Seismic vulnerability assessment methods applied to the historic built-up of Arsita within the 2009 post-earthquake reconstruction plan

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Abstract: In the framework of the reconstruction plan of the historical centre of Arsita, hit by the 2009 L'Aquila earthquake, different seismic vulnerability assessment methods for local masonry buildings have been used. In particular, the 2nd level GNDT form, the FaMIVE method and a new vulnerability form appropriately conceived for building aggregates have been applied to the inspected historical centre. Moreover, for each building wall, a special form inherent to the masonry characteristics has been filled in order to achieve a masonry quality index. The results obtained from the above methodologies applied to the 91 structural units composing the 17 aggregates of Arsita have been compared with each other aiming at obtaining a clear picture of both the reliability of the used methodologies predictions and the real vulnerability condition of the constructions under study.

Keywords: L'Aquila earthquake; reconstruction plan; RP; seismic vulnerability; masonry aggregates; masonry quality index.

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Giuseppe Marghella received his Bachelor of Arts with honour in Science Applied to the Conservation of Cultural Heritage at La Sapienza University. He gained his PhD in Chemistry in 2009. He began working for the enterprise Il Cenacolo, carrying out on site diagnostic analyses. Since 2012, he is a researcher in the Seismic Engineering Unit at ENEA.

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1 Introduction

Arsita is a small town in the district of Teramo, Abruzzo. It is located at about 470 m above the sea level, along the foothills of the Gran Sasso massif (Figure 1). The origins of Arsita date back to the pre-Roman age, while its current urban layout comes from the late Middle Age and early Renaissance. The old town was developed from the so-called 'Bacucco' castle, of which some parts of the 12th or 13th century wall fence, reinforced by towers, are still recognisable, and then spread along the main street, namely the Vittorio Emanuele street.

Figure 1 Global view of the Arsita town (see online version for colours)

The M_w = 6.3 earthquake that hit the city of L'Aquila on 2009 April 6th caused collapse and severe damage in many buildings not only in L'Aquila (Indirli et al., 2013; Formisano et al., 2010a), but also in villages far away from the epicentre, such as Arsita. The large number of unsafe buildings found in the centre of Arsita, compared to the moderate macro-seismic intensity (VI degree on the MCS scale), is due to several factors, including structures vulnerability, lack of maintenance and geological conditions.

Therefore, for the town of Arsita, included in the seismic crater, a reconstruction plan (RP) of the historic centre, according to the Law n. 77 promulgated on 2009 June 24th, has been adopted. The RP aim is the definition of strategic guidelines to ensure the sustainable reconstruction of buildings, the economic upturn and the town improvement.

The Municipality of Arsita entrusted a multidisciplinary group of experts from ENEA, University of Naples 'Federico II', University of Chieti-Pescara 'Gabriele D'Annunzio' and University of Ferrara for the RP realisation. They started from the in depth knowledge of the area and its history, by acquiring diversified data related to environment, urban planning, building structural features, geological and seismological soil properties, demographic aspects and so on.

In the RP preliminary phase, the municipality identified and delineated the perimeter of the aggregates included in the plan. Subsequently, the group of experts enlarged the RP original perimeter adding previously excluded aggregates by means of comparable damage, similar construction materials/techniques, interaction with viability, completeness inside the historic centre. A total of 17 aggregates and 91 structural units (SUs) were identified and classified through an accurate in situ investigation. During the in situ campaign, several information on each structural unit were collected by means of appropriate hard copy or digital forms and then they were used for a 3D building inventory of the city (Figure 2) (Geremei et al., 2013).

Figure 2 The 3D building inventory model of Arsita (see online version for colours)

All information was used for implementing the RP, whose results have been reported on a dedicated website (http://www.pdrarsita.bologna.enea.it). Seismic performance of buildings was determined through a vulnerability index assessment. Firstly, this activity was performed by using appropriate vulnerability survey forms for isolated and aggregated constructions. Later on, a more refined approach based on excel spreadsheet was employed to assess the in-plane and out-of-plane vulnerabilities of facade walls of masonry SUs. Finally, application of an appropriate form for evaluating a proper masonry quality index was done.

The results achieved for the historic centre of Arsita allow to have a clear picture of the real vulnerability of inspected SUs, as well as to conduct a study comparison between the various analysis methods investigated.

2 The built-up seismic vulnerability

The construction evolution process of the town Arsita followed the territory morphology: most of the houses run along the main road, which moves forward in a nearly straight line, while only few aggregates follow secondary hilly segments, perpendicular to the main direction (Figure 3). Buildings are mainly two-three storey terraced or pitched houses with masonry vertical structures, almost totally residential units, often in slope with staggered floors between adjacent units (Indirli et al., 2015).

For each compound structural unit, after the usability evaluation on the basis of the AEDES form (AeDES 2013) (Figure 4), an investigation campaign has been performed, herein reported with reference to the seismic vulnerability assessment.

In literature different approaches for seismic vulnerability assessment exist. Generally, they range from rigorous methods, applied to single buildings, to more general ones, used for large scale evaluation of urban centres. In particular, the former are used to reduce the levels of physical damage, loss of life and the economic impact of future seismic events, whereas the latter, with major emphasis to first level methods, have the aim of identifying building fragilities and reducing seismic risk through both the assessment of physical damage and its connection with seismic grade (Vicente et al., 2011; Alam et al., 2012, 2013).

The vulnerability study of the Arsita historic centre ordinary buildings has been carried out taking into account the following methodologies:

a GNDT II Level form for r.c. and masonry buildings (GNDT, 2010a, 2010b)

b Formisano's form for masonry building aggregates (Formisano et al., 2010b, 2011, 2015)

c FAMIVE spreadsheet for masonry buildings (D'Ayala and Speranza, 2002, 2003)

d MEDEA form for r.c. and masonry buildings (MEDEA, 2005; Papa and Zuccaro, 2004; Zuccaro and Leone, 2010)

e Masonry quality index (Binda and Cardani, 2009).

Other general information have been obtained with a special urban-architectonic form containing information on geometry (volume, surface and number of floors), age, use, architectural quality and maintenance of buildings investigated, which are not considered in this study.

Figure 3 The 17 building aggregates of the Arsita municipality (see online version for colours)

