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THE LIMIT ANALYSIS OF MACRO-ELEMENTS IN MASONRY AGGREGATE BUILDINGS AS A METHODOLOGY FOR THE SEISMIC VULNERABILITY STUDY: AN APPLICATION TO UMBRIAN CITY CENTERS.

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ABSTRACT
The results of an automatic procedure developed at the University of Padova and based on numerical models calculating the accelerations which activate local collapse mechanisms of macro-elements that can develop in historical masonry buildings, are presented: the Vulnus methodology, based on the fuzzy set theory, provides global vulnerability assessments of individual structural units or groups of buildings, as well as fragility curves related to the achievement or overcoming of the limit state of heavy damage. Moreover, Vulnus is able to identify the vulnerability class for each structural unit, as defined by the European Macroseismic Scale EMS98. The EMS98 scale separates the definitions of building typologies from the corresponding vulnerability class and thus from the expected behaviour in case of seismic event: in this way, it provides a common framework for the evaluation of seismic vulnerability and the estimation of the damage of buildings on a large scale.
Analytical applications for buildings sampled in two historic centres in Umbria located in seismic area (Campi Alto di Norcia and Castelluccio di Norcia) characterized by various building typologies and different levels of aggregation of the buildings are presented.

KEYWORDS: masonry structures, seismic vulnerability, vulnerability classes, EMS98 macroseismic scale, limit analysis of macro-elements, Vulnus, aggregate buildings

INTRODUCTION
The empirical observation of the damages caused to buildings by earthquakes of medium or high intensity highlighted that buildings subject to the same seismic excitation show radically different behaviour, related to their typology, construction rules, used materials and maintenance level. In case of complex buildings, that are the result of subsequent changes, the analyses of the

historic centres need a proper structural modelling: this is necessary in order to appraise the specific vulnerability of complex buildings, due to their typical historical evolution (constructive sequence, damages, previous interventions, etc.).

Since the 80s in Italy, empirical evaluations, by the so called "vulnerability indexes" (particularly for masonry buildings [1]), have been proposed, based on weighted sums of vulnerability factors, related both to structural irregularity aspects recorded by rapid systematic or sample surveys and to the actual calculations of the resistance to horizontal actions of the masonry walls. The aim was to compare the vulnerability of different buildings (and thus the priorities for strengthening operations), and to provide damage scenarios for different seismic intensities.

The available structural analysis methods for masonry buildings subjected to static and dynamic actions are reflected in codes: their application is allowed both for the design of new buildings and for the analysis of existing ones. Through these methodologies, transferred in easily accessible automatic procedures, it is possible to achieve fragility curves of buildings: these curves represent the state of damage, or the likelihood of damage, on the basis of objective measures of the seismic shaking, e.g. peak acceleration of ground motion (PGA).

Within these methodologies and with specific reference to historic masonry buildings, some procedures have been proposed: they are based on the identification of the values of horizontal static-equivalent forces (and therefore of the values of the masses accelerations) that can activate specific mechanisms of local failure / overturning of structural macro-elements (composed by single walls or subassemblages, as intersecting walls, walls and floors or roof, etc.) in-plane and, especially, out-of-plane. In these buildings, in fact, the absence of systematic connections between intersecting walls and between walls and horizontal structures may cause kinematic mechanisms related to the loss of equilibrium of structural portions rather than to states of stress exceeding the materials ultimate capacity [2]; this limit analysis approach depends on few geometric and mechanical parameters and therefore it does not require an extremely accurate survey and time-consuming computation. Moreover, these calculation models process the inevitable uncertainty of the prediction by the use of appropriate numerical techniques that take into account the lack of sufficient information in calibrating probabilistic methods (this problem makes often illusory the precision of complex linear or nonlinear behavioural models) [3].

In the last years, the authors have studied and proposed methodologies for the assessment of the seismic vulnerability of buildings based on the limit analysis. The paper discusses the main results of the application of one of these procedures to historic centres (Campi Alto di Norcia and Castelluccio di Norcia, in the province of Perugia - Umbria region) differently damaged and located in sites in current hazardous conditions; they are characterized by different building typologies: row buildings in Campi and complex buildings in Castelluccio.

STRUCTURAL MODELS

Lessons learned from recent earthquakes in Italy and in particular from the 1997 Umbria-Marche seismic event allowed to deepen the knowledge of the behavioural peculiarities of existing masonry buildings, in order to develop a general framework of vulnerability and forecasting, especially for “minor” centres and buildings typologies.

Common buildings in historic centres were often built following a traditional “code of practice” and according to typologies (multi-material masonry, multi-leaf walls) and constructive details (in particular poor connections) which, in some cases, can show important deficiencies for the safety under seismic actions [4].

Under these conditions, the ultimate capacity of the building depends on the stability of its macro-elements. Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond (potential damage pattern, cracks, borders of poor connections, etc.) and restraints (e.g. the presence of ties or ring beams), the constructive deficiencies and the characteristics of the constitutive materials. They behave independently as a whole without any support by other portions of the building, but they follow kinematic mechanisms, both out- and in-plane. Thus they are elements in hazardous conditions for possible incipient brittle collapse [2].
Out-of-plane mechanisms, also called "first-way" collapses, involve walls subjected to horizontal actions orthogonal to their plane. Their overturning is the main result, which is counteracted by the possible presence of connection elements (ties, ring beams) or intrinsic resisting effects (e.g. arch effect of the wall in its thickness). The proposed analysis method is based on equilibrium equations which can take into account also the strength of the materials (as well crushing of masonry, tension in the tie, etc.).
In-plane mechanisms relate to walls parallel to the seismic action. They are also named "second-way mechanisms", because the relative damage (shear cracks), generally does not lead the structure to collapse, in comparison with the out-of-plane mechanisms. Kinematics chains describe the in-plane rigid rotation of the resisting structural portions of the building, defined by particular geometrical (dimensions of septa, openings) and bond conditions (connections, presence of ties), subjected to in-plane horizontal actions.
Once the critical structural configuration is defined, the subsequent step is the identification of the most probable collapse mechanisms of each macro-element. The studies based on in-situ surveys after seismic events allowed to create collections (called abaci) of the typical damages occurring in constructive typologies (buildings, churches), which led to a systematization of the mechanical models able to describe their behaviour by kinematic models [5].
Kinematic models provide a coefficient $c = a/g$ (where a is the ground acceleration and g the gravity acceleration), which represents the seismic masses multiplier characterizing the limit of the equilibrium conditions for the considered element. In simplified assessment procedures, the mechanism connected to the lowest value of c is the weakest one and, consequently, the most probable to occur: in-plane mechanisms are characterized by c coefficients higher than the out-of-plane ones [2].
This approach of limit analysis applied to existing masonry buildings in seismic areas is now provided by the updated Italian seismic code [6, 7, 8], which finally takes into account the high vulnerability of existing masonry buildings not satisfying assumptions commonly more suitable for new earthquake-proof structures. In this field, another important document is represented by the Guidelines for the evaluation and mitigation of seismic risk of the architectural heritage [9].

A PROCEDURE FOR THE VULNERABILTY ASSESSMENT

An automatic procedure for the vulnerability assessment, set up at the University of Padova in the last decade and based on the limit analysis of macro-elements in masonry buildings, has been recently implemented in Visual Basic and updated according to the new requirements of the Italian seismic codes.
Vulnus [10] is a procedure for global vulnerability assessment of masonry buildings with sufficient regularity (in plane and in elevation) and limited height, both isolated and grouped in complex nuclei of interacting constructions. Processing the data obtained from the survey of selected buildings, the methodology is able to combine different mechanisms, by evaluating the

ratio between the critical value of the mean seismic acceleration response, corresponding to the in-plane resistance of the wall systems (I1 index) and to the out-of-plane mechanisms activation limit of each wall restrained by the floor slabs and transverse walls (I2 index), and the acceleration of gravity *g*. The local acceleration at the level of the different floors is estimated assuming a distribution proportional to the height. Once the seismic hazard of the zone is known, it is possible to execute preliminary safety assessments of the buildings in seismic conditions, according to codes prescriptions.

Moreover, the two coefficients I1 and I2 are combined together with another vulnerability index (I3), giving further qualitative information on buildings and soil characteristics: this index is obtained from the data collected by a detailed survey form (G.N.D.T. 2nd level survey form for the vulnerability evaluation of masonry buildings). This is performed through a knowledge based fuzzy vulnerability model [3], in order to get a linguistic judgement on the probability of heavy damage of the single building or of a selected group of buildings: five different levels are proposed (probability “0 -very small”, “1 -small”, “2 -average”, “3 -high”, “4 -very high”). In the end, it is possible to get the expected values of heavy damage, through the computation of vulnerability curves for the single building or for a group of buildings, and to compare these results with the curves related to the macroseismic intensity scale EMS98 [11]: Vulnus in fact permits, through a pattern recognition procedure, to select for each building the EMS98 vulnerability class that better fit with the fragility (probability of exceeding a fixed damage level) of the building.

Figure 1-a clarifies the concept of vulnerability class, according to the EMS98 macroseismic scale: it is possible to see that buildings of the same type (such as masonry buildings) may belong to different vulnerability classes (especially A, B and C vulnerability classes), although in each case a frequent central class is identified. In fact, the belonging of a building or of a group of buildings to a vulnerability class depends on the relative frequency of the levels of damage occurrence (the scale defines six levels from level 1 *negligible damage* to level 5 *destruction* - Figure 1-b), varying the macroseismic intensity degrees (from fifth degree, when damages to the more vulnerable buildings appear, to twelfth degree).

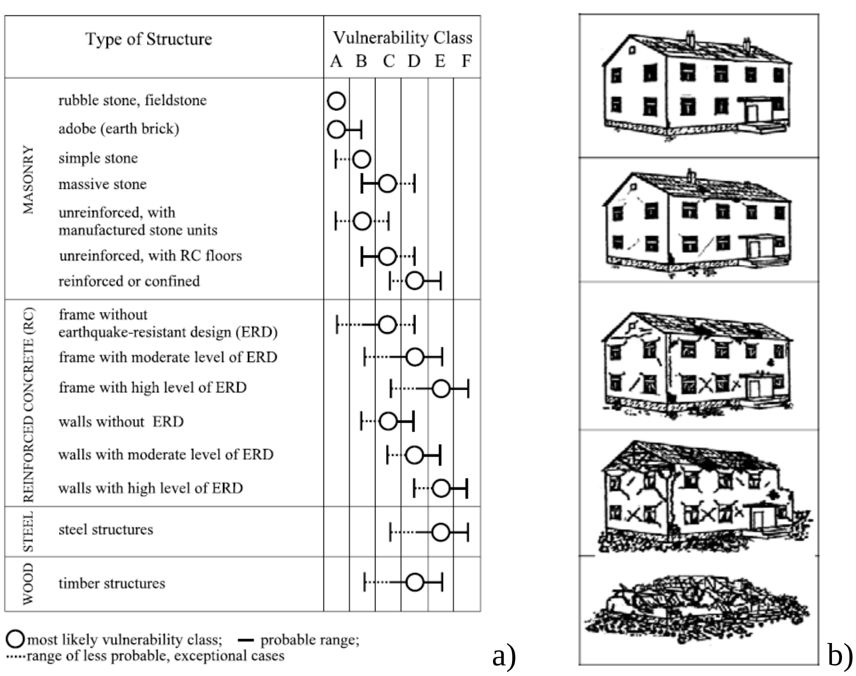


Figure 1:
a) Distribution of building types in the more reliable, possible and exceptional vulnerability classes according with the EMS98 scale;
b) Classification of damage (5 degrees: D1: Negligible; D2: Moderate; D3: Substantial to heavy; D4: Very heavy damage; D5: Destruction) according with the EMS98 scale [11].

Applications of the procedure on different building typologies are compared in the following section for the two above mentioned centres (Campi Alto di Norcia and Castelluccio di Norcia).
A reliable investigation methodology was applied on these centres: it is based on the on-site survey of a significant sample of buildings using specific forms, the collection of data on interventions, damage mechanisms, etc. and a minimum number of laboratory and on-site (non-destructive and minor destructive) tests, realized in order to characterize the texture, the structure and the materials of the investigated walls [12]. This general methodology allowed to gather all the data requested by the Vulnus procedure.

