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EMPIRICAL AND MECHANICAL ANALYSIS METHODS FOR SEISMIC VULNERABILITY ASSESSMENT OF CLUSTERED BUILDINGS OF HISTORICAL CENTRES: A CASE STUDY

A. Formisano[1], **G. Mochi**[2] **and N. Chieffo**[3]

[1] Department of Structures for Engineering and Architecture
University of Naples "Federico II"
Piazzale V. Tecchio 80 – 80125 Naples (Italy)
antoform@unina.it

[2] Department of Civil and Environmental Engineering
University of Perugia
Via. G. Duranti 93 – 06125 Perugia (Italy)
giovanni.mochi@unipg.it

[3] Department of Architecture and Urbanism
Politehnica University of Timisoara
Traian Lalescu Street 2/A – 300223 Timisoara (Romania)
nicola.chieffo@student.upt.ro

Abstract

Presently, in historical centres, it is very difficult to analyse buildings as independent structures, since they share the same boundary walls with adjacent structural units. These constructions of the building aggregate interact among themselves under seismic actions, so that their behaviour differs from that of the individual buildings considered as isolated structures. Therefore, it is emerging the need to assess seismic vulnerability of building aggregates. Thus, in this paper both simple empirical and mechanical refined vulnerability evaluation methods of masonry building aggregates are examined in general terms and illustrated in detail through the application on a case study in Mirandola, a district of Modena. On one hand, two empirical assessment methodologies, mainly based on the basic observational data of masonry constructions and properly calibrated on macro-element analysis results on a significant number of clustered buildings, are proposed taking properly into account the interactions among adjacent constructions. On the other hand, a mechanical analysis method at the individual building scale is also applied to evaluate more realistically the seismic behaviour of clustered structural units through the development of appropriate capacity curves.

Keywords: Seismic Vulnerability, Masonry Aggregates, Empirical Methods, Quick evaluation, Mechanical Methods, Capacity curves.

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1 INTRODUCTION

The seismic safety of existing masonry buildings represents, as it is known, one of the main priorities for reducing the seismic risk of historical centres and is conditioned from multiple geometrical and mechanical factors that influence their behaviour against earthquakes [1].

Nowadays, in most Italian centres, it is easy to find a building heritage characterized by historic masonry constructions without an adequate structural apparatus to resist the increasingly frequent and disastrous seismic actions. This structural inadequacy generates a drastic increase of the global vulnerability and, therefore, of the seismic risk of entire urbanized sectors.

Buildings erected in aggregate conditions are often made up according to the traditional constructive practice with very variable types of vertical structure (i.e. heterogeneous or multi-leaf masonry walls) and deficient construction details (bad connections between orthogonal walls and between walls and floors, variation in the thickness of the walls along with the building height, etc.), which implicitly involve behavioural deficiencies in terms of stability in areas characterized by considerable seismicity. Furthermore, the interactions among the contiguous structural cells must be appropriately considered in the study of the vulnerability of the whole aggregate, since the dynamic response of each cell is strongly influenced by both the number of aggregate units and the position within the clustered building [2].

Based on these considerations, the present study aims to focus on the seismic response of a masonry aggregate located in the historical Centre of Mirandola, a municipality within the province of Modena. The selected masonry aggregate is made of brick walls with deformable floors, which is a typical structural typology representative of the building classes present in the examined urban area. The main objective of the present research is to study seismic vulnerability through empirical and mechanical procedures in order to provide a judgement on the effectiveness of simple analysis methods in predicting seismic vulnerability of masonry structural units of clustered buildings.

2 CASE STUDY MASONRY AGGREGATE

The case study historical building is a row masonry aggregate (Figure 1) composed of different structural units (SUs), mutually interacting to each other, which occupy different positions (heading or intermediate) within the examined clustered compound.

Figure 1: Case study aggregate placed in the historical centre of Mirandola.

From a structural point of view, the height of the structural units varies from 2 to 4 floors above ground, with an average inter-storey height of 2.80 m. The vertical structures, characterized by solid brick walls, have an average thickness ranging from 0.24 m to 0.50 m.

The horizontal structures are mainly made of wooden beams with double planking. The street views of the study building compound, together with the division of the masonry aggregate in different SUs, are depicted in Figure 2.

Figure 2: Structural layout and identification of the SUs.

Concerning the physical conditions, it has been observed that the main facades along Franciacorta street do not show, globally, a marked deterioration of the materials. Nevertheless, there are evident spots of humidity and partial detachment of the plaster, which, however, do not to alter the static behaviour of buildings. Similarly, the façade facing Dei Quartieri street does not display signs of structural decay or cracks.