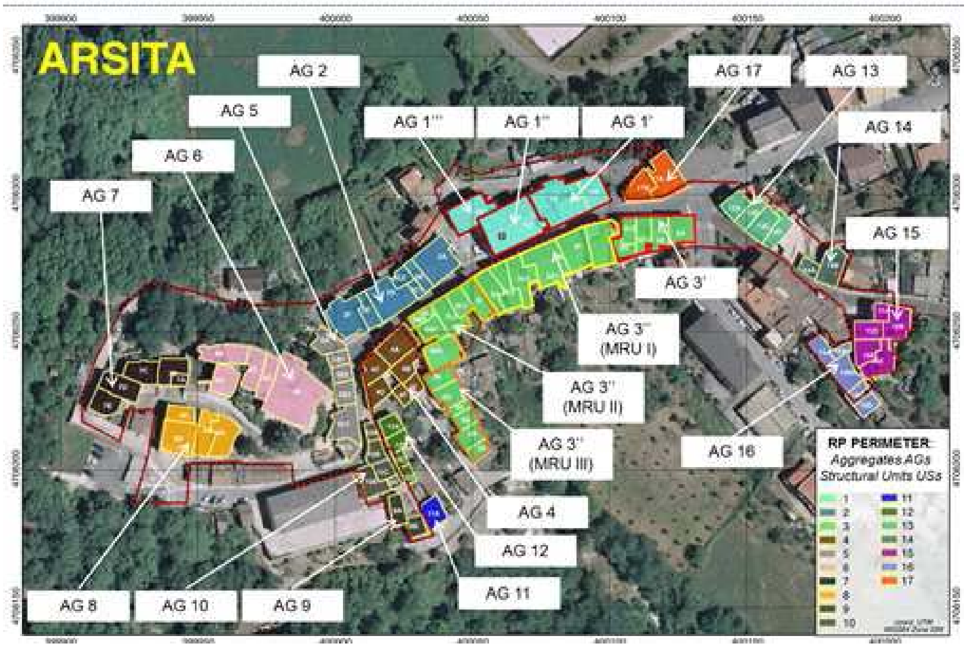
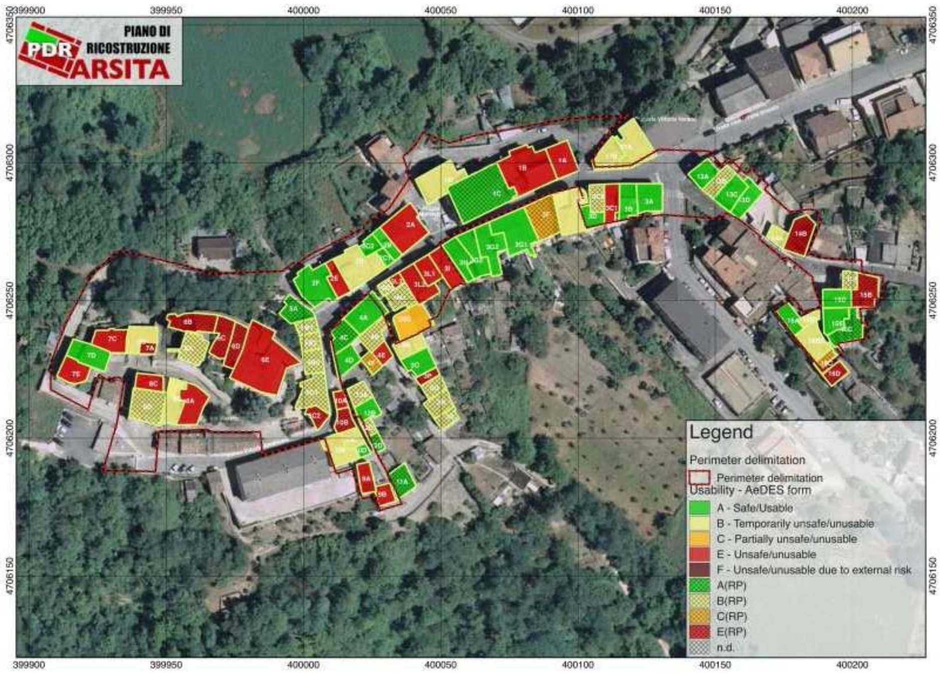


Figure 4 The usability checks resulting from AEDES forms (see online version for colours)



2.1 The GNDT II level and Formisano's methods

The GNDT II level and Formisano forms provide a vulnerability index Iv, measured with reference to two different scales based on several parameters, which consider geometrical, structural and mechanical peculiarity of each structural unit. The two indexes have been done comparable by using a base 100 scale. So, if the construction has not any structural lacking, the index is equal 0, while the significant damage corresponds to an index equal to 100.

Analysis results have shown that about 8% of the buildings have low vulnerabilities ($I_V < 30$), about 75% have medium-low vulnerability ($30 < I_V < 60$) and about 17% have a medium to high vulnerability ($I_V > 60$). In particular, the SUs characterised by medium-high vulnerability are the 1D, 2E, 3C1, 3L1, 3L3, 3M3, 3P, 4F, 6B, 6C, 6D, 6E, 7E, 9A and 14B buildings. In absolute terms, the most vulnerable unit is the 4F one, with an index of 74.18.

The Formisano's method is inspired by the GNDT II level one to specifically appraise the seismic vulnerability of building aggregates. In particular, it associates to the typical GNDT ten parameters, five additional parameters (in-plane interaction, in-elevation interaction, presence of staggered floors, typological and structural heterogeneity, difference of opening areas between adjacent facades) considering the interaction among SUs belonging to the same masonry building complex.

Analysis results summarised in Table 1, have shown that the vulnerability of buildings is low ($I_v < 30$) for the 8% of the SUs, medium-low ($30 < I_v < 60$) for the 90% and medium-high ($I_v > 60$) for the 2%. In particular, 6E and 9A units have medium-high vulnerability, with the first being absolutely the most vulnerable construction ($I_v = 74.25$).

Table 1 Synthesis of results achieved from GNDTII level and Formisano's methods

Group	*Vulnerability level*	I_v	*Building percentage (%)*	
			GNDT II level method	*Formisano's method*
I	Low	< 30	8	8
II	Medium-low	[30 ÷ 60]	75	90
III	Medium-high	≥ 60	17	2

The application of the GNDT II level and Formisano's methods for structural masonry units surveyed have provided the vulnerability results shown in Figures 5, 6, 7 and 8, where the vulnerability indices I_v have been normalised in the range [0 ÷ 100] (Figures 5 and 7) and the SUs vulnerability maps are plotted (Figures 6 and 8).

Figure 5 Vulnerability assessment indexes for the 91 SUs according to the GNDT II level form (see online version for colours)

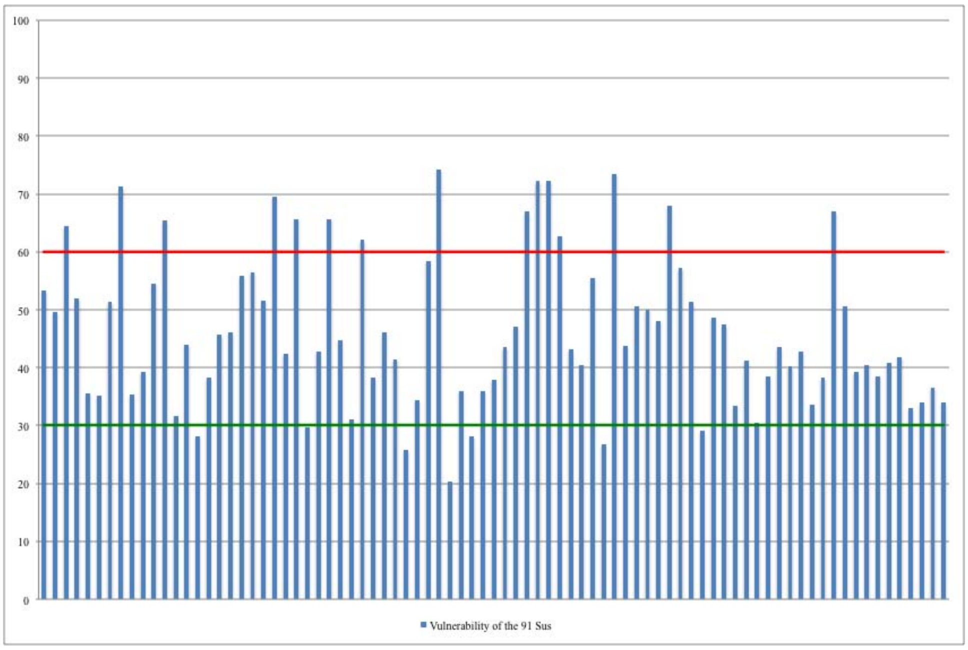


Figure 6 Vulnerability map according to the GNDT II level form (see online version for colours)

