Vulnerability assessment of the historical masonry building typologies of Vittorio Veneto (NE Italy)

A. Bernardini[1], M.R. Valluzzi[1], C. Modena[1], D. D'Ayala[2] and E. Speranza[2]

[1] *Dipartimento Costruzioni e Trasporti, Università di Padova, Italy*
[2] *Department of Architecture and Civil Engineering, University of Bath, U.K.*

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ABSTRACT The vulnerability assessment of the different buildings identified in the historical centre of Vittorio Veneto (NE Italy) is here proposed. The preliminary classification of the masonry building typologies allowed us to identify the main, typical characteristics affecting the seismic vulnerability of existing structures. The analysis is performed at a global level for the whole centre and then focused on the oldest and most vulnerable part, namely Serravalle. Two procedures, developed at the University of Padova and the University of Bath, both based on the macro-modelling approach, have been used. The prediction of damage scenarios obtained through fragility curves calibrated on the EMS98 damage classification and on the parameters obtained by the AeDES survey form, is also discussed.

1. Introduction

Existing buildings in seismic areas are often characterized by specific vulnerabilities, mainly due to both intrinsic deficiencies and to the concomitance with several modifications occurring over time. They can be summarized as follows:

i) the use of poor constitutive materials (different types of masonry, presence of voids, etc.);
ii) the lack of collaboration both at local (irregular textures, multi-leaf sections with low or null interlocking) and global level (reduced connection between intersecting walls and between walls and floors and roof);
iii) the presence of irregularities (both geometrical and of mass or stiffness distribution) due to their specific construction typology (civilian buildings, palaces, terraced buildings, complexes, churches, towers, etc.) and to continuous transformations and superimpositions (damage, interventions, change in use, etc.);
iv) the scarce in-plane stiffness of horizontal components (floors and roof);
v) the presence of ground slopes.

In such conditions, common assessment procedures usually adopted for structural evaluations based on the box-behaviour of single buildings under seismic actions are not reliable and, when applied, can lead to inaccurate results (D'Ayala, 2000; Valluzzi *et al*., 2001).

More suitable methods for the evaluation of the seismic vulnerability, based on the application of single or combined kinematic models, involving the equilibrium of macro-elements, have been recently validated by direct comparison with the real damage that occurred (Valluzzi *et al*., 2001, 2004a, 2004b; D'Ayala and Speranza, 2002). Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual connections and constraints (e.g. the presence of steel ties or concrete ring-beams), the constructive deficiencies and the characteristics of the constitutive materials (Giuffrè, 1993; Doglioni *et al*., 1994).

Two procedures based on the above mentioned approach, namely FaMIVE and VULNUS, developed at the University of Bath (UK) and the University of Padova (Italy), respectively, have been applied to the two historical centres which compose Vittorio Veneto (NE Italy): Serravalle and Ceneda. They comprise several typologies, characterized by buildings having different dimensions, often connected in arrays and with presence of colonnades and large halls at the ground level, or loggias and attics at the medium and upper ones.

A preliminary, accurate investigation was performed, in order to identify the specific vulnerabilities and to rely the analysis upon systematic classifications. In particular, the results obtained in the typological classification phase allowed us to focus the study on the most vulnerable centre, Serravalle, which has been considered a pilot site for the possible extension of the results to the whole centre of Vittorio Veneto.

The results obtained are compared with preliminary and independent classifications of the buildings based on data obtained through the inspection of the buildings with the so-called AeDES survey form (Bernardini, 2000, 2004; Bernardini *et al.,* 2008). The EMS98 definitions of vulnerability classes, grades of damage and implicit Damage Probability Matrixes have been employed to evaluate the EMS98 classes of each building and to compare the fragility curves obtained through the mechanical approaches.

2. The historical centre of Vittorio Veneto

Vittorio Veneto is a small town located along the foothills of the Alps in the Veneto Region (Treviso Province). It is composed of two historical centers, Serravalle in the north and Ceneda in the south, whereas the middle portion comprises now more recent buildings (Fig. 1). Its origins go back to around 1000 B.C. (*paleo-Veneto* period), but it became quite renowned only later, during Roman times, when a military settlement was first built in Serravalle (*Castrum*). Following the fall of the Roman Empire, the area was subjected to many barbaric invasions of Longobards, Franks and many others. Since the 10^{th} century, a very important family of Serravalle, named De Camino, led and raised the town to a notable cultural and artistic centre; the construction of many buildings, among which the Loggia, the Monastery of St. Giustina and a new city wall with 12 towers pertains to this period. The economic development of Serravalle over these centuries favoured a substantial urban expansion with the centre on the roman *Castrum* and development mainly along the road and the River Meschio (Fig. 2).

During the supremacy of Venice, Serravalle also became a prosperous centre of commercial and craftsmanship activities. In this period (16^{th} century), several monumental buildings were erected, among which “Palazzo della Comunità”, and many private mansions, often with porches at ground level, were built along the most important roads of the town (currently named Via Roma, and Via Martiri della Libertà). The architectural layout of these buildings is inspired by the Venetian style, with commercial activities at ground level, and a large longitudinal room, a main floor with wide decorated windows, often with rullioned windows.

After 1500, with the German invasion, between 1508 and 1521, the town suffered a period of decay, made worse by a major landslide that occurred over the small lake Forcal (now

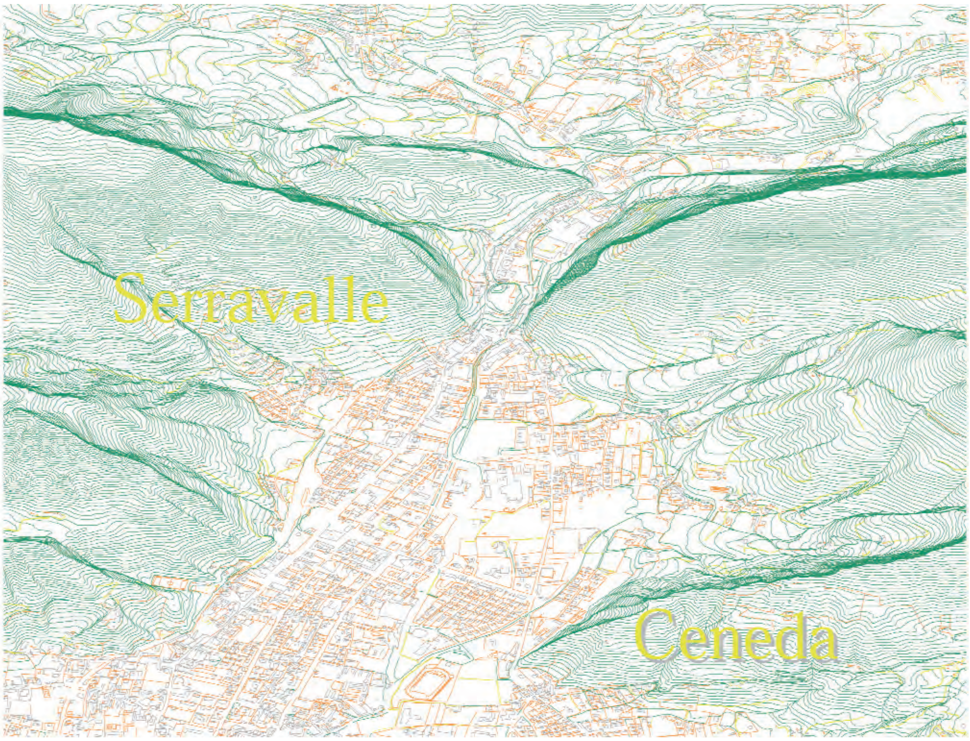


Fig. 1 - Orography of the zone of Vittorio Veneto, showing the location of the two original centres.

extinguished), which caused Serravalle in flooding and destruction of many private and public buildings. The landslide also caused the deviation of the riverbed from its original position into lateral and smaller channels within the city walls. The original riverbed was filled in and an important road with distinguished buildings was erected in its place: Via Tiera, today known as Via Casoni. The buildings along this road, together with the ones located in Via Roma, have been the specific focus of this study.

