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COMPARISON AMONG ANALYSIS METHODOLOGIES FOR SEISMIC VULNERABILITY ASSESSMENT OF MASONRY SCHOOL BUILDINGS IN TORRE DEL GRECO

Formisano Antonio[1], *Mazzolani Federico M.*[2]

ABSTRACT

The paper is framed within activities of the Working Group 4 "Risk Assessment for Catastrophic Scenarios in Urban Areas "of the concluded European research project COST Action C26 "Urban Habitat Constructions under Catastrophic Events "(chair: M. F. Mazzolani) and deals with the seismic vulnerability evaluation of some schools located in Torre del Greco. The school buildings, made of tuff masonry blocks, have been detected under the geometric and mechanical point of view and their seismic vulnerability has been assessed by different investigation methods. In particular, the following analytical procedures have been applied to the examined school sample: 1) the GNDT-CNR method, based on the quick compilation of survey sheets; 2) the VM method, a semi-qualitative approach based on the compilation of a specific spreadsheet which provides the building PGA with reference to specific limit states; 3) the FaMIVE procedure, which allows to assess the in-plane and out-of-plane vulnerability of building walls, once their main geometric and mechanical properties are defined; 4) the 3MURI software, which permits to evaluate the global vulnerability of masonry buildings by means of static non-linear analysis. The results obtained from different evaluation methods have been examined and compared each other, allowing for the definition of a seismic vulnerability ranking of schools under investigation useful for planning future retrofitting interventions.

Keywords: *School buildings, Vulnerability, Survey sheets, VM procedure, FAMIVE method, 3MURI program*

1. INTRODUCTION

After the 2002 Molise earthquake in Italy, where the collapse of the primary school "Francesco Iovine" in San Giuliano di Puglia caused the death of 27 children and one teacher, a large attention to the problem of the seismic vulnerability of schools has been deserved [1].

Five months after the earthquake, an Ordinance of the Prime Minister [2] stated that the seismic vulnerability of all public strategic buildings had to be evaluated within five years in order to setup a seismic rehabilitation programme. Nowadays, the provisions of the new technical Italian code, promulgated through a Ministerial Decree [3] explained in detail by means of an appropriate Circular [4] in February 2009, are the only normative reference to be used from 2009 July 1st both in the design of new structures and in the retrofitting of existing ones.

Starting from these premises, the current paper deals with the problem of assessing the seismic vulnerability of masonry schools in Torre del Greco, a city nearby to Naples. This activity is framed within the COST C26 project "Urban Habitat Constructions under Catastrophic Events" [5] which has the purpose to evaluate the vulnerability of the urban built-up towards catastrophic actions with particular reference to the risk scenario deriving from a possible Vesuvius eruption, which has been assumed as a study case in the WG4 "Risk Assessment for Catastrophic Scenarios in Urban Areas". In the framework of this project, an in situ survey activity was organised with the aim to survey

[1] Department of Structural Engineering, University of Naples "Federico II", antoform@unina.it
[2] Department of Structural Engineering, University of Naples "Federico II", fmm@unina.it

residential and school buildings. In this activity, the following Institutions were involved: University of Naples 'Federico II', PLINIVS Centre, Second University of Naples and ENEA from Italy, University of Malta and University of Aveiro from Portugal. Four teams (A, B, C and D), each composed of four people, investigated three different urbanized zones. The first, including 281 buildings, coincides with the historic centre of Torre del Greco; the second one, with 20 buildings, is relative to a decentralized residential zone, 4 km far from Vesuvius crater; the third one comprises 15 schools, located on the whole city territory. Each team inspected one area of the selected ones [6]. The attention is herein focused on school buildings, which have been subjected to a visual examination, completed by a photographic survey, with the aim to fill an *ad hoc* survey form, developed by the PLINIVS Centre and subsequently to assess the seismic and volcanic vulnerability through appropriate simplified and refined methodologies. In particular, different seismic vulnerability assessment methodologies have been applied to the studied schools, aiming at defining a classification about their susceptibility to damage under earthquakes. This activity should be of a primary importance for the priority programming of future retrofitting interventions.

