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VULNERABILITY OF HISTORICAL CENTRES IN SEISMIC AREA: RELIABILITY OF ASSESSMENT METHODS FOR DIFFERENT BUILDING TYPOLOGIES

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Abstract

The application of simplified models for the limit analysis of existing masonry structures in seismic area is discussed in the paper. The procedure is mainly based on equilibrium conditions of macro-elements, involving kinematics mechanisms of structural components and assemblages. It allows evaluating the safety level of existing buildings in old centres according to the real conditions detectable in situ, often not satisfying the main hypothesis at the base of calculation methods designed and aimed at modern masonry structures (insufficient connections among components, presence of poor and non-homogeneous materials, lack of bond in the thickness of masonry wall, etc.). Different typologies of buildings located in three historic centres of the Umbria Region (Italy) are analyzed, characterized by various levels of damage.

Key Words

Seismic vulnerability, historic masonry buildings, macro-elements, improvement interventions.

1 Introduction

The extensive in-situ surveys of some masonry buildings centres damaged during the 1997 Umbria-Marche earthquake in Italy pointed out the importance of a correct design and control of the execution of the repair interventions, based on the deep knowledge of the structure and its mechanical behaviour (Binda et al 1999, Penazzi et al 2000). Retrofitting after a previous earthquake, mainly performed with heavy interventions

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(substitutions of timber floors and roofs with r.c., jacketing, etc.), showed unforeseen and serious out-of-plane effects (large collapses, local expulsions), due to the "hybrid" behaviour activated from the new and the old structures (Penazzi et al 2001). That is often not clearly predictable by assessment methods, also suggested by the national standards, based on hypotheses often not easy to be satisfied in old centres as: effective strong connection among the structural components, presence of stiff floors able to transmit the horizontal forces to shear walls, both characterizing the favourable "box" behaviour of buildings under seismic actions.

Recently, procedures for the evaluation of the seismic vulnerability, based on the application of single or combined kinematics models involving the equilibrium of macro-elements (Bernardini et al 1988, Giuffrè 1993), have been developed by direct comparison with the real damage occurred (Valluzzi et al 2001, Avorio et al 2002).

Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond and restraints (e.g. the presence of steel ties or tie concrete beam insertions), the constructive deficiencies and the characteristics of the constitutive materials. Once the critical structural configuration is defined, the subsequent step is the identification of the most probable collapse mechanism/s characterizing each macro-element.

Several studies based on the in-situ observations after seismic events allowed to arrange abacuses of the typical damages occurring in constructive typologies (buildings, churches), which led to the consequent systematization of the mechanical models able to describe their specific behaviour by kinematics models, both for in-plane and out-of-plane mechanisms. Kinematics models refer to a collapse coefficient $c=a/g$ (where a is the ground acceleration and g the acceleration of gravity), which represents the masses multiplier able to led the element to failure. In the simplified assessment procedures, the mechanism connected to the lowest value of c is the weakest one and, consequently, the most probable. The collapse is thus due to a loss of equilibrium of its structural portions rather than to the overcoming of the material ultimate capacity.

Automatized procedures able to combine the different possible mechanisms have been implemented at the University of Padova, both concerning global and local analyses (VULNUS, by Bernardini et al 1988, and C-SISMA, respectively). They have been recently updated in Visual Basic ambient, in order to allow vulnerability analyses in a more large scale, more quickly and easily in comparison to the first applications.

In particular, VULNUS is able to define two indexes, I1 and I2, related to the in-plane and out-of-plane collapse mechanisms, respectively, still defined by a proper combination of the collapse coefficients c=a/g (Bernardini et al 1990).

In the paper, the procedure is preliminarily validated for a damaged isolated building (Montesanto), by comparing the results of the analysis with the surveyed crack pattern. As following step, the same procedures was applied on a more complex building (Roccanolfi): such phase pointed out some limits of the general methods working at global level, as the related required simplifications can be too far from the real configuration of the construction. Finally, the analysis was updated on the low damaged row buildings typology (Campi), in order to predict the current seismic vulnerability and to simulate some proposal of rehabilitation and improvement interventions.