Once the supremacy of Venice ended, both Serravalle and Ceneda fell under the control of Treviso, and in 1866 became part of the Italian Kingdom and were joined in the new town of Vittorio [which became Vittorio Veneto later in 1923: Tranchini and Foti (1975)].

Ordinary buildings have, mainly, 3-4 storeys made of rubble stone masonry and poor quality mortar, with scarce connections in thickness and among walls; timber floors and roofs and some tie-rods connecting the main walls are also present. Some are in brickwork, and better materials (cut stones with good mortar and improved connections) are generally recorded for more important constructions (palaces, churches, etc.). Specific vulnerabilities are due to the presence of colonnades on the ground floors and loggias, especially in buildings aligned in arrays with common party walls; attics of reduced height at the top; and large halls in the palaces. Alterations in the construction systems in time led to substitutions of roofs and floors with combined solutions of concrete joints and lightweight extruded tiles or r.c. slabs.

The surrounding area was subjected to signficant earthquakes during the last centuries (up to

Fig. 2 - View of Vittorio Veneto from the Meschio River.

VIII MCS intensity), resulting in the classification of the region to medium-high seismic hazard zone (Fig. 3).

3. Classification of the existing building typologies

Today Serravalle and Ceneda consist of about 420 and 690 buildings respectively; notwithstanding the short distance between the two towns, they have grown independently and are rather different. Starting from data of a previous database available from the Town Council (Astengo database), the integration with the direct survey and investigations performed during

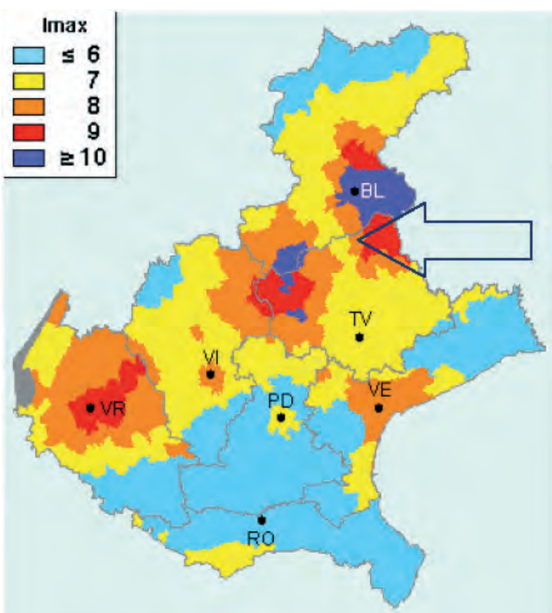
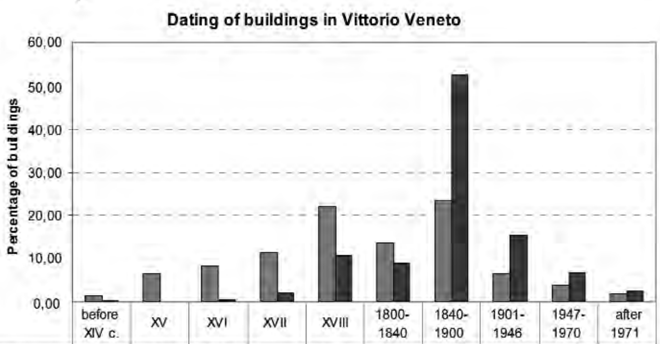


Fig. 3 – Map of the macroseismic intensities of the Veneto Region. The arrow indicates the location of Vittorio Veneto.



	before XIV c.	XV	XVI	XVII	XVIII	1800-1840	1840-1900	1901-1946	1947-1970	after 1971
Serravalle	1,50	6,70	8,40	11,40	22,10	13,60	23,60	6,70	4,00	2,00
Cenada	0,15	0,00	0,40	2,30	10,80	9,10	52,50	15,40	6,90	2,35

Fig. 4 - Comparison of the information about dating, identified for the two centres.

this study has resulted in an accurate recording of the most recurring typologies (Valluzzi *et al*., 2005). Specifically, this new catalogue has been organised with reference to the following parameters:

a) dating;
b) global architectural value;
c) construction typology.

The distribution of each parameter in the two centres has been visualised using a GIS system to create the maps shown in Figs. 5 and 7.

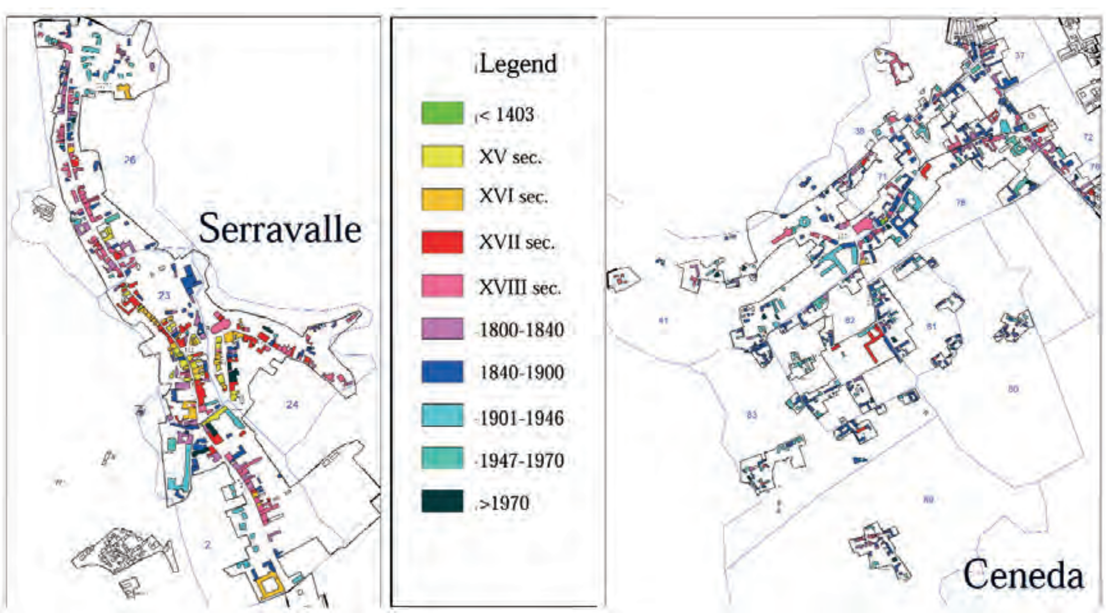
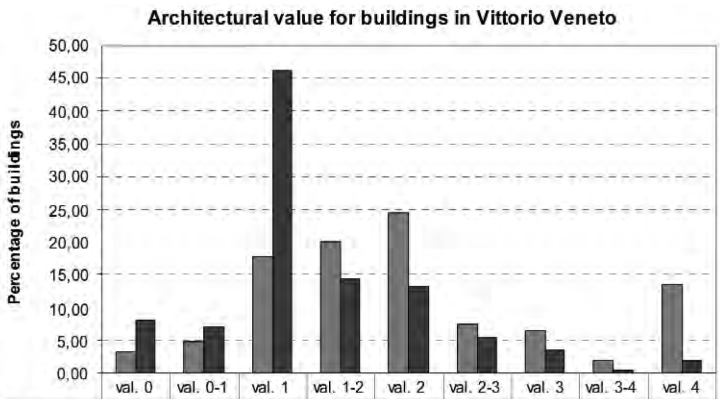


Fig. 5 - Maps of the distribution of the different age of buildings in the two centres.



	val. 0	val. 0-1	val. 1	val. 1-2	val. 2	val. 2-3	val. 3	val. 3-4	val. 4
Serravalle	3,30	4,80	17,80	20,10	24,40	7,50	6,50	2,00	13,60
Ceneda	8,10	7,10	46,20	14,40	13,10	5,40	3,40	0,30	2,00

Fig. 6 - Comparison of the architectural value detected for the two centres.

