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Mechanical Analysis for the Assessment of the Seismic Capacity of Masonry Buildings' Classes in the City Centre of Sulmona (Italy)

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Abstract A mechanical based method for the evaluation of the seismic capacity of masonry buildings' classes in terms of damage limit states is presented: the purpose of the study is to achieve, in the framework of vulnerability analyses at territorial scale, reliable values for the damage level of vulnerability classes of masonry buildings, depending on the seismic input level. This approach is, in fact, designed as a "1st level" tool based on easily traceable information provided by expeditious surveys. Once identified a limited number of typological, physical and mechanical parameters that are necessary to define each vulnerability class, a significant number of simplified models of masonry buildings belonging to each class has been created. Non-linear static analysis of these models allowed the creation of bilinear elastic perfectly plastic capacity curves: the displacement capacity described by these curves is related with the actual displacement values required by seismic intensities associated to different return periods. It is so possible to identify, for different vulnerability classes and different seismic inputs, the loss of capacity in terms of damage level of each building. An application of the method to models representative of masonry buildings in the historical centre of Sulmona, in L'Aquila province, and a comparison of the results with others obtained with other methodologies of assessment are presented.

Keywords: Masonry building, seismic capacity, vulnerability class, EMS98 macroseismic scale

Introduction

In the framework of Task 5/7 of the Research Line 10 of the research project ReLUIS 2005-2008, a study that realized mechanical analysis for assessing the earthquake resistance capacity of some classes of existing masonry buildings was conducted: the loss of capacity (loss of functionality) suffered under various seismic actions has been associated to the physical damage through analysis based on physical and mechanical parameters derivable from synthetics/speditive investigations and surveys. This study represented a contribution to the development of a general model for the analysis of Urban Systems (Cherubini et al. 2009).

The conducted study considered as reference urban centre the historical centre of Sulmona: therefore, the analysis carried out, while maintaining a general character, connected to the approach by classes of the analysis, are often related to the buildings typologies representative of the Center.

The work considered simplified models of buildings types, representative of the building types of Sulmona, on which nonlinear static (pushover) analysis were performed, from which to derive curves of capacity. These models are differentiated and are divided into different classes on the basis of the parameters that define them.

Identification and Selection of the Parameters

To identify the physical and mechanical parameters needed to describe the initial earthquake resistance capacity of the considered buildings prototypes, referring to the identified level of analysis, different sources of information were taken into account.

The analysis of the different sections of the AeDES 1st level survey form (damage detection and useability for ordinary buildings in post-earthquake emergency - Bernardini 2000) and in particular

the analysis of Section 3 was useful to select those data that are routinely collected through typological 1st level on site survey.

Other important parameters were obtained by the typological classification proposed by the 1998 European Macroseismic Scale (EMS98 - Grünthal 1998) , partially modified by (Giovinazzi and Lagomarsino 2001): for each structural material (masonry, reinforced concrete, steel and wood) are thus identified different constructive typologies: for masonry buildings seven typologies, that represent the Italian building tradition, that include different materials, techniques and construction details, are considered.

Finally, to take into account the typological parameters of the masonry buildings of the city centre of Sulmona, the data obtained by two survey campaigns (1999 Abruzzo Region project; 2006 SISMA Project - Cifani et al. 2006) were analysed: The results of the investigations are collected in a database that contains information on about 158 masonry nuclei (about 1200 structural units) and 52 reinforced concrete buildings (about 60 structural units). The most widespread structural typology in the centre of Sulmona is made up of units with stone masonry walls, slabs made with steel beams and brick elements (but masonry vaults are often present on the ground floor) and wooden roofing (often replaced by reinforced concrete roofing during restoration interventions). Vertical structures are usually well connected and ties are often present at the floors levels, although they are rarely present at all the levels of the building.

The most significant parameters were then identified: they allowed the division into vulnerability classes of the simplified models that represent the masonry structures of the city centre of Sulmona. In particular, the considered parameters are: the type of masonry (according to the types identified in the Italian code: disordered rubble masonry, masonry of roughly worked stone, brick masonry, squared stone blocks masonry), the types of slabs and roofs (masonry vaults, wooden slabs, steel beams and brick elements, reinforced concrete slabs), the number of floors (from 2 to 4), the inter-storey height (270 or 320 cm), the presence of internal bearing walls and the presence of elements that reduce the seismic vulnerability (ties or tie-beams, properly sized). The thickness of the walls varies with the mechanical properties of the material that forms the walls and the other previously mentioned parameters: the values obtained were always compared to those typically observed in real cases (Munari et al. 2010).