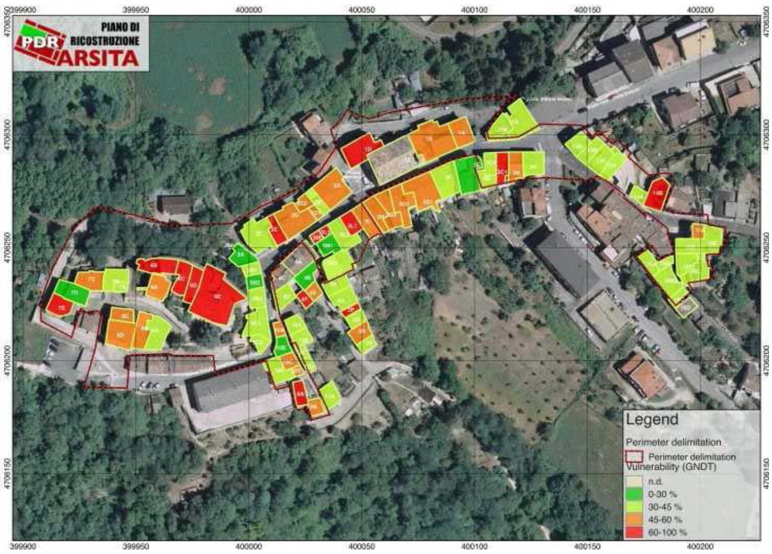


Figure 7 Vulnerability assessment indexes for the 91 SUs according to the Formisano's method (see online version for colours)

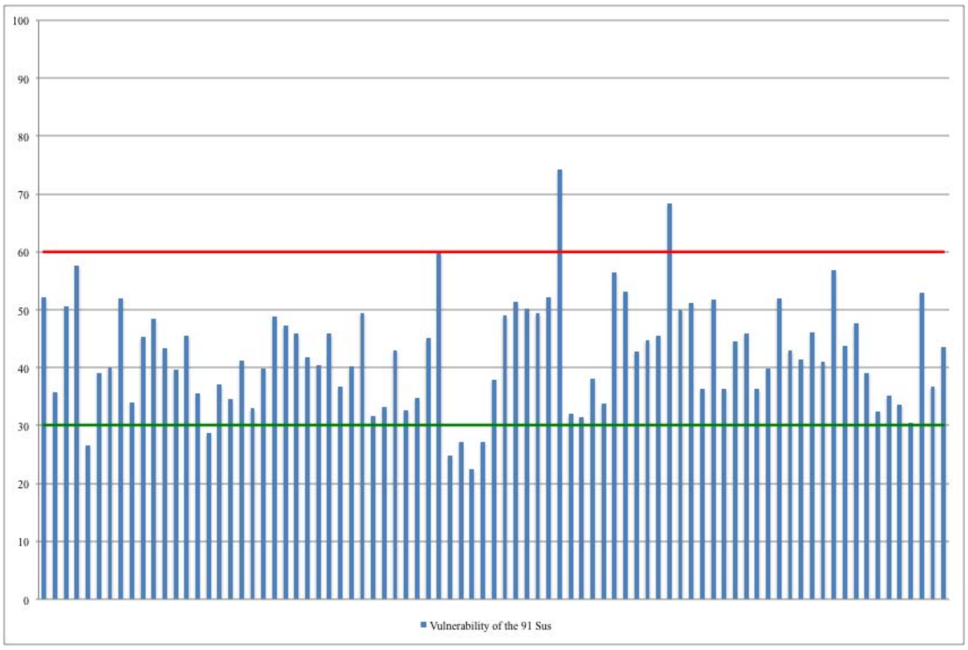
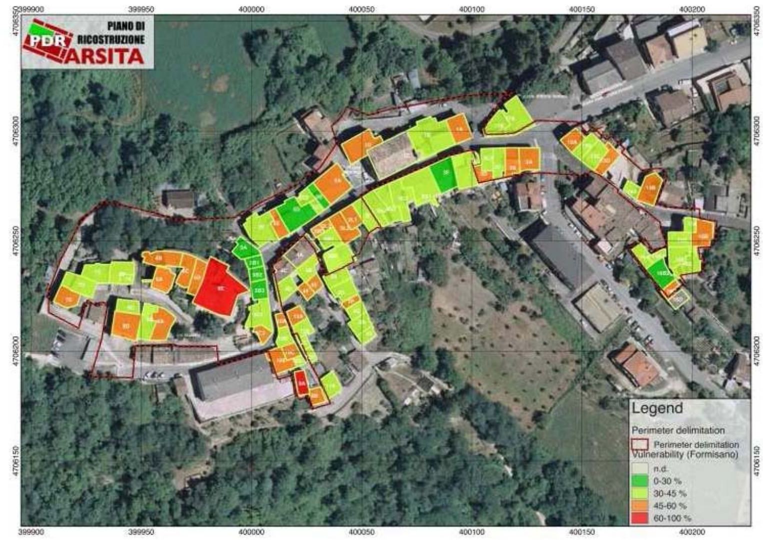


Figure 8 Vulnerability map according to the Formisano's method (see online version for colours)



2.2 *The FaMIVE method*

FaMIVE method evaluates the vulnerability of masonry buildings located in historical centres by considering the possible collapse mechanisms and the related importance factors associated to them.

Each mechanism is evaluated with reference to the probability of occurrence, which depends on the walls typology and materials. Then, an equivalent static analysis should be performed aiming at the evaluation of the collapse multiplier related to each collapse mechanism. Subsequently, a prevision about damage levels for single constructions or aggregates can be defined. Finally, the vulnerability reduction thanks to any seismic protection technique can be evaluated.

The application of the FaMIVE method has allowed to identify the predominant failure mechanisms (I mode in-plane and II mode out-of-plane) of structural unit external walls. The obtained results for the mentioned mechanisms are illustrated in Figures 9 to 12, where the vulnerability indexes I_V are normalised in the range [0 ÷ 100] (Figures 9 and 11) and the chromatic GIS maps are plotted (Figures 10 and 12). The analysis results have shown that, differently from other examined methods, higher vulnerability situations linked to in-plane mechanisms occur. Specifically, vulnerability of buildings according to the FaMIVE method is illustrated in Table 2. From analysis results, it is stressed that, with reference to all mechanism types, units 2C1, 3D, 3G1, 3G2, 3M1, 3M2, 3M3, 3P, 4E, 5B1, 5B2, 5B3 and 6E are characterised by high vulnerability. Particularly, the most vulnerable units, able to attain the maximum index, are 3D, 3G2, 3M1, 3M2, 4E and 6E buildings, for which corrective action destined to the aforementioned vulnerability source elimination must be suitably designed and applied.