3.1. Dating

The preliminary analyses confirmed that buildings still standing in Ceneda are older than in Serravalle. Serravalle is currently composed of around 24% of buildings built in 1840-1900, while around 50% are dated before 1800 (14% of this was built in the 15th-16th centuries); Ceneda has more than 50% of its buildings built in 1840-1900, and only around 14% before 1800 (see Figs. 4 and 5).

3.2. Architectural value

The architectural value is represented by a parameter which summarizes information about the

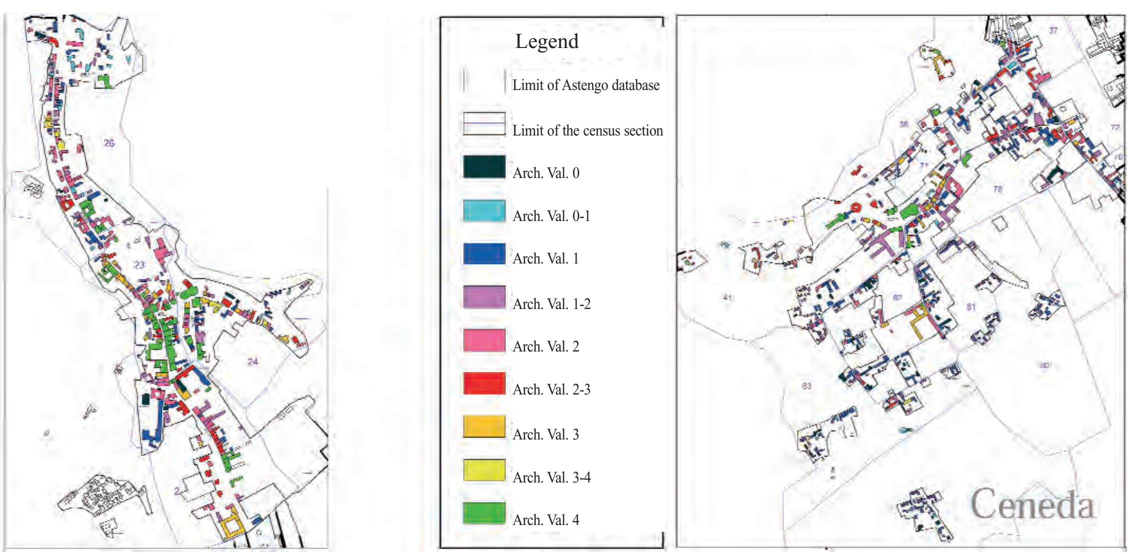


Fig. 7 – Maps of the distribution of the different architectural value of buildings in the two centres.

architectural quality, age and conservation conditions. Five levels are considered: 0 (no value); 1 (absence of elements having architectural values); 2 (presence of original elements with architectural value even if not extended to the whole construction); 3 (remarkable architectural value extended to the whole construction); 4 (historical and monumental value). Results show that 22% of the building stock in Serravalle is classified in levels 3 and 4, while in Ceneda only less than 6% belongs to these categories (Figs. 6 and 7). This distribution agrees with dating results, as the correspondence among highest value classes and oldest buildings is confirmed.

3.3. Typology

The two centres include a large variety of buildings, having different morphology and use. The typologies have been classified grouping the different categories following the combination of three criteria:

a) dimensions: houses, palaces, large complexes and annexes have been classified separately;
b) presence of contiguous constructions: isolated buildings or buildings in arrays;
c) presence of colonnades at ground level, considered for all the abovementioned cases.

Constructions having specific functions such as churches or towers-bastions have been also classified separately. The study led to a selection of 11 cases, as follows (Fig. 8):

a) isolated palaces with colonnades;
b) isolated palaces without colonnades;
c) palaces in array with colonnades;
d) palaces in array without colonnades;
e) houses in array with colonnades;
f) houses in array without colonnades;
g) isolated houses;
h) large complexes;
i) annexes (mainly used as stores or garages);
j) churches;
k) towers and bastions.

Results are summarized in Fig. 9. They show that in Serravalle more than 8% of the building stock are palaces, and more than half of these have colonnades at ground level, while in Ceneda almost all the palaces (7% of the building stock) are without colonnades. The most common typology is the houses in array without colonnades (58% in Serravalle, about 66% in Ceneda), but colonnades are present in 15% of the constructions in Serravalle (10% of which are houses in array) and only in 2% in Ceneda (1% in houses in array). Finally, Serravalle has the highest percentage of large complexes.

According to their historic developments over the centuries, the urban setting of Serravalle has resulted in long rows of buildings, with the oldest ones located along the main streets, while Ceneda has a more random distribution, which developed into an intricate streets pattern.

4. The procedures for the vulnerability assessment

The seismic vulnerability of the historical centre of Serravalle in Vittorio Veneto has been evaluated by using two procedures, based on the identification of failure mechanisms of

Fig. 8 - Examples of building typologies in Vittorio Veneto: a) isolated palace with colonnades (Palazzo Casoni - Serravalle); b) isolated palace without colonnades (Palazzo Palatini - Ceneda); c) palace in array with colonnades (Loggia della Comunità - Serravalle); d) palace in array without colonnades (Palazzo Muzzi - Serravalle); e) building in array with colonnades (Via Casoni 10,12 - Serravalle); f) building in array without colonnades (Via Roma 81 - Serravalle); g) isolated building (Via Tiziano 159 - Ceneda); h) large complexes (Bacologia - Serravalle); i) annexe (to Palazzo Palatini - Ceneda); j) church (Cathedral of Ceneda); k) l) towers-bastions (Torre di San Martino and Porta di San Giovanni, both in Serravalle).

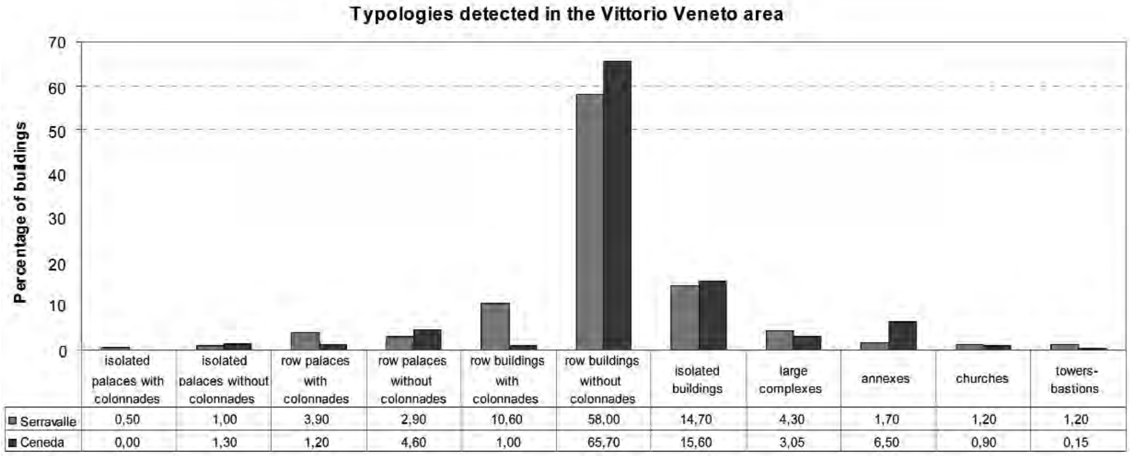


Fig. 9 - Comparison of the different typologies detected for the two centres.