THE HISTORICAL CENTRES OF CAMPI ALTO DI NORCIA AND CASTELLUCCIO DI NORCIA

Throughout the Norcia territory the most frequent housing typology consists in buildings with two or more floors, built according to a simple technique with stone masonry walls and wooden floors and roofs. The different ways in which the house can aggregate is the only factor determining the different building typologies: single or double row buildings, simple or complex blocks.
Campi Alto di Norcia is a medieval centre (it dates back to 1288) on a mountainside, at an altitude of about 900 m, with houses arranged in a series of terraces surrounded by concentric streets linked by short radial ramps (Figure 2). Campi still looks like a castle: the town walls have collapsed, but the entry arch and a tower still exist. The building characteristics of the town show, despite the damages caused by time and earthquakes, the importance of the castle of Campi.
As a result of the difference in height of the side where Campi Alto is located (over 100 meters from the base to the top of the village), the buildings follow the natural evolution of the contour of the land and develop in rows, generally on three levels: one with access from the lower street (for stalls, warehouses or cellars), an intermediate one and the last accessible from the upper road (for housing). The lower floor is in many cases partially excavated in the natural rock and extends below the upper road, with different depths. These rooms are usually vaulted with stone barrel vaults, usually separated from the façade, that, despite the numerous seismic events, are still well preserved, even in partially collapsed buildings [13].

Figure 2: View of the historical centre of Campi Alto di Norcia.

Figure 3: View of the historical centre of Castelluccio di Norcia.

Castelluccio di Norcia is located on the top of a hill (1453 m) and dates back to 1276. The topographic structure of the town is conditioned by the soil orography. The main streets develop concentrically to the top of the hill and divide the town into four terraces. The main streets, which in the upper part of the centre are nearly flat, are connected through short and narrow radial ramps, that present high slope.

The houses are positioned on the south slope, while the north slope is desert, for the adverse weather and topography conditions (Figure 3). There is no isolated house, apart from two recently constructed buildings. The town is all organized within a very compact housing configuration, and the most spread building typology is represented by complex aggregates. The urban development of the centre followed two stages: the first was centralized around the Cassero, the top of the hill, and maintains the plant layout and the road grid, the second developed towards the foot of the hill, where buildings used as stables are present. It is worth noticing that for aggregate buildings, the study of the seismic behaviour is much more complex and generally less clear than for more regular buildings [14].

The Appenini mountains, especially in the Umbria and Marche Regions, present a high and widespread seismic activity: among the major seismic events of the past 1703, 1730, 1859 and 1979 are relevant. The maximum macroseismic intensity historically detected at Campi Alto has been 9 (1730 earthquake); in Castelluccio the maximum intensity was 7 (1979 earthquake) [15]. Using the equation proposed by Guagenti and Petrini [16] it is possible to get the values of a/g (at the site) corresponding to those values of intensity: for Campi it is possible to assume a/g = 0.19, for Castelluccio a/g = 0.06.

The seismic hazard values have been calculated by the National Institute of Geophysics and Volcanology on a grid of points that covers, with steps of 0.02 degrees, the entire national territory, indicating for each point the reference values of the maximum peak ground horizontal acceleration on rigid ground a_g: [17]: considering the codes, fixed the exceedance probability (10% in 50 years - the limit state of preservation of life), the return period (475 years), the foundation ground type (A - very rigid homogeneous soils), the topographic factor (S_T = 1.2) and chosen the value for the behaviour factor (q = 2.25), for the considered buildings a value of a/g = 0.32 is obtained (seismic intensity 10 according to Guagenti and Petrini).

Twelve row buildings in the historical centre of Campi (identified as Row 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 - Figure 4) and ten aggregates of the historic centre of Castelluccio (identified as ISO 1, 5, 10, 11, 13, 17, 19, 20, 21 and 39 - Figure 5) were considered.