Definition of the Vulnerability Classes The vulnerability classes are a tool for the grouping of different buildings that are characterized by similar behaviour toward the seismic action: to each vulnerability class is then associated a relationship between damage and intensity of the earthquake.

A direct correlation between construction typologies and more probable vulnerability classes is proposed: starting from the identified parameters a grouping that considers only three vulnerability classes that represent existing masonry buildings (classes A, B and C) is defined. Each class is characterized by a set of parameters whose variables identify the total number of models to be analysed for each group (Table 1).

Applying this classification parameters to the sample of buildings found in the centre of Sulmona and in the database, it appears that a significant number can be considered in Class B (856 out of a total of about 1000), 116 have the characteristics of Class A, while only 10 are in class C.

Mechanical Modeling

Within the seismic analysis, the pushover analysis is, for different reasons, of great importance, being recognized as an effective tool for rough estimates of the seismic response of structures. The updated Italian seismic code proposes a method that is based on a simplified procedure in which the problem of assessing the maximum expected response is reduced to the study of a nonlinear single degree of freedom system, that is equivalent to the model with n degrees of freedom, which represents the real structure. The system can be represented by capacity curves, that represent the envelope of the hysteresis cycles generated during the earthquake and shows the trend of the base shear versus the resulting horizontal displacement of a control point of the structure: the curve is obtained by assigning

a fixed distribution of forces (in this case a distribution proportional to the masses has been considered), that simulate the inertial forces induced by the earthquake, and by increasing them statically and monotonically, until the collapse. Each point on the curve corresponds to a specific state of damage of the entire system and it is therefore possible to associate certain levels of displacement to certain expected degree of functionality and to the related damage: the curve is converted to a bilinear, having a first elastic part and a second perfectly plastic part, normally calculated assuming an equivalent period (of damaged structures) and an equivalent dissipation energy.

Table 1: Definition of the vulnerability classes depending on the chosen parameters

Vulnerability class	*Parameter*	*Variables*	*Number of models*
A CLASS	Masonry typology	disordered rubble masonry	16
	Slab typology	masonry vaults / wooden slabs	
	Roofing	wooden roofing	
	Number of floors	2 / 3	
	Inter-storey height	270 / 320 cm	
B CLASS	Masonry typology	masonry of roughly worked stone / brick masonry	48
	Slab typology	masonry vaults / steel beams and brick elements	
	Roofing	wooden / reinforced concrete	
	Number of floors	2 / 3 / 4	
	Inter-storey height	320 cm	
	Ties presence	Yes / No	
	Internal walls presence	Yes	
C CLASS	Masonry typology	squared stone blocks masonry	12
	Slab typology	reinforced concrete slabs	
	Roofing	reinforced concrete roofing	
	Number of floors	2 / 3 / 4	
	Inter-storey height	270 / 320 cm	
	Tie-beams presence	Yes	
	Internal walls presence	Yes / No	

The program used to perform this type of analysis is the 3Muri software, developed by a group of researchers of the University of Genova and of the EUCENTRE of Pavia. The reference model is the three-dimensional equivalent frame, where the structure is modelled by assembling planar structures (walls and slabs), with no out of plane bending stiffness; the modelling of the global behaviour is therefore based solely on the behaviour of the walls in their own plans. Certain portions of masonry, in which deformation and damage are concentrated, are modelled with finite two-dimensional macroelements. The remaining portions of the walls are considered as two-dimensional nodes, which connect the macroelements. This division into nodes and elements allows to compare the model of the walls to a plane frame.

With this program several simplified models, with rectangular shape, representing the different vulnerability classes, have been investigated, in order to determine the respective capacity curves: in particular, 16 models for class A, 48 for Class B and 12 for class C were examined. For example, in Fig. 1 some views of the models with two floors, with and without internal walls are presented.

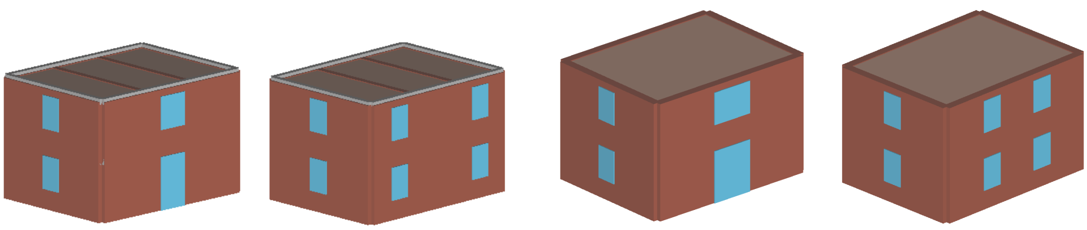

Figure 2: Isometric views of the considered models (2 floors case, with and without internal walls)

Bilinear capacity curves represent the evolution of the structural response to a horizontal seismic action starting from the initial not damaged condition (elastic behavior), passing through the

formation and progress of cracks, until the collapse: they are characterized by the value of the yielding shear base and by the displacement values dy (corresponding to the yielding condition) and du (ultimate displacement: maximum displacement capacity of the building). Fig. 2 shows the capacity curves determined by 3Muri, assembled in a diagram related to the A vulnerability class. The geometric and structural choices made in the modelling phase influenced the seismic response gave by the different models and the elaboration of the capacity curves.

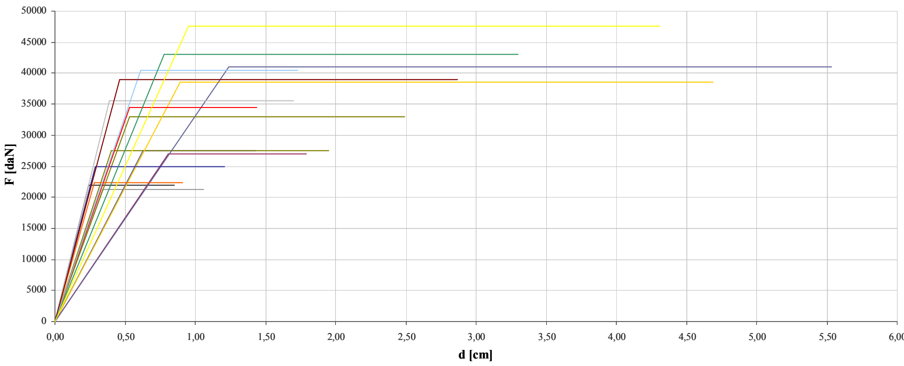

Figure 3: Capacity curves of the models belonging to A vulnerability class

Identification of the damage degree The expected performances have been investigated for each model, depending on the occurrence of a given seismic event. The effective displacement response d_{max} can be represented by identifying the "perfomance point", obtained by the intersection between the capacity curve and the adequately reduced response spectrum. This methodology is referred to the non-linear static procedures, as the Capacity Spectrum Method, adopted in the American code, and the *N2* Method, included in the European and Italian codes.

The capacity provided by the structure and the requests of the earthquake are mutually dependent and related to the variation of stiffness and damping developed by the system during the event: the increasing of the displacement and the evolution of the damage state in non-linear state correspond, in fact, to an extension of the fundamental period and to an increase of the damping of the structure and it is therefore necessary, in general, to make a reduction in the demand curve.

Regarding the definition of the response spectrum, the parameters proposed by the Italian code for the city centre of Sulmona were considered. For the carried out analysis different return periods of the seismic action, corresponding to different values of the effective displacement demand of the building d_{max} were considered (30, 50, 200, 475 and 975 years).

The link between capacity and damage is explicitly defined identifying directly on the capacity curve the displacement ranges within which the possible damage limit state is included (referring to the damage degrees defined by EMS98), according to the following relationships (Cattari et al. 2004):

D0:	$0 < d_{max} < 0,3\ d_y$	D3:	$1,5\ d_y < \mathrm{d_{max}} < 0,5\ (d_y + d_u)$
D1:	$0,3\ d_y < \mathrm{d_{max}} < 0,7\ d_y$	D4:	$0,5\ (d_y + d_u) < d_{max} < d_u$
D2:	$0,7\ d_y < \mathrm{d_{max}} < 1,5\ d_y$	D5:	$d_{max} > d_u$

Comparing the values of the displacement level d_{max} for the five considered return periods, it is possible to identify the degree of damage of any specific model. For each vulnerability class and for each return period, the percentages of buildings that undergo a certain degree of damage are so deterministically obtained (damage histograms). Given the real nature of the used parameters, starting from the definition of the damage limit state, it is more appropriate to set the study in probabilistic terms. For the representation of the distributions obtained from the statistical analysis of damages through a probability distribution, it was considered appropriate to use the binomial law:

$$p_k = \frac{5!}{k!(5-k!)} d^k (1-d)^{5-k} \qquad (1)$$

Where p_k is the probability of damage of a level k ($k = 0, 1, 2, 3, 4, 5$) and the symbol "!" indicates the factorial operator. The binomial distribution is a function of the only free parameter d, defined between 0 and 1, that is called "average damage" in that, if multiplied by five, it represents the barycentric abscissa of the damage histograms.

Once the values of the average damage have been determined, the damage probability can be calculated: for example, Fig. 3 shows the values of the occurrence probabilities of each damage limit state, for each vulnerability class and for two return periods (T_R = 50 and T_R = 475 years): keeping constant the value of seismic intensity, the buildings of A class (the most vulnerable, considering the typological and constructive choices) suffer a higher damage than buildings of class B and C; increasing T_R the probability that buildings of all classes suffer higher damage gradually increases.

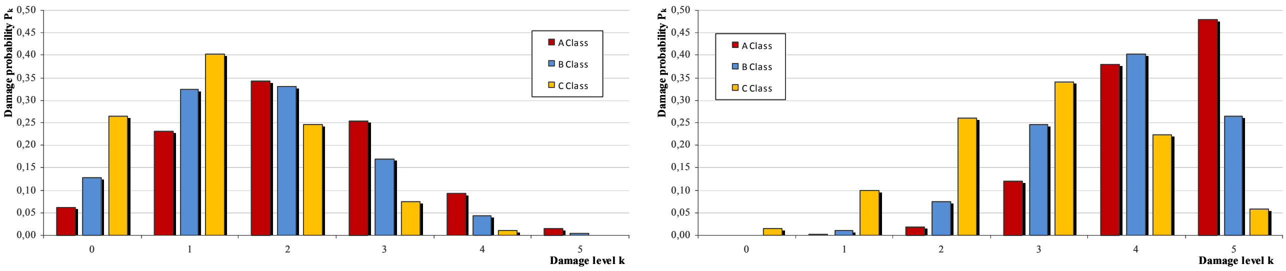

Figure 4: Histograms of the damage probability for the return periods T_R = 50 and T_R = 475 years