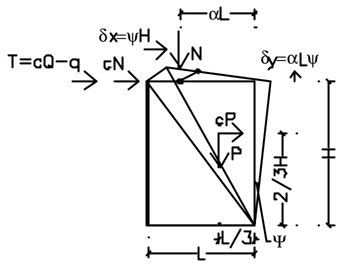
2 Structural macro-modelling

2.1 In-plane mechanisms

In-plane mechanisms involve walls parallel to the seismic action, when connections among components can assure a proper "box" behaviour of the structure. They induce the typical shear damage, which often is not sufficient to lead the structure to collapse,

in comparison with out-of-plane mechanisms. Therefore, in-plane mechanisms are characterized by collapse coefficients higher than the out-of-plane ones.
Kinematics chains describe the in-plane rigid rotation of the vulnerable structural portions of the building, defined by particular geometrical (dimensions, openings) and bond conditions (connection, presence of ties), under in-plane horizontal actions.
For each wall, the resisting sects and the related involved seismic forces are identified. Fig. 1 shows the single and multiple-panel cases (Giuffrè 1993). Symbols are as follows: *N* is the vertical load acting at a distance of aL from the compressed edge, *P* is the weight of the detaching portion and *T* is the tensile force in the tie, obtained by the difference between the weight *cQ* of the supported portion of the wall and the counteraction *q* allowed from the supporting base of the wall.

a)



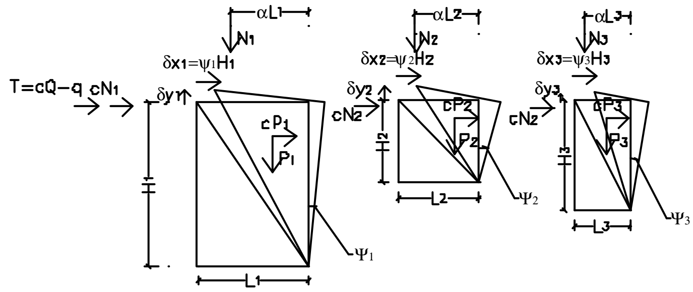
Equilibrium condition:

$$-N\times aL - P\times\frac{L}{3} - q\times H + c\left(N\times H + Q\times H + P\times\frac{2}{3}H\right) = 0$$

Collapse coefficient:

$$c = \frac{N\times aL + P\times\frac{L}{3} + q\times H}{N\times H + Q\times H + P\times\frac{2}{3}H} = \frac{L}{H}\times\frac{Na + \frac{P}{3} + q\frac{H}{L}}{N + 2\frac{P}{3} + Q}$$

b)



Equilibrium condition:

$$-N1\times 0.75L1 - N2\times 0.75L2\times\frac{H1}{H2} - N3\times 0.75L3\times\frac{H1}{H3} - P1\times\frac{L1}{3} - P2\times\frac{L2}{3}\times\frac{H1}{H2} - P3\times\frac{L3}{3}\times\frac{H1}{H3} - q\times H1 +$$
$$+c\left(N1\times H1 + N2\times H2\times\frac{H1}{H2} + N3\times H3\times\frac{H1}{H3} + P1\times\frac{2}{3}\times H1 + P2\times\frac{2}{3}\times H2\times\frac{H1}{H2} + P3\times\frac{2}{3}\times H3\times\frac{H1}{H3} + Q\times H1 = 0\right.$$

Figure 1 In-plane kinematics model for a wall under in-plane actions: a) single wall, b) multiple-wall system (wall sects separated by windows)

2.2 Out-of-plane mechanisms

Out-of-plane mechanisms involve walls orthogonal to the seismic action. The overturning of portions or whole walls is the main action, which is counteracted by the possible presence of connection elements (steel ties or concrete ring beams) or intrinsic resisting actions (e.g. arch effect of the wall in its thickness).
The method is based on equilibrium equations which can take into account also the strength of the materials (crushing of masonry, tension in the tie, etc.).

