13th International Brick and
Block Masonry Conference
Amsterdam, July 4-7, 2004

# MULTILEVEL APPROACH TO THE ANALYSIS OF THE HISTORICAL BUILDINGS: APPLICATION TO FOUR CENTERS IN SEISMIC AREA FINALISED TO THE EVALUATION OF THE REPAIR AND STRENGTHENING TECHNIQUES

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## Abstract

An investigation procedure proposed by the authors is here applied on a building patrimony in seismic area previously considered as minor, but meaningful testimonies of cultural heritage, aimed to a critical review of the effectiveness of the applied repair techniques. The research suggests a "minimal" investigation program, which can support the designers in their projects. The knowledge of existing buildings is approached by considering different analysis levels: history, materials, structural morphology of the wall section, observed damage mechanisms, effectiveness of retrofitting techniques. The methodology was applied to four historic centres situated in Umbria (Italy) and the survey of the buildings allowed to define an abacus of the typical collapse mechanisms, useful to define the seismic vulnerability also for other similar centres and to critically evaluate the past and future repair techniques.

## Key Words

Stone masonry, historic centres, repair and strengthening techniques, seismic area.

## 1 Introduction

A research has been carried out within a three years contract supported by the Civil Protection Agency of the Italian Minister Council and involving three Research Units: Politecnico of Milan, University of Padua and the Italian Ministry of Cultural Properties. It has the strategic aim to collect information on the effectiveness of the repair

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techniques, but also to define a methodology for the analysis of the vulnerability of a building patrimony previously considered as minor, but with meaningful testimonies of cultural heritage. Furthermore, the research suggests a "minimal" investigation program, which can support the designers in their projects.
The approach leads to the knowledge of existing buildings by considering different levels of analysis: history, materials, morphology of the wall section, observed damage mechanisms, effectiveness of retrofitting techniques.
The selection of the centres was very accurate in order to limit the sample population to the most significant buildings. Information from each building of four historic centres in the Umbria region, are being collected in a data-base containing history, overall geometrical (plan, views etc.) and masonry (material properties, section morphology, flat jack and sonic tests) data, representation of the structural system, possible retrofitting, detailed description of the damage, and mechanical interpretation of the damage or collapse processes.
The research has been carried out on four centres placed in Umbria region: Montesanto di Sellano, Roccanolfi di Preci, Campi di Norcia e Castelluccio di Norcia. The four centres were repaired after the 1979 earthquake but the subsequent earthquake of 1997 seriously damaged two of them: Montesanto and Roccanolfi. The extensive survey of the buildings was useful to produce an abacus of collapse mechanisms, to define the seismic vulnerability of the other analysed centres, and a critical evaluation of the repair techniques and suggestions for future interventions (Penazzi et al 2000, Binda et al. 2003).

## 2 Building and masonry typologies and abacus of collapse mechanisms

The investigation started with a series of surveys aimed to the identification of the most recurrent masonry typologies and constructive techniques in the two historic centres which were more damaged during the seismic events of 1997 (Montesanto and Roccanolfi) (Penazzi et al 2000). Priority was given to these centres because the collected data on the damage mechanisms were used to build an abacus of the collapse mechanisms, useful to predict damages on buildings of the other two historic centres, which were not damaged.

### 2.1 Montesanto and Roccanolfi

The castle of Montesanto was built in the 12th cent. on the top of a hill facing the river Vigi (Figs.1 and 2). In 1500 the castle population was composed by around 300 families and remained constant until 1703. In that year due to a heavy earthquake the village was badly damaged and some houses were lost.
At the beginning of the 19th cent Montesanto was classified as a Municipality with an independent administration. After the unification of Italy until nowadays, due to its low population, Montesanto became dependent on the municipality of the nearby Sellano.
The Montesanto Castle had a very long compact shape. It was completely surrounded and protected by a fortified wall of which some traces remain still today as the one at the entrance of the village. The Castle had a system of orthogonal streets with three main streets placed at different levels forming terraces. Many areas of the urban tissue are now free due to collapses caused by subsequent earthquakes.
The castle of Roccanolfi was built since 1460 and develops along a slope on the top of a hill, dominating the three accesses to the “Oblita” velley. (Figs. 3 and 4). The ancient name of Roccanolfi was *arcem Arnulphi*, longobardic word composed by an appellative followed by a personal Germanic name.
The rules applied to the village focused on particular items: walls and entrances for conservation and defensive aspects. These roles established that the streets inside the city should be 7 feet wide, while near entrances and other strategic zones, streets

