THE EARTHQUAKE OF 1997 IN THE MARCHE REGION (ITALY): DAMAGE MECHANISMS, REPAIR METHODOLOGY AND RELATIVE COSTS FOR MASONRY BUILDING CONSTRUCTIONS.

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ABSTRACT :

This report summarizes the most significant aspects of research financed by the Marche Region's Scientific and Technical Committee (CTS) for the coordination and re-establishing of post-seismic activities; this research was the result of close collaboration between the Structural, Water, and Soil Engineering Department of the University of L'Aquila, the Marche Region and the National Research Council-Construction Technologies Institute (CNR-ITC) in L'Aquila.
Damage and collapse mechanisms and the efficacy of restoration and anti-seismic measures were studied through the analysis and classification of the damage to masonry buildings caused by the Umbro-Marchigiana earthquake of 1997. The efficacy and economical benefit of the techniques used and the strategies adopted to reduce seismic vulnerability were studied in particular detail. The research therefore developed along two lines: damage mechanisms and cost of intervention. This paper summarizes the work and results of this study which are fully documented in a book published by the CNR-ITC.

KEYWORDS: masonry buildings, vulnerability, collapse mechanisms.

1. INTRODUCTION

Masonry buildings were the buildings most badly affected by the earthquake that hit the Marche Region in 1997, as they have been in other earthquakes that have hit Italy over recent years.
The considerable data base built up during the course of post-seismic activities has been used in this project to look at the instruments and methods for evaluating earthquake damage and assessing vulnerability as well as the identification of appropriate post-seismic repair work, the means of reducing seismic vulnerability and the economical benefits of these measures. The aim of this research project was to classify and understand damage mechanisms in masonry buildings and classify the varying types of post-seismic work. This involved studying: damage and collapse mechanisms; post-seismic restoration work and improvements in anti-seismic features; the efficacy and economical benefits of the techniques and strategies used in planning. It is hoped that this project will also form a platform for studies on the identification of earthquake vulnerability factors, causes of damage and safety assessment. The Marche Region set up a information system (Tellus) connected to a large data base for the administration and management of reconstruction activities. The database was created with information from "Project Accompanying Technical Forms" (STAP) which were completed by planners. The forms were used to collect data on earthquake damaged buildings undergoing restoration work; this data included information concerning construction type, vulnerability and damage as well as financial contributions and actual costs. Two hundred and one damaged buildings were identified over the course of the investigation, all situated in the area most badly hit by the earthquake. All of the affected buildings were publicly owned and had been hit by a earthquake of 6.5 MSK or over. An illustrated report was drawn up for these buildings detailing type, construction characteristics and damage assessments. A new method was devised for estimating the costs involved in the restoration of damaged buildings based on the identification and characterization of the correlations between seismic vulnerability, damage mechanisms, type of restoration work and reduction of vulnerability. This method was the outcome of a specific study of the technical plans drawn up by those involved in reconstruction. Work costs were analyzed by dividing work into categories based on the structures involved (vertical structures, horizontal structures, roofing) and the entries in the Marche Region's price lists for building work. A study was carried out on the relationship between damage mechanisms and seismic

vulnerability factors and the efficacy of restoration in terms of cost. This involved the drawing up of evaluation models which could be used to check the congruity of the cost estimates established by regional norms for the reconstruction of privately-owned masonry buildings. These models could also be used for future programming concerning this type of patrimony. Part of the research project also involved the identification and study of the most frequent type of local collapse mechanisms in existing masonry buildings and the definition of mathematical models according to the criteria of the equilibrium limit.

2. THE CHARACTERISTICS OF SAMPLE BUILDINGS AND DAMAGE AND VULNERABILITY ANALYSES

Research activities were based on the information inserted into the Tellus database originating from the technical forms and from the work projects deposited at the Region’s technical office in Muccia (MC). The Tellus database contains an archive of 5,218 buildings of which 4,833 are in masonry. The studies that are described later were carried out on the latter group. More detailed analyses were also performed on a sample group of 201 buildings chosen on the basis of type and damage (Figure 1).