Figure 9 In-plane vulnerability index of the aggregate masonry walls of the 91 SUs according to the FaMIVE method (see online version for colours)

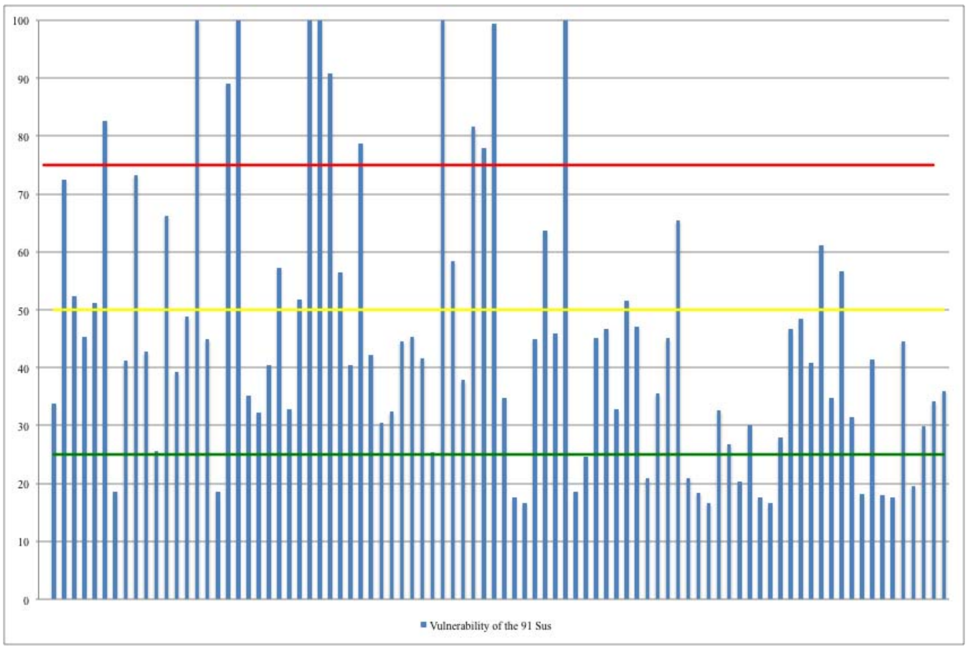


Figure 10 In-plane vulnerability map of aggregate masonry walls according to the FaMIVE method (see online version for colours)

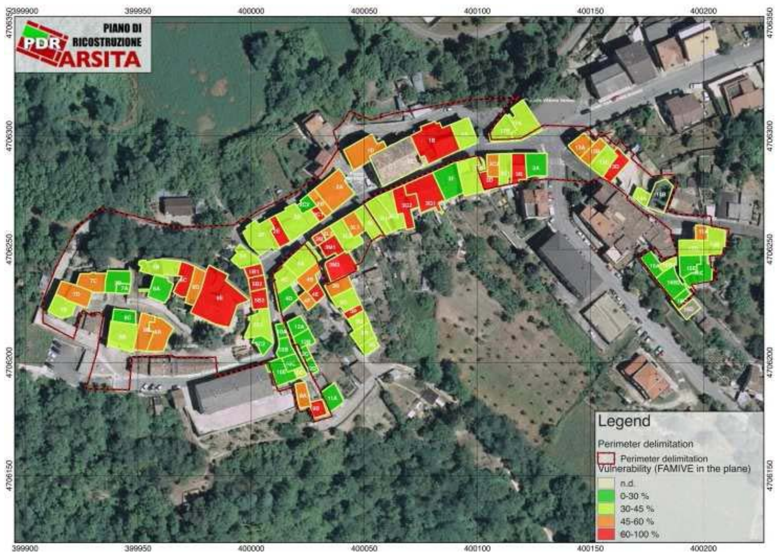


Figure 11 Out-of-plane vulnerability index of the aggregate masonry walls of the 91 SUs according to the FaMIVE method (see online version for colours)

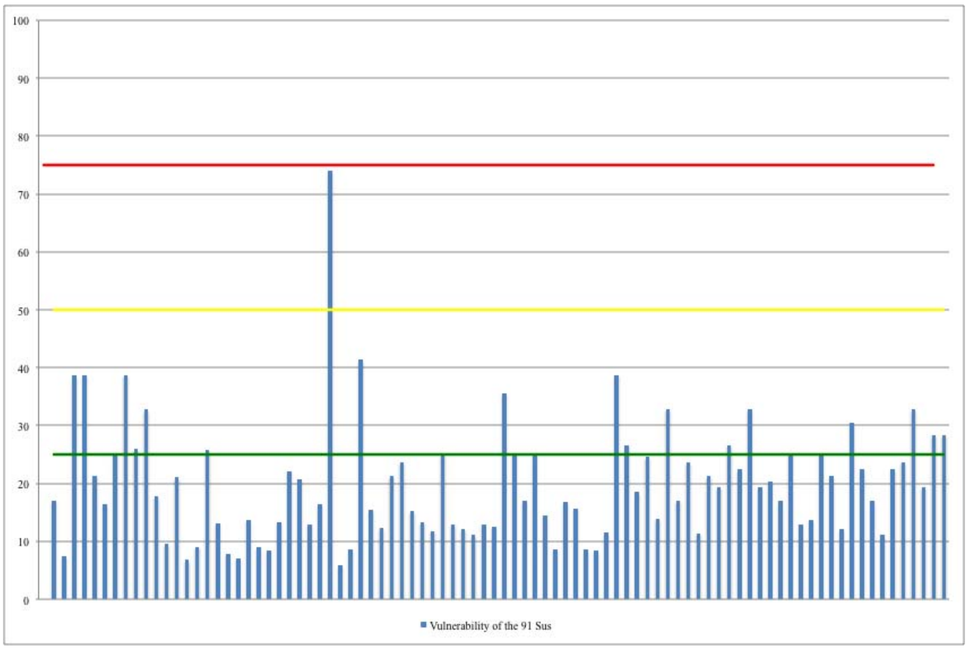


Figure 12 Out-of-plane vulnerability map of aggregate masonry walls according to the FaMIVE method (see online version for colours)

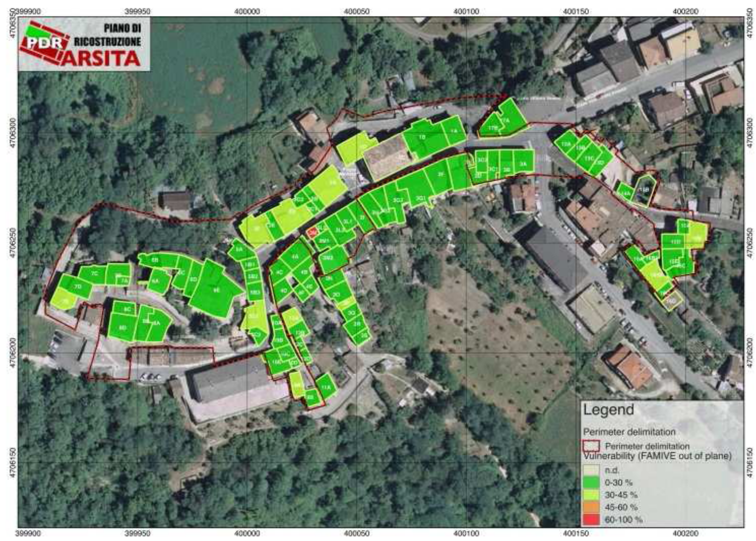


Table 2 Synthesis of results achieved from FaMIVE method

Group	*Vulnerability level*	I_v	*Building percentage (%)*
		In-plane mechanisms	
I	Low	< 25	19
II	Medium-low	[25 ÷ 50]	50
III	Medium-high	[50 ÷ 75]	16
IV	High	≥ 75	5
		Out-of-plane mechanisms	
I	Low	< 25	73
II	Medium-low	[25 ÷ 50]	26
III	Medium-high	[50 ÷ 75]	1
IV	High	≥ 75	/

2.3 The MEDEA method

The MEDEA form is conceived for post-earthquake damage evaluation, but it is useful even in pre-seismic case, for both masonry and r.c. buildings.