should be 5 feet wide and the streets close to the defensive walls should be 3 feet wide. The municipal rules remarked the importance of having free streets and limited dimensions of the projections of the buildings on the streets, the minimum heights allowed for vaults and balconies and the maximum overall dimension of the external stairs.

*Figure 1 View of Montesanto di Sellano*

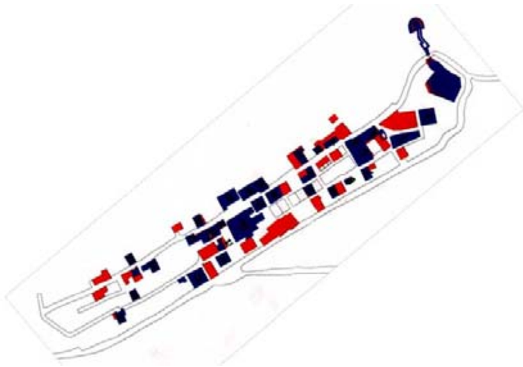


*Figure 2 Plan of Montesanto*

*Figure 3 View of Roccanolfi di Preci*

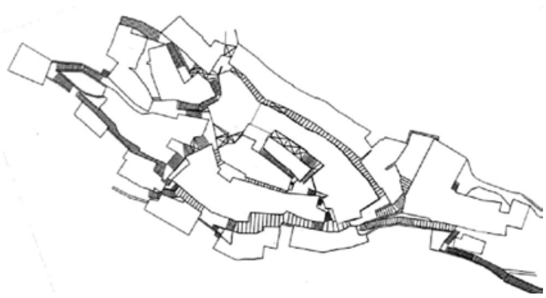


*Figure 4 Plan of Roccanolfi*

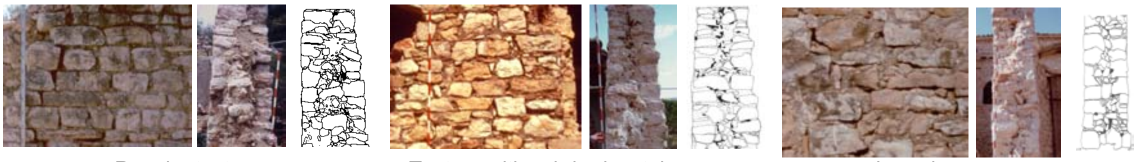
## 2.2 Masonry Typologies

The investigated masonry typologies of the historic centres of Montesanto and Roccanolfi were classified. A procedure for the investigation of the texture and, where possible, of the masonry section is the base for the study of the masonry morphology.

The masonry is surveyed by pictures, obtained as parallel as possible to the masonry surface, and by placing close to the section or to the texture a graduated stick in order to know the wall dimension. The dimensions are then verified by the archaeological survey method (scale 1:1). The 2D graphic plotting is realised with a special care in the representation of stones, joints and voids. Successively, the surface occupied by the different materials, which compose the masonry, is measured, evaluating the stone, mortar and voids percentages, the dimension and the distribution of voids. This information is useful both for the definition of the geometry and mechanical behaviour necessary to the modelling phase and for the design of possible strengthening intervention (e.g. grout injection).

Figure 5 shows some example of masonry texture with the corresponding cross section, which was possible to survey on damaged buildings after the seismic event. In Montesanto and in Roccanolfi were found mainly three masonry typologies for the external walls: regular, sub-horizontal and irregulars courses.