ANALYSIS OF THE VULNUS RESULTS

As pointed out by the codes for the analysis of aggregate buildings, it is essential to determine the Structural Units (US), identifying the spatial connections, juxtapositions and overlaps and taking into account that these portions of aggregate must have a unitary structural behaviour under static and dynamic loads. Even in the application of the Vulnus methodology, it is necessary to simplify the structural aggregates subdividing them in different structural parts which have uniform height and volume. It is therefore possible to identify 50 units to be analyzed in Campi and 66 in Castelluccio.

Regarding the results obtained with Vulnus, according to the analysis of the in-plane and out-of-plane resistance, the index I1 is higher than I2 for most of the buildings: this confirms the greater vulnerability of the masonry walls of historical buildings towards out-of-plane mechanisms, rather than towards in-plane damage mechanisms. Moreover, the highest values of the indexes are for buildings belonging to strengthened units, or placed inside the blocks (not in a tip position in the aggregate).

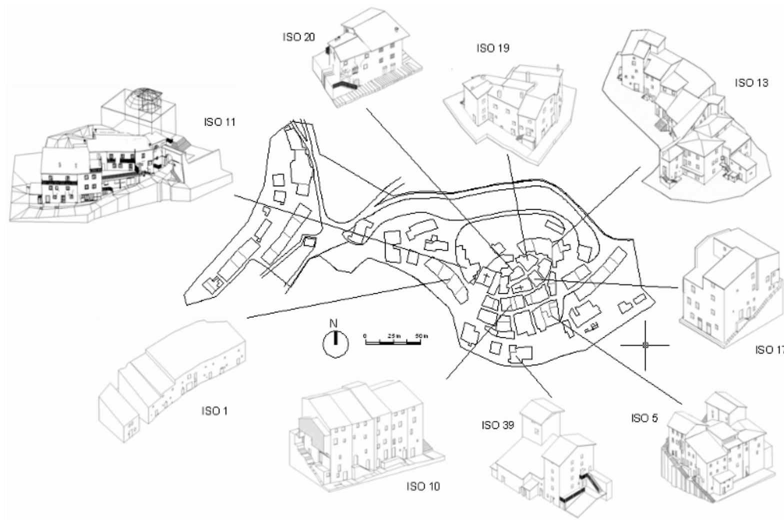
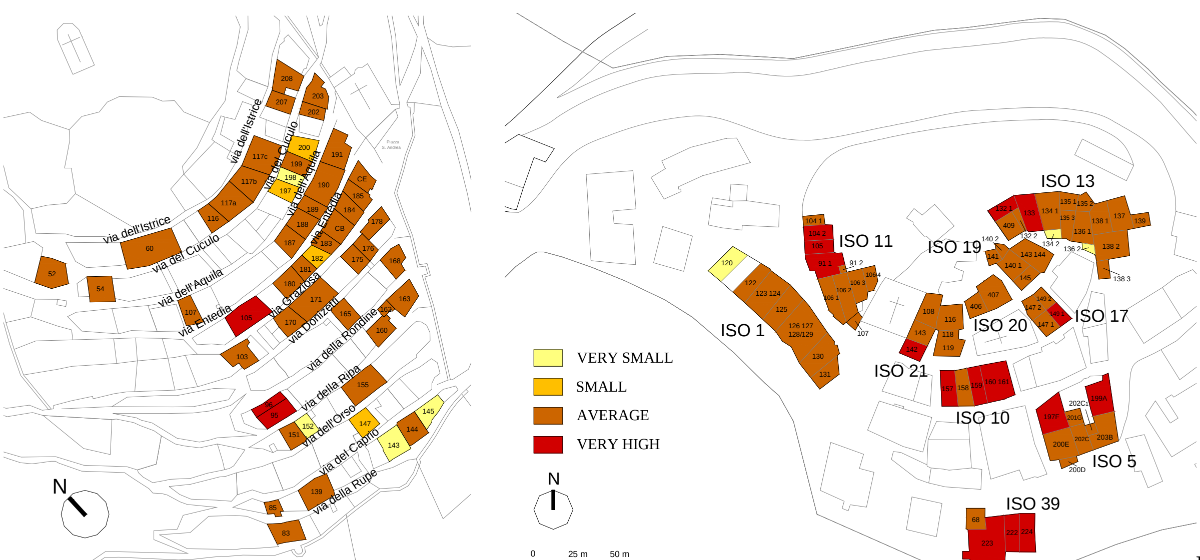


Figure 4: Analysed buildings in the historical centre of Campi.