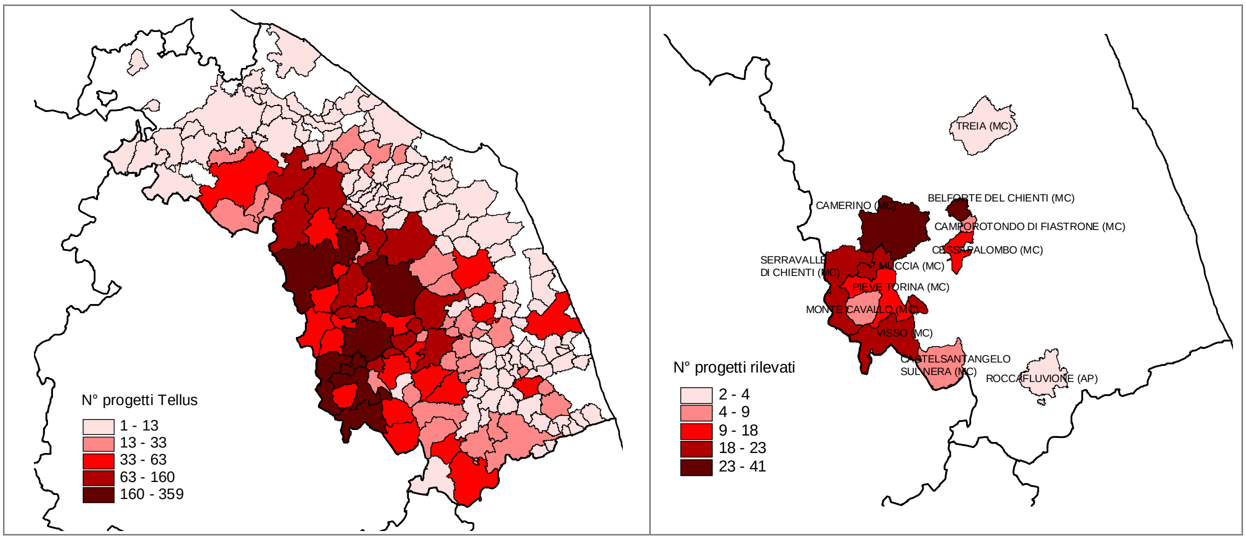


Figure 1 Number of projects analyzed (left) and distribution of the 201 buildings in the sample (right)

The contents of 126 projects from the 201 sample group were studied; the contents included illustrated technical reports, metric calculations, photographs and details concerning the present state of buildings. A graphical inventory was also drawn up for damage mechanism correlations; figure 2 illustrates one of the forms used. This database and the metric calculations were used to define a model for estimating the cost of post-seismic reconstruction and is briefly described later. Thanks to the quantity of data available, a series of type and vulnerability analyses could be performed on existing buildings in the earthquake affected zones with the aim of providing criteria and guidelines for future activities as well as more detailed information on buildings within the area. The analyses highlighted that more than half of the buildings, approximately 55% of the sample group, were built before 1919 whilst 20% were built between 1919 and 1960. The majority of buildings, approximately 72%, had not been altered or undergone structural improvements since construction; only 2% of buildings had undergone work to reduce the risk of earthquake damage whilst the remaining buildings had undergone some kind of restructuration work. From the correlation between vertical and horizontal structures, it emerged that masonry buildings with wooden floors were the most common type. Wood floors are frequently associated with walling in roughly hewn stone, brick masonry and hollow brick masonry. This same type of walling is also often associated with heavy RC and brick floors (probably used to replace old wood floors) and occasionally with steel girders and brick floors.