2. THE STUDY SCHOOL BUILDINGS

The study performed in the paper deals with five building schools, namely Orsi, Chiazzolelle-Camaldoli, Leopardi-Campanariello, Sauro and Mazza.
The seismic vulnerability assessment of these buildings has required the knowledge of their geometrical and mechanical properties.

Fig. 1 The masonry schools in Torre del Greco under investigation: Orsi (a), Chiazzolelle-Camaldoli (b), Leopardi-Campanariello (c), Sauro (d) and Mazza (e)

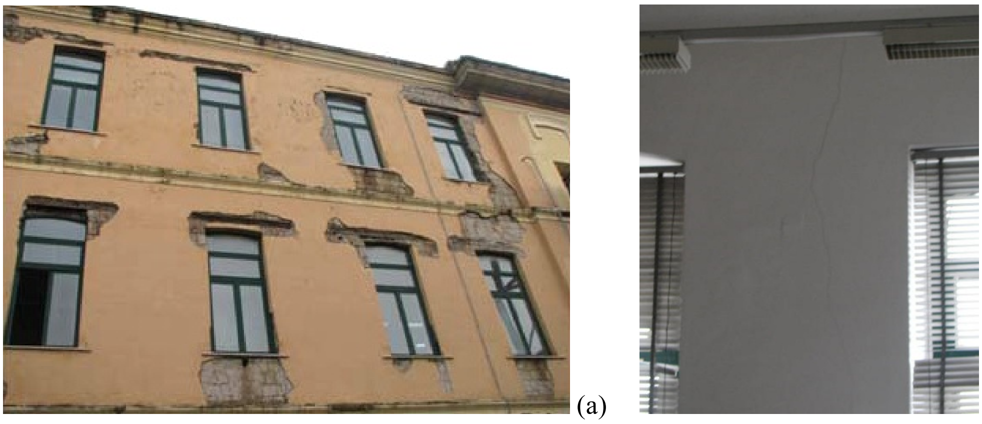
The schools are made of tuff blocks, whose mechanical features are determined according to the provisions of the Ministerial Circular (M.C.) [4] considering the limited knowledge level (LC1) attained for them. Such a knowledge level has required the geometrical survey, limited *in-situ* checks on constructive details and *in-situ* check of material properties of schools. In particular, for compressive strength and Young modulus of the examined masonry type the minimum value and the average one of intervals reported in the M.C. have been considered, respectively. So, the confidence factor to be used for defining the material properties is 1.35. In addition, taking into account that investigated schools were built between 1919 and 1960, no conformity checks on masonry blocks has been done and no certain information on the used mortar have been achieved. For this reason the partial safety factor γ_M has been assumed as equal to 2.5.

Schools Orsi and Chiazzolelle-Camaldoli were built between 1946 and 1960, whereas schools Leopardi-Campanariello, Sauro and Mazza were erected between 1919 and 1945. The roofs are exclusively with plain geometry and predominantly made with concrete-tile structure, while the openings are of aluminium without protection and their extension is ranged, on the average, between 25 and 50% of the building surface for schools Leopardi-Campanariello and Mazza and between 10 and 25% for remaining ones.

The bird-eye-views of the school buildings under investigation are shown in Figure 1.

The school building Orsi (Figure 1a) arises with two storeys, with an inter-storey height of 4.00 m and covered area of about 460 m^2. Floors are made by steel beams and hollow tiles. General conditions are good.

The school building Chiazzolelle (Figure 1b) is built with two storeys, with an inter-storey height of 3.00 m and covered area of about 370 m^2. Floors are made of steel beams and hollow tiles. No crack patterns are visible. The school building Leopardi-Campanariello (Figure 1c) shows two storeys with an inter-storey height of 3.00 m and covered area of about 560 m^2. Floors are made of steel beams and hollow tiles. No crack patterns are visible. The school building Mazza (Figure 1d) arises with three storeys (inter-storey height of 5.10 m) having a surface of about 1200 m^2. It has steel beams-hollow tiles mixed floors, but at the first floor a part of the lobby is covered by vaults. The construction is characterised by a crack pattern both on the facade (Figure 2a) and in the internal space of the building corresponding to the support of steel beams (Figure 2b), which are not connected by tie beams. Finally, the school building Sauro (Figure 1e) is developed on two storeys (inter-storey height of 5.00 m) having a surface of about 1725 m^2. Floors are made by steel beams and hollow tiles and are connected to the masonry walls by RC tie beams. Cracks on the external walls have been recently repaired.