The stones are mainly limestone and travertine, laid in courses with stone ashlars and rough cut stones. The dimension varies from 5 to 25 cm. In some cases also sandstone is present. The mortar joints height is very variable, from 1 cm up to 5 cm, due to the irregularity o the stones. Mortar is compact with colours varying from white to yellow and grey.



Regular texture Texture with sub-horizontal courses Irregular courses

*Figure 5 Constructive masonry typoligies.*

A first sampling was carried out in order to characterise the materials belonging to the surveyed masonry typologies. The masonries are made with irregular elements from the following stones: a) *pink* or *red scaglia*, a limestone from calcareous origin pink or dark red with pebbles and pieces of flintstone; b) *mixed scaglia*, composed by marls and clayey marls red and grey and by minor quantities of red marl limestone with inclusions of calcarenite; c) *grey or white scaglia*, composed by marls and clayey marls of grey-green colour or alternate grey colour and at the base of grey limestone; d) *travertine* or *sponga*, a porous travertine of light brown colour from the Menotre valley (Pale, Scopoli, Sellone) and from Sellano (Postignano). Antique quarries can be found in the area of the Martani Mountains and along the Subasio. This stone is used in the corners of the walls, for the opening frames and for arch voussoirs. Its property is to harden as exposed to the environment; e) *sandstones*, with a compact structure, the grains have a medium size and under visual analysis it shows calcite and quartz inclusions. Traces of its use can be found only in Roccanolfi.
In Figure 6 some of the physical tests are given on the sampled stones, showing the same capillarity behaviour. In Figure 7 some results of compression tests carried out on four types of stones sampled in Montesanto and Roccanolfi are shown (white and pink calcareous stone, sandstone and travertine). From the plot it is very clear the difference between the *scaglia* strength and the *travertine* strength. This explains the higher use of the *scaglia* in the walls and the use of travertine only for lintels and vaults. Nevertheless in a more recent past when the “rules of art” were lost, the *travertine* was more and more used also in the wall construction both as irregularly or regularly cut elements.

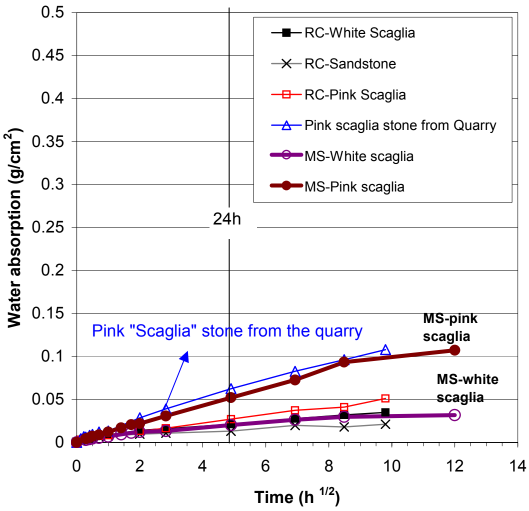



*Figure 6 Water absorption due to capillary rise of the stones specimens*

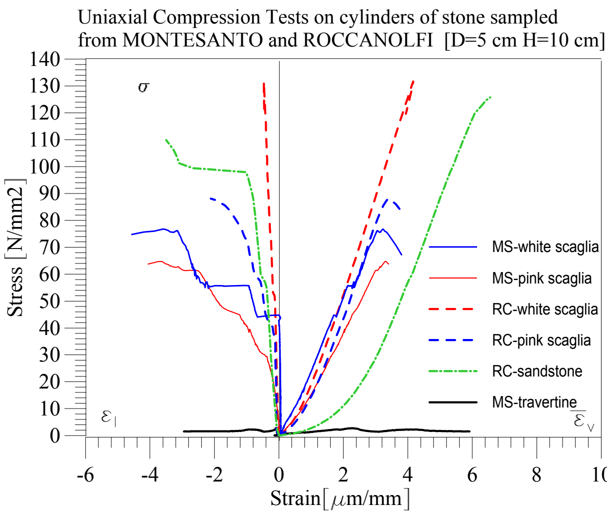



*Figure 7 Compression tests on stone specimens sampled in the two centres*

## 2.3 Collapse mechanisms and repair techniques

The village of Montesanto seriously damaged by two earthquakes in the last twenty years, shows an interesting scenario for the study of the behaviour of masonry historic buildings repaired and consolidated in the eighties.