In Fig. 2 and 3 mechanisms involving horizontal and vertical strips of the walls are grouped, respectively. Nearby the kinematics scheme the formulation of the collapse coefficient is given.

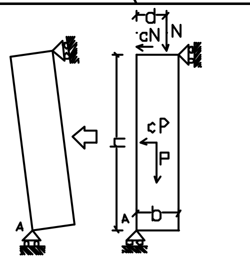
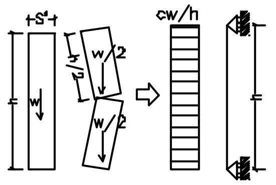
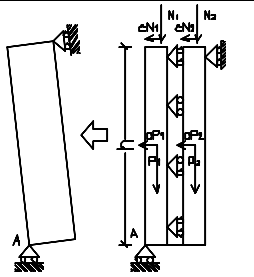
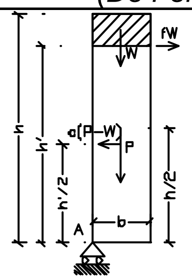
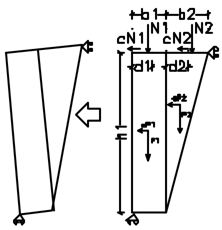
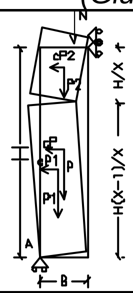
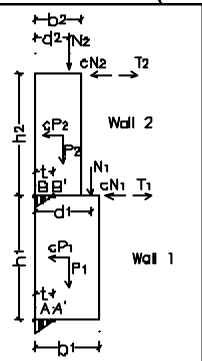
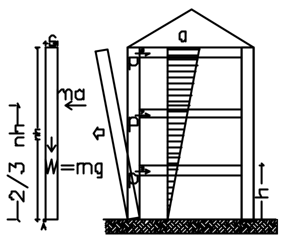
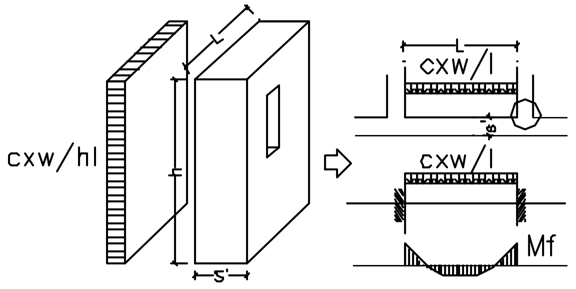
Overturning of a monolithic wall simply supported by the orthogonal wall (Avorio et al 2002)		*Out-of-plane collapse of a wall subjected to high confining forces (Bernardini et a 1988)*	
	$c=\dfrac{P\times\frac{b}{2}+N\times d}{P\times\frac{h}{2}+N\times h}$		$c=\min\left(\frac{2s'}{h};\frac{(s_t+\frac{w}{2})\frac{4}{3}s'^2}{wh^2}\right)$
Overturning of a double-layer wall simply supported by the orthogonal wall (Avorio et al 2002)		*Overturning of a wall restrained at the top by a ring beam (De Felice et al 1999)*	
	$c=\dfrac{P_1\times\frac{b_1}{2}+N_1\times d_1}{(P_1+P_2)\times\frac{h}{2}+(N_1+N_2)\times h}$		$c=2f\,\frac{h-h'}{h}+\frac{bh}{h'^2}$
Overturning of a wall connected to a perpendicular weak wall (Avorio et al 2002)		*Overturning of a wall restrained at the top by a tie (Giuffrè et al 1999)*	
	$c=\dfrac{P_1\times\frac{b_1}{2}+N_1\times d_1+P_2\times\left(b_1+\frac{b_2}{3}\right)+N_2\times(b_1+d_2)}{P_1\times\frac{h_1}{2}+N_1\times h_1+P_2\times\frac{2h_1}{3}+N_2\times h_1}$		$c=\frac{B}{H}\cdot\dfrac{2x+\left(\frac{N}{P}\right)(x+1)x}{x-1}$
Overturning of multi-floor walls not connected to an orthogonal wall (Avorio et al 2002)		*Global overturning of a wall with the counteracting action of the floors (Bernardini et al 1988)*	
	$c=\dfrac{P_2\times\frac{b_2}{2}+P_3\times\frac{b_3}{2}+N_2\times d_2+N_3\times d_3}{P_2\times\frac{h_2}{2}+N_2\times h_2+P_3\times\left(h_2+\frac{h_3}{2}\right)+N_3\times(h_2+h_3)}$		$c=0.75\frac{s}{h}\times\frac{1}{n}+\frac{p'}{W}n$