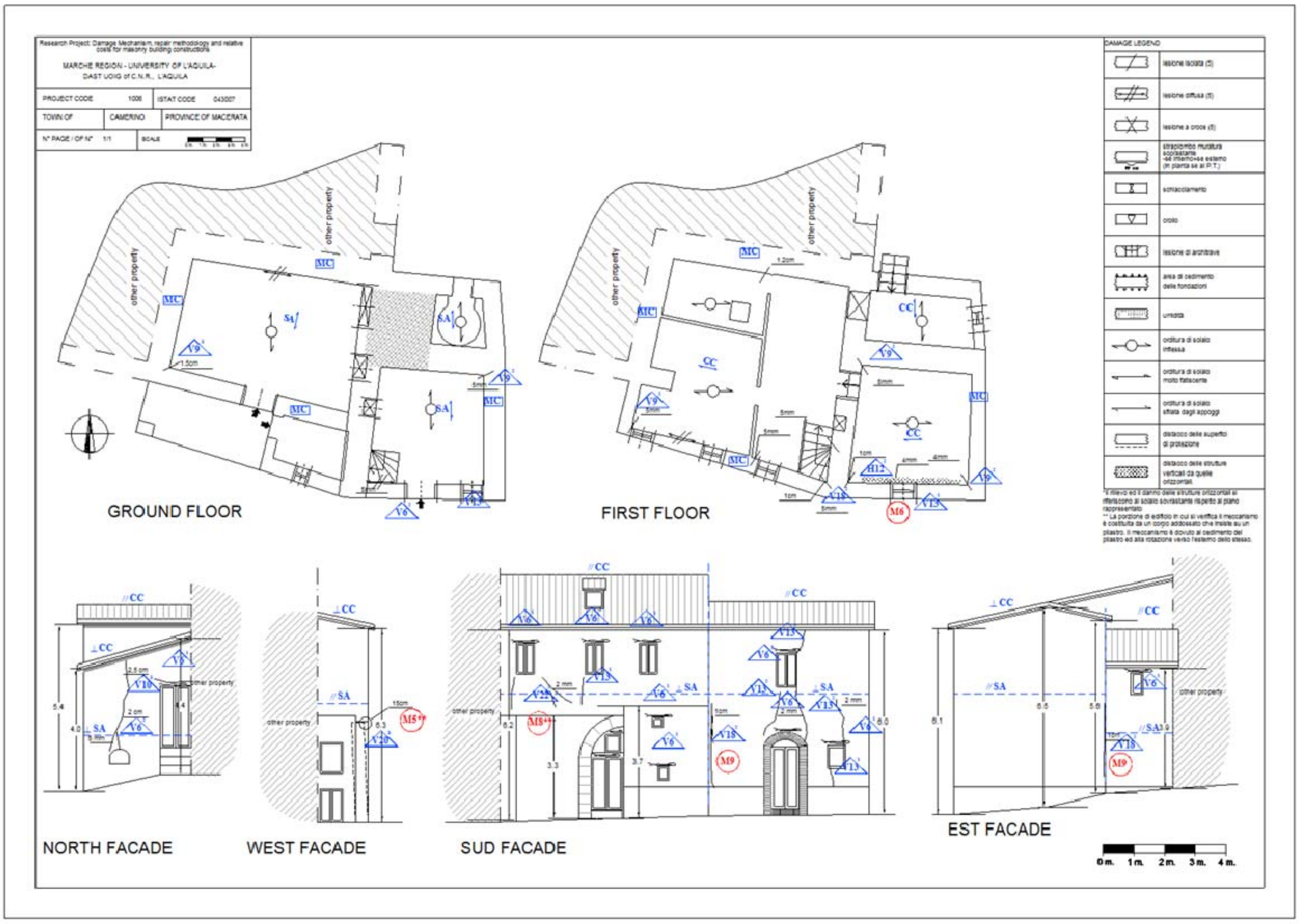
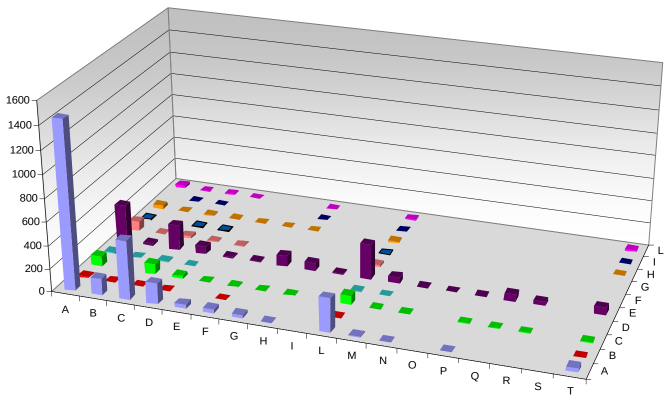