structural macro-elements, namely FaMIVE (Failure Mechanisms Identification and Vulnerability Evaluation), developed at Bath University (D'Ayala *et al.*, 1997, D'Ayala and Speranza, 1999, 2003, 2004; Speranza, 2003), and VULNUS (Bernardini *et al.*, 1989, 1990), developed at the University of Padova. They are both based on the grouping of buildings in different vulnerability classes and using these they produce descriptions of damage scenarios through fragility curves. The way in which results are presented also lends itself to correlation with Damage Probability Matrices (DPM). In both procedures, the reference parameter for the analysis is the ultimate load factor or critical seismic coefficient, that is, the mass multiplier able to activate the failure mechanisms. As in most of the analyses where the kinematic approach of limit state analysis is used, the ultimate load factor typically identifies a loss of equilibrium, rather than to overcome the materials strength.

VULNUS defines three indices: I_1 and I_2, related to the seismic coefficient connected to the

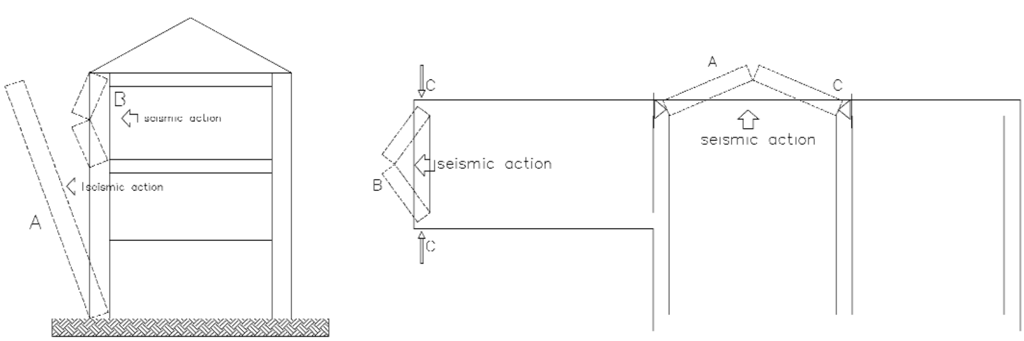


Fig. 10 - Basic kinematic mechanisms considered by VULNUS for out-of-plane failure.

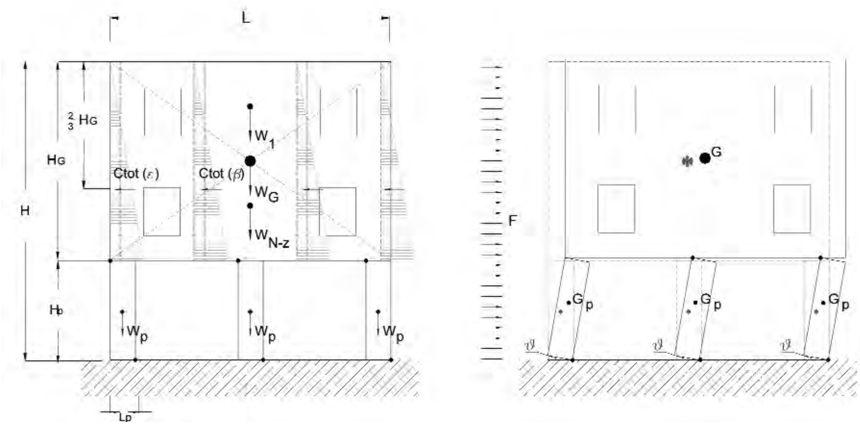


Fig. 11 - Additional mechanism implemented in FaMIVE to take into account the specificity of the buildings in Serravalle.

in-plane shear resistance and out-of plane weakest mechanisms, respectively (Fig. 10); I_3 is obtained through judgements on seven qualitative vulnerability factors of the building (Bernardini *et al*., 1989); it is able to define five vulnerability classes (very low, low, medium, high, very high), conditional to the intensity of the ground motion (mean response acceleration).

FaMIVE defines two indices for each of the possible mechanisms: the structural index $I_{s(m,i)}$ and the failure extent index $I_{f(m,i)}$, the product of which identifies the seismic vulnerability associated to a given mechanism *m* involving *i* storeys ($I_{v(m,i)}$); the greatest value of $I_{v(m,i)}$, represents the final Vulnerability Index (I_v) of the *façade* under observation. The procedure defines four vulnerability judgements (low, medium, high and very high) and was upgraded on purpose to take into examination some structural features specific of the architecture of Serravalle: a new damage mode, depending on the presence of columns on the ground floor (Fig. 11), as well as on the modification of form and database to include storeys with reduced height, was performed.

5. Results obtained for the pilot-site of Vittorio Veneto

The vulnerability analysis has been performed for a total of 65 buildings located both in Serravalle and Ceneda using VULNUS, and 42 buildings in Serravalle using FaMIVE. The great influence of the colonnades at ground level, the lack of connections among walls, floors and roof, the poor conditions of the structures and materials, and the variability in the soil, have been highlighted as major factors affecting the propensity to brittle, out-of-plane collapses.

Results have been obtained from:

- vulnerability analyses using the two procedures, performed separately and then by comparison;
- comparison between typologies of buildings (VULNUS);
- comparison of the fragility curves obtained using the two procedures with the implicit Damage Probability Matrices in the EMS98 macroseismic scale (Grunthal, 1998; Bernardini *et al*., 2008). A criterion to evaluate the EMS98 vulnerability class of each

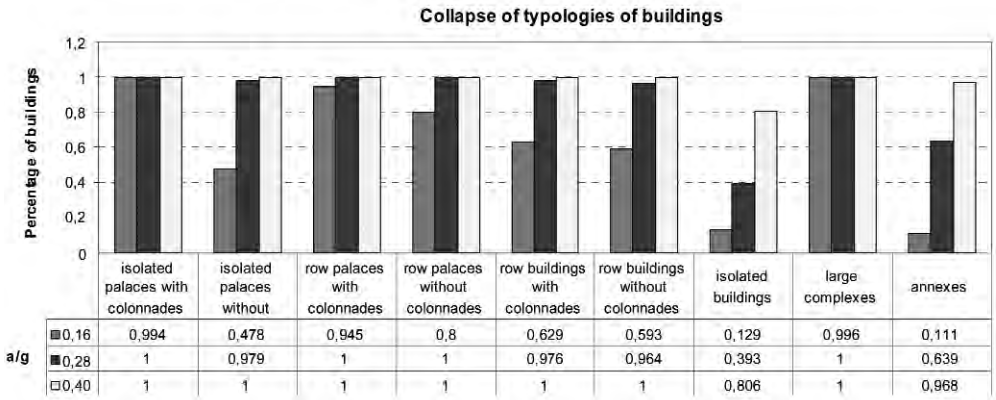


Fig. 12 - Percentage of buildings belonging to different typologies collapsing at different seismic levels (VULNUS).