(a) (b)

Fig. 2 Presence of cracks on the external (a) and internal (b) walls of the school Mazza

3. SEISMIC VULNERABILITY ASSESSMENT METHODS

3.1. The CNR-GNDT procedure

The seismic vulnerability of the selected buildings has been first established by the procedure setup by the National Group for Defence against Earthquakes of the Italian Research National Council (CNR-GNDT).The method evaluates the seismic vulnerability of masonry and RC buildings by providing a normalized index of vulnerability, which is obtained by filling an appropriate survey form where information on building properties (type of construction, building use and state of preservation, quality of materials, structural system, geometric aspects of the structure, etc.) are found [7, 8].

These characteristics are shared in eleven parameters, each of them having four classes (A, B, C and D) with relative scores and a weight factor. The weight factors associated to these classes tried to recognize the degree of importance of the vulnerability factors in the structural resistance of the

building. The conventional strength capacity has a weight factor value greater than the rest of the vulnerability factors, because it considers the building capacity to resist seismic actions through both the type of masonry and the number of resisting walls.
The normalized index of vulnerability is finally obtained as the weighted sum of the product of the class score of each vulnerability factor by its corresponding weight factor. In order to facilitate the comparison between buildings in a sample, the index is normalized by making the ratio with the maximum value that can be obtained, that is 382.50. When the building is very susceptible to collapse during an earthquake, the maximum normalized value is 1.0. Otherwise, this value tends to be 0.0 when the structure is free of damage.

3.2. The VM procedure

The methodology used in the framework of the SAVE research project "Adjourned tools for the seismic vulnerability of the building heritage and the urban systems" [9] allows to evaluate the vulnerability of both RC (VC method) and masonry buildings (VM method), with particular reference to public and strategic constructions, such as schools and hospitals, aiming at reducing their seismic risk. Such methods, which allow to evaluate the operational and collapse acceleration levels of buildings, provide their vulnerability as complement to one of the ratio between these values and the corresponding demand spectra peak accelerations given by the code.
The VM method, based on simplified calculation models implemented within an excel sheet, is applied neglecting the activation of out-of-plane mechanisms, therefore considering effective wall-floor connections, achieved by means of RC tie beams, as well as the presence of adequately stiff floors. As a consequence, only in-plane mechanisms are considered. For this reason, when the above conditions are not meet, the building seismic vulnerability is not really estimated. The model considers the plasticity and collapse mechanisms due to shear and/or bending-compression of masonry piers, leading to the global shear of the structure. The shear resistance to horizontal forces is evaluated according to the formulation reported in [10]. In order to consider a possible compression-bending behaviour of piers, a reduction factor of the shear resistance, depending on their slenderness and average compressive stress, is applied [2]. The building resistance is obtained by summing the contribution of piers for each direction considered. Instead, the stiffness is achieved by considering the shear and bending deformability. Then, the method allows to transform the storey force into the ground accelerations which determine the achievement of the critical conditions. Subsequently, the most unfavourable demand/capacity ratio is determined, it being related to the ground acceleration which allows to achieve that condition. After that, the seismic vulnerability of the building is evaluated in terms of Peak Ground Acceleration (PGA) which attains the two performance levels above specified. Finally, the maximum acceleration is first reported to the building site, also including amplification produced by the foundation soil, allowing to obtain a seismic safety index and, consequently, the corresponding vulnerability index is determined.