Figure 2 An example of one of the forms used for the graphic inventory



VERTICAL STRUCTURES
A - "A sacco" masonry
B - Reinforced "a sacco" masonry
C - Hewn stone
D - Reinforced Hewn stone
E - Round stone masonry
F - Reinforced Round stone masonry
G - Tuff block masonry
H - Heavy concrete block masonry
I - Light concrete block masonry
L - Brick masonry
M - Hollow brick masonry
N - Plain concrete shear walls
O - RC shear walls
P - RC bare frames
Q - Infilled RC frames (weak infill)
R - Infilled RC frames (strong infill)
S - Steel
T - Mixed
U - Other

HORIZONTAL STRUCTURES
A - Wooden
B - Wooden with iron ties
C - Steel beams and bricks
D - Steel beams and bricks with iron ties
E - RC slab or RC and bricks
F - Vaults without iron ties
G - Vaults with iron ties
H - Vaults and horizontal floors
I - Vaults and horizontal floors with ties
L - Other

Figure 3 Correlation between horizontal and vertical structures

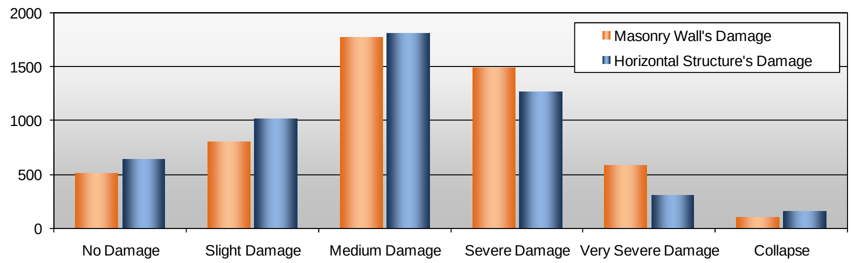


Figure 4 Distribution of structure damage

Data on the damage caused by the earthquake collected using the technical forms included the degree of damage from 1 to 6 for: masonry walls, horizontal structures, structural damage caused by the lowering of foundations, instability arising from hammering between buildings, partial or total collapse of structures. Figure 4 shows the distribution of damage to masonry walls and horizontal structures. Correlation between local collapse mechanisms and recorded damage was analyzed in the sample of 201 buildings. The most frequent types of global damage to vertical structures were (Papa and Zuccaro, 2001):

- V09: vertical cracks at wall junctions (corners) usually due to inefficient connection between orthogonal wall;
- V13: vertical cracks in the parapets between openings or in the band above and under windows, usually as a result of differing thicknesses and hence rigidity between parapet walling and masonry wall;
- V16: local collapsing/flattening of walling caused by excessive compression as a result of an increase in the vertical load
- V06: diagonal cracks in the parapets above and across door and window architraves which are generated by shear forces.

Figures 5 and 6 give examples of the correlation between vertical and horizontal structures and the corresponding mechanisms activated. The most frequently activated local mechanisms are: M11(weakening or collapse of architraves) M09 (irregularities between adjacent structures) and M10 (from the exit of girders from their fixtures).