Figure 5: Analysed buildings in the historical centre of Castelluccio.

Figure 6 shows a graphical representation obtained from the linguistic vulnerability assessments given by the program for the individual units, in which the aggregates were divided, and for the reference value a/g = 0.32: the vulnerability of the buildings in Campi is, in most cases, Average [12]; in Castelluccio the vulnerability is in more than half the units, Very High, while the other buildings show an Average vulnerability [18].



a) b)

Figure 6: Linguistic vulnerability judgments given by Vulnus for the individual units in Campi Alto (a) and Castelluccio (b) for the reference value a/g = 0.32.

In addition to the assessment of vulnerability carried out for the individual units in which the aggregates were divided (Vu), the procedure is able to perform an analysis referred to the group of buildings (Vg). According to the linguistic judgement of Vulnus, the vulnerability degree of the entire group of buildings is Average in Campi and High in Castelluccio.
Through the Vulnus methodology it is also possible to assess the vulnerability of the groups of buildings through fragility curves (Figure 7), comparing three curves, in order to estimate the expected value of the frequency of Heavy damage E[Vg] for the different values of PGA/*g* (central values) and the uncertainty related to this value (the lower and upper limits). Referring to PGA/*g* = 0.32, it is possible to obtain for Campi a value of E[Vg] = 0.4 with a high uncertainty on these values, while for Castelluccio is E[Vg] = 0.65. Considering the historical earthquakes, for Campi (PGA/*g* = 0.19) is E[Vg] = 0.15 and for Castelluccio (PGA/*g* = 0.06) is E[Vg] < 0.1, although the reliability of this historical value is low.

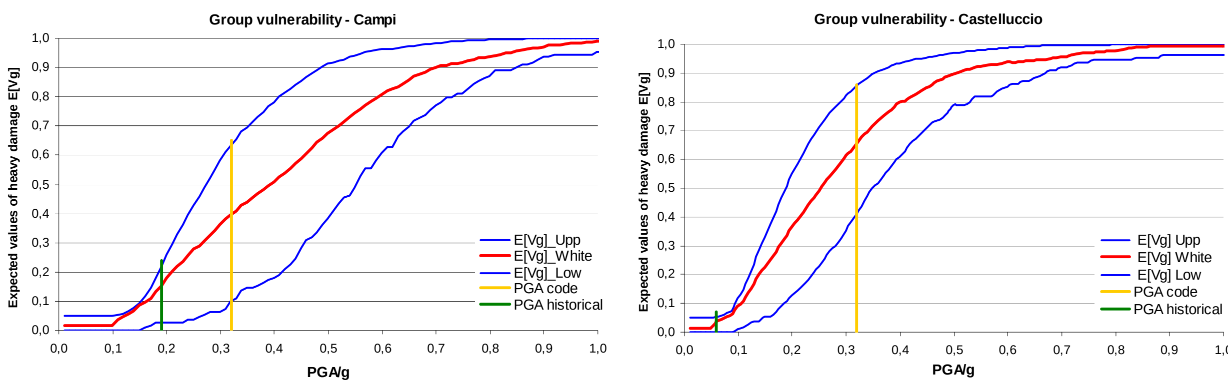


Figure 7: Vulnerability curves obtained with Vulnus for the entire group of aggregates in Campi Alto and Castelluccio.

Using a pattern recognition procedure it is possible to select for each considered unit the EMS98 vulnerability class that better describes the fragility of the unit. According to this criterion, it results that for Campi 1 unit of the sample are classified into B class and 49 in C class; for Castelluccio 18 units of the sample are classified into B class and 48 in C class.