3.3. The FaMIVE method

The FaMIVE method"Failure Mechanisms Identification and Vulnerability Evaluation" is based on the limit analysis of external walls of masonry buildings [11]. Such an analysis procedure makes a detailed examination of main geometrical and structural parameters of masonry buildings obtained from a street survey. So, in this phase, the structure under investigation is identified. After that, the method associates to each external wall both the loading and restraint conditions, so individuating possible in-plane and out-of-plane mechanisms. Finally, the program provides the ultimate multiplier of lateral loads, indicated as ESC (acronym of Equivalent Shear Capacity), which activates the beginning of each of these mechanisms. This allows to evaluate the vulnerability index of each building façade by means of the following relationship:

$$V = \frac{d_i \cdot d_e}{ESC} \tag{1}$$

where ESC is function of the friction coefficient, of the slenderness and of the connection of the wall with both floors and other walls, while d_e and d_i are related to the extension of the façade interested from failure and to the catastrophic character of the collapse, respectively. Starting from the value of V, four vulnerability classes are defined: low ($V < 3.5$); medium ($3.5 < V < 7$); high ($7 < V < 15$); very high ($V > 15$). Such classes are in a good correlation with the damage levels defined in the modified macroseismic Mercalli scale. Then the program calculate a damage index D for each wall, which can be framed within three ranges [0-0.4], [0.4-0.8] and [0.8-1.5]. Finally mechanisms are classified as a function of the ESC factor associated to the damage occurring in the building parts interested from the same mechanism. On the basis of such information it is possible to express a judgment about the hazard level of each collapse mechanism, which provides the real building vulnerability.

3.4. The 3MURI analysis program

3MURI is a structural analysis software for assessing the behaviour of masonry buildings by means of linear and non linear analyses [12]. It is based on an innovative computational analysis procedure, the so-called Frame by Macro Element method, which is used to simulate the behaviour of new and existing masonry and mixed structures, allowing to evaluate their vulnearbility grade. When the seismic behaviour of buildings is not satisfactory, the program allows to either reinforce the existing masonry walls or insert new structural elements made of masonry, reinforced concrete or fibre reinforced polymers. 3MURI is a user-friendly calculation software which permits to draw the building geometry in intuitive way. Also, it has both an analysis solutor to create computational models and a post-processor for both immediately presenting the analysis results and implementing the calculation report.

4. VULNERABILITY ANALYSIS

The vulnerability analysis of the selected school buildings has been carried out by applying the simplified GNDT-CNR method (based on survey sheets), the semi-quantitative VM method, which requires a higher knowledge level of the building, the FaMIVE method, an analysis procedure more precise than the previous ones, and the 3MURI calculation program, which represents the most complex analysis tool herein used.

The application of the GNDT-CNR procedure has led to the results summarised in Table 4.1, where both the absolute vulnerability indices ($I_{v,abs}$), deriving from the survey form, and the relative ones ($I_{v,rel}$), normalised by dividing the former by one half of the maximum achievable index (related to the building collapse and equal to 382.50), are reported. This has been done because, as demonstrated in previous study [13], the attainment of the maximum vale is difficult to be obtained and the assumed limit is representative of extreme vulnerability cases.

Table 1 Vulnerability indices of school buildings according to the GNDT-CNR method

School	$I_{v,abs}$	$I_{v,rel}$
Orsi	82.50	0.44
Chiazzolelle – Camaldoli	93.75	0.50
Leopardi – Campanariello	101.25	0.52
Sauro	46.25	0.68
Mazza	131.25	0.24

From this table, it is apparent that the most vulnerable building under the seismic point of view is the school Mazza, due to the presence of an existing crack pattern on the walls and the absence of RC tie beams, able to give the structure a box behaviour.

Except the school Sauro, which is provided with RC tie beams, able to achieve a low vulnerability index, all the other schools present more or less the same susceptibility to be damaged under a seismic event, since either steel chains or RC tie beams are absent.

In the whole, the GNDT simplified quick procedure provide a prompt, effective and reliable estimation of the building vulnerability, giving a good forecast on the priority of retrofitting interventions to be performed.