Some buildings presented eartquake-proof interventions made before the 1979 seismic event. They are buildings of light historic importance or public buildings continuously subjected to maintenance. These buildings showed various repair techniques as the use of: timber rods with steel connections to the walls, steel rods, use of buttresses or buttressed walls. The above mentioned techniques can be defined as traditional and were commonly used in the past before the use of reinforced concrete. Furthermore, buildings repaired according to the code (P.diR. 1982) were identified. The following repair techniques were applied: stiffening or substitution of timber floors, tie concrete beam insertion in the walls, cementitious grout injections, reinforced injections, roof substitution, jacketing, local replacement in the walls, joint re-pointing, etc. In some buildings interventions made before and after 1979 were mixed.
The overall evaluation of the damage scenario shows that highest percentage of collapses is represented by the buildings repaired before the 1979 earthquake (all these buildings were never submitted to maintenance), whereas the buildings repaired after 1979 were interested by a medium level of damage.
The historic centre of Roccanolfi also suffered high damage, occurred to buildings which never had maintenance for years. Such condition was increased by the interaction between repaired and non repaired buildings due to the perticular morphological aggregation of the village, where buildings form winding rows connected by vaulted passages. The more frequent types of damage found in the consolidated buildings were: diffused crack patterns and loss of renders.

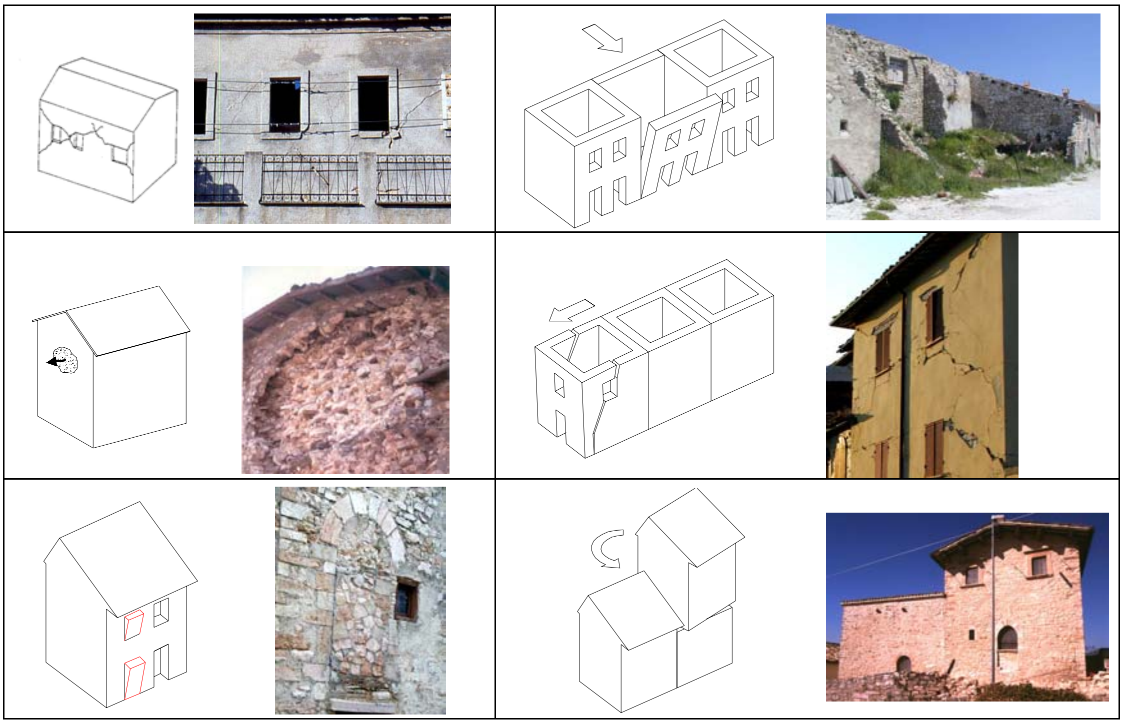


*Figure 8 Some examples from the collapse mechanisms abacus*

No collapses were detected for those buildings, but the previous mechanisms were worsened with out of plane movements and passing through cracks. In the non consolidated buildings other types of damage are present and, worsened by the high decay due to lack of maintenance, which lead to several collapses.
The two centres fit in the preliminary studies aimed to analyse the collapse mechanisms of masonry buildings due to earthquake and to interpret them on the basis of knowledge of the original constructive techniques and of changes following the interventions (also including the recent retrofitting). The aim is to supply useful indication for the rescue plans of the two centres and for their return to usefulness.

These indications will be useful to prevent and protect from future seismic events. The abacus gives a complete case history of all collapse mechanisms possible for isolated and row buildings (Fig. 8).

## 3 Application of the methodology to the analysis of Campi and Castelluccio di Norcia

The second part of the research, after conclusion of the survey campaign of Montesanto and Roccanolfi, was focused on the other two case studies of Campi Alto and Castelluccio di Norcia (PG). Laboratory and in situ investigations were carried out in order to characterise structures, the masonry textures and materials.