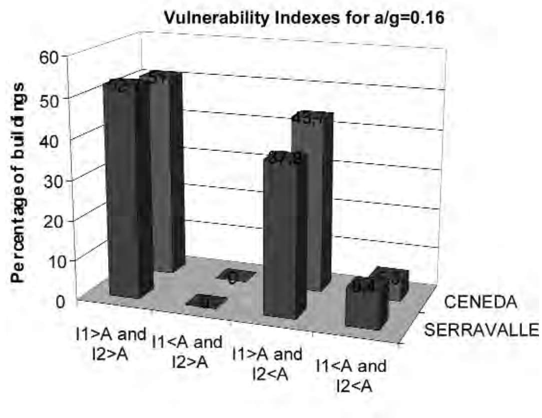
building has been proposed both for VULNUS and FaMIVE, and resulting classifications have been compared with the class identified for each building by means of the criterion based on data obtained through the AeDES survey form (Bernardini, 2008). The more pessimistic hypothesis about the quality of the repairing intervention (CR hypothesis) has been summarized here.

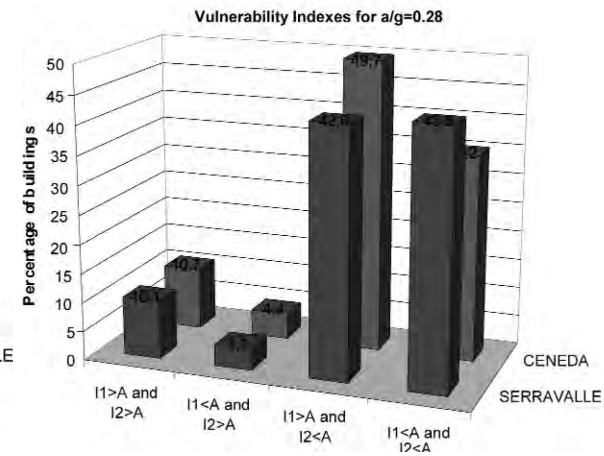
Results obtained with VULNUS showed that:

- the vulnerability level is strongly dependent on the presence of the colonnades at ground level and on the large dimensions of some of the constructions. Palaces and large complexes are more vulnerable than others as they often present storey heights higher than 3 m and very slender pillars and walls. For this class, shear capacity is particularly critical, when colonnades are present, as they reduce the resisting section at the base. Isolated palaces and houses have generally lower vulnerability than constructions in arrays. Isolated houses and annexes present the lowest seismic vulnerability: they are usually characterised by modest storey height (often lower than 2.4 m) and often present ties connecting opposite walls at least in one direction;
- the simulation of different seismic hazard levels (a/g = 0.16, 0.28 and 0.40, where a is the mean response acceleration and g the acceleration of gravity) shows that, except for isolated buildings and annexes, that give a more linear increase of vulnerability with hazard, for the rest of the building stock with a value of the base acceleration greater than 0.16, the entire population is vulnerable (Fig. 12);
- the survival probability for the two centres, for different seismic levels is comparable.

Table 1 - Global percentage of collapse for the two centres for different seismic levels (VULNUS).

Center	***a/g =0.16***	***a/g =0.28***	***a/g =0.40***
SERRAVALLE	55.7	87.9	97.0
CENEDA	51.0	85.5	96.8





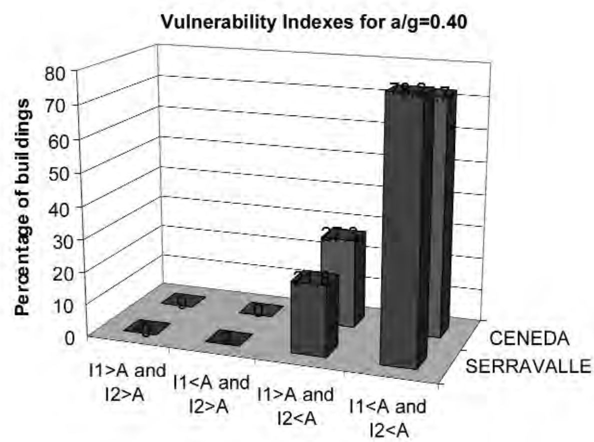


Fig. 13 - Survival [min(I_1, I_2)>A] and collapse [max(I_1, I_2) <A] percentage of buildings for different seismic levels (A=a/g) related to in-plane and out-of-plane mechanisms (VULNUS).

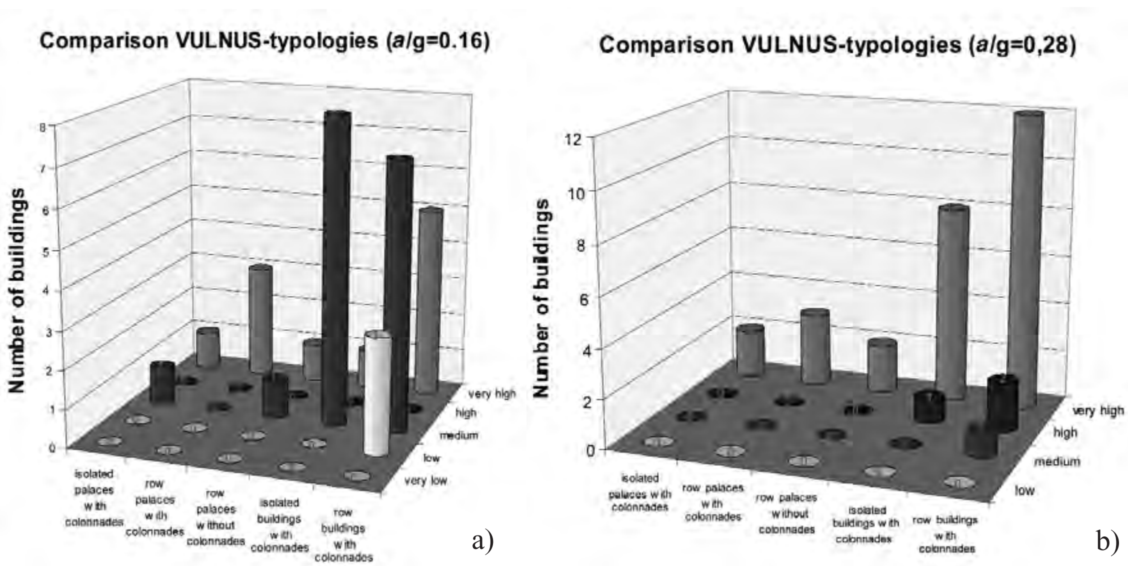


Fig. 14 - Vulnerability classes of different typologies for low (a) and higher (b) seismic level (VULNUS).

Ceneda has the highest probability of collapse for in-plane shear mechanisms (I_1 index), whereas Serravalle has the highest probability for simultaneous shear and flexural collapses (Fig. 13);
- a more detailed assessment of the kinematic models confirmed the high vulnerability of the *façade* pillars to global overturning mechanisms, both for whole walls and at corners;
- the global collapse probability is higher for Serravalle than Ceneda for every seismic level, even if values are very close for both centres (Table 1).

The grouping of the most significant typologies (palaces and buildings, isolated or in arrays, with or without colonnades) allowed us to compare the VULNUS results as shown in Figs. 14 and 15. It is possible to notice that for a lower seismic level VULNUS is able to detect the differences among typologies of buildings, better than for higher levels.