On the other hand, if we observe the results obtained from applying the VM method, other conclusions can be drawn. This methodology provides for each school the maximum acceleration level, indicating at the same time both the structural level and the direction (longitudinal, along the longest facade, and transversal, orthogonal to the former) where this acceleration limit is attained. Subsequently, the achieved PGA values are divided by the maximum acceleration level of the Life Safety Limit State response spectrum considered in the new Italian code [3] for the area of Torre del Greco, so providing a seismic safety index I_s. Therefore, the vulnerability index is obtained as complement to one of I_s. The results deriving from VM method application are shown in Table 2, where irt is noticed that all schools have a medium-high vulnerability and that the most vulnerable school is the Leopardi.Campanariello one, which was placed in the ranking initial positions according to the CNR-GNDT method. Nevertheless, with this method schools having large masonry wall area have low vulnerability. For this reason, the schools Mazza and Chiazzolelle-Camaldoli, with a significant planimetric extension, result to be the less vulnerable buildings, in disagreement with the results of the previous analysis method. Such a result could be acceptable for buildings having a box-behaviour under seismic actions. As a result, the method is not able to perform a seismic vulnerability reliable estimation of buildings without effective floor-wall connections.

Table 2 Vulnerability indices of school buildings according to the VM method

School	PGA (g)	Floor	Direction	$I_{v,SLV}$
Orsi	0.182	Ground	Transversal	0.75
Chiazzolelle – Camaldoli	0.235	First	Longitudinal	0.67
Leopardi – Campanariello	0.143	First	Transversal	0.80
Mazza	0.217	Ground	Longitudinal	0.70
Sauro	0.171	First	Longitudinal	0.76

The FaMIVE method, able to evaluate the in-plane and out-of-plane vulnerability of masonry buildings, has been applied to the facades of all examined schools. The method provides both the ultimate multiplier of lateral loads (ESC) of different mechanisms, individuating the first to be activated, and a damage index, which assess the damage extension on the facade. In Table 3 such results are reported with reference to the most severe in-plane and out-of-plane failure mechanisms occurred. In the table failure mechanisms are indicated with a capital letter. The association of a given failure mechanism with the corresponding letter is illustrated in Figure 3.

Table 3 Analysis results according to the FaMIVE method

School	ESC	$I_{v,abs}$	$I_{v,rel}$	Damage index	Failure mechanism	Vulnerability judgement
Orsi	0.15	6.8	0.51	1.1	H	High
	0.18	5.6	0.24	1.5	B2	High
Chiazzolelle -	0.14	7.1	0.53	1.04	H	High
Camaldoli	0.13	7.9	0.34	1.3	A	High
Leopardi -	0.07	13.4	1.00	1.04	H	Very high
Campanariello	0.17	6.1	0.26	0.91	D	High
Mazza	0.10	10.2	0.76	1.12	H	High
	0.05	21.0	0.89	1.5	A	Very high
Sauro	0.12	8.6	0.64	1.12	H	High
	0.17	6.0	0.26	1.2	E	High

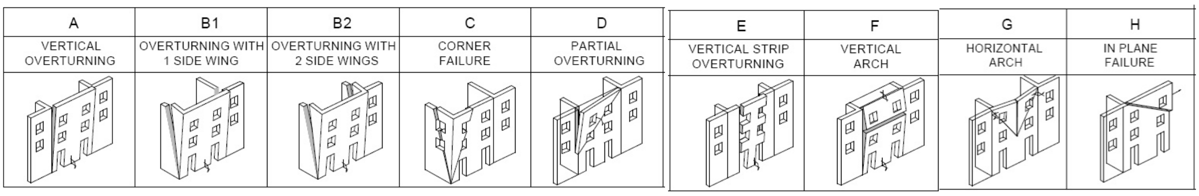


Fig. 3 Failure mechanisms contemplated in the FaMIVE method

In order to operate a comparison of results with other methods, the gotten in-plane and out-of-plane vulnerability indices have been divided by 13.4 and 23.5, respectively, which represent the maximum values attained in previous studies [11], so to obtain relative indices.