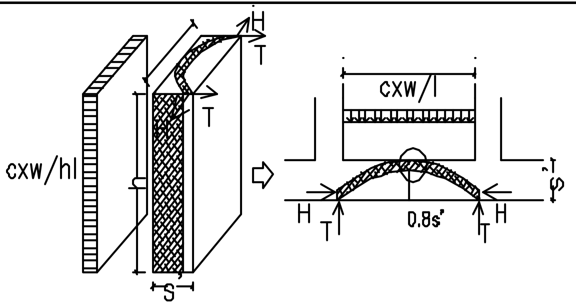
Figure 2 Kinematics models for out-of-plane mechanisms: vertical strips

Fixed beam mechanism



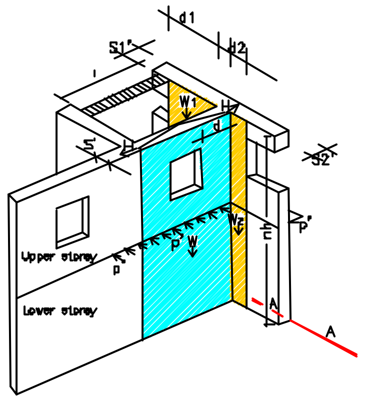
$$c = \frac{2 s_t \times h \times s'^2}{w \times l}$$

Arch effect in the thickness of the wall: ultimate condition for masonry crushing



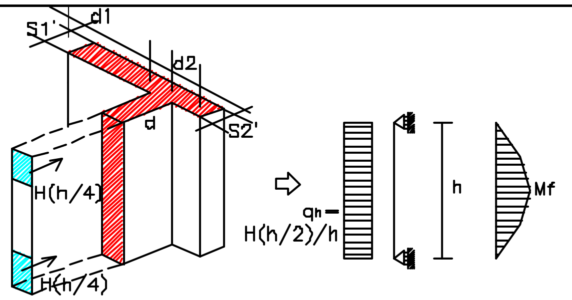
$$c = 1.28 \frac{s_c \times s'^2 \times h_{netta}}{w \times l}$$

Arch effect in the thickness of the wall: ultimate condition for abutments overturning



$$c = \frac{P_e\left[\frac{d_1^2 s_1^2 + d_2^2 s_2^2}{2} + (s+l)^2 \frac{s''}{8}\right] + p'\left(d_1 + d_2\right)\frac{2}{3} n}{P_e \frac{l^2}{6.4}}$$

Arch effect in the thickness of the wall: ultimate condition for compressive failure in the section



$$c = \frac{(s_t + P_e \times \frac{h}{2}) \times (2d \times \frac{d_1 s_1' + d_2 s_2'}{3} + d \frac{ds'}{6})}{\frac{P_e}{64} s \frac{l^2}{1.6 s'} h^2}$$

Figure 3 Kinematics models for out-of-plane mechanisms: horizontal strips (Bernardini et al 1988)

3 Application on real cases

3.1 Isolated highly damaged building

To validate the proposed procedure a first application was performed on isolated masonry buildings located in a centre highly damaged during the 1997 Umbria-Marche earthquake (Montesanto), on the basis of accurate surveys performed by the Polytechnic of Milan, the University of Genova and the University of Padua (Binda et al 1999), which allowed to systematize the possible mechanisms of collapse (both in original and retrofitted conditions) in a reference abacus. Therefore, the assessment of the reliability of the macromodelling method was performed by direct comparison of the obtained results with the real damage occurred (Valluzzi et al 2001).
The analysis of an isolated building (Fig. 4) showed that the kinematics models which correspond to the lowest *c* coefficients (values lower than 0.28, which is the safety limit for the considered seismic zone prescribed by the national standards) are consistent with the main collapse mechanisms ascribable to the real damage (Fig. 5). In particular, they concern out-of-plane effects like the overturning of the most damaged façade (East) and of the corners. The presence of typical shear sloped cracks is related, in fact, to in-plane mechanism connected to higher *c* coefficients (s. Fig. 5).

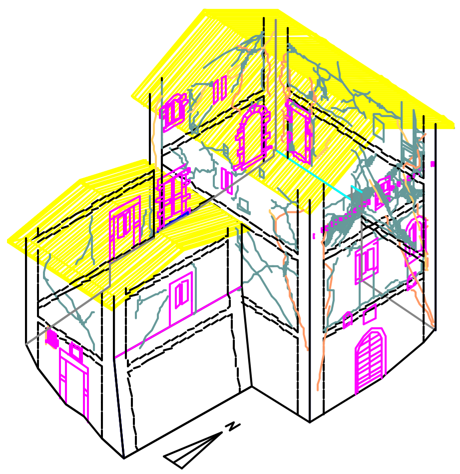


Figure 4 View of the building with survey of the crack pattern: the most damaged portions are the Eastern wall and the Nord-Eastern corner (overturning effects)

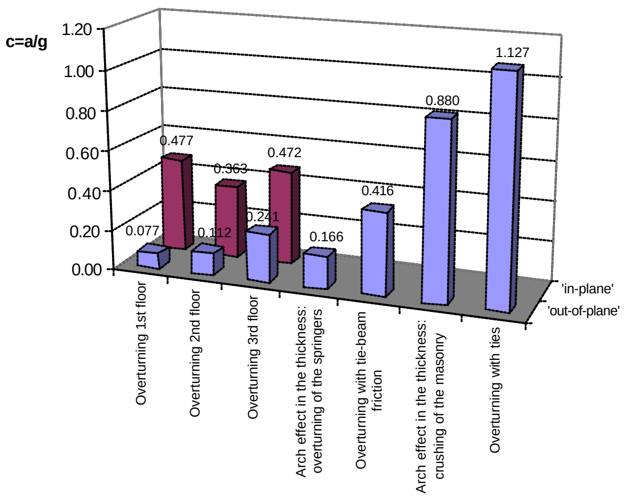


Figure 5 Comparison among the single kinematics models: the lowest seismic coefficients are related to the out-of-plane mechanisms involving the most damaged portions of the building

3.2 Highly damaged aggregate

The study of a large complex located in Roccanolfi was considerd (Fig. 6 and 7), with reference to one of the most damaged aggregates of buildings (Fig. 8) (aggregate "C", evidenced in Fig. 6). For buildings characterized by more adjacent constructions (rows, complexes) the general procedure for the vulnerability assessment consists in performing first of all the global analysis, then to control some local aspects by using the single kinematics models.
Nevertheless, some cases detectable in historical centers can have very complex architectural and constructive aspects, so a critical approach is necessary in every phase. The considered complex is particularly irregular both in plan than in section (Fig.

6 and Fig. 7); it can be subdivided in eleven units (from RcC1 to RcC11), considered separately in the study (Fig. 6).