With reference to masonry buildings, 23 types of damages have been defined for vertical, V_i, elements (walls, pears, tympani, etc.) and 13 for horizontal ones, H_i, (vaults, floors, stairs, etc.). The analysis of both vertical and horizontal damages allows the identification of 16 collapse mechanisms M_i, associated to a seismic event: 10 of them are global mechanisms, being referred to the entire construction and involving many structural elements which produce a global static and dynamic un-equilibrium; the remaining 6 mechanisms are local ones and involve secondary elements only, with possible local collapses. On the other hand, the MEDEA forms for r.c. structures define ten types of damages for vertical structures CV_i, four types for horizontal ones CH_i, four types for the partition walls CT_i, and three types for the walls CP_i. In addition, the method considers several structural features that can increase the vulnerability of the analysed building.

MEDEA method has been applied to the Arsita town SUs aiming at evaluating the more common damage/collapse mechanisms verified. The MEDEA methodology consist on the following steps:

1 identification and labelling of the SUs; this operation requires an in depth survey due to the interconnection between adjacent constructions

2 qualitatively evaluation of any elements which increase the structural vulnerability, according to the typical cases proposed

3 definition of both vertical and horizontal cracking maps according to the damage/collapse mechanisms scale considered: this activity requires particular attention about the identification of the more significant mechanisms

4 classification of the damage levels according to the EMS98 scale for masonry structures (from d_1 to d_5 corresponding to slow, middle-slow, middle, severe and very heavy damage, respectively).

With reference to the aggregates under inspection, the MEDEA method has provided the results plotted in Figures 13 to 16, where the distribution of the SUs which have suffered in-plane (M1-M2), out-of-plane (M3-M6), global (M7-M10) and local (M11-M16) mechanisms are shown. The MEDEA forms referred to the r.c. buildings has not been filled for Arsita historical centre being only one r.c. construction located there.

Figure 13 Damage/collapse mechanisms map according to the MEDEA method for masonry in-plane mechanisms (see online version for colours)

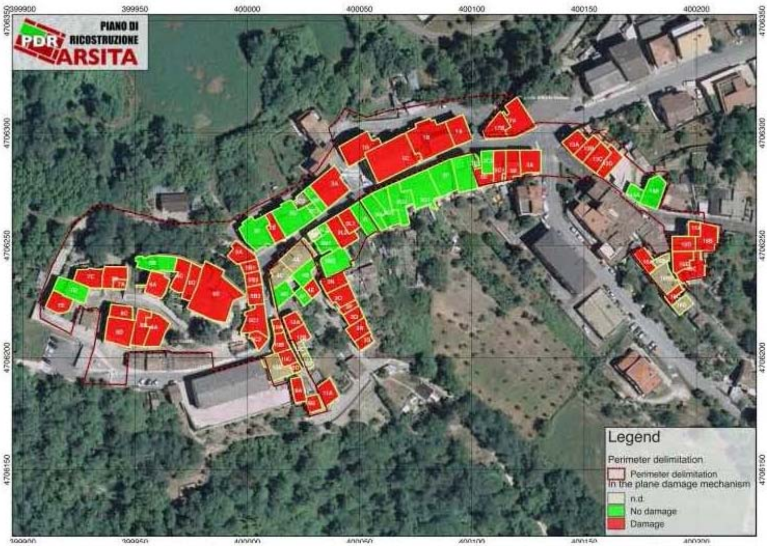


Figure 14 Damage/collapse mechanisms map according to the MEDEA method for masonry out-of-plane mechanisms (see online version for colours)

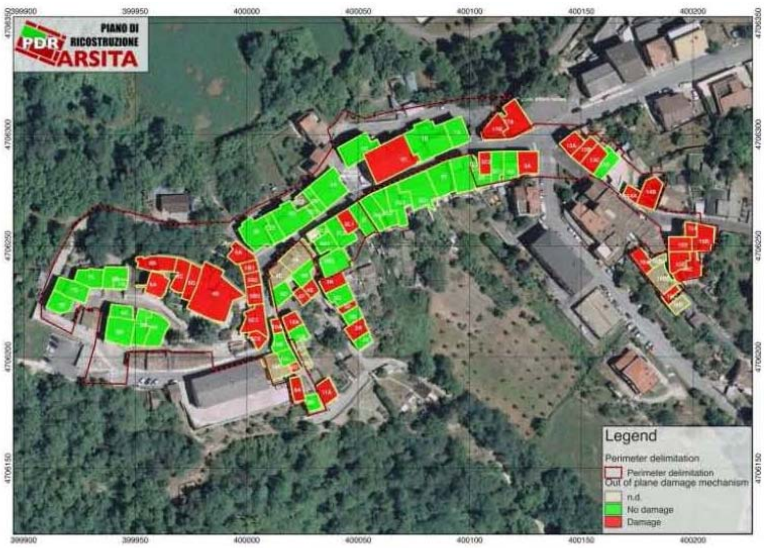


Figure 15 Damage/collapse mechanisms map according to the MEDEA method for masonry global mechanisms (see online version for colours)

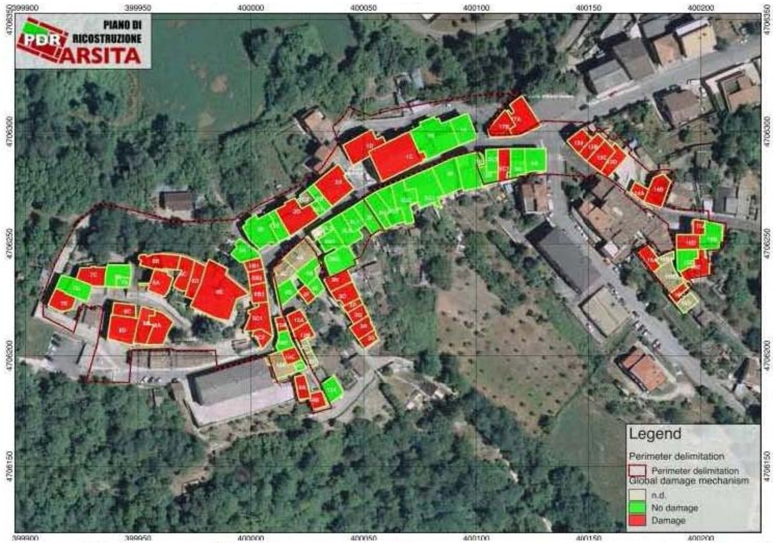
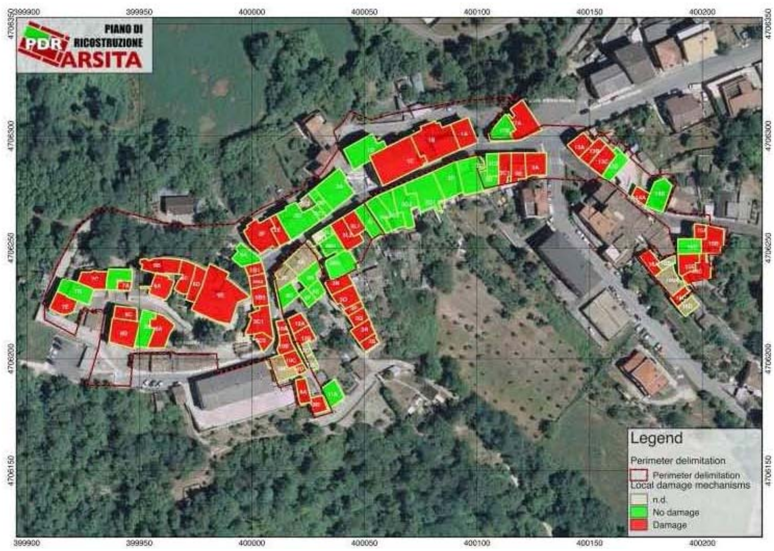