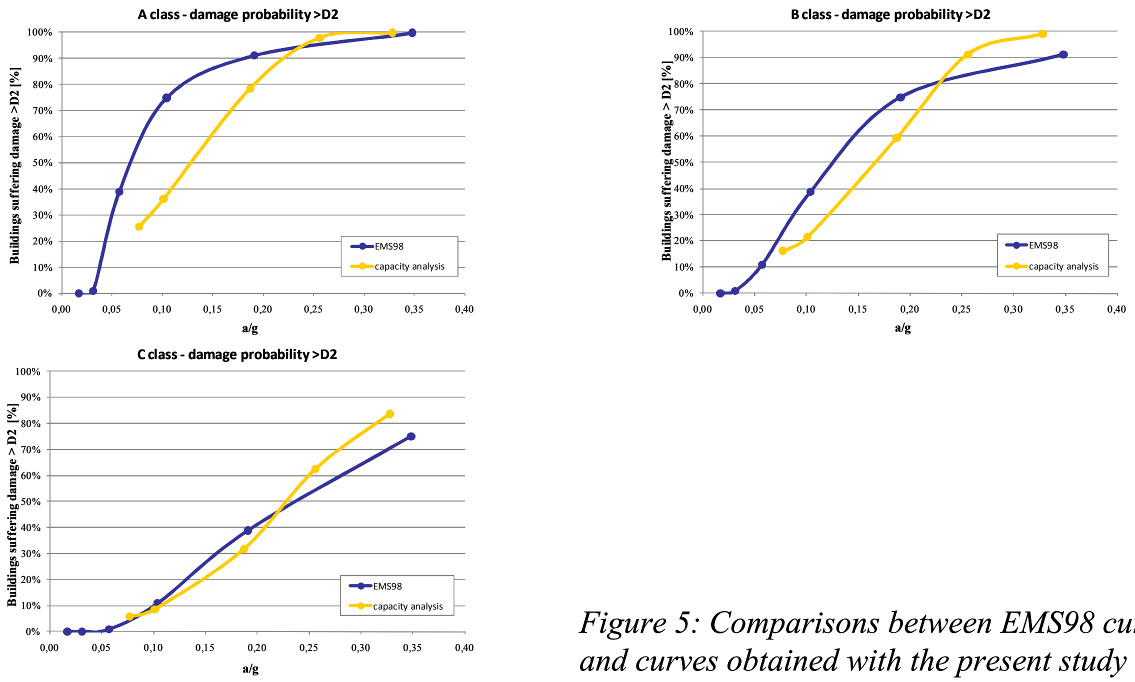

Figure 5: Comparisons between EMS98 curves and curves obtained with the present study

Analysis of the results The assessment of the probability that a group of buildings (vulnerability class) suffers a certain damage degree considering a defined seismic input allows the creation of simplified damage estimations. To compare the results with the damage values of provided by the EMS98, a level of damage >D2 was considered and the fragility curves, that indicate for each class, the probability that the damage is higher than the defined limit versus the ground acceleration, were identified (Fig. 4). The graphs also show the vulnerability curves derived from the EMS98 scale: in fact, the definition of the scale allows to calculate, for different classes and for different macroseismic intensities, cumulative distributions for the probabilities of different damage degrees. Using the relationship for the transition from the macroseismic intensity to the horizontal ground acceleration proposed by (Guagenti and Petrini 1989), it is possible to obtain fragility curves comparable with those obtained from the capacitive approach carried out in the present study.

The percentage of buildings that suffer damage was also associated to the number of buildings in the database built after the survey campaigns realized in Sulmona, divided into classes following the previously mentioned criteria. The developed damage scenarios identify for each vulnerability class the number of damaged buildings. The probabilities of damage >D2 and >D5 and the return period T_R = 50 and T_R = 475 years were considered (Fig. 5).

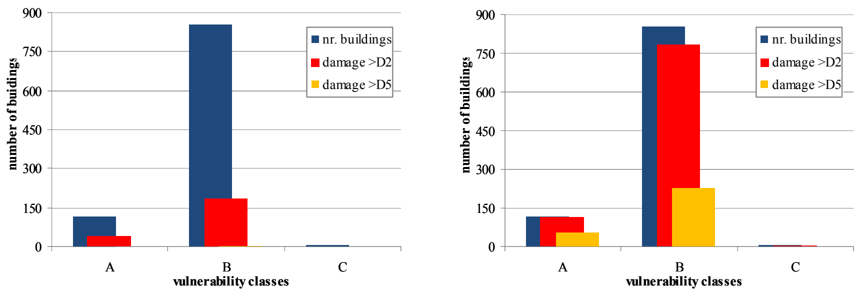

Figure 6: Damage scenarios for the return periods T_R = 50 and T_R = 475 years

Conclusions

The substantial good agreement between the results obtained with the capacitive approach and those implicit in the EMS98 scale confirms the reliability of the developed methodology. The two approaches still have substantial differences: in particular, the values implicit in the definitions of the EMS98 scale are essentially based on statistical processing of the damage observed during seismic events that affected many different areas. In the capacity analysis, the modelling of the buildings considered the behaviour of the masonry walls only in their plane, ignoring the out of plane resistance. Furthermore, the study considered ideal isolated models without assessing any effect of interaction between units. It would therefore be interesting to consider, even in a simplified way, the out of plane mechanisms and the aggregation effects. In any case to obtain more significant results intensive studies are needed in order to further expand the series of analysed models.

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