An extensive historical research was performed in archives and libraries, not only in the local area but also in Rome, as the land was in the past under the religious government. The aim was to detect the origin and the evolution of these two centres and the history of the seismic events occurred in that area in order to better understand some recurrent buildings vulnerabilities, and to observe their subsequent evolution during the centuries.

### 3.1 The historic centres of Campi and Castelluccio di Norcia (PG)

Campi Alto is a castle perched on a slope surrounded by walls, and whose buildings are arranged in concentric terraces and narrow streets connected by short radial flights (see Figs.9 and 10). The buildings follow the orography and are arranged in rows. Campi situated 11 km away from Norcia and at 900 mt above the sea level, belongs to the municipality of Norcia. It still preserves the original medieval aspect. Campi is divided in two parts: the old and lower one, "Campi basso", named “La Civitas Campli”, whereas the new one, “Campi alto”, is situated on the top of the hill.

*Figure 9 View of Campi alto di Norcia (PG)*


*Figure 10 Plan of Campi di Norcia*

When the lower part was destroyed by continuous barbaric invasions, the citizens decided to move on the top of the hill and in 1288 they built the Castle of Campi, also called “Campi nuovo” (New Campi), which is in the object of the research. The medieval gateway arch and the tower are still preserved; the characteristics of the buildings show the importance of the castle of Campi, although the damages due to earthquake and the effects of time and lack of maintenance are evident. Twenty-two churches and some monastery were built and 13 churches are still present.

Figure 11 View of Castelluccio di Norcia (PG)


Figure 12 Plan of Castelluccio

The little village of Castelluccio is situated on top of a hill and is following a helicoidal structure, 1453 metres above sea level. The houses are arranged in concentric half-circling patterns on a slope facing south, whereas the northern side is mainly desert due to the unfavourable climatic and orographic conditions (see Figs.11 and 12). The first written documents on Castelluccio date back in 1276. Until about half of the twentieth century there was only one centre, the one included within the old town walls, whereas outside and down the hill there were the stables. Castelluccio has preserved almost entirely its old and original structure. Due to unfavourable climatic conditions, the old house windows, especially those facing the north, were very small and deep into the wall, in order to protect the dwelling from cold and wind. The time of the main development of Castelluccio was in the 16th century, whereas during the first half of the 18th century damages caused by two strong earthquakes (in 1703 a nd in 1730) were repaired.

## 3.2 Analysis of the building typologies and vulnerability

The only type of building observed in the area is the single family house with two or more floors, built with a simple technique in stonework and timber roof and floor. Different building typologies are derived only by different aggregations of this typology: isolated buildings, row buildings simple or double, block buildings. Due to the ground slope (more than 100 meters from the base to the top of the village), buildings develop following a row typology generally with three floors: the first one with an entrance at the lower street (for stables or deposits), one in the middle and the last with the entrance at the upper street (for living places). The lowest floor is partially excavated in the natural rock. The rooms are covered by barrel vaults, that, despite the several seismic events, are still well preserved even in the collapsed buildings. A detail observed in almost all buildings is that the vaults are backward from the facade of about 1 meter (Fig.13): the reason of that is still unknown.
The numerous past seismic events (1705, 1730, 1859 and, more recently, in 1979) deeply marked this historic centre together with the lack of maintenance throughout the last decades after the second world war.
The topographic structure of the village is subjected to the soil orography. Thus, the main streets wind around the hill dividing the village in four sloping rings. Unfortunately, in the first years of 1980 all the streets of the village were paved with concrete. After the 1979 earthquake that caused many damages to the building structures, the centre of Campi Alto has undergone several interventions of retrofitting that unfortunately changed almost all the original masonry features that now are very hard to study. The damages found in Campi after 1997 were of irrelevant nature, and mainly located in those buildings that were not repaired since a very long time.

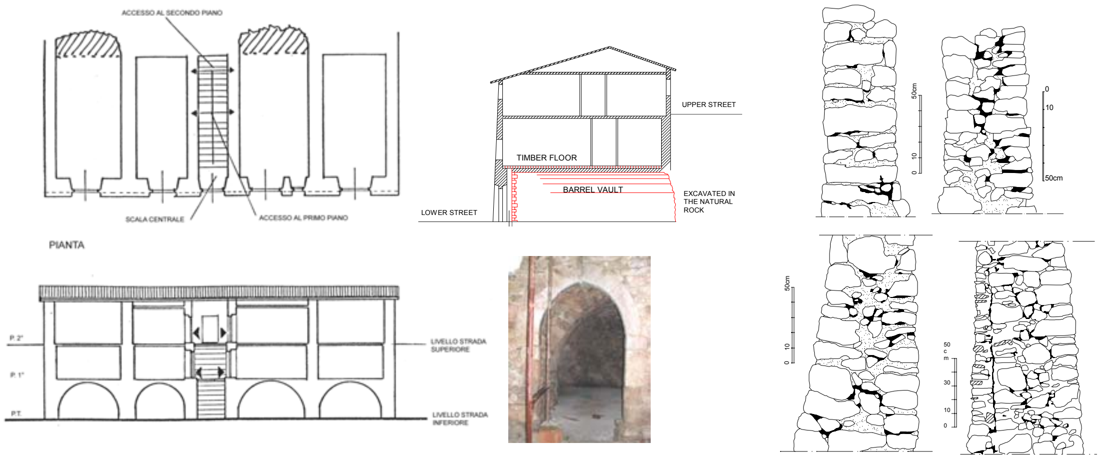



*Figure 13 The row buildings typology of Campi Alto and some typical wall cross sections*

The town-planning development of Castelluccio is shown in two parts: the first one, gathered around Cassero (the highest part of the village, of which only the planimetric plan and the grid of old streets are still preserved) and the second part at the bottom of the hill where there are still standing the old stables. The typology of the top part is very complicated as shown in figure 14a, while the stable typology is very simple (Fig.14b).


*Figure 14 The building typology of Castelluccio: a) complex civil buildings and b) simple rural buildings*

## 3.3 Laboratory and in situ testing

A diagnostic investigation has been carried out on some private (houses and stables) and religious buildings of Campi and Castelluccio. The Cultural Property Office of the Regione Umbria has made them available for this survey.

On the basis of the geometric and material surveys of the single buildings and of the surveys of the crack patterns, the in situ tests consisted in: 1) flat jacks tests; 2) sonic tests; 3) sampling of materials for their chemical-physical-mechanical characteristisation (Cardani 2004).

