Chapter 3.4

COMPATIBILITY OF MATERIALS USED FOR REPAIR OF MASONRY BUILDINGS: RESEARCH AND APPLICATIONS

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Abstract: The research emphasizes the necessity of a deep knowledge of the structure morphology, the materials, and their characteristics and eventual the state of damage and its causes when approaching the repair of an historic masonry building,. The relevant damages surveyed in stone-masonry buildings after the Umbria-Marche earthquake (1997-98), together with the contributions of several theoretical and experimental studies carried out in the '90s has confirmed the need to improve the knowledge of the seismic response of old masonry buildings and of the reliability of retrofitting techniques. Retrofitting or repair of this damage is a very difficult task. In many cases grout injection or wall jacketing fail due to incompatibility with the construction technique of the walls. The present paper describes and critically analyses the main repair techniques applied to the repair of stone masonry and their effectiveness.

Key words: stone masonry; earthquake; strengthening; repair; grout injections; jacketing.

1. INTRODUCTION

The 1997 earthquake which hit Umbria and Marche in Italy, clearly showed that several repair and strengthening work carried out in recent times (after the previous earthquake of 1979), were not of real effectiveness. On the contrary some interventions performed on historic stone-masonry buildings caused damages to the original structure (Penazzi et al., 2000).

In fact, after the 1976 Friuli earthquake and following, the collapse of old masonry dwellings made with poor masonry walls and timber floors, convinced structural engineers and authorities that in order to resist the seismic

S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, 167–182.

actions the masonry buildings should be treated from the structural point of view as structures having “box” behaviour. This meant stiff connections between the bearing and shear walls, stiff connection between walls and floors and floors stiff in their plane.

These assumptions caused a systematic substitution of timber floors and roofs, with concrete-clay floors, stiff reinforced concrete tie beams at every floor, reinforced injections through the walls, jacketing of very poor walls. The same assumptions were also supported by the Italian Seismic Code.

The last earthquakes showed that these techniques hardly apply to the stone-masonry buildings when walls are made by multiple leaf stone masonry with poor connection between the leaves, weak mortar and irregular stones. Collapses of heavy roofs, hammering of adjacent buildings by the ones which were heavily repaired, out of plane collapses, ineffectiveness of the grout injections, failure of jacketing, are some of the phenomena shown by the 1997 earthquake; nevertheless the techniques themselves can be successful in the case of other types of masonry (e.g. brick masonry or regular stone masonry in new buildings) (Binda et al., 1999).

The ineffectiveness of these techniques in the case of the above mentioned masonry buildings are mostly due to the incompatibility in terms of stiffness between the original and the new structural elements, to the poor workmanship, but mainly to the lack of knowledge on the material and structural behaviour of historic buildings (Penazzi et al., 2000; Penazzi et al., 2001) .

The authors have proposed within Italian Research Contracts supported by the Italian Department of Civil Protection a multilevel approach based on site and laboratory investigation at the level of historic centres with the aim of studying the vulnerability of stone-masonry buildings made with irregular texture and multiple leaf walls and to calibrate appropriate mathematical models (Binda et al., 2004a and 2004b).

In the meantime the authors continued their research on the effectiveness of two techniques: grout injection and deep repointing, showing that a good knowledge of the morphology and behaviour of masonry contributes to successful application of these techniques particularly to irregular stone masonry.

2. MATERIALS AND MASONRY CONSTRUCTION TECHNOLOGY

The structural performance of a masonry can be understood provided the following factors are known: (i) its geometry; (ii) the characteristics of its texture (single or multiple leaf walls, connection between the leaves); (iii) the physical, chemical and mechanical characteristics of the components (brick, stone, mortar); (iv) the characteristics of masonry as a composite material (Binda et al., 2003).

The worst defect of a masonry wall is to be not monolithic in the lateral direction, and this can happen for instance when the wall is made by small pebbles or by two external layers even well ordered but not mutually connected, containing a rubble infill (Giuffrè, 1993; Binda et al., 2003). This causes the wall to become more brittle particularly when external forces act in the horizontal direction (Figure 1). The same problem can happen under vertical loads if they act eccentrically.

Given the great number of existing cross sections and the great influence of the construction technique, a systematic study on the mechanical behaviour of stonework masonry should in fact begin from an extensive investigation of the different geometry and building techniques which takes into account the different layers constituting the wall and the kind of constraints which may or may not be present between the layers themselves (Binda et al., 2003).

3. LACK OF KNOWLEDGE AND FAILED REPAIRS

The last earthquake effects have shown that: a) for some building typologies and masonry morphologies the adopted structural models need to be adjusted to their real behaviour, b) the retrofitting techniques applied after the previous earthquake of 1979 still need improvement.

The interventions, carried out according to the code suggestions were made in order to retrofit all the existing buildings (damaged and undamaged) assuming the safety criteria applied to new buildings designed and constructed according to the current seismic code. Masonry and historic masonry structures were considered too weak to bear future earthquakes, therefore they needed invasive interventions to respect the imposed safety coefficients.

The code suggested that these criteria can be attained for all the masonry buildings, especially for the weakest ones by:

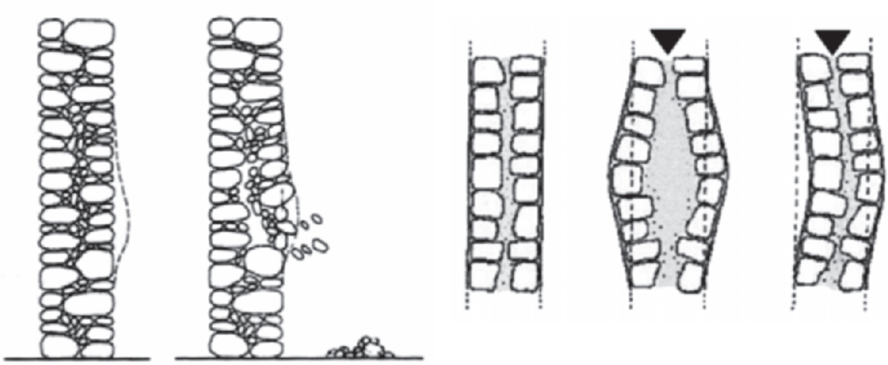


Figure 1. Deformation and failure of a two leaves wall (Giuffrè, 1993).

a) substituting the original timber floors and roofs with reinforced concrete ones.
b) constructing r.c. tie beams in the wall thickness at every floor level and under the roof.
c) jacketing and/or injecting the walls in order to improve their shear strