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SEISMIC VULNERABILITY ASSESSMENT OF HISTORICAL URBAN CENTRES: THE CASE STUDY OF CAMPI ALTO DI NORCIA, ITALY

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ABSTRACT:

Seismic damage assessment is a valuable opportunity to evaluate the accuracy of vulnerability and risk methodologies applied to historic masonry buildings, giving the possibility of enhancing and optimizing mitigation and retrofit strategies. Vulnerability index methodologies are flexible and powerful tools for the seismic assessment at urban scale, able to provide a first screening of the critical issues present in masonry structural aggregates. The different structural features of the buildings, directly and indirectly influencing their structural behaviour, are measured through different weights and scores finally achieving a vulnerability indicator. In the present paper, four different vulnerability index methodologies are applied to the medieval city of Campi Alto di Norcia in Valnerina, Umbria, recently stroke by the 2016 Central Italy earthquakes. The accuracy of the adopted I_v methods is assessed based on the real damages' analysis performed in the surrounding area, comparing results achieved from the application of considered methodologies to direct in-situ observations. Data collected during the 2016 post-earthquake damage surveys and usability assessment, together with the external visual inspections carried out and with the information coming from retrofitting design interventions performed between 1979 and 1997, are used.

1. INTRODUCTION

The historical building heritage is the result of an evolution interactive process, occurred over the centuries, between people and the surrounding area: the heterogeneous architecture often recognizable in old city centres is the expression of the cultural modifications, natural transformations and anthropic events.

The masonry buildings constituting the urban environment are interconnected in Structural Aggregates (SAs) without following a well-organized development, and the construction typology consequently changes according to the different places and realization periods (Giuffré, 1993). The different Structural Units (SUs) constituting the above-mentioned SA, that can be determined within historical city centres, normally differ for geometrical configurations in plan and elevation, construction techniques adopted, materials, structural features, etc. By the way, the resulting performance of SA is strictly influenced by each SU developed inside. The modifications and the changes undergone by the structural aggregate generally involve the superposition of different materials and construction technologies, the alteration of the structural homogeneity of the aggregate, the differences in realization respect to the original design, etc (Caprili et al., 2016). The morphological variety of the urban settings gives an added value to the cultural heritage of a place (Martines, 2011), but, at the same time, increases local and global vulnerabilities towards static and seismic actions.

The seismic prevention policies frequently carried out by public authorities require the deep knowledge of the risk to which existing buildings in aggregates are subjected at large-scale/territorial level (MIBACT, 2008) the deep understanding of materials, construction techniques, structural features and morphological evolution of the aggregates, interaction between the SUs and the SA need to be highlighted and kept in mind.

According to what present in the current scientific literature, the seismic vulnerability of masonry aggregates in historical city centres can be analysed, at territorial level, using statistical (or observational) methods, allowing the quick and easy determination of Vulnerability Index (I_V) for each masonry building through the identification of selected structural parameters owing different importance in the resulting structural behaviour (Ortega et al., 2018). The statistical approach allows to summarize achieved data through Damage Probability Matrices (DPMs) globally analysing vulnerabilities and forecasting the expected damage for different construction typologies (Giovinazzi et al., 2004), (D'Ayala et al., 1997).

Even if characterized by a very easy and quick application, the accuracy of the above-mentioned methodologies decreases when applied to structures relevantly different from the ones used for the calibration of the method. In such cases, achieved results often become meaningless and need to be improved and re-calibrated for drafting relevant conclusions (Ferreira et al., 2017).

With the aim of simplifying this issue, a new methodology for the seismic risk assessment of structural aggregates is under development, starting from the deep analysis of pros and cons of existing methods and introducing innovative aspects coming from the direct observation of structural damages before and after seismic events.

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In the present work, the first part of the above-cited research is presented: four different well-accepted methodologies for the determination of Vulnerability Index (I_V) are applied to the representative case-study historical city centre of Campi Alto di Norcia (Bianchi et al., 1998), strongly damaged after the 2016 Central Italy earthquake and nowadays consequently uninhabited. Thanks to the execution of past in-situ surveys assessing the structural condition of the SA *before* the seismic event and highlighting vulnerabilities, deficiencies and critical features, the direct observation of the consequences of the 2016 event allows to assess the accuracy of the considered methodologies in predicting the structural performance of the SUs constituting the SAs, evidencing deficiencies and issues of each applied method.

2. URBAN ORGANIZATION OF THE HISTORICAL CITY CENTRE OF CAMPI ALTO DI NORCI

2.1 General features and Structural Aggregates

The building heritage of Campi Alto di Norcia (Figure 1) covers an area of approximately 35,000 m^2 with a perimeter of 750 m. 32 different structural aggregates can be identified within the area, globally resulting in 75 different structural units. Three Churches (Madonna della Piazza, Sant'Andrea and Santa Maria delle Grazie), completely damaged by the 2016 earthquake, are also present.

According to the ground morphology, SAs develop on three different level curves, perpendicular to the slope of the hill on which the settlement is located, with the first level having the entrance in correspondence of the downstream road and the top floor at the level of the upstream road. The different levels and SAs are then connected through an internal organized system of staircases

The building heritage of Campi Alto di Norcia is made up of both row-aggregates with masonry structure and isolated buildings, generally following the topography of the land. The whole building volume is equal to about 15000 m^3 for a resulting covered surface around 3065 m^2, evaluated as the total area of the ground floor.

Figure 1. General organization of Structural Aggregates in Campi Alto di Norcia according to the Gregorian cadastre.

The aggregates differ in relation to the number, shape and height of the SUs constituting them. Isolated buildings are the 29% of the whole heritage, while external and internal structural units cover, respectively, the 44% and 27% of whole constructions.

2.2 Structural units: main features and classification

Within each structural aggregate, the different inter-connected structural units are recognized basing on the analysis of the different features characterizing them. In general, SUs can be determined looking at variations in masonry typologies, structural and construction techniques adopted, interstorey height and misalignments among floors, different slope of roofs, etc.

In general, in the case of Campi Alto di Norcia the number of storeys and the corresponding interstorey height vary from SU to SU, as well as their conservation condition. The different organization of masonry walls, materials and construction techniques adopted for horizontal storeys and roofs is directly related to the realization period and is function of eventual retrofit interventions applied over the years. Figure 2 shows the organization of SUs within the historical city centre of the case study, according to deep in-situ surveys performed before and after the 2016 seismic event. About the 16% of buildings inside Campi Alto di Norcia old city centre are characterized by one single floor, owning originally the function of storage areas and representing the remaining portion of ancient medieval houses. The 7% of buildings is organized on two levels, while the 67% - representing most of the masonry heritage – develops on three storeys. A limited number of four storey buildings is also present (Figure 2).

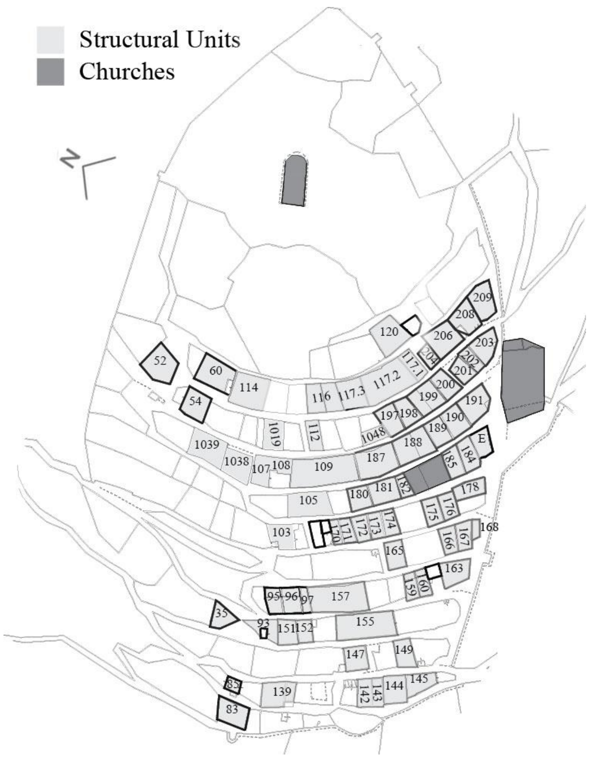

Figure 2. Identification of the Structural Units (SUs) in the case study according to the Gregorian cadastre.

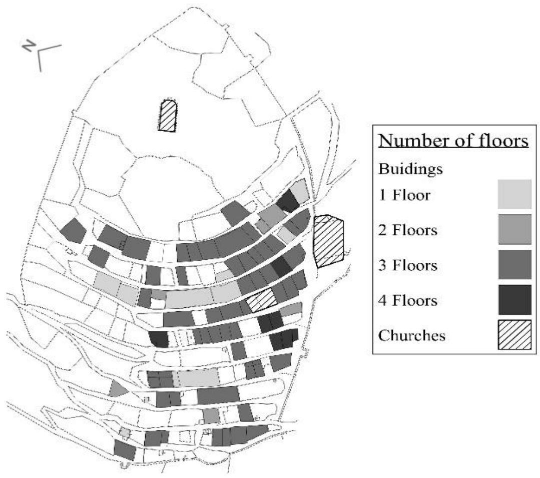

Figure 3. Distribution of the number of floors for each SU in Campi Alto di Norcia.

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The 'traditional' structural unit is organized on three different floors: the ground floor (partially underground following the cleavage of the hill) and characterized by the presence of a barrel stone vaulted surface carved into the rock and two additional floors normally presenting the traditional wooden structure of the storeys, sometimes replaced by reinforced concrete elements if retrofit interventions took place over the years (Figure 4). The average interstorey height (considering ground, first and second floors) of the SU is about 3 meters. The same organization in elevation can be recognized also in SUs made up of two and four levels, i.e. a barrel vault at first floor and timber/concrete slabs at the other ones. Concerning bearing vertical elements, masonry walls highlight differences in thickness and materials, with average thickness around 120 cm at the ground floor reducing to 80 cm and 50 cm going to the upper levels. In particular, looking at material properties, four different masonry typologies are determined in the different SUs, all characterized by irregular distribution of components. The mechanical properties of the materials are evaluated, through the execution of flat jack tests on different walls, carried out in the past, allowing to determine the stress-state on bearing vertical elements and the elastic moduli of the considered masonry typologies (Cardani, 2003; C.M. n.7, 2019).

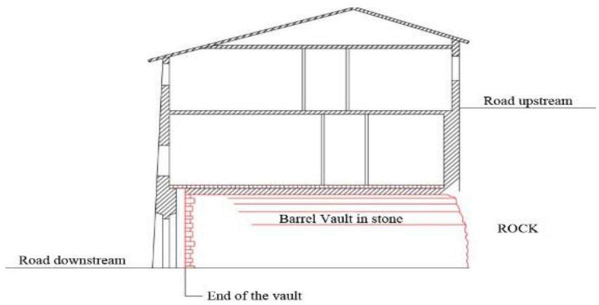

Figure 4. Schematic representation of the typical Structural Unit presents in Campi Alto di Norcia.

The execution of in-situ surveys allows to identify the different horizontal floor typologies present in SUs, mainly divided in rigid, semirigid or deformable storeys in relation to the presence, respectively, of concrete slabs (i.e. associated, usually, to the application of recent retrofit techniques), of double crossed or single wooden plank. The presence of a system of steel chains or ties to connect masonry walls and to create continuity between walls and horizontal floors is also evaluated; Figure 5 shows the graphical representation of different floor typologies and the presence of connection systems within the different SUs in Campi Alto di Norcia.

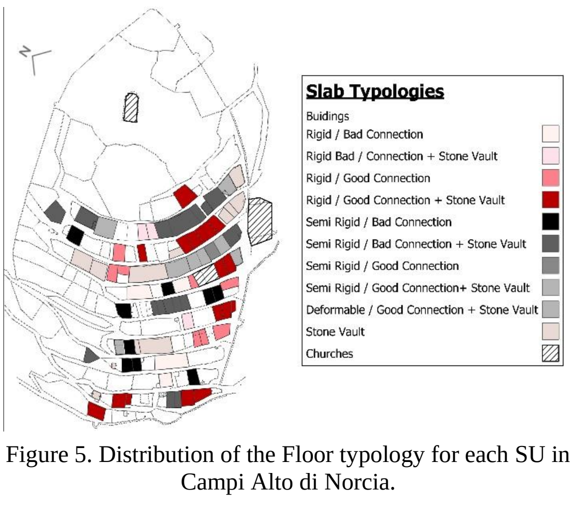

Figure 5. Distribution of the Floor typology for each SU in Campi Alto di Norcia.

3. DAMAGE DATABASE EVALUATION

The elaboration of a damage database is fundamental to calibrate a statistical method, where the *expected* damage scenario – evaluated through the application of different methodologies - can be compared with the *real* damage detected from in-situ post-earthquake surveys.

Campi Alto di Norcia was, in the past decades, subjected to deep investigations allowing to assess the structural features and conditions of buildings before the dramatic seismic event of Central Italy (2016) providing a general overview of the structural conditions of SUs and SAs. Besides, thanks to the availability of local authorities, in the post-event phase surveys are again performed to state the entity of structural damages and the practicability of buildings.

The European Macroseismic Intensity Scale EMS98 (Grünthal, 1998) is adopted for the damage estimation of Campi Alto di Norcia after the 2016 earthquake (Figure 6), providing graphical illustrations and descriptions of six different increasing level of damages (D0, D1, D2, D3, D4 and D5 – corresponding, respectively, to the lack of damages, negligible to slight damages, moderate, substantial to heavy, very heavy and full destruction, Figure 6) for different structural typologies. Stating that for the attribution of the damage level the sensibility of the surveyor plays a major role (Baggio et al., 2007) the procedure is repeated by three different independent observers achieving finally a reasonable average estimation. Table 1 and Figure 8 show the results of EMS98 classification applied to the considered case-study aggregate, in terms of percentage of buildings and volume of the whole construction heritage. Most SUs show a Damage Level D2-D3 and D4-D5, but most of the volume turns out to be in the range D2-D3, since many SUs, used as storage areas and cellars with a low volume, nowadays are fully collapsed.

Figure 6. Structural Unite #165. Damage class D4 is assigned (EMS98).

Damage Class	N° Buildings involved	% Buildings
D0	0	0.0%
D0 - D1	11	16%
D1 - D2	9	13%
D2 - D3	26	38%
D3 - D4	9	13%
D4 - D5	6	9.0%
D5	7	10%
Total	68.0	100%

Table 1. Damages distribution in Campi Alto di Norcia (EMS98).

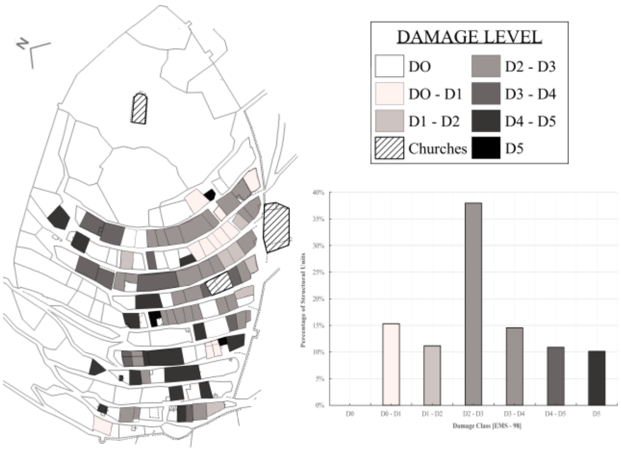

Figure 7. Damages distribution in Campi Alto di Norcia according to the EMS98 in a GIS environment.

4. APPLICATION OF VULNERABILITY ASSESSMENT METHODOLOGIES

4.1. Traditional I_V methodologies: results and discrepancies

As already mentioned in the introduction, four different vulnerability index (I_v) methodologies are applied to the considered case study aggregate of Campi Alto di Norcia. This tool, originally developed by (Benedetti et al., 1984) and more recently revisited by (Bernardini, 2000), (Lagomarsino et al., 2007), (Barbat et al., 2008), (Vicente et al., 2011), is based on the definition of the seismic vulnerability of a SU in a SA checking selected relevant vulnerability parameters able to fully describe the structural performance of the construction and evaluating the I_v considering a 'weighted sum', giving different importance to difference parameters. The vulnerability indexes are then normalized, providing values in the range 0-100 (Cherubini et al., 1999). The evaluation is performed based on a comprehensive survey of the building and the weight of each parameter is calibrated considering observed damages after seismic events. Moreover, after determining the hazard of the territory in terms of the macroseismic intensity scale, it is possible to evaluate the expected damage scenarios of an urbanized area, using semi-empirical methods, based on historical records (Vicente et al., 2011).

$$I_V = \sum p_i \cdot c_i \quad ,where \begin{cases} c_i = score\ of\ the\ parameter\ "i" \\ p_i = weight\ of\ the\ parameter\ "i" \end{cases} \tag{1}$$

The well-known I_v methodologies are developed and calibrated on the base of specific construction typologies: therefore, if masonry aggregates have almost the same structural features, it is possible to evaluate a medium I_V for the entire historical centre; otherwise, additional considerations and modifications are required.

The four methodologies applied to Campi Alto di Norcia are the Ferreira method (Ferreira et al., 2012), the GNTD method (GDNT, 1994), the Formisano method (Formisano et al., 2009) and the Vicente method (Vicente et al., 2011). Storage areas and cellars aren't taken into account for the vulnerability assessments and therefore the number of the total amount of SUs analysed, decrease to 67.

The first method (Ferreira et al., 2012) is relatively simple since requires the definition of only five almost qualitative parameters (i.e. the quality of masonry, the presence of misalignments among openings, the presence of irregularities in elevation, the organization of building plan and the location and soil category), finally assigning a vulnerability index to the whole SA. Four classes are determined for the 'score' assignment (A, B, C and D) of each parameter, to which a specific weight (between 0.50 and 1.50 in relation to importance) is associated (Table 2). No distinction is made among SUs in the reference SA.

Vulnerability Parameter		Class Score				Weight
		A	B	C	D	
P1	Quality of the masonry fabric	0	5	20	50	1.50
P2	Misalignment of openings	0	5	20	50	0.50
P3	Irregularities in height	0	5	20	50	0.75
P4	Plan geometry	0	5	20	50	0.75
P5	Location and soil quality	0	5	20	50	0.75

Table 2. Structure of the Ferreira Method.

The assessment of the historical city centre of Campi Alto di Norcia, performed using the Ferreira method, finally highlights I_V values evaluated according to (1) between 20 and 30 for the 16% of the SAs analysed, between 30 and 40 for the 16% of the SAs, between 40 and 50 for 25% of the SAs and between 50 and 60 for 44% of the SAs. As a general remark, aggregates have a medium predisposition to suffer damage following an earthquake, showing an average a vulnerability of 40 and a Standard Deviation (SD) of 12 (Figure 8).

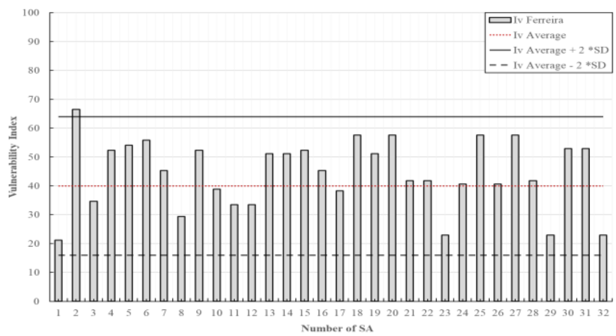

Figure 8. Results of the application of Ferreira method.

The GDNT method adopts 11 different parameters to evaluate the seismic vulnerability of isolated buildings, accounting for the geometry and resistance of structural and no-structural elements, floors and roof typologies, walls' thickness and decay's level (Table 3). The application of the GNDT method to Campi Alto di Norcia evidences an average I_V index equal to 47 and a Standard Deviation (SD) of 14. More in details, achieved values of the I_V – evaluated according to (1)– are between 20 and 30 for the 6% of the SUs analysed and between 30 and 40 for 19% of the SUs. The 43% of the buildings show a vulnerability index distributed between 40-50, 9% are between 50-60, 7% are between 60-70 and 12% are between 70-80. Remaining SUs evidence a seismic vulnerability below 20 (Figure 9).

Vulnerability Parameter		Class Score				Weight
		A	B	C	D	
P1	Organization of vertical structures	0	5	20	45	1.00
P2	Nature of vertical structures	0	5	25	45	0.25

P3	Qualitative resistance	0	5	25	45	1.50
P4	Location of building and type of foundation	0	5	25	45	0.75
P5	Floor Typology	0	5	15	45	1.00
P6	Plan regularity	0	5	25	45	0.50
P7	Height regularity	0	5	25	45	1.00
P8	Distribution of plan resisting elements	0	5	25	45	0.25
P9	Roof Typology	0	15	25	45	1.00
P10	Non - structural elements	0	0	25	45	0.25
P11	Physical conditions	0	5	25	45	1.00

Table 3. Structure of the GDNT II Method.

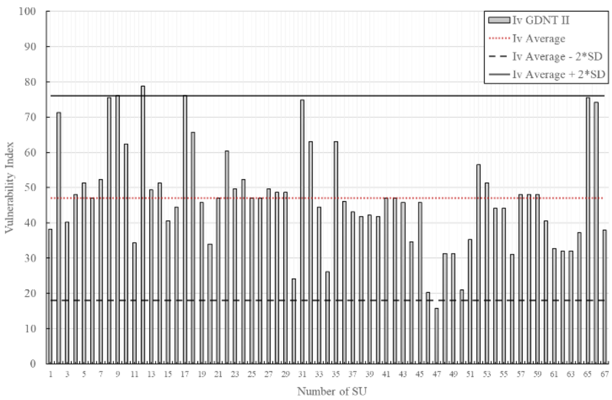

Figure 9. Results of the application of GNDT method.

In order to complete the (GDNT, 1994) procedure, taking into account also the behaviour of the structural aggregate, Formisano et al. (2009) introduces five additional parameters representative of the interaction among buildings, i.e. the position of the SU in the SA, the openings' percentage in walls, the presence of staggered slabs, the structural difference between to close SUs and the interaction of near SUs with different heights. Several additional modifications are also made (Table 4).

Vulnerability Parameter		Class Score A	B	C	D	Weight
P1	Misalignment of openings SU	-20	0	25	45	1.0
P2	Masonry disconnections	-15	-10	0	45	1.2
P3	Presence of adjacent buildings with difference height	-20	0	15	45	1.0
P4	Position of the building in the masonry aggregate	-45	-25	-15	0	1.5
P5	Presence and number of staggered floors	0	15	25	45	0.5

Table 4. Additional parameters of the Formisano method.

Since the Formisano method is developed for SA, the isolated buildings are ignored in the analyses, therefore only the 50 SUs in aggregate are taken into account. Achieved values of the I_V – evaluated according to (1) – are between 0 and 10 for the 13% of the SUs analysed, between 10 and 20 for 44% of the SUs and between 20 and 30 for the 35% of SUs (Figure 10). The 2% of the buildings shows a vulnerability index equally distributed between 30-40 and between 40-50. This method shows a low seismic vulnerability of the masonry aggregates in the historical centre of Campi Alto di Norcia, where the average I_V index is 17, with a Standard Deviation (SD) of 9.

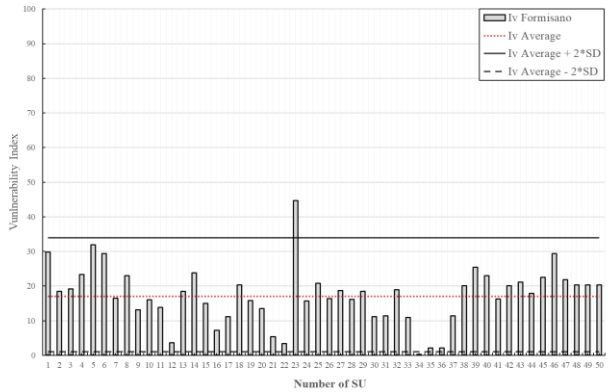

Figure 10. Results of the application of Formisano method.

Finally, the Vicente et al. (2011) method is based on the GNDT II level module, dividing the parameters in four macro-classes and introducing three additional (Table 5).

Vulnerability Parameter		Class Score A	B	C	D	Weight
P1	Type of resisting system	0	5	20	50	0.75
P2	Quality of the resisting system	0	5	20	50	1.00
P3	Conventional strength	0	5	20	50	1.50
P4	Maximum distance between walls	0	5	20	50	0.50
P5	Number of floors	0	5	20	50	1.50
P6	Location of building and type of foundation	0	5	20	50	0.75
P7	Aggregate position and interaction	0	5	20	50	1.50
P8	Plan configuration	0	5	20	50	0.75
P9	Height regularity	0	5	20	50	0.75
P10	Wall façade openings and alignments	0	5	20	50	0.50
P11	Horizontal diaphragms	0	5	20	50	1.00
P12	Roof Typology	0	5	20	50	1.00
P13	Fragilities and conservation state	0	5	20	50	1.00
P14	Non-structural elements	0	5	20	50	0.50

Table 5. Structure of the Vicente Method (Vicente et al., 2011).

The average seismic vulnerability index is 41, with a Standard Deviation (SD) of 11. More in details, the application of the method shows a medium seismic vulnerability of the masonry aggregates in the historic centre of Campi Alto di Norcia, with I_V index in the range 10 – 20 for the 4% of the buildings, and 20 – 30 for the 12% of the buildings, between 30 and 40 for the 30% and between 40 and 50 for 35% of the SUs analysed. Remaining SUs present higher vulnerability indexes (Figure 11).

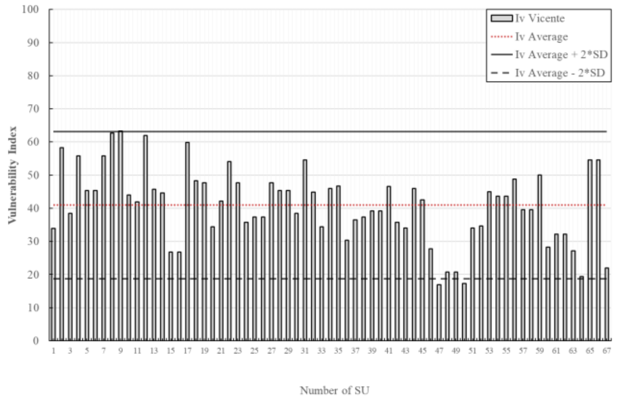

Figure 11. Application of Vicente method, representation of results.

Trying to summarize, the GDNT method shows the highest I_V in comparison to the other approaches, also considering the influence of the aggregates. Regarding the trend of the data, the higher scattering of results is observed for the Vicente method, accounting for different vulnerability indexes for multiple buildings. The results highlight the influence that the weights and scores of the different methods own in the seismic vulnerability assessment: for example, the Formisano method generates low vulnerability values because P4 (i.e. position of the building in the masonry aggregate) and P1 (i.e. percentage of opening areas among adjacent facades) lead to improve the seismic performance of the construction typology of the analyzed case study. Similarly, P7 of the Vicente method (i.e. aggregate position and interaction) reduces the seismic performance of the SUs positioned at the corners, improving otherwise the behavior of SUs inside the aggregates.

4.2. Accuracy of the seismic vulnerability assessment

The accuracy of the selected statistical methods, applied to the considered case study, is then performed comparing the real damage detected during the survey after the 2016 earthquake, with the expected (or theoretical) damage scenario evaluated through the I_V methods. The theoretical damage is defined through formulation proposed by Bernardini (2007), for each building.

$$\mu_T = 2.5 + 3 \cdot \tanh\left(\frac{I + 6.25 \cdot V - 12.7}{Q}\right) \cdot f(V, I) \qquad (2)$$

$$f(V, I) = \begin{cases} e^{\frac{V}{2} \cdot (I-7)} & I \leq 7 \\ 1 & I > 7 \end{cases} \qquad (3)$$

$$V = 0.56 + 0.0064 \cdot I_v \qquad (4)$$

Being V the vulnerability class, I the macroseismic intensity, Q the ductility factor and μ_T the average value of the damage distribution in the EMS-98. According to the post-seismic damage evaluation of irregular brick masonry buildings and on the basis of the studies performed by Sandi et al. (1995), a ductility factor equal to 2.5 is adopted, as suggest for masonry buildings with enough ductile behaviour.

The macroseismic intensity of the 2016 seismic events is evaluated with the MCS scale (Galli et al., 2017). Since the formulation (2) is developed through the EMS-98 scale, it is necessary to equalize the two intensities providing a coherent comparison, using the simple approach proposed by Margottini et al. (1992) (5).

$$I_{EMS-98} = I_{MSK} = 0.734 + 0.814 \cdot I_{MCS} = 7.65 \qquad (5)$$

The relative error of the seismic vulnerability assessment is considered as the difference between the theoretical and the real damage. In this sense, the I_v method accuracy is evaluated as the mean relative error of the historical centre analysed.

Vulnerability evaluations are affected by an uncertainty associated to the classification of the exposed building stock into a vulnerability class or into a building typology, and by the uncertainty associated with the attribution of a characteristic behaviour to the vulnerability class or building typology (Spence et al., 2003). To overcome these issues and to control the accuracy of the I_v method, the seismic vulnerability of each building is evaluated also in a range, considering the assessment of the entire case study. According to an accurate statistical interpretation of the results, upper and lower bounds of the vulnerability index are defined for each SU, considering the standard deviation of the vulnerability assessment of the historical centre. Using the formulation (2) is possible to obtain the plausible and possible area of the expected damage.

The statistical method accuracy can be then evaluated as the minimum relative error, considering the theoretical damage scenario defined with the reduced I_V and with the increased I_V. A range of variation of the initial level of expected damage can be then established to perform the parametric study of the seismic vulnerability of this construction typology and evaluate the weight influence of the I_V methods in the seismic response of the buildings. This procedure allows to compare the real damage with a range of possible damages, keeping in mind the global behaviour of all buildings and overcoming the limits deriving from the knowledge of the single building. The accuracy of the I_V method is assessed not only at the individual building level but also at the global level according to (6).

$$I_v \text{ method Accuracy} = \begin{cases} \overline{Err_{Range\ measure}} = \left(\frac{\sum min[|Err_{-}; Err_{+}|]}{n}\right) \\ \overline{Err_{Direct\ measure}} = \left(\frac{\sum Err_{mean}}{n}\right) \end{cases} \qquad (6)$$

The procedure applied to the case study of Campi Alto di Norcia, considering the vulnerability range for each building, is summarized in Figure 12.

The procedure is applied for each I_V method, comparing finally the results obtained, checking which method shows the minimum relative error for the case study.

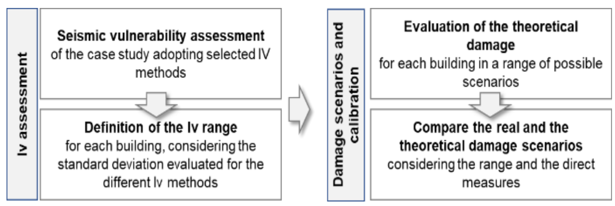

Figure 12. Procedure used in accuracy evaluation of vulnerability assessment methods.

Table 6 shows the average relative error of the theoretical damage with respect to the real damage detect for the different statistical methods employed. As visible, the adopted methods are unable to assess the real damage scenario of the selected case study after the 2016 earthquake. The difference between real and theoretical damage, evaluated for each building, is higher than 0.85 for all methods. Considering a probable theoretical damage range, the relative errors decrease anyway remaining higher than 0.58 for all the methods.

This analysis highlights the lower accuracy of these methods, used in different case studies than those for which they are calibrated. At the same time, the vulnerability assessment for each building is established by considering a range of possible values of the I_v index, rather than a single value, to avoid the uncertainties related to the building survey.

To check if the relative error is caused by an *overestimation* or *underestimation* of the real damage scenario, the damage distribution in the case study is analysed. Considering the mean value of the I_v range for each masonry building in the analysed SA, the comparison of the different methods in a local and urban scale becomes possible.

I_v Methods accuracy (direct measure)		
I_v Methods	Average relative errors	Variance relative errors
Formisano	1.13	0.72
Ferreira	0.92	0.78
GDNT II	0.87	0.67
Vicente	0.85	0.61
Iv Methods accuracy (range measure)		
Iv Methods	Average relative errors	Variance relative errors
Formisano	0.73	0.55
Ferreira	0.72	0.35
GDNT II	0.67	0.37
Vicente	0.58	0.34

Table 6. Evaluation of the Iv method accuracy in the case study.

Figure 13 shows the comparison between the theoretical and real damage distribution in Campi Alto di Norcia: the comparison is carried out locally, evaluating for each SU the distance between the real and expected damage, and at urban scale evaluating the differences between the various damage averages. As visible, while real damage shows very scattered values, the estimated damage evidence a distribution concentrated around average values. This aspect highlights a limitation of the formulation (2) in estimating high or low damage classes for different vulnerability values.

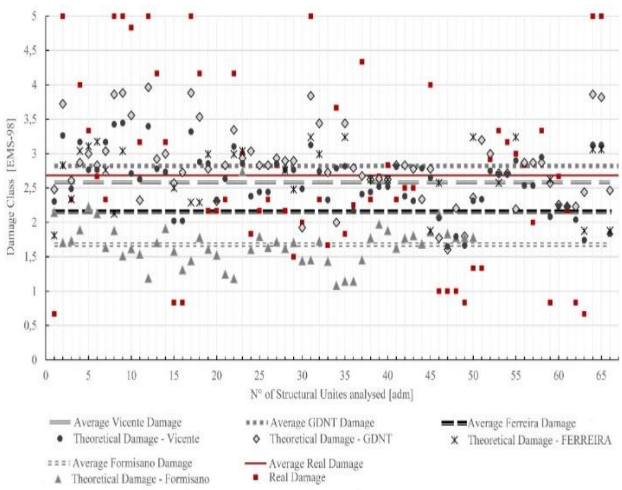

Figure 13. Comparison between the Real Damage detected in the case study and the Theoretical Damage evaluated through different vulnerability methodologies for each SU.

The Formisano method, defining a low seismic vulnerability for the SAs of the case study, underestimates the possible damage in comparison with the one detected after the 2016 earthquake. The Ferreira method, similarly, results in average a lower damage class in respect to the real one. The median value of the real damage is found between the GDNT and the Vicente method, showing that the latter one better explains the aggregate effect for the considered case study, reducing not too much the seismic vulnerability. Considering the average vulnerability values obtained for the different approaches and changing the macroseismic intensity, it is possible to develop various damage scenarios following formulation (2). The vulnerability curves (Figure 14) show the tendency of these methods to overestimate or underestimate the real possible damage even for different macroseismic intensities

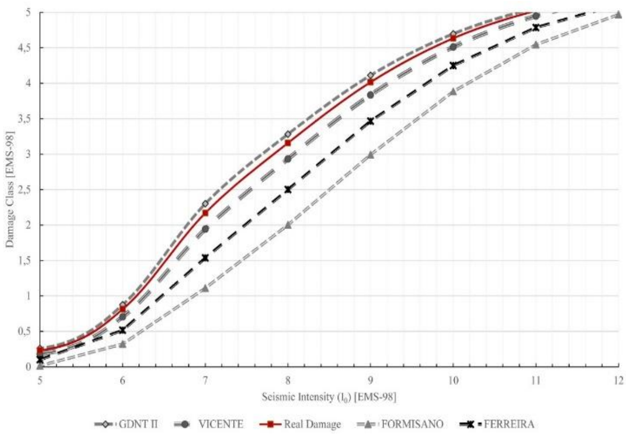

Figure 14. Vulnerability curves for different seismic intensities using the IV methods selected.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The seismic vulnerability assessment methods based on statistical evaluations and damages' observation are suitable for urban scale analysis because with less information and fewer resources provide a first screening on the fragility degree of the cultural heritage towards seismic events.

In the present work, vulnerability index methods are employed checking their accuracy in the damage scenario estimation of a case study, stroke by the recent 2016 Central Italy earthquake.

Before starting with IV methods application, a deep in-situ survey of Campi Alto di Norcia is performed, with the aim of developing a good knowledge of the considered building heritage. The survey aims to recognize different SAs and SUs and, besides, main construction techniques, structural typologies of storeys and roofs, masonry properties, recent and past retrofit interventions, etc.

The results coming from the application of the different Iv methods show the main issues of the methods themselves, linked to the definition of a single value for the vulnerability evaluation, increasing the relative error between the real and expected damage, strongly dependant on the quality of the information concerning building features (Ferreira et al., 2013). This problem highlights the need of the development of an enhanced methodology restricting the variability of results and well defining – for example – additional parameters to account for with the aim of achieving good agreement with expected damage and observed one.

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REFERENCES

Baggio, C., Bernardini, A., Colozza, R., Corazza, L., Della Bella, M., Di Pasquale, G., Dolce, M., Goretti, A., Martinelli, A., Orsini, G., Papa, F., Zuccaro, G., 2007. *Field Manual for post-eartquake damage and safety assessment and short term countermeasures (AEDES)*. JRC Scientific and Technical Reports - European Commission.

Barbat, A.H., Pujades, L.G., Lantada, N., Moreno, R., 2008. *Seismic damage evaluation in urban areas using a capacity spectrum based method: application to Barcelona*. Soil Dyn Earthq Eng, 28(10–11):851–865.

Benedetti, D., Petrini, B., 1984. *A Method for Evaluating the Seismic Vulnerability of Masonry Buildings*. L'industria delle Costruzioni, 66–74.