The recommended tests represent the minimum level for the knowledge of masonry, particularly in cases of shortage of funds, but placed in strategic positions for the study of the vulnerability of the historic centre. Samples of mortar and of some of the most recurrent stone materials have been taken (Fig. 15). Mechanical-physical tests and chemical analyses have been carried out.

The mortars sampled from private and religious buildings have revealed a high presence of lime pebbles that (as the chemical analysis have confirmed) means putty lime as binder (Fig.16). The aggregate is mainly calcareous and the ratio binder-aggregate may be stated around 1:2 1:2,5.

Cylindrical specimens were cored from the stones to be tested mechanically in dry and saturated conditions in two directions.
In Figure 17 the results of the tests with simple and double flat jack carried out on some sample buildings of Campi di Norcia are reported. The results allow to see the difference of behaviour between the masonry of the important buildings or of complex structures (church or the bell tower) and the private buildings.
At the same time it is possible to compare the sonic velocity values measured in the same areas where the flat jack test has been carried out (Fig.18). As an example it is possible to see that the dwelling masonry is the weakest one (UI199) both for flat jack and sonic test.

## 4 Conclusions

The survey carried out by the 3 U.R., well co-ordinated, has allowed to gather a great amount of data on:

1. history and evolution of the buildings and of the centres taken into consideration;
2. characteristics of the type of buildings, of structures and of the materials;
3. damages and interventions after the 1979 and 1997 earthquakes;
4. effectiveness of the restorations after 1979;
5. possible damage mechanisms of the restored and non restored buildings in the future.


*Figura 15 Sampling of local masonry materials: a) mortar carried out from a religious building, presence of lime pebbles; b) stones variety present in the buildings.*

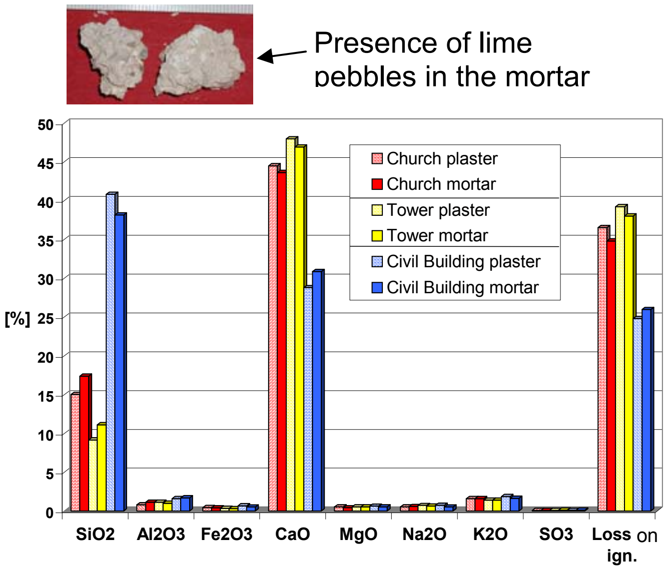



*Figura 16 Chemical analysis of the mortars sampled from the three diffeent buildings.*

The methodology applied to the four centres is now well calibrated and can be used for other similar cases. The research allowed to detect three main diffused construction typologies: isolated houses, row of buildings and complex aggregates, and to show that for the last typology a still hard work has to be made concerning structural behaviour, failure mechanisms, structural analysis and hence choice of appropriate repair techniques (Modena et al 2001, Binda et al 2004).

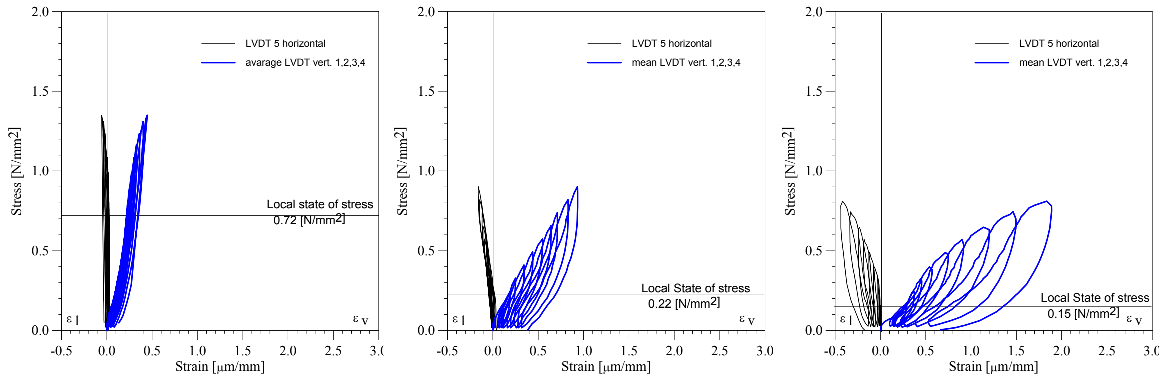



*Figure 17 Some results obtained with single and double flat-jack tests on: the external wall of a church, of a bell tower and of a civil building..*

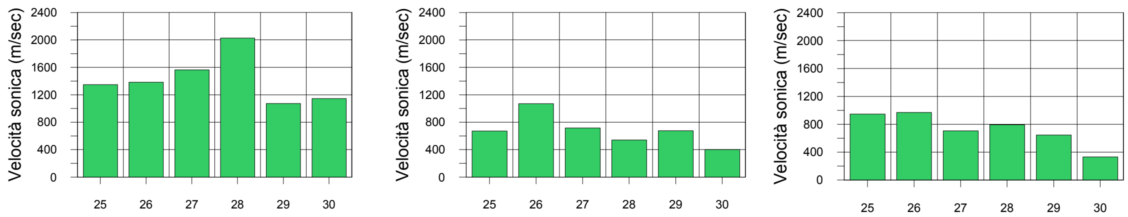



*Figure 18 Representative results of the diagonal surface sonic measurements*

## Acknowledgment

The authors thanks M. Antico, M. Cucchi, M. Iscandri, l'arch. L. Cantini e la Sign.ra C. Arcadi for their help during the experimental works. The research was supported by GNDT.

## References

Binda, L., Cardani, G., Penazzi, D., Saisi, A. 2003. Performance of some repair and strengthening techniques applied to historical stone masonries is seismic areas, Proc. ICPCM a New Era of Building, Cairo, Egypt, 18-20/2/2003, 2, 1195-1204.

Binda L., Modena C., Marchetti L., Cardani G., Valluzzi M.R., 2004, Indagine sulla consistenza dell'edilizia storica, sul danno pregresso e sull'efficacia degli interventi svolta su quattro centri campione in Umbria, Proc. XI Cong. Naz. "L'Ingegneria Sismica in Italia", ANIDIS, CD-ROM, Genova.

Cardani, G., 2004, La vulnerabilità sismica dei centri storici: il caso di Campi Alto di Norcia. Linee guida per la diagnosi finalizzata alla scelta delle tecniche di intervento per la prevenzione dei danni, Ph.D. thesis, Politecnico di Milano, Italy.

Modena, C., Riva, G., Valluzzi, M.R., Mar, G., Sonda, D., Zonta, D., Berti, M., da Porto, F., Franchetti, P., Zanardo, G., 2001. Caratterizzazione strutturale e consolidamento di costruzioni in muratura; MURST 1998-2000 'Il progetto di conservazione: linee metodologiche per le analisi preliminari, l'intervento, il controllo di efficacia, Rapporti di ricerca, a cura di Serena Pesenti, Alinea (ed.), Milano, Dic. 2001; ISBN 88-8125-537-5; 415-457, Milano, Italy.

Penazzi D., Valluzzi M.R., Cardani G., Binda L., Baronio G., Modena C., 2000, Behaviour of Historic Masonry Buildings in Seisimic Areas: Lessons Learned from the Umbria-Marche Earthquake, Proc. 12th Int. Brick/Block Masonry Conf., Madrid, Spain, 217-235