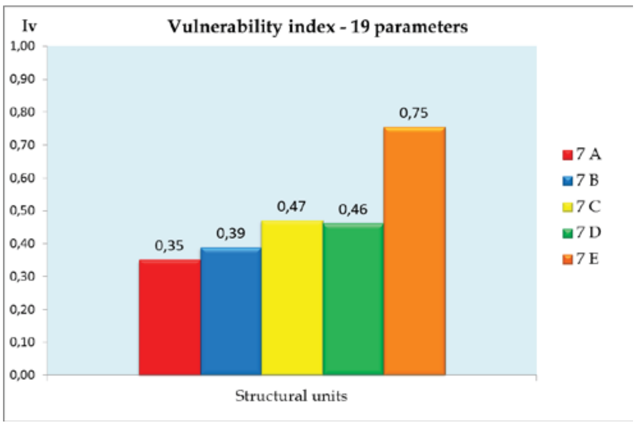


Fig. 5: Global seismic vulnerability of the aggregate n. 7.

The analysis of results shows that the most vulnerable structural unit is the 7E one, that is the unit occupying a heading position in the aggregate, with a vulnerability index I_v = 0.75.
This S.U. is depicted in Figure 6, where both the location in the aggregate and some plan layouts and external photos are reported.

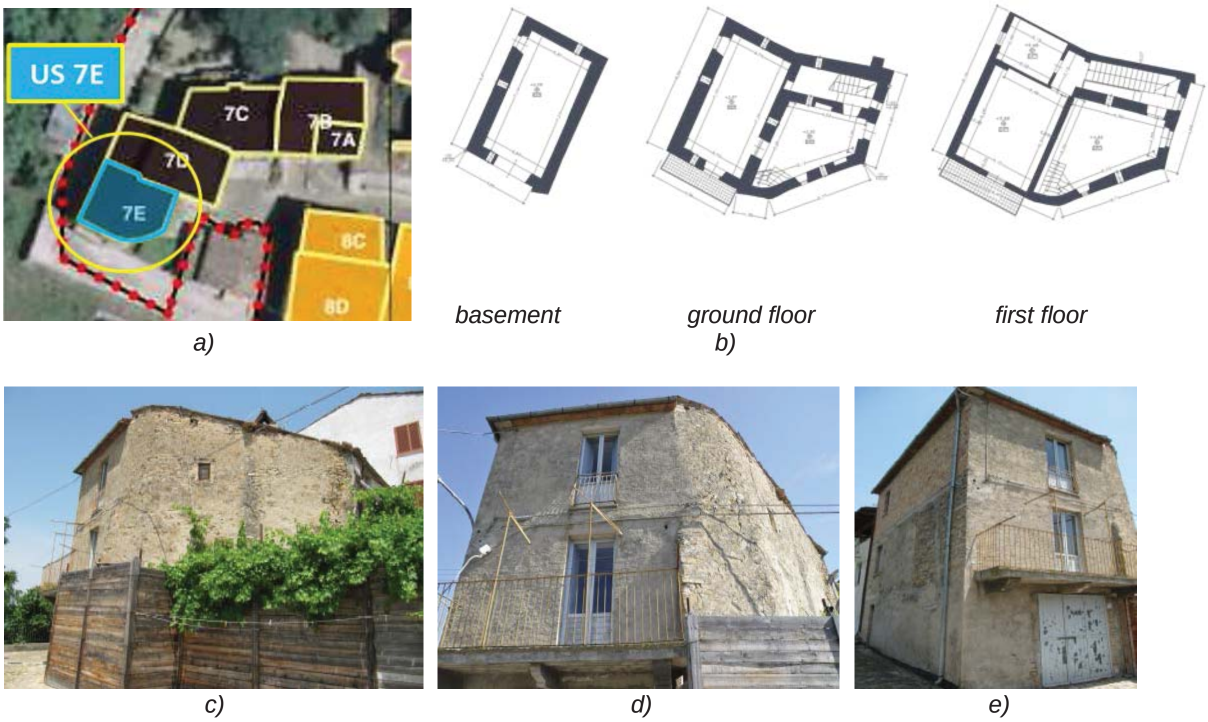


Fig. 6: The structural unit 7E: a) plan view, b) plan layouts, c) east view, d) south view and e) west view.

Furthermore, for each structural unit, the vulnerability indices related for the last four parameters of the form are calculated (Fig. 7) in order to obtain a comparison among the five buildings with reference to the most significant out-of-plane mechanisms of collapse.