Figure 16 Damage/collapse mechanisms map according to the MEDEA method for masonry local mechanisms (see online version for colours)



2.4 Analysis of masonry quality and typology

The analysis of the Arsita masonry has been addressed through a specific survey form (Figure 17). The systematic data acquisition about the morphological/compositional characteristics of masonry typologies through this form, in order to obtain a unique qualitative description as objective as possible, is undoubtedly effective and quick. In fact, the masonry is a non-homogeneous system obtained by assembling more elements. Therefore, its structural behaviour depends on both the characteristics of the individual constituents and the interactions between them. Moreover, the recognition of the masonry typology is the starting point for the evaluation of the vulnerability in the masonry itself and, by extension, in the structure which it belongs to.

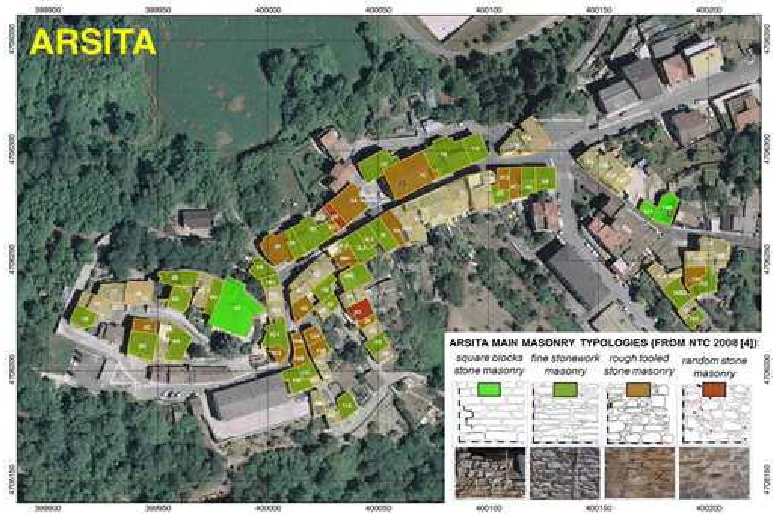
Figure 17 The masonry form (see online version for colours)

The form is divided into three parts: the first is devoted to the identification of the masonry under investigation; the second to the evaluation of the masonry characteristics; the third to the masonry attribution to one of the classes indicated by the Italian NTC08 code (MD, 2008). Many structural characteristics are taken into account by the form, both for the wall surface and the wall section: among others, the horizontal offset of the rows and the vertical joints, which indicate the regularity of the masonry, the number of layers, the presence of horizontal courses, the presence of wedges to fill the mortar joints of larger dimensions, the number of tiers and their thickness, the presence of connections between tiers, the presence of vacuums. The characterisation of the constituent materials is also expected, with the indication of: nature, shape and size of ashlars or bricks, their origin, processing, conservation status; the mortar texture, its colour, the particle size and the morphology of the aggregate.

Data has been gathered for about half of the 91 SUs, directly entered in digital and geo-referenced format using a tablet, in order to bypass the traditional acquisition step on paper (Figure 18). Among the huge amount of results, just the principals are reported here (Figure 19).

Figure 18 In situ data acquisition and processing (see online version for colours)

Figure 19 The main masonry typologies of Arsita (see online version for colours)

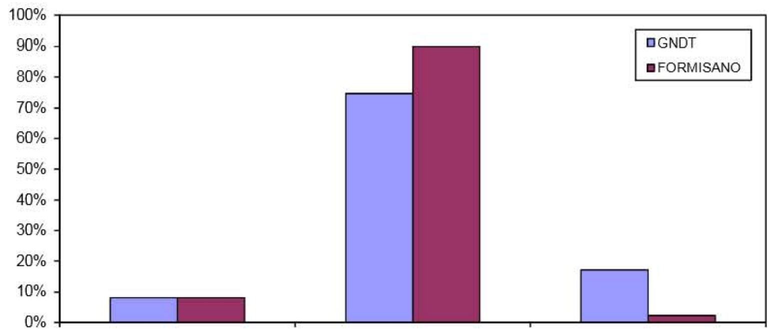


For the remaining part of buildings, the presence of plaster coating has not made possible a direct observation of the masonry surface; therefore, a second phase of investigation will be carried out in the framework of the appropriate diagnostic campaign foreseen by the RP. During the RP survey, some samples of ashlars and mortars have been picked up and then analysed in laboratory to obtain more information about the constituent materials. All samples have been preliminarily observed by stereo-microscope with the aim to describe the morphology and to identify the most significant areas for following SEM analysis and microanalysis. With regard to the stone elements, the tests showed the presence of calcium, silicon and aluminium as main elements, with lower concentrations of iron, sodium, magnesium and potassium; therefore, it can be assumed that the ashlars used in the Arsita masonry are made from the sandstones collected widespread in the territory. The analysis of mortar samples showed a similar chemical composition, except for two samples deteriorated by deposition or efflorescence of saline substances: the composition is characterised by an high concentration of silicon, iron and aluminium, with traces of magnesium and potassium, all elements related to the minerals present in silicate sands, which may have been used as aggregate of the mortar. The picture emerging from the survey is rather homogeneous, despite some predictable differences that can be observed between the SUs. The masonry typology found in most of the buildings is basically very similar, and consists of two layers walls built with stone elements, coming from the surrounding area, only partially processed, arranged in an orderly manner to form sub-horizontal courses. Mortar joints are quite large and there is a widespread presence of stone or brick wedges. The Arsita masonry typologies show some typical characteristics that differentiate them from those common in other parts of the Abruzzo region, for example, in L'Aquila, where the stone elements are smaller in size, have an elongated shape and are generally arranged in a quite chaotic manner.

3 Comparison of results

The comparison between the vulnerability assessment methods is plotted in Figure 20, where the distribution of the vulnerability levels referred to the whole SUs is summarised. In particular, the comparison shows that the 8% of the buildings is classified in slow vulnerability level ($I_v < 30$) for both methods. The Formisano's method collocates more SUs in middle-slow vulnerability level than the GNDT one (90% against 75%); on the contrary, it considers less buildings in middle-high vulnerability level than the GNDT method (2% against 17%). Therefore, the Formisano form allows a more accurate evaluation of the seismic performances of the constructions located in the aggregates. According to this methodology, the building located in an aggregate provides a better seismic performance than the single one, by a reduction of about 15% of the vulnerability level.