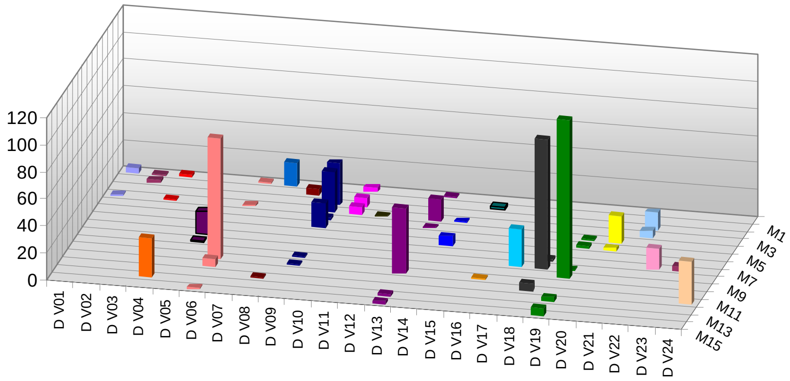


Figure 5 Correlation between damage to vertical structures and activated mechanisms

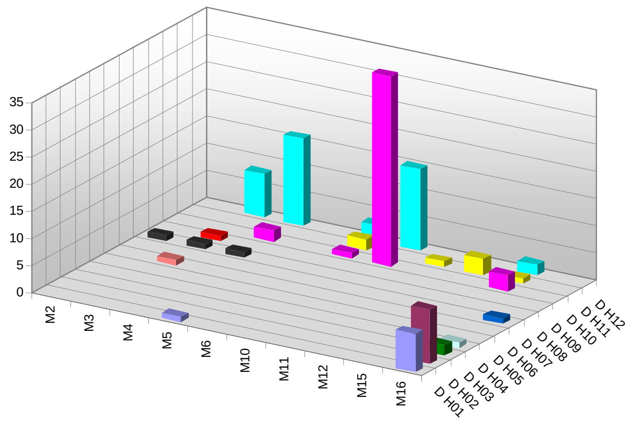


Figure 6 Correlation between damage to vertical structures and activated mechanisms

The study of over 4,800 projects in the database containing the information collected using the Project Technical Forms enabled us to look at the correlations between the structural defects identified in buildings and damage and collapse mechanisms activated. The results obtained were then cross-checked by a detailed analysis of the sample group of 201 buildings.

The correlations between mechanisms and defects associated with them, based on criteria linked to the identification of the necessary conditions for their activation are illustrated in the table in figure 7. The structural defects and construction characteristics that generally permit activation are indicated for every damage and collapse mechanism catalogued.

STRUCTURAL DEFECTS	POSSIBLE COLLAPSE MECHANISMS															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Deformable horizontal structures	NO	NO					NO									YES
Horizontal structures badly connected to vertical structures	NO	NO	YES	YES	NO	YES	NO			YES			YES	YES	YES	
Thrusting coverings		NO	YES*	YES*		YES*				YES*				YES*	YES*	
Soil Settlement								YES								
Building not built to earthquake norms	NO	NO	YES	YES				YES*	YES	YES*	YES*	YES*		YES		
Building without tie beams or iron ties	NO	NO	YES	YES	NO	YES*				YES*					YES	YES
Resistance defects in masonry resistant panels					YES		YES			YES	YES	YES				
Defects in the joining of structural elements	NO	NO	YES	NO	YES	NO	NO							YES		
Horizontal forces not balanced			YES*	YES*		YES*				YES*			YES	YES*	YES*	YES
Deformability of diaphragms (also due to split floors)	NO						NO		YES							
Irregular distribution of stiffness	NO								YES							
Defects in the joining of non-structural elements												YES				
CSG 0: No serious structural defect																
CSG 1: Wall resistance defects: poor materials, lack of joining elements, Hollow brick masonry			YES*	YES*	YES*	YES*					YES	YES				
CSG 2: masonry panels on floors																
CSG 3: Serious irregularities in plant									YES*							
CSG 4: Serious irregularities in elevation									YES*							
CSG 5: Roof lacking transversal joints			YES*	YES*		YES*				YES			YES*	YES*	YES*	

Condition	Description
YES	it is necessary that the defect is present to activate the mechanism
NO	to activate the mechanism the defect must not be present
YES*	The presence of a defect is not important to activatate mechanism but may promote it

Figure 7 Relationships identified between structural defects and activation mechanisms