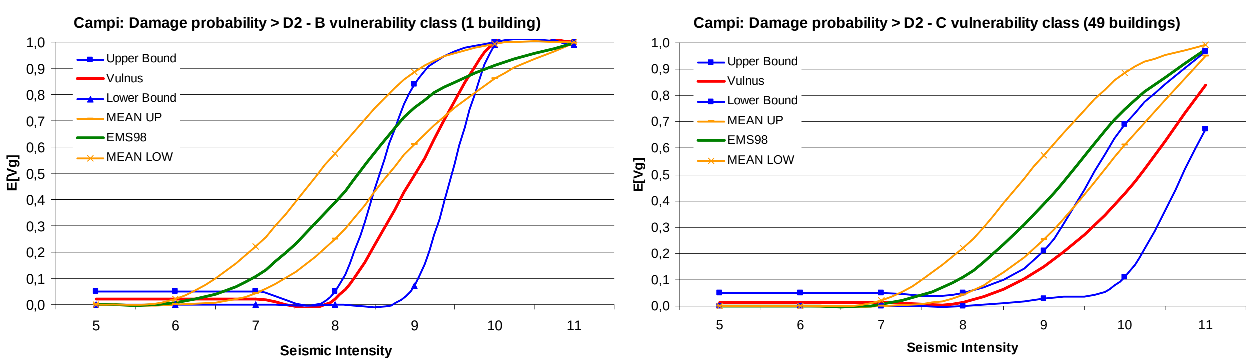


Figure 8: Comparison of the fragility curves for damage >D2 for the homogeneous groups of buildings in B and C vulnerability class within the sample of 12 row masonry buildings surveyed in the historical centre of Campi Alto di Norcia (PG), with the corresponding values implicit in the EMS98 scale definition.

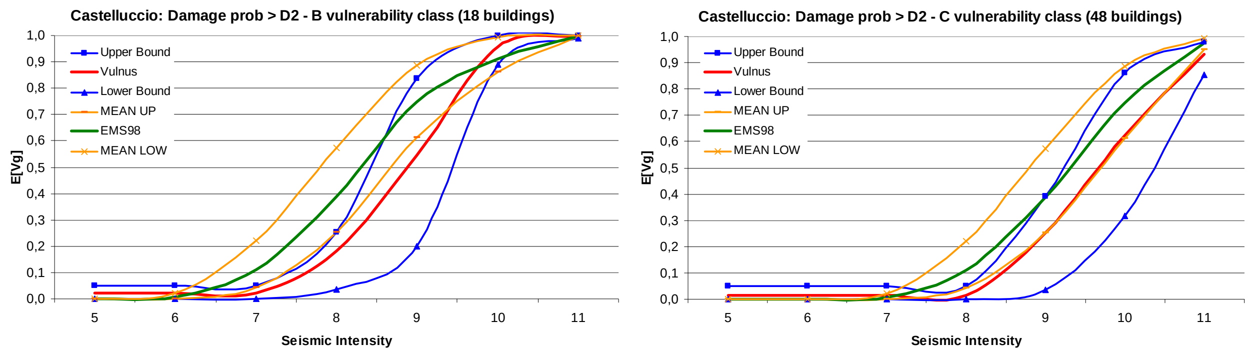


Figure 9: Comparison of the fragility curves for damage >D2 for the homogeneous groups of buildings in B and C vulnerability class within the sample of 10 masonry aggregates surveyed in the historical centre of Castelluccio di Norcia (PG), with the corresponding values implicit in the EMS98 scale definition.

Figure 10 and Figure 11 show, separately for the 3 homogeneous groups in which the sample can be divided according to the EMS98, the comparisons between the fragility curves related to damage >D2 calculated by Vulnus and the similar values implicit in the EMS98 scale definition, essentially based on statistical information of observed damage due to earthquakes that hit different areas. It is possible to observe a reduction of uncertainty considering rather homogeneous samples.

CONCLUSIONS

Despite the approximations made by the developed calculation method, based on the analysis of the collapse mechanisms of structural macro-elements, the results obtained with the Vulnus automatic procedure are reliable, especially for more complex typologies. In fact, as expected, the considered historical centres, characterized by different levels of aggregation, show a different vulnerability and safety level. In Castelluccio di Norcia the number of units classified with Vulnus in the B EMS98 vulnerability class is relevant (about 30%): these elements confirm a highly fragile seismic behaviour of very complex aggregates, especially if compared with the results obtained for less complex typologies, as the row buildings of Campi Alto di Norcia.

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