A detailed analysis on the centre of Serravalle has been conducted with FaMIVE. Results showed that:
- an increase in vulnerability could be readily correlated to less orderly masonry fabric. Specifically, of the two sets of buildings, one in Via Casoni, the other in Via Roma, the first is the oldest and the ones that display a relatively poor rubble masonry construction (56% of the analysed samples) and shows an average collapse load factor of 0.21 *a*/g, while the Via Roma set, made of either roughly squared stone block (30% of the samples) or dressed stone masonry (11% of the samples) have an average collapse load factor of 0.26 and 0.30 respectively;
- the cumulative results relative to the vulnerability levels, plotted in Fig. 16, show that 26% of *façades* is characterized by low vulnerability, 42% by medium, 30% by high, and 2% by extreme vulnerability, yielding overall a medium level of vulnerability of the samples;
- according to FaMIVE, the new mechanisms depicted in Fig. 11 (type M: failure with pillars, 25.7%) and the overturning of one/two side wings (type B1/B2, 21.2%) are the most common in the sample, followed by mechanism E (vertical strip overturning) and H (in-plane failure) with 15.15% (Fig. 17). The cumulative percentage shows that 51.5% of *façades* is damaged by out-of-plane failure mechanisms (A: vertical overturning of the *façade*, B1/B2, E, F: vertical arch), 40.9% by in-plane failure mechanisms (H, M), while the remaining percentage by partial damage modes (C: corner failure, D: partial overturning, G: horizontal arch) (Fig. 18). The histogram of Fig. 17 also establishes a correlation between the percentage occurrence of each damage mode with the vulnerability classes I_v. It can be observed that, among the in-plane mechanisms (H, M), while failure mode H is always associated to low values of I_v, mode M produces notably higher vulnerability levels, with a high percentage of buildings in high vulnerability. This result provides evidence of how the presence of colonnades and arcades at ground level influence the seismic performance of these buildings;
- the distribution of the failure mechanisms in the *façades* characterised by colonnades at ground level, amounting to 24 and evenly distributed between the two sets of buildings, is shown in Fig. 19. It can be noted that the failure mechanism M is undoubtedly a critical mechanism as it is associated to 71% of these types of buildings;
- Fig. 20 shows the dependence of the cumulative distributions of I_v on the reliability of information. In each of the two plots, the three histograms represent, from left to right, the

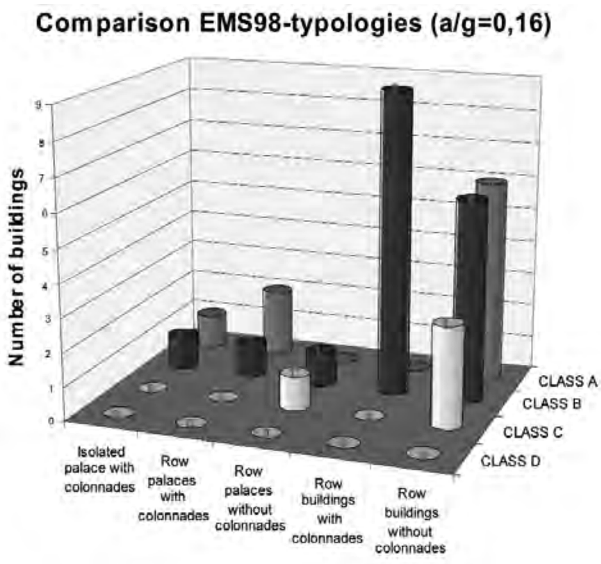


Fig. 15 - Vulnerability classes associated to different typologies of buildings for the EMS98 scale (VULNUS).

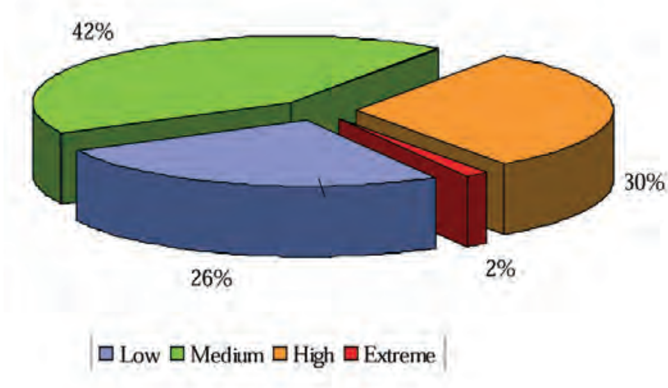


Fig. 16 - Distribution of vulnerability by class (FaMIVE analysis).

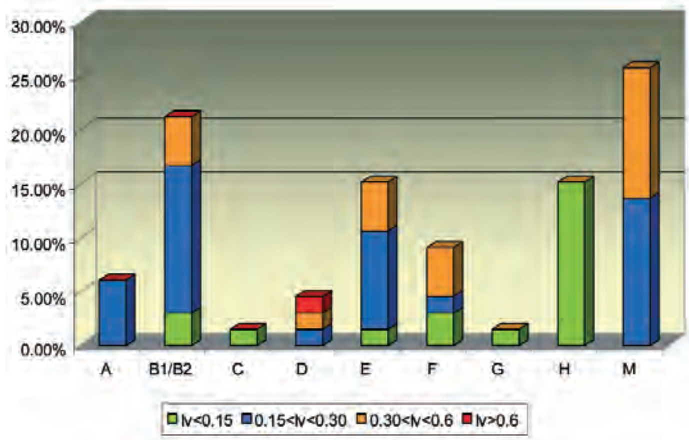


Fig. 17 - Distribution of failure mechanism as function of I_v (FaMIVE).

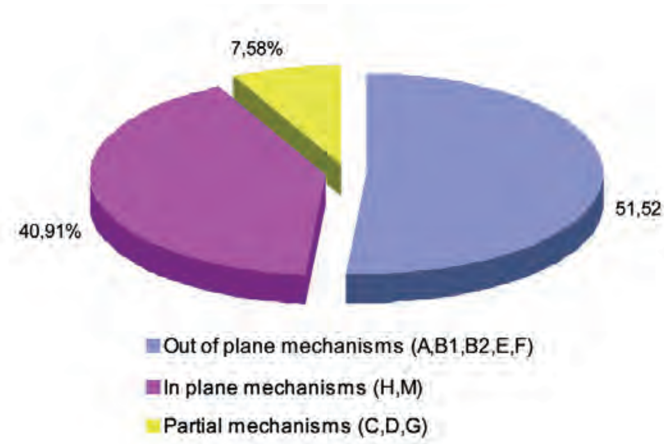


Fig. 18 - Cumulative distribution of failure mechanisms (FaMIVE).

lower bound, central values and upper bound of I_v, respectively. This data has been plotted separately for the two sets of buildings in Via Casoni and Via Roma to reflect the different level of accuracy of the survey and corresponding reliability. The influence of the reliability measure is apparent in the relative shift in class membership, which is much wider in the case of Via Roma. Here is it possible to observe a change in the greater class from low to high vulnerability, moving from lower to upper bound. Furthermore the cumulative vulnerability, of the sample would shift from medium to high (with a shift in the high class from 24% to 48% membership), if the upper bound were considered. The membership of the class of extreme vulnerability is only marginally affected by the reliability weighting.

6. Correlation of results

The correlation of the results has been made on a total 39 buildings, whose both VULNUS and FaMIVE analyses and AeDES survey were available. Results obtained in terms of I_v or

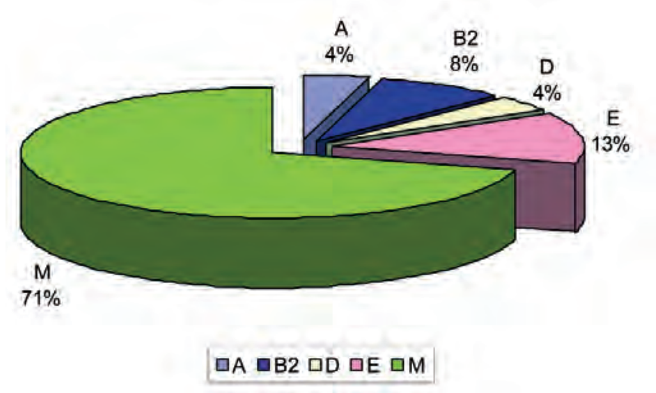


Fig. 19 - Distribution of failure mechanisms in buildings with colonnades (FaMIVE).