Figure 20 Comparison between GNDT and Formisano methods (see online version for colours)



The comparison among analysis methods in terms of vulnerability indices is reported in Figure 21. In Figure 21, other than the best forecast of the building aggregate behaviour considered by the Formisano's method with respect to the GNDT one, it is apparent that in the FaMIVE method masonry units are more susceptible to undergo in-plane mechanisms, even if the detected damage extension on walls is greater for I mode collapse mechanisms.

Afterwards, mediating vulnerability indices derived from the used methods, the values depicted in Figure 22 are achieved. The obtained results show that, on average, mostly of the Arsita masonry buildings (about 90%) have a medium-low vulnerability. On the other hand, low and medium-high vulnerability indicators are respectively recorded in the percentage of 2% and 8% and the most vulnerable structural unit is the 3M3.

Figure 21 Seismic vulnerability indices of structural units according to GNDT, Formisano and FaMIVE methods (see online version for colours)

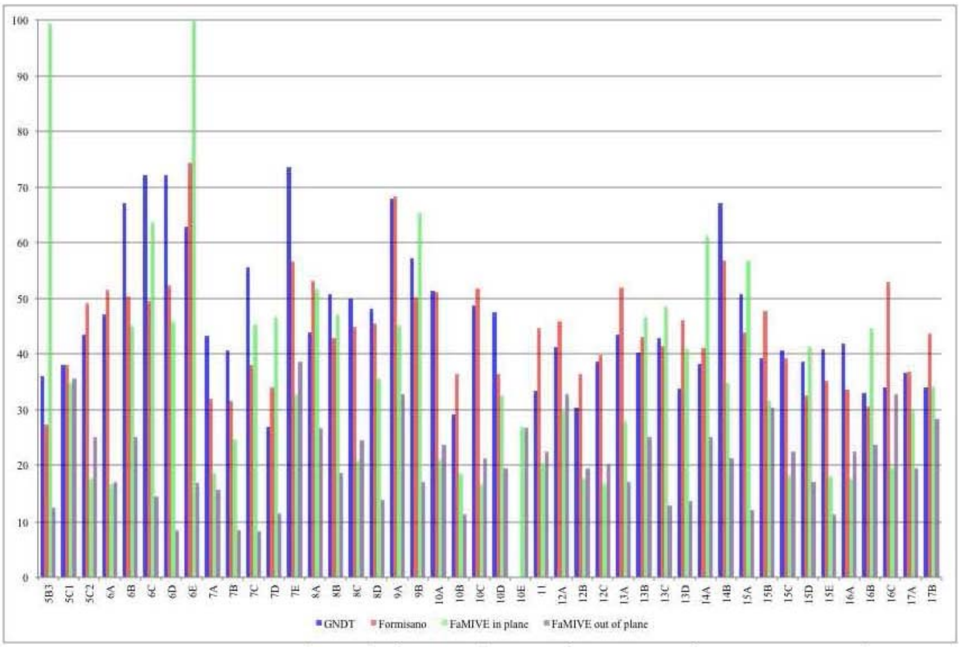


Figure 22 Average vulnerability indices of structural units (see online version for colours)

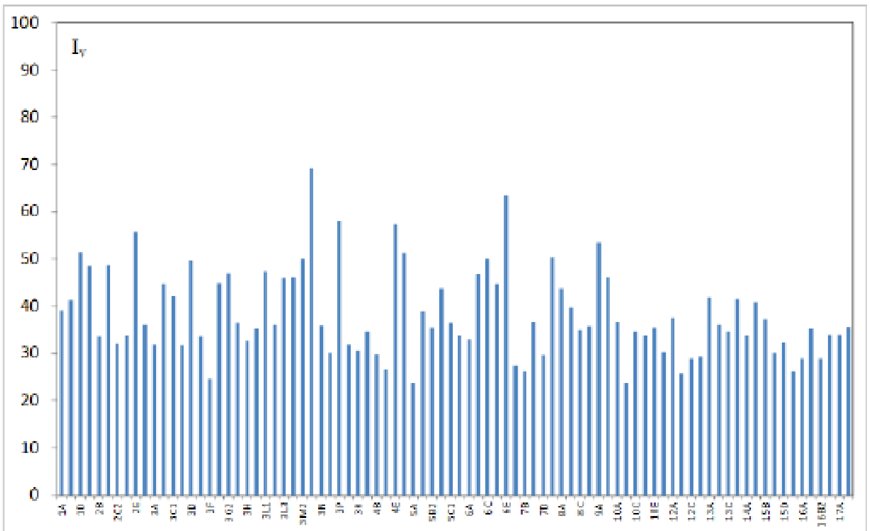


Figure 23 Average vulnerability indices of structural aggregates (see online version for colours)

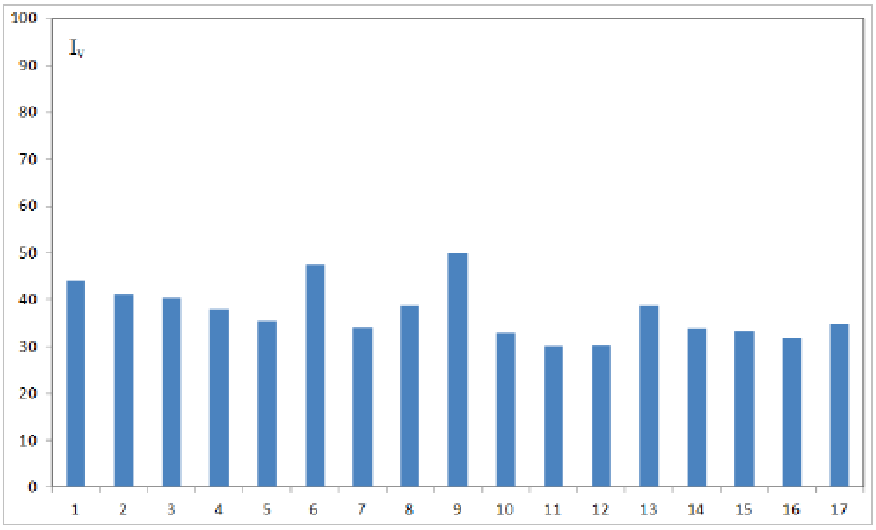


Figure 24 (a) Investigated units (b) Typical masonry wall of the Arsita built-up (see online version for colours)

(a) (b)

In Figure 23, a seismic vulnerability ranking for aggregates, whose indices are obtained as mean values of those of constituting SUs, is given. It is apparent that the building aggregate n.9 has the greatest average vulnerability index, it assuming value close to 50. In addition it is clear that all the aggregates exhibited an average medium-low vulnerability level, with indicators in the range [25 ÷ 50].

Finally, a survey campaign on masonry types has been performed. Appropriate survey forms inherent the masonry type and quality have been filled for the 55 SUs, in which the masonry surface was directly observable: those units are filled in green in Figure 24(a). Although only 55 SUs have been investigated, thanks to the substantial homogeneity of the situations encountered in the various aggregates, the information gathered can be voted as sufficient to obtain a first evaluation of different masonry types within the municipality of Arsita. The most common construction type dates back the 19th century, when most of the town were built. Masonry walls are those typical of Abruzzo minor historical centres, they being mostly made of little stones without both ordinary setting and headers [Figure 24(b)]. The method application has provided the results of Figure 25, where it is shown that about 26% of the buildings have a medium-low masonry quality index ($2.5 \leq I_Q < 5.0$), approximately 53% have medium-high index ($5.0 \leq I_Q < 7.5$) and about 21% have high index ($I_Q \geq 7.5$). In particular, the SUs characterised by medium-low index are those marked with 2B, 2F, 3C1, 3H, 3L1, 3M1, 3O, 3P, 10A, 10B and 12A. In absolute the most vulnerable units are the 2B and 10A ones, with a masonry quality index slightly above 3.