From the previous table it is evident that all schools have high vulnerability towards in-plane and out-of-plane actions, with the buildings Leopardi-Campanariello and Mazza occupying a leading position since they show a very high vulnerability to in-plane mechanism and out-of-plane one, respectively. It is worth to notice that overturning (either global type, with or without involvement of orthogonal walls, or partial type, interesting only a facade vertical strip) is the most recurrent out-of-plane mechanism with very high vulnerability index often larger than in-plane mechanism ones.

Finally, the seismic vulnerability of five schools towards in-plane failure mechanisms has been evaluated by means of the 3MURI analysis program. Static non-linear analyses have been carried out conisderin the two load distributions foreseen by the seismic Italian code [3], which takes into account also an accidental eccentricity between mass barycenter and stiffness one in order to consider both tha spatial variability of the earthquake and probable uncertanties in the location of masses.
The analyses provide the capacity cruves of buildings, which can be compared in the spectral acceleration- spectral displacement plane with the demand spectrum of a seism having 10% of probability of exceedance during the building life. The intersection between curves allows to define the vulnerability index [14]. In particular, this index, which is calculated as the ratio between the maximum displacement required by earthquake and the ultimate one of the structure, can assume value greater than one. The FEM models of investigated buildings implemented within the 3MURI software are reported in Figure 4.

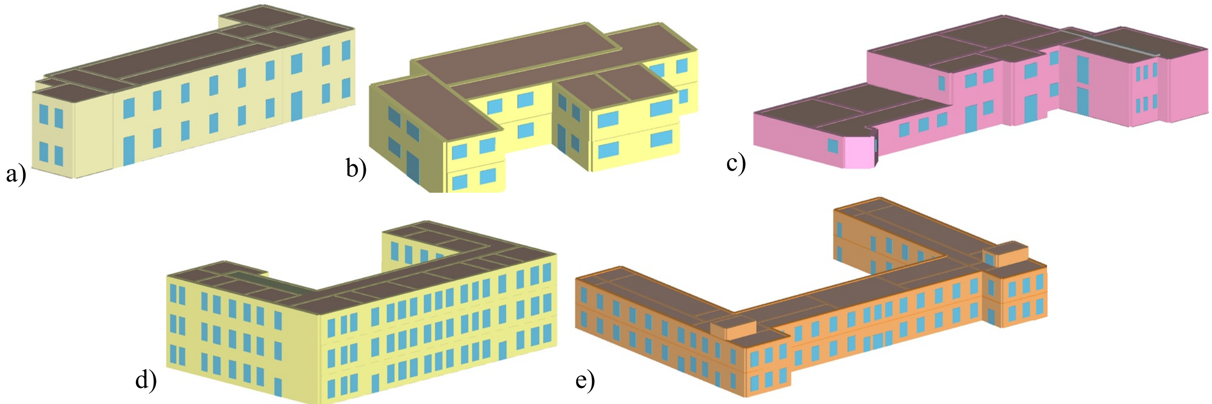


Fig. 4 FEM model of investigated school buildings: Orsi (a), Chiazzolelle-Camaldoli (b), Leopardi-Campanariello (c), Sauro (d) and Mazza (e)

The analysis results under form of vulnerability indices are reported in Table 4, where it is apparent that, since they are greater one, all schools do not withstand the seismic action considered. The building Mazza is the most vulnerable school, as foreseen by both the CNR-GNDT method and the FaMIVE procedure.

Table 4 Vulnerability indice of school buildings according to the 3MURI program

School	D_{max} (cm)	D_u (cm)	$I_v = D_{max}/D_u$
Orsi	1.31	0.84	1.56
Chiazzolelle – Camaldoli	0.95	0.80	1.19
Leopardi – Campanariello	1.09	0.84	1.30
Mazza	5.27	3.06	1.72
Sauro	1.49	1.29	1.16

As conclusion of the study, results deriving from different analysis procedures have been compared each other in order to both perform a comparison among methods and to define a vulnerability ranking of examined schools (Fig. 5). In particular, the FaMIVE indices have been achieved before by multiplying the two relative vulnerability indices (in and out-of-plane) by the corresponding damage indices and subsequently selecting the most large value between the calculated ones.
From comparison it is emerged that:

- The building Mazza is the most vulnerable school according to all methods except than the VM procedure, which provides reliable results only when masonry buildings have a box type behaviour.
- The CNR-GNDT and FaMIVE methods, which evaluate the in-plane and out-of-plane behaviour of masonry buildings, give rise to a final vulnerability ranking very similar each other, but with indices having different values. The same ranking, with the exception of the school Orsi having a poor in-plane behaviour due to slender piers collapsing under compression and bending moment, is also achieved with the 3MURI calculation program.

– By making for each school the average value among calculated indices, the following raking in decreasing order of vulnerability is obtained: 1) Mazza; 2) Leopardi-Campanariello; 3) Orsi; 4) Chiazzolelle-Camaldoli; 5) Sauro.
– The CNR-GNDT method and the 3MURI software keep better than other methods this ranking.
– The FaMIVe method is the best procedure able to foresee the vulnerability indices achieved by making the mean value of results deriving from different analysis herein performed.

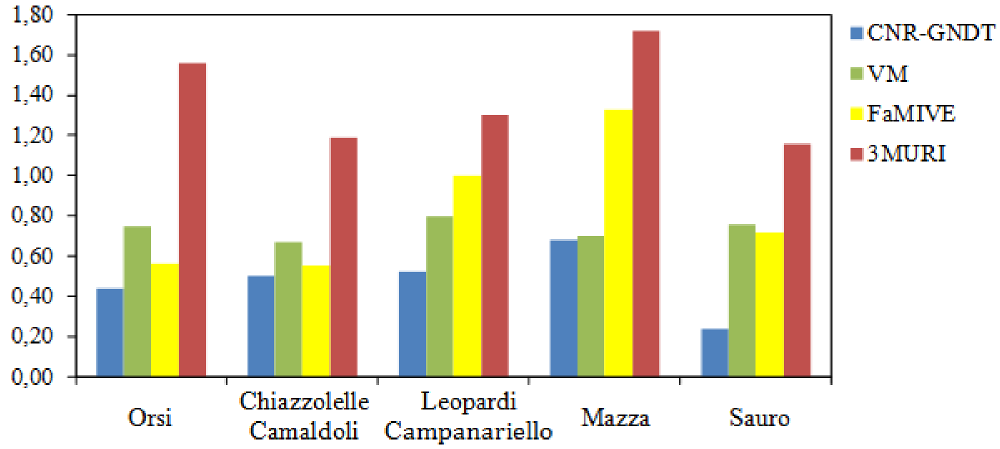


Fig. 5 Comparison among examined seismic vulnerability analysis methods applied to the five masonry school buildings of Torre del Greco

5. CONCLUSIONS

In the current paper the seismic vulnerability assessment of five masonry school buildings in Torre del Greco has been performed. This activity has been carried out by comparing the results of quick, simplified and refined analysis methodologies, which have allowed to drawn the following conclusions::

1) The building Mazza is the most vulnerable school according to all methods except than the VM procedure.
2) The CNR-GNDT method, based on simple survey sheets which do not require detailed information of buildings, provides a good forecast of in-plane and out-of-plane behaviour of examined buildings, even if the structural lacks are not identified.
3) The VM method, considering the in-plane behaviour of masonry walls only, is not able to foresee into accurate way the vulnerability level of schools since almost all of them do not have effective wall-floor connections and rigid diaphragm conferring to the building a box type behaviour.
4) The FaMIVe method, considering all types of mechanisms, is a complete and effective tool for seismic vulnerability assessment of investigated masonry school buildings.
5) The 3MURI calculation program is of course the most precise analysis tool to foresee the in-plane behaviour of masonry buildings. The program application has allowed to estimate in a correct way the vulnerability ranking of investigated schools. Nevertheless, it should be used together with an analysis tool able to evaluate the out-of-plane behaviour of masonry walls, which has been recently implemented within the software.

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