3 EMPIRICAL VULNERABILITY ASSESSMENT

To estimate the seismic vulnerability of the reference case study aggregate, firstly, it is adopted a specific vulnerability index method (V.I.M.) proposed in [3], which is appropriately conceived for historical buildings aggregates. The proposed survey form takes into account the effects of mutual interaction among SUs under seismic actions with suitable five parameters accurately calibrated on mechanical analyses. So, the vulnerability index of each SU is achieved as the weighted sum of the score of each parameter multiplied by the respective weight. Consequently, the seismic vulnerability of the entire aggregate is estimated as the weighted mean of the vulnerability indices of each SUs, considering the ratio between the cell volume and that of the entire aggregate, as shown in the following Equation 1:

$$V_{I,agg.} = \sum_{i=1}^{n} \left(V_I^{SU_i} \cdot \frac{Vol_{SU^i}}{Vol_{agg.}} \right) \tag{1}$$

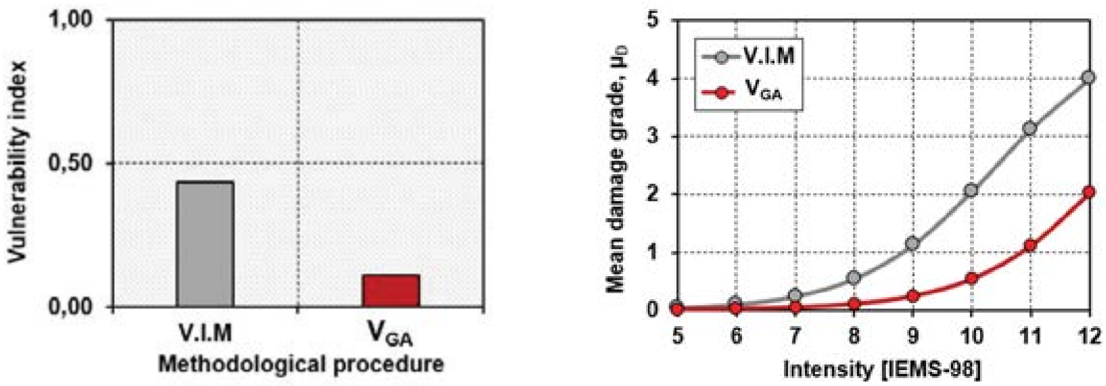
Subsequently, the methodology proposed in [4] is applied. This seismic vulnerability assessment procedure is essentially based on specific vulnerability indices, which describe, according to various constructive and functional parameters (geometric characteristics, construction period, collapse mechanisms, etc.), the seismic criticality degree of each aggregate.

This methodology allows estimating the seismic vulnerability based on a global analytical vulnerability index (V_{GA}) of the aggregate, providing an immediate quantification of the hazard of the single aggregate. Mathematically, the used analytic expression is shown in the following Equation 2:

$$V_{GA} = DM \cdot P_{DM} + RF \cdot P_{RF} + RT \cdot P_{RT} + LP \cdot P_{LP} + VT \cdot P_{VT} + MRC \cdot P_{MRC} + MSS \cdot P_{MSS} \quad (2)$$

where: DM is the masonry disconnection index, RF is the index of façades overturning, RT is the index of the gable overturning, LP is the index of strut-cracks, VT is the shear index, MRC is the R.C. hammering index and MSS is the hammering index due to staggered floor. The above mentioned factors are vulnerability indices identifying the portion of the aggregate, which results to be exposed at seismic damage. Moreover, the coefficients P_i (P_{DM}, P_{RF}, .., P_{MSS}) are the weights associated to the previously defined indices, whose numerical values are assigned proportionally to the corresponding collapse mechanism activated [4].

The two assessment methods are applied to the case study building aggregate. Figure 3 shows the comparison between the analytical indices assessed using the applied methodologies and the respective typological vulnerability curves [5] of the entire aggregate case study.



(a) (b)

Figure 3: Comparison between the proposed methodologies in terms of vulnerability index (a) and vulnerability curves (b).