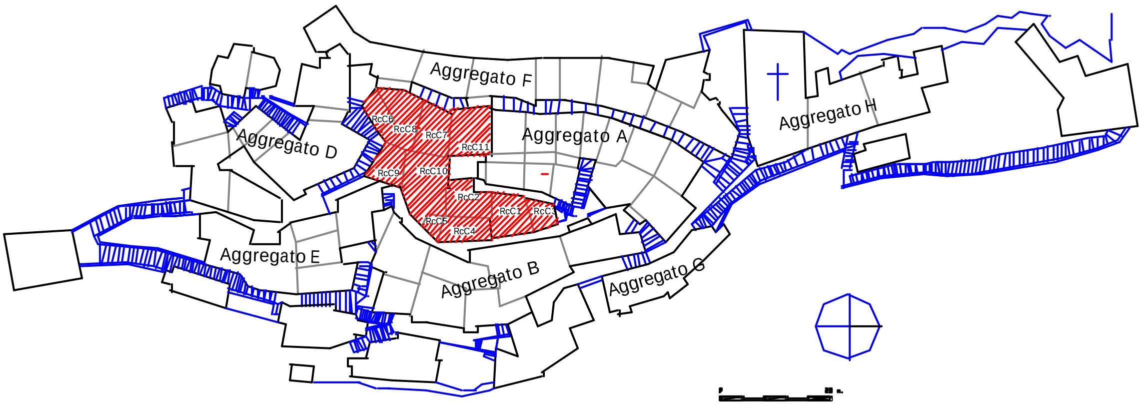


Fig. 6 Plan of Roccanolfi, where the hatched area corresponds to the "aggregate C"

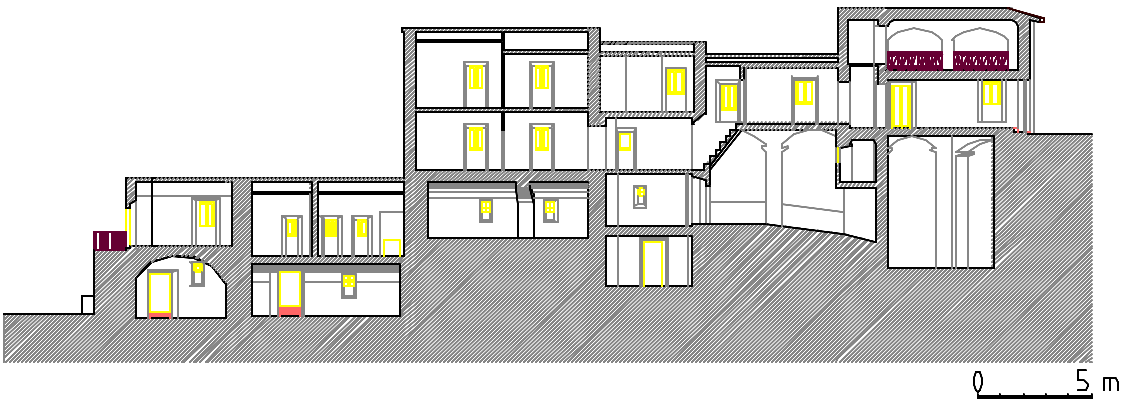


Fig. 7 Typical longitudinal section of the aggregate "C"

Analysis performed at global level by VULNUS showed that a prevalent number of units composing the complex have out-of-plane index (I2) lower than the safety limit imposed by the national standards (c=0.28) (Fig. 9). Those results are in agreement with the in-situ survey, as the highest values correspond to the most damaged portions. By operating with simulation of three degrees of seismic intensity, it was also possible to identify the vulnerability classes related to the several units of the building. Fig. 10 shows the synthesis of the analysis, by considering the different seismic hazard levels. Again, results are consistent with the observed damage; in fact, units belonging to high vulnerability class suffered severe damage (especially collapse of the upper floors), whereas for lower vulnerability classes units evidenced lower damage. Nevertheless, for some units (e.g. RcC1 and RcC10), having very irregular configuration, excessive simplifications were adopted to describe conditions not easy to foresee in automatic procedures (floors at different heights, presence of arcades and loggias, very bad quality of masonry walls in the thickness). As results, those elements conducted to very low coefficients, which even if increasing the global safety, are not responding to the real conditions detectable in-situ.