4 Conclusions

In this paper, framed in the reconstruction plan of Arsita (TE), the seismic vulnerability of historic centre buildings grouped in aggregates has been examined through different series of expeditious investigation methods (GNDT II level, Formisano, FaMIVE, MEDEA, Quality of walls).

The analysis results showed that the Arsita historic centre built-up is characterised by a substantial medium-low vulnerability. In-plane collapse mechanisms are those prevailing in masonry walls, as it was also observed after the earthquake. Absolutely it is evidenced that, according to the different methodologies applied, the most vulnerable structural unit is the construction 6E, whose medium-high masonry quality index is not able to overcome its intrinsic seismic deficiencies.

The comparison among analysis methods examined showed that the Formisano's method allows to estimate with greater precision the seismic behaviour of buildings grouped into aggregates, reducing their vulnerability with respect to the isolated construction one. In particular, with this method a reduction of medium-high vulnerability cases of the order of 15% in comparison to GNDT II level form predictions is noticed. The analysis results obtained from the FaMIVE method based on vulnerability of aggregates external walls with reference to I and II modes collapse mechanisms, have shown that masonry facades of the built-up are most affected by in-plane mechanisms rather than out-of-plane ones. Finally, with regard to the analysis of construction masonry qualities, it has been found that more than half of buildings have a medium-high performance level, through which the damages induced by the earthquake have been limited.

References

AeDES (2013*) Scheda di 1° livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell'emergenza post-sismica (AeDES 07/2013)*, in Italian, Department of Civil Protection [online] http://www.protezionecivile.gov.it/resources/cms/documents/scheda_AeDES_07_2013_corretta_.pdf (accessed 28 April 2016).

Alam, M., Tesfamariam, S. and Alam, M. (2013) 'GIS-based seismic damage estimation: case study for the city of Kelowna, BC', *Nat. Hazards Rev.*, Vol. 14, No. 1, pp.66–78.

Alam, N., Shahria Alam, M. and Tesfamariam, S. (2012) 'Buildings' seismic vulnerability assessment methods: a comparative study', *Nat. Hazards*, Vol. 62, No. 2, pp.405–424.

Binda, L. and Cardani, G. (2009) *Masonry Quality Form: Report and Guidelines for Filling the Masonry Quality Evaluation Form*, ReLUIS Report, Research line No. 1 'Evaluation and reduction of the masonry buildings vulnerability', in Italian.

D'Ayala, D. and Speranza, E. (2002) 'An integrated procedure for the assessment of seismic vulnerability of historic buildings', *Proc. of the 12th European Conference on Earthquake Engineering*, London, UK.

D'Ayala, D. and Speranza, E. (2003) 'Definition of collapse mechanisms and seismic vulnerability of masonry structures', *Earthquake Spectra*, Vol. 19, No. 3, pp.479–509.

Formisano, A., Di Feo, P., Grippa, M.R. and Florio, G. (2010a) 'L'Aquila earthquake: a survey in the historical centre of Castelvecchio Subequo', in Mazzolani, F., Formisano, MA., Marzo, A., Marghella, G. and Indirli, M. (chair): *Proc. of the COST Action C26 Final Conference 'Urban Habitat Constructions under Catastrophic Events'*, Naples, Italy, 16–18 September 2010, pp.371–376, ISBN: 978-0-415-60685-1, Taylor & Francis Group, London.

Formisano, A., Mazzolani, F.M., Florio, G. and Landolfo, R. (2010b) 'A quick methodology for seismic vulnerability assessment of historical masonry aggregates', in Mazzolani, F.M. (chair): *Proc. of the COST Action C26 Final Conference 'Urban Habitat Constructions under Catastrophic Events'*, Naples, Italy, 16–18 September 2010, pp.577–582, ISBN: 978-0-415-60685-1 Taylor & Francis Group, London.

Formisano, A., Florio, G., Landolfo, R. and Mazzolani, F.M. (2011) 'Numerical calibration of a simplified procedure for the seismic behaviour assessment of masonry building aggregates', *Proc. of the 13th International Conference on Civil, Structural and Environmental Engineering Computing (CC 2011)*, Chania, Crete, 6–9 September.

Formisano, A., Florio, G., Landolfo, R. and Mazzolani, F.M. (2015) 'Numerical calibration of an easy method for seismic behavior assessment on large scale of masonry building aggregates', *Advances in Engineering Software*, Vol. 80, pp.116–138.

Geremei, F., Moretti, L., Marzo, A., Marghella, G. and Indirli, M. (2013) '3D modelling of Arsita town in the framework of the reconstruction', *Proc. of the 14th International Conference on Civil, Structural and Environmental Engineering Computing*, Cagliari, Italy, 3–6 September 2013.

GNDT (2010a) *GNDT-INGV II Level Form for Masonry Buildings*, in Italian, Department of Civil Protection.

GNDT (2010b) *GNDT-INGV II Level Form for r.c. Buildings*, in Italian, Department of Civil Protection [online] http://www.pdrarsita.bologna.enea.it (accessed 28 April 2016).

Indirli, M., Kouris, L.A.S., Formisano, A., Borg, R.P. and Mazzolani, F.M. (2013) 'Seismic damage assessment of unreinforced masonry structures after the Abruzzo 2009 earthquake: the case study of the historical centres of L'Aquila and Castelvecchio Subequo', *Int. Journal of Architectural Heritage*, Vol. 7, No. 5, pp.536–578.

Indirli, M., Marzo, A., Marghella, G., Gambatesa, T., Tralli, A.M. and Formisano, A. (2015) 'From in situ quick surveys to analytical procedures for vulnerability assessment in the framework of the Arsita reconstruction plan', *Proc. of the XVI Convegno ANIDIS*, L'Aquila, Italy, 13–17 September 2015.

MEDEA (2005) *Manuale di Esercitazioni sul Danno ed Agibilità per edifici ordinary*, in Italian, Dipartimento della Protezione Civile.

Ministerial Decree (MD) (2008) *Technical Codes for Constructions*, Official Gazette of the Italian Republic published on 14 January 2008.

Papa, F. and Zuccaro, G. (2004) *MEDEA: A Multimedia and Didactic Handbook for Seismic Damage Evaluation*, European Seismological Commission, Potsdam.

Vicente, R., Parodi, S., Lagomarsino, S., Varum, H. and Mendes Silva, J.A.R. (2011) 'Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal', *Bull. Earthquake Eng.*, Vol. 9, No. 4, pp.1067–1096.

Zuccaro, G. and Leone, M.F. (2010) 'Structural damage and vulnerability assessment for service life estimation through MEDEA tool', in Mazzolani, F.M. (chair): *Proc. of Final Conference of COST Action C26, Urban Habitat Constructions under Catastrophic Events*, Naples, Italy, 16–18 September 2010, pp.1023–1029, ISBN: 978-0-415-60685-1, Taylor & Francis Group, London.