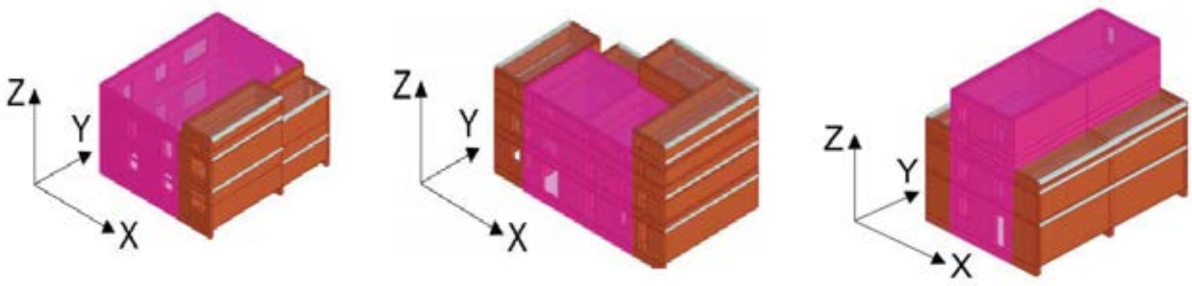
From the results acquired, it is shown how the V.I.M shows a significant increase in vulnerability (+ 26%) compared to the V_{GA} method (Figure 3a). This discrepancy is essentially due to the parameters monitored in the two methods used. The V.I.M. establishes its applicability mainly on the interactions of structural units, considering the incidence of the plane-altimetric configuration of the single SUs. On the contrary, the V_{GA} method is based on the definition of a set of indices, that affect the behaviour of the façades of the building examined. The comparison results are also presented in terms of vulnerability curves in Figure 3b, where it is seen that, starting from a macro-seismic intensity of nine, the V_{GA} method tends to underestimate of one level the expected damage compared to that of the other method proposed.

4 MECHANICAL VULNERABILITY ASSESSMENT

The numerical analyses are performed according to the 3Muri software [6] based on the Frame Macro-Elements (FME) theory. In this analysis method, it is assumed that masonry walls are considered as a set of single-dimensional macro-elements suitably interconnected to each other by rigid nodes.

The strength criteria of deformable elements are assumed based on EN 1998-3 provisions [7], which establish as maximum drifts for shear and flexural collapse failures the values of

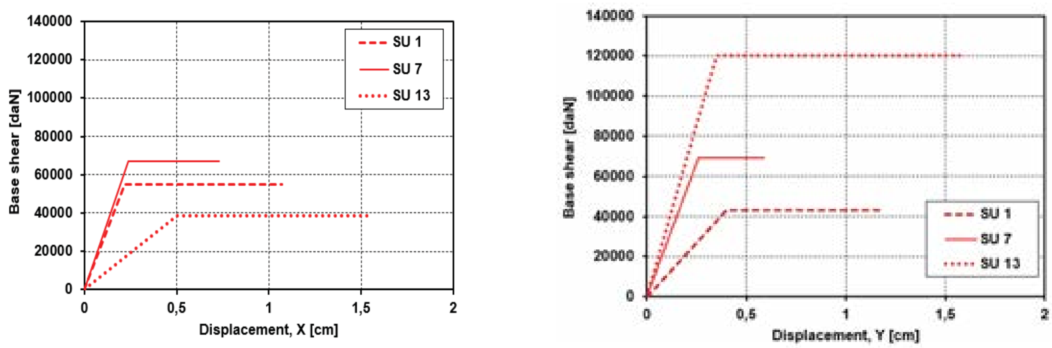
0.4% and 0.6%, respectively. Furthermore, to consider the confinement effect of the structural units contiguous to the reference one, the SUs are modelled with the 3Muri software considering half part of adjacent structural cells accounting for their contribution in terms of stiffness and mass. In Figure 4, the most representative SUs extrapolated from the whole aggregate, namely head unit (SU1) confined on one side only, intermediate unit (SU7) confined on three sides and intermediate unit (SU13) confined on two sides, are depicted.



(a) – SU1 (head) (b) – SU7 (intermed. on 3 sides) (c) – SU13 (intermed. on 2 sides)

Figure 4: Numerical models of some structural cells: head SU (a) intermediate SU confined on 3 sides (b) and intermediate SU confined on 2 sides (c).

Subsequently, the above-presented structural configurations are compared in terms of capacity curves, as reported in Figure 5.



(a) (b)

Figure 5: Capacity curves of the inspected SUs in X (a) and Y (b) analysis directions.

From the analysis of the achieved results, it is possible to appreciate how the structural behaviour of the examined SUs in the two analysis directions is very different to each other.