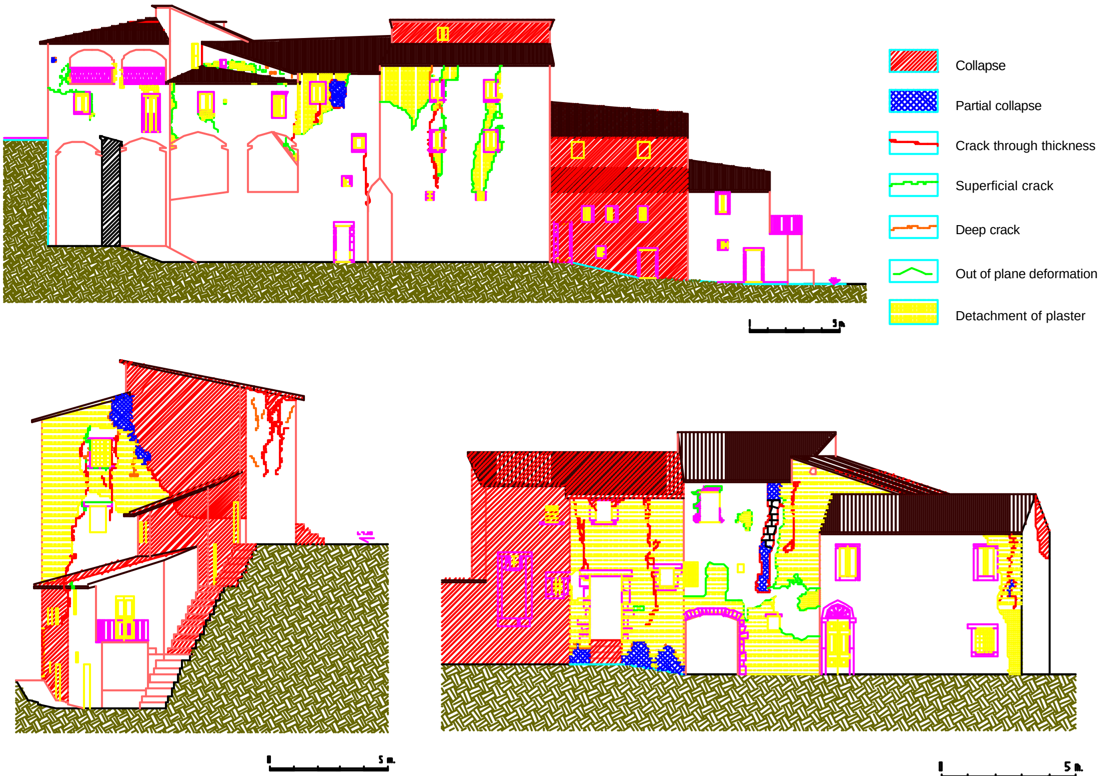


Fig. 8 Crack pattern and damage observed on the aggregate "C"

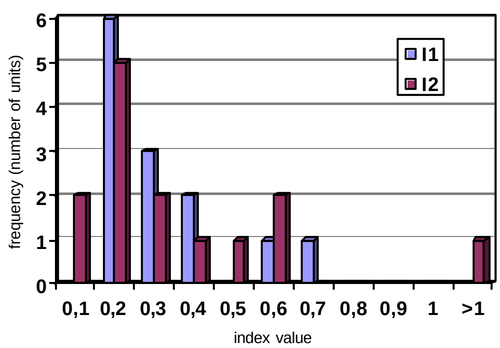


Fig. 9 Comparison between the indexes I1 (in-plane mechanisms) and I2 (out-of-plane mechanisms) for the various buildings of the aggregate "C"

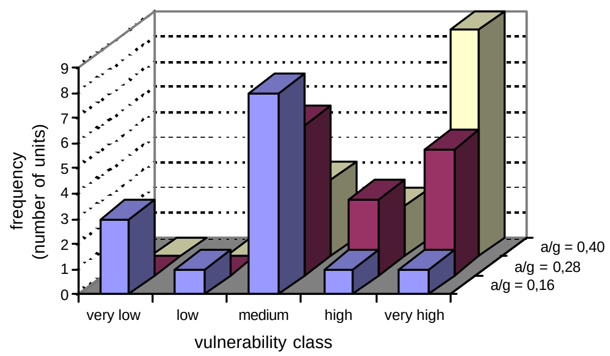


Fig. 10 Estimation of vulnerability for different classes of limit seismic coefficient

3.3 Row buildings in low damage conditions

A typical centre arranged in concentric rows surrounding a slope is Campi Alto of Norcia (Fig. 11). After the 1979 earthquake that caused many damages to the building structures, buildings were retrofitted with heavy interventions that unfortunately changed almost all the original medioeval masonry features, even if the seismicity in the valley was of minor entity. Damages found in Campi after the 1997 seism were, in fact, of irrelevant nature, and mainly located in buildings not repaired since a very long time.