STRUCTURAL UNIT 7A						
PARAMETER	CLASS SCORE				WEIGHT	VULNERABILITY INDEX
	A	B	C	D		I_v
16. Overturning	0	15	30	45	1,5	22,5
17. Vertical arch effect	0	15	30	45	1,5	0
18. Horizontal arch effect	0	15	30	45	1,5	0
19. Corner overturning	0	15	30	45	1,5	0
Total						22,5

STRUCTURAL UNIT 7B						
PARAMETER	CLASS SCORE				WEIGHT	VULNERABILITY INDEX
	A	B	C	D		I_v
16. Overturning	0	15	30	45	1,5	45
17. Vertical arch effect	0	15	30	45	1,5	0
18. Horizontal arch effect	0	15	30	45	1,5	0
19. Corner overturning	0	15	30	45	1,5	0
Total						45

STRUCTURAL UNIT 7C						
PARAMETER	CLASS SCORE				WEIGHT	VULNERABILITY INDEX
	A	B	C	D		I_v
16. Overturning	0	15	30	45	1,5	45
17. Vertical arch effect	0	15	30	45	1,5	0
18. Horizontal arch effect	0	15	30	45	1,5	0
19. Corner overturning	0	15	30	45	1,5	0
Total						45

Fig. 7: Vulnerability indices of S.U. in terms of first mode failure mechanisms.

STRUCTURAL UNIT 7D						
PARAMETER	CLASS SCORE				WEIGHT	VULNERABILITY INDEX
	A	B	C	D		I_v
16. Overturning	0	15	30	45	1,5	67,5
17. Vertical arch effect	0	15	30	45	1,5	0
18. Horizontal arch effect	0	15	30	45	1,5	0
19. Corner overturning	0	15	30	45	1,5	0
Total						**67,5**

STRUCTURAL UNIT 7E						
PARAMETER	CLASS SCORE				WEIGHT	VULNERABILITY INDEX
	A	B	C	D		I_v
16. Overturning	0	15	30	45	1,5	45
17. Vertical arch effect	0	15	30	45	1,5	0
18. Horizontal arch effect	0	15	30	45	1,5	67,5
19. Corner overturning	0	15	30	45	1,5	0
Total						**112,5**

Fig. 7: Vulnerability indices of S.U. in terms of first mode failure mechanisms. (continued)

The vulnerability indices of the S.U. related only to the inspected local mechanisms are reported under form of histograms in Figure 8, where such indices are normalised in the range [0÷1]. From the obtained results it appears that the vulnerability increases from the unit A to the unit E, with the latter having the highest vulnerability index I_V.
This outcome is in agreement with the FaMIVE method [7] 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%) (Fig. 9).
As a result, the reliability of the quick assessment method proposed for local failure mechanisms has been proved.

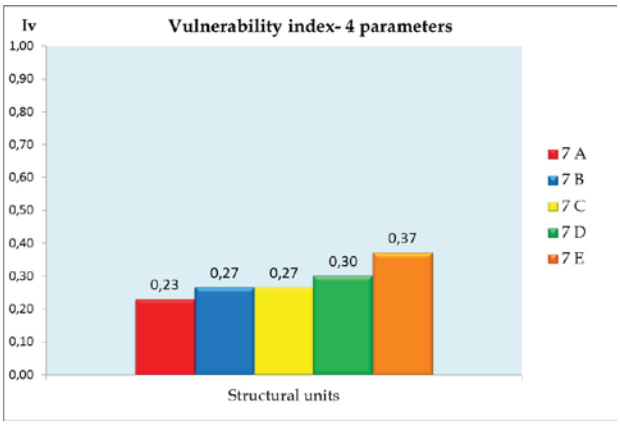


Fig. 8: Local seismic vulnerability of the aggregate n. 7.

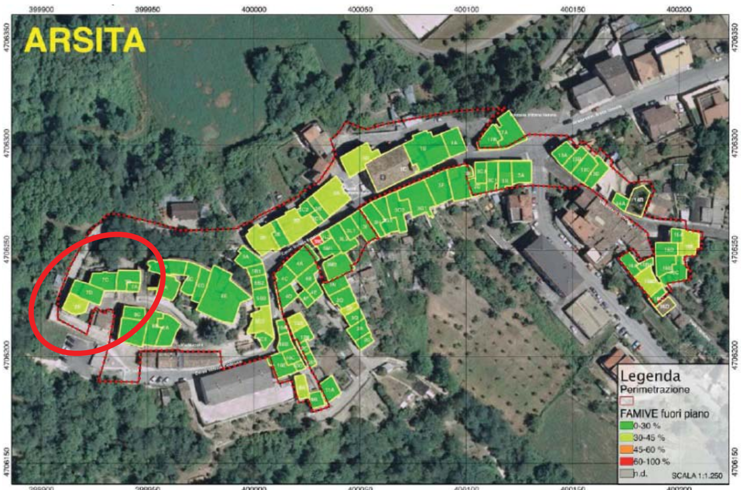


Fig. 9: Out-of-plane vulnerability indices of the aggregate n. 7 through the FaMIVE method.

Finally, the proposed quick seismic evaluation procedure can be usefully applied to investigate, other than the in-plane behaviour of masonry aggregates [8, 9], also the susceptibility at damage of masonry compounds against first order mechanisms. In conclusion, a complete analysis tool can be entrusted to structural engineers to investigate the seismic behaviour of constructions belonging to historical centres [10, 11].

5. 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 results is in agreement with the provision of the well known FaMIVE method which, applied to the whole historic centre of the inspected town, has confirmed the reliability of the implemented large scale speedy analysis method.

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