3. CINEMATIC MODELS FOR THE ANALYSIS OF LOCAL COLLAPSE MECHANISMS

The definition of more suitable structural analysis models, able to take into account the real behaviour of differing building types during an earthquake, giving more valid and reliable results, was an interesting outcome of this study. The aim of the study was to devise an approach in line with recent Italian earthquake legislation and in particular OPCM 3274/2003. With this aim, and with reference to masonry buildings, the careful examination of the most frequently used construction technology and the type of damage caused by the earthquakes led us to the study and testing of the activation of collapse mechanisms affecting single areas of wall structures. All too often, building elements are not joined efficiently (deformable horizontal structures often simply resting on top of walls, wall intersections of poor quality) and in the event of an earthquake do not offer any joint resistance, usually known as box behaviour. So as a result of the loss of equilibrium, a portion of the building detaches and collapses. These are fragile mechanisms mainly affecting portions of walls, determining seismic damage of a modest entity which requires careful prevention work.

In order to study these aspects, highlighted in the abovementioned OPCM but insufficiently catered for by previous legislation, several analysis models were devised for the most frequent local collapse mechanisms. Limit equilibrium conditions of macro-elements under earthquake conditions were evaluated for each case studied (portions of wall that separated from the rest of the structure as a result of the lack of any holding structures). A cinematic approach was used in line with attachment 11.C of the OPCM and the multiplier expressions of horizontal actions, which cause a loss of equilibrium of the macro-element and hence the collapse of the structure, were calculated.

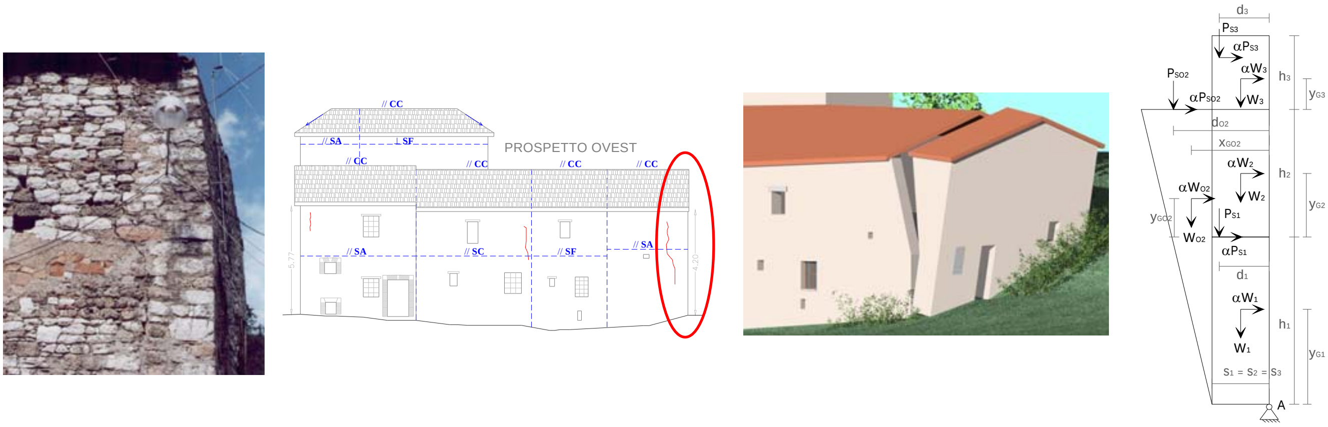


Figure 8 Application of the cinematic models for the analysis of local collapse mechanisms on a sample building

The number of cases examined (approximately 15 different collapse mechanisms) and the method used to obtain the relative formulations allow variables characterizing the problem to be considered in relation to the differing situations to be found in reality. This, together with the possibility of estimating, starting with the multiplier, the entity of peak ground acceleration (PGA) that causes the activation of the kinematics, directly comparable with the reference values for the seismic zone in which the building is located, makes the product in question an extremely valid and efficient instrument for the execution of seismic tests. The formulations were implemented in a software (called C.I.N.E.) that allows rapid and automatic testing with just geometric and load measurements which can be obtained with even minimal knowledge of the structure thus reducing analytical and calculating phases and contributing to an area on the Italian technical and applicable panorama that is completely lacking in instruments. Figure 8 illustrates the identification of an activated collapse mechanism and the calculation of its collapse multiplier for a building from the sample group.