Bernardini, A., 2007. *Vulnerabilità e Previsione di Danno a Scala Territoriale*. XII Conference Italian National Association - ANIDIS. Genova.

Bernardini, A..2000. *The vulnerability of buildings—evaluation on the national scale of the seismic vulnerability of ordinary buildings*. CNR-GNDT, Rome.

Bianchi, A.., Accardo, G., 1998. *Primo repertorio dei centri storici in Umbria: il terremoto del 26 settembre 1997*. Rome, Italy.

C.M. n.7., 2019. *Istruzioni per l'applicazione dell'«Aggiornamento delle "Norme tecniche per le costruzioni"» di cui al decreto ministeriale 17 gennaio 2018*." di cui al d.m. 21/01/2019. g.u. n. 35 del 11/02/2019 (in italian). Ministero delle Infrastrutture e dei Trasporti, Roma.

Caprili S., Mangini F., Mussini N., Salvatore W., 2016. *Palazzo la Sapienza in pisa: Structural assessment and retrofit of an historical masonry building in Italy.* ECCOMAS Congress 2016, Crete Island, Greece, 5–10 June 2016.

Cardani, G., 2003. *La vulnerabilità sismica dei centri storici: il caso di Campi Alto di Norcia*. Rom: PHD Thesis.

Cherubini, A., Corazza, L., Di Pasquale, G., Dolce, M., Martinelli, A., Petrini, V, 1999. *Censimento di vulnerabilità degli edifici pubblici, strategici e speciali nelle regioni Abruzzo, Basilicata* - Cap.4. Roma: Risultati del Progetto. Dipartimento della Protezione Civile.

D'Ayala, D., Spence, R., Oliveira, C., Pomonis, A., 1997. *Earthquake Loss Estimation for Europe's Historic Town Centers*. Earthquake Spectra, 13(4), 773–793. doi.org/10.1193/1.1585980.

Ferreira, T.M., Maio, R., Costa, A., Vicente, R., 2012. *Vulnerability assessment of building aggregates: A macroseismic approach*. 15 WCEE. Lisboa.

Ferreira, T.M., Maio, R., Vicente, R., 2017. *Seismic vulnerability assessment of the old city centre of Horta, Azores: calibration and application of a seismic vulnerability index method*. Bull Earthquake Eng (2017), 15:2879-2899.

Ferreira, T.M., Vicente, R., Mendes da Silva,J a. R, et al., 2013. *Seismic Vulnerability Assessment of Historical Urban Centres: Case Study of the Old City Centre in Seixal, Portugal*. Bull Earthquake Eng (2013) 11:1753–1773 DOI.

Formisano, A., Florio, G., Landolfo, R., Mazzolani, F.M., 2009. *Un metodo per la valutazione su larga scala della vulnerabilità sismica degli aggregati storici*. XIII Congresso ANIDIS "L'ingegneria sismica in Italia". Bologna.

Galli, P., Castenetto, S., Peronace, E., 2017. *Rapporto sugli effetti macrosismici del terremoto del 30 ottobre 2016 (Monti Sibillini) in scala MCS*. Roma: Rapporto congiunto DPC-CNR-IGAG.

GDNT, (Gruppo Nazionale per la Difesa dai Terromoti), 1994. *Manuale per il rilevamento della vulnerabilità sismica degli edifici*. Rome, Italy.

Giovinazzi, S., Lagomarsino, S., 2004. *A Macroseismic method for the vulnerability assessment of buildings*. 13Th Word Conference on earthquake engineering. Vancouver (Canada).

Giuffrè, A., 1993. *Sicurezza e conservazione dei centri storici. Il caso di Ortigia*. Roma: Editore Laterza.

Grünthal. 1998. *European Macroseismic Scale 1998 (EMS-98).*European Seismological Commission. Working Group Macroseismic Scales, 15:101.

Lagomarsino, S., Giovinazzi, S., Bernardini, A., et al., 2007. *Vulnerabilità e Previsione di Danno a Scala Territoriale*. XII Conference Italian National Association - ANIDIS. Genova.

Margottini, C., Molin, D., Narcisi, B., Serva, L., 1992. *Intensity versus ground motion: a new approach using Italian data*. Eng Geolog, 33: 45-48.

Martines, R. 2011. *Responsabilità nella conservazione del costruito storico*. Roma: Gangemini Editore.

MIBACT, 2010. *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme tecniche per le costruzioni (D.M. 14/01/2008).* Ministero per i beni e le attività culturali e per il turismo, Roma.

Ortega, H., Vasconcelos, G., Rodrigues, H., Correia, M., 2018. *Seismic vulnerability assessment method for vernacular architecture*. 16th European Conference of Earthquake Engineering. Thessaloniki.

Sandi, H., Floricel, I., 1995. *Analysis of the seismic risk affecting the existing IX building stock*. Proceedings of the 10th European Conference on eartquake engineering, (pp. pp 1105-1110).

Spence, R., Bommer, J., Del Re D., Bird, J., Aydinoglu, N., Tabuchi, S., 2003. *Comparison Loss Estimation with Observed Damage: A study of the 1999 Kocaceli Earthquake in Turkey*. Bulletin of Earthquake Engineering, Vol. 1, pp: 83-113.

Vicente, R., Lagomarsino, S., Varum, H., Silva, R.M., 2011. *Seismic vulnerability and risk assessment: Case study of the historic city centre of Coimbra, Portugal*. Bulletin of earthquake Bull Earthquake Eng (2011) 9:1067–1096 DOI.