Fig. 11 Localization of the analysed row in the historic centre of Campi (dark coloured buildings are the still standing ones)

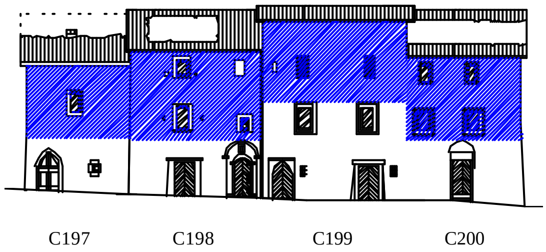


Fig. 12 Evidence of the panels with lowest seismic coefficient (global overturning of a two floor wall)

As expected, results of the general analysis conducted on the rows with "Vulnus" denote a particular sensitivity of the most brittle mechanisms (overturning) for the head buildings of the rows; this was detected also by the application of the single collapse mechanisms. As an example, Fig. 12 and Fig.13 show the analysis performed on a row composed by four units, where the weakest mechanism (overturning of the upper floors), was found.

For the same row, the simulation of some intervention as the strengthening of the masonry walls with injections (where applicable), the possible filling of the openings too close to the corners of load bearing walls, and the rehabilitation of wooden floors and roofs with stiffening compatible techniques (Modena et al. 1998), can induce a significant improvement. This is quantifiable with a proper reduction of the specific vulnerability, as shown in Fig. 14 (in the figure, the only reduction of the coefficient is related to the C199 unit, where the rebuilding with original stones of one of its panels which was previously substituted with clay bricks is simulated; it is possible to notice that changing is still assuring a proper safety level of the building).

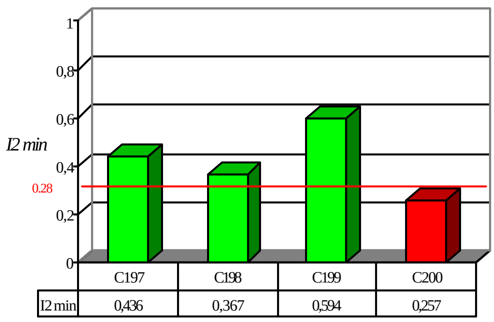


Fig. 13 Comparison among the building of the row of the I2 index (out-of-plane mechanisms)

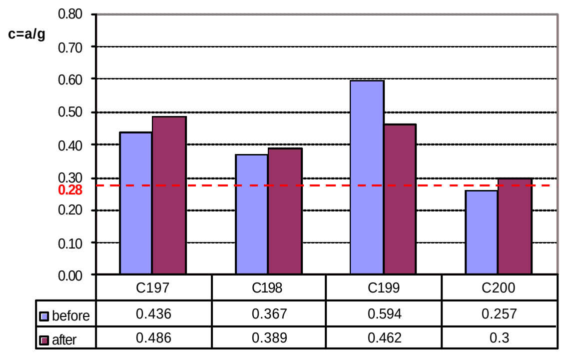


Fig. 14 Simulation of intervention with "Vulnus" for out-of-plane mechanisms

4 Final remarks

The study of the existing patrimony of masonry buildings in seismic area can be performed by using the macro-modelling analysis. The procedure is based on the observation and survey of the real conditions detectable in-situ (morphology, constituent materials, connections, possible damage, etc.). It is reliable for different typologies of

buildings (isolated, rows, aggregates) both in assessment and in intervention proposal phases. Nevertheless, too complex cases need a more cautious approach, as the adopted simplifications can lead to too rough estimations.

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