4. A MODEL FOR ESTIMATING POST- EARTHQUAKE RECONSTRUCTION COSTS

An in-depth study of the technical plans drawn up by those involved in rebuilding allowed us to perform a series of calculations concerning the cost of work. New methods for estimating costs were based on the results of the studies performed and the identification of correlation between earthquake vulnerability estimates, damage mechanisms and earthquake resistance measures. The most important choice was that of identifying a series of categories of interventions with reference to which a study could be carried out on the relationships between damage mechanisms, earthquake vulnerability factors and cost efficiency. This allowed us to formulate rational evaluation models that could be used to check the congruity of cost estimates identified in the Regional retrofitting code for the reconstruction of privately owned masonry buildings and for the programming and management of future work on the building patrimony. One of the results of this research was an analytical methodology for the definition of earthquake vulnerability prevention work for homes, that estimates the series of interventions with the best ratio for reduction in vulnerability/cost of work. For earthquake damage buildings, the series of interventions required for the repair of damage and the implementation of earthquake measures is also a function of local and global activated collapse mechanisms and the percentage of damage recorded. The general principals set down can guide planners implementing earthquake vulnerability measures. The methodology developed can also be easily automated and applied on a large scale as it does not require in-depth details on structures or damage. The application requires a minimal knowledge of structural and non-structural

building elements: structural defects and the following building measurements: a) the area of each floor; b) the height between floors c) the volume below and above ground; d) the average height of the building above ground. A further aspect is the estimate of repair costs for which the following is necessary: 1) a qualitative and quantitative calculation of damage; 2) the unit cost per type of intervention. This procedure can be applied to both earthquake damaged buildings and undamaged buildings requiring earthquake measures to reduce vulnerability. For the latter buildings an estimate can be calculated by selecting the interventions that can give the best results in terms of reduction of probability of the activation of the most damaging local mechanisms. For damaged buildings an estimate is also given for the costs of repair in light of the local collapse mechanism activated or that could be activated. Clearly repair work is rarely just simply that, and usually entails measures aimed at reducing vulnerability, all of which is taken into consideration, allowing the choice of the most appropriate intervention. In brief, decisions regarding the type of intervention are based on estimates concerning the probability of activating one of the possible collapse mechanisms. This probability is established by analyzing the structural defects of the building and the characteristics of its resistance system. In order to identify the best series of interventions, a correlation was created between possible collapse mechanisms and interventions that can oppose these mechanisms. For the most frequent types of work an evaluation of the costs involved was made determining the average unit costs of the same tasks from the regional price lists. The table below gives the possible categories of work and relative costs. The next phase concerns the association between single mechanisms and intervention measures that can block activation. Each intervention was assigned a level of efficacy: low, medium or high. Each intervention reduces the probability of setting off collapse mechanisms and therefore the vulnerability of the building. The table's colour scheme indicates the costs involved: green, low ; yellow, intermediate; orange, high.
The choice of intervention can be made through functions that maximize the ratio: reduction in vulnerability/cost of intervention, and in function of the efficacy of the intervention in contrasting each individual mechanism. The aim of these interventions is to bring building behaviour as close as possible to a shear type collapse mechanism. The procedure is divided into steps highlighting the reduction of vulnerability that can be obtained by increasing the number of interventions. An example is given in figure 9 which shows the reduction in vulnerability obtained in each step in function of the cost per m^3 of the interventions in one of the sample buildings.

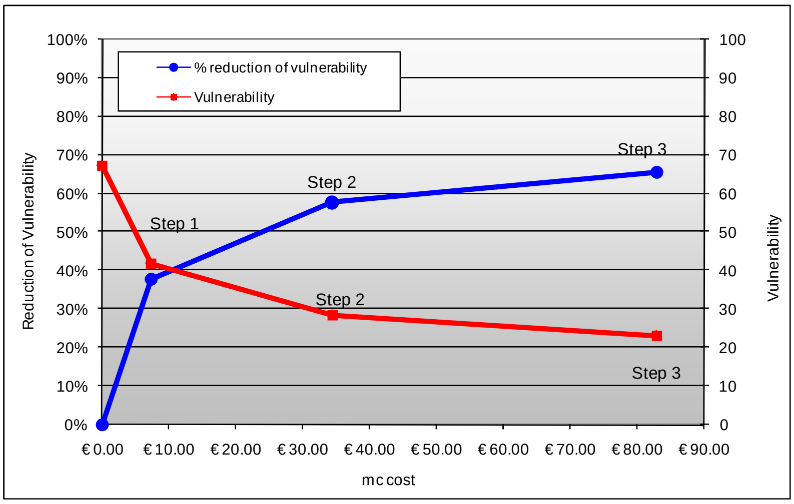


Figure 9 Reduction in vulnerability versus unit cost of the intervention

Given the degree of variability in real cases and types of intervention that are possible on masonry buildings, the costs given here can only be considered a guideline. Analyses showed that the standard deviation of these costs was approximately 30% with respect to the average cost of individual interventions. However the statistical levels of these approximative estimates are acceptable as emerges from a comparison with the data obtained from the statistical analyses of the costs for the planned interventions carried out on the 201 building sample studied in detail.

CONCLUSIONS

This research has allowed us to clarify various aspects tied to the seismic behaviour of masonry buildings and the management of post-earthquake work. It has also led to the design of an instrument for calculating collapse multipliers and the corresponding PGA; hence it is possible to estimate the real behaviour of buildings relatively simply, using alternative analyses and hypothesizing differing mechanisms and the corresponding macroelements.
In addition, a useful methodology was developed for economical evaluations linked to programming policies, post-seismic interventions and reductions in building vulnerability. This methodology, on the one hand allows an estimation of the approximate costs involved in relatively brief times without the need for in-depth investigations, and on the other helps identify the most efficient types of intervention, in relation to the constructive and behavioural characteristics of buildings, with the best ration reduction of vulnerability/cost of intervention.

REFERENCES

AA. VV. (2007). Repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura, Osimo, Ancona, Italy.
AA. VV. (2007). Sisma del 1997 nella Regione Marche: repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura. Atti del 12° Convegno Nazionale L’ingegneria Sismica in Italia, Pisa, Italy.
AA. VV. (2007). Marche 1997: Modello per la stima dei costi di ricostruzione post-sisma. Atti del 12° Convegno Nazionale L’ingegneria Sismica in Italia, Pisa, Italy.
AA.VV. (2000). Censimento di vulnerabilità degli edifici pubblici, strategici e speciali nelle regioni Abruzzo, Basilicata, Calabria, Campania, Molise, Puglia e Sicilia, Dipartimento della Protezione Civile – GNDT, Roma, Italy.
Avorio, A., Borri, A., Corradi, M., (2003). Ricerche per la ricostruzione. Regione dell’Umbria. Edizioni DEI, Roma, Italy.
Giuffrè, A., (1993). Sicurezza e conservazione dei centri storici. Il caso Ortigia. Edizioni Laterza, Bari, Italy.
Gurrieri, F., (1999). Manuale per la riabilitazione e la ricostruzione post-sismica degli edifici. Edizioni DEI, Roma, Italy.
Dolce, M., Martinelli, A., (2007). Una nuova metodologia di valutazione della vulnerabilità e del rischio sismico degli edifici in muratura applicata agli edifici pubblici dell’Italia centro-meridionale. Atti del XII Congresso Nazionale L’ingegneria Sismica in Italia. Pisa, Italy.
Papa, F., Zuccaro, G., (2001). MEDEA (Manuale di Esercitazio-ni sul Danno Ed Agibilità per edifici ordinari in muratura), CAR progetti s.r.l., Napoli, Italy.
Di Pasquale, G.., Orsini, G., Serra, C., (1999). Assessment of economic loss from the GNDT-DPC-SSN. Proceedings of the International Workshop on Measures of Seismic Damage to Masonry Buildings. Monselice, Padova, Italy.