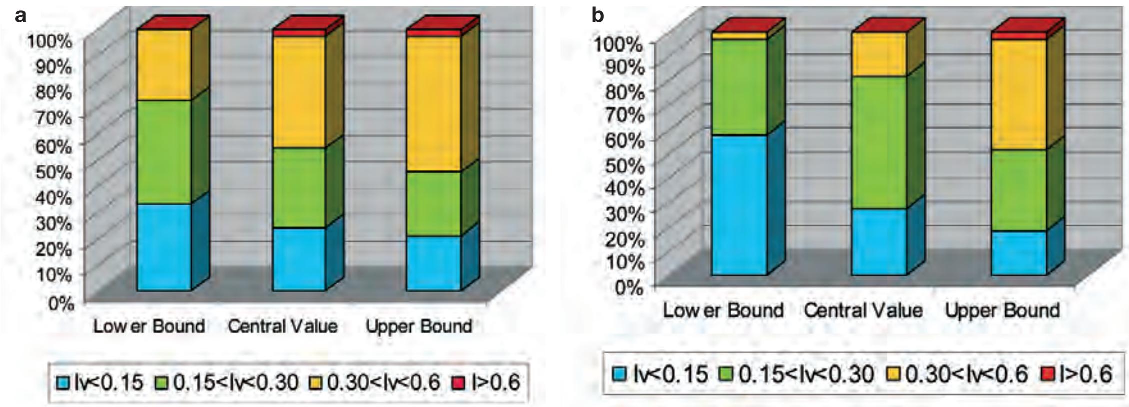


Fig. 20 - Distribution of *Iv* as a function of the reliability of information for the two sets of facades: (a) Via Casoni, (b) Via Roma (FaMIVE).

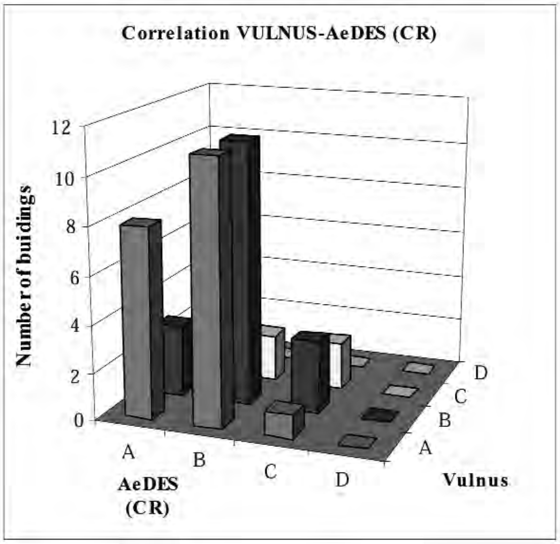
vulnerability classes and the EMS98 scale has been combined under the hypothesis that for earthquakes of medium intensity (between VII and IX degree), five levels of vulnerability judgment of VULNUS and the four of FaMIVE, considered as damage probability >D2 after the first activation of the collapse mechanisms, correspond to the first four EMS98 vulnerability classes, as shown in Table 2.

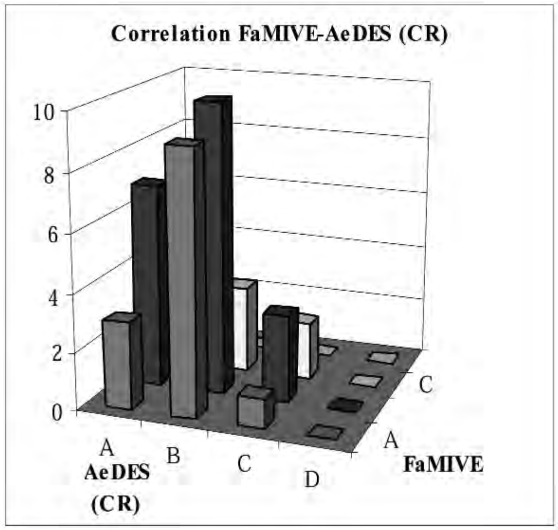
Results are shown in Fig. 21. It is worth observing that most of the buildings analyzed with VULNUS are in the highest vulnerability classes, pointing to a high probability of severe damage or collapse also for low peack ground acceleration (*PGA*) levels. On the contrary, FaMIVE considers most buildings as having a medium vulnerability and points out that damage ≥D3 is activated for *PGA* of 0.05 g to 0.33 g. In spite of that, both methods classify most of the buildings in the EMS98 A and B classes, with very few buildings of better quality in class C or D (VULNUS). The correlation between mean response acceleration *a*/g and the EMS98 macro-seismic intensity in VULNUS application has been obtained evaluating the *PGA* through the Slejko *et al.* (2008) formulation; moreover *a* is assumed equal to an Equivalent *PGA* (= 0.8 *PGA*) (Bernardini, 1999).

The main differences in the vulnerability judgment given by the two procedures are ascribable

Table 2 - Correspondence of vulnerability classes defined in VULNUS (VII: a = 0.107 g; VIII: a = 0.1817 g; IX: a = 0.3085 g) and vulnerability index defined in FaMIVE with the EMS98 classification.

Procedure	EMS98 class A	EMS98 class B	EMS98 class C	EMS98 class D
VULNUS	Very high (VIII) ; High (VIII) and ≥Low (VII); ≥Medium (VII)	Medium or Low (VIII) and Very Low (VII); ≤Medium (VIII) and Low (VII);	Low (VIII) and Very Low (VII); Very Low (VIII) and ≥≥Low (IX)	Very Low (IX)
FaMIVE	Extreme and High	Medium	Low	





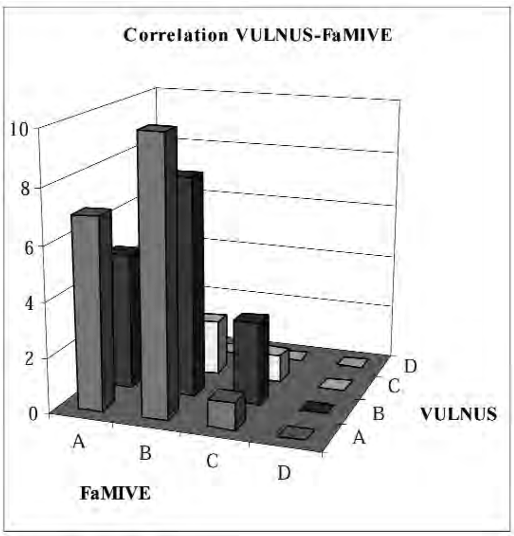


Fig. 21 - Comparison VULNUS-AeDES (42 buildings), FaMIVE-AeDES (38 buildings) and FaMIVE-VULNUS (38 buildings).

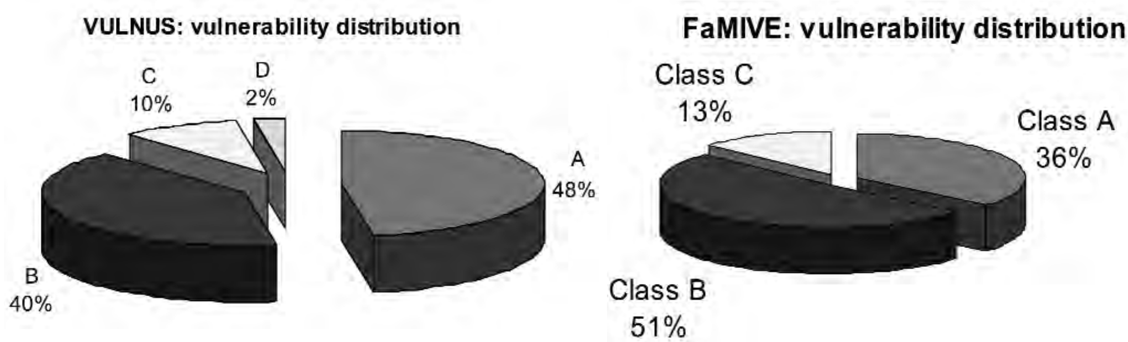


Fig. 22 - Distribution of vulnerability grades obtained from VULNUS and FaMIVE.

mainly to the in-situ observations and to the mechanical models adopted for the cinematic analyses. The global distribution of vulnerability grades for the analysed buildings for the two procedures is depicted in Fig. 22.

Fig. 23 shows the damage distributions for each vulnerability class (A, B, C), defined by cumulative percentage of buildings suffering an intermediate level of damage (≥D3) for different earthquake intensities. The conversion from a/g values into MCS intensities has been carried out according to the Slejko *et al.* (2008) formulation.

The results show that the EMS98 distribution is always included between the two FaMIVE boundaries. Moreover, the FaMIVE central distribution correlates fairly well with EMS98, especially for buildings of class B. It should be noted that for buildings of class A, the best correlation would occur with the FaMIVE upper bound, i.e. considering the buildings as more vulnerable, while for class C the best fit would be with the lower bound, i.e. considering lower than calculated vulnerability. This is related to the fact that most buildings of the considered sample would be described as class B, according to the EMS98, which does not pay specific attention to strengthening devices (shifting the building to the lower percentile of class C) or to specific defects, such as lack of connections among orthogonal walls (shifting the building to the upper percentile of class A).

The results obtained by VULNUS are globally more pessimistic than the ones of FaMIVE and the EMS98 matrices, especially for intensities over VIII. Of course, for middle intensities (VII or VIII) the good correlation of the VULNUS fragility curves and EMS98 "Mean White" DPM is implicitly assured by the criteria for macroseismic class identification displayed in Table 2. In fact, it is clearly reasonable that results of analytical models of the seismic response underestimate the real strength, as given by statistical calibration of the observed damage.

7. Conclusions

An extensive analysis of the historical centre of Vittorio Veneto (NE Italy) has been presented. A preliminary acquisition of knowledge phase, based directly on the survey and on the typological characterization of the buildings, allowed us to identify the main aspects affecting the vulnerability of the site. Reliable simplified methods, based on kinematic models describing the loss of equilibrium of structural macro-elements have been used. The presence of colonnades at ground level and the high dimensions of halls in the palaces are the parameters that strongly influence seismic vulnerability. Palaces and large complexes (which can include a storey height of 3 m and over, and very long and slender sections) are particularly vulnerable for in-plane actions, especially when colonnades are present at ground level. Buildings in arrays and isolated ones, in this order, are less vulnerable, as they have more regular geometrical characteristics and often present ties connecting opposite walls. The simulation of different seismic hazard levels pointed out the increase of vulnerability for every typology except than for the isolated buildings, whose risk is kept low.

The study has been developed to provide damage scenarios through fragility curves to calibrate macroseismic scale analyses taking into account distributions defined by cumulative percentage of buildings suffering various damage levels for different earthquake intensities.

The numerical results suggest that the mechanical models (and particularly VULNUS)

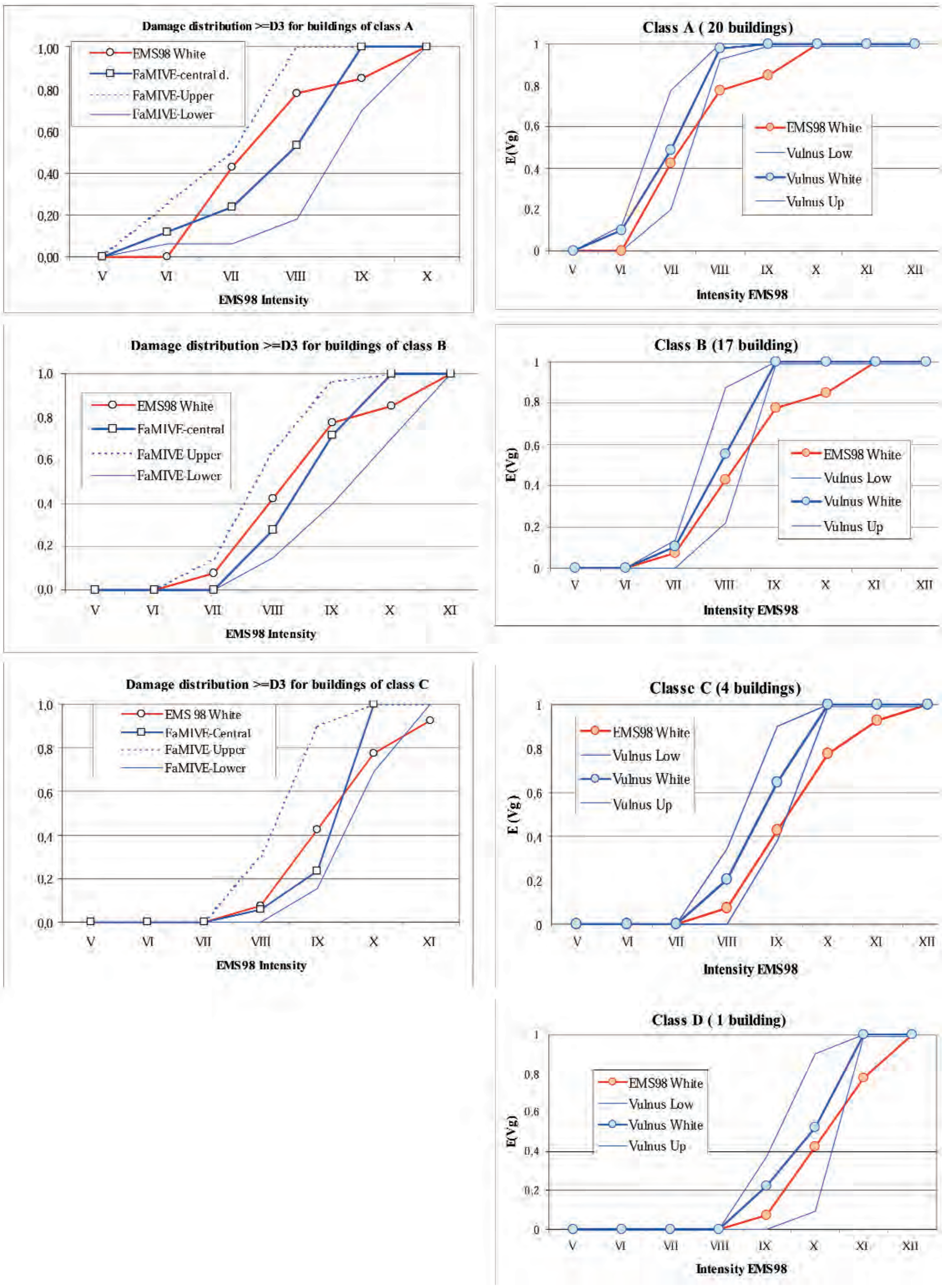


Fig. 23 - Damage distribution for different earthquake intensities (EMS98 scale) using FaMIVE (left) and VULNUS (right) compared to EMS98 implicit DPM (red lines).

underestimate the strength (or overestimate the damages) of masonry buildings struck by earthquakes of EMS98 intensity over VIII.

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Corresponding author: Alberto Bernardini
Dipartimento Costruzioni e Trasporti
Università di Padova
Via Marzolo 9, 35131 Padova, Italy
phone: +39 049 8275624; fax: +39 049 8275604; e-mail: alberto.bernardini@unipd.it