In particular, it is observed that in the transverse direction (X) the SU1 (head) and SU7 (intermediate, confined on three sides) provide an increase of strength about of 42% and 72%, respectively, with respect to the SU13 (intermediate, confined on two sides). Moreover, considering the comparison in terms of the ultimate displacement, d_u, the SU13 exhibits the best performance, with a value from 1.5 to 2.0 times greater than that of the other above-mentioned SUs. Conversely, in the longitudinal direction (Y), the examined structural cells display a different structural behaviour. In fact, as it is seen from the results attained in Figure 5b, the SU13 shows strength of about 3 and 2 times greater than that of SU1 and SU7, respectively. In addition, by comparing the ultimate displacements of the examined clustered units, it is noticed how the SU13 provides a value about 1.5 and 2.5 times greater than those of SU1 and SU7, respectively. Finally, the V.I.M method is applied to each of the SUS of the building compound to highlight the differences detected with the results gotten from the mechanical analyses applied to each of the SUS of the whole buildings aggregate. The comparison of results deriving from the used analysis procedures are shown in Figure 6.

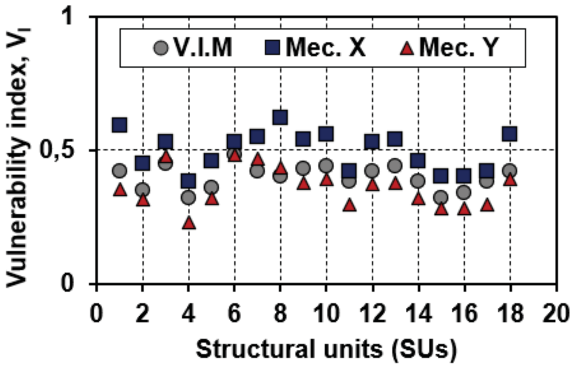


Figure 6: Comparison between V.I.M. results and mechanical method ones.

From the comparison presented, it is clear how, globally, the vulnerability level obtained by the empirical method is not very dissimilar from what is obtained by mechanical analysis. In particular, in the direction X, the mechanical analysis indices differ on average by +25% (estimated dispersion concerning the entire sample of data examined) compared to the mean value of the empirical procedure. On the contrary, in the direction Y, the data obtained by the mechanical approach differ on average by -10% compared to the average empirical one. This circumstance leads to consider that the proposed V.I.M. method is almost effective for the simplified estimation of the seismic vulnerability of SUs of masonry building compounds.

5 CONCLUSIONS

The present research applied different analysis procedures for seismic vulnerability evaluation of historical buildings in aggregate condition. In particular, two different approaches, namely empirical (V.I.M. and A.V.I.) and mechanical, were used to determine the seismic vulnerability of a clustered building located in the municipality of Mirandola. From the application of empirical methods, based on specific and synthetic survey forms, it was found that:

- The V.I.M method, specifically conceived for cluster buildings, allowed to estimate the vulnerability of the whole building aggregate as a weighted average of the indices of the individual structural units (SUs), providing a medium-low vulnerability level equal to 0.43;
- The method proposed by Gulli et al., which was derived as a weighted sum of specific local vulnerability indices, mainly taking into consideration the behaviour of the façade walls, provided a synthetic vulnerability index equal to 0.106 (low vulnerability);
- The comparison between the empirical methodologies showed how the V_{GA} index underestimates, on average, the expected vulnerability by + 26% compared to the V.I.M. one. This discrepancy was reflected in the evaluation of the average damage degree too. In fact, starting from a macroseismic intensity equal to nine, a mean underestimation of the expected damage degree of 33% was found by applying the methodology proposed by Gulli et al.

Subsequently, mechanical analysis was carried out on each of the SUs composing the aggregate to compare the achieved results with the corresponding ones deriving from the empirical V.I.M. method. From comparison, it was noticed that:

- In the two analysis directions, a variation of the seismic capacity was observed for the SUs examined. In particular, in the direction X, the monitored base shear provided by the SU1 and SU7 was 42% and 72% higher than those of the corresponding SU13, respectively.

Moreover, the SU13 exhibited a significant increase of the capacity displacement, with a value from 1.5 to 2.0 times greater than that of the other above-mentioned SUs. On the contrary, in direction Y, it was observed how the SU13 provided a shear strength about 3 and 2 times higher than that of SU1 and SU7, respectively. In addition, by comparing the ultimate displacements of the examined clustered units, it has been noticed how the SU13 provided a value about 1.5 and 2.5 times greater than those of SU1 and SU7, respectively.

- The vulnerability level attained by the empirical V.I.M. method did not result dissimilar from what was obtained by the mechanical approach. In particular, in the direction X, the mechanical simulation overestimated by +25% the mean index of empirical procedure. On the contrary, in the direction Y, the vulnerability index obtained by the mechanical approach underestimated on average by 10% the seismic safety condition deriving from the simple empirical method.
- In conclusion, based on the above-mentioned results, it was found that the V.I.M. method is quite suitable in predicting, through a simple analysis tool, the seismic vulnerability of SUs of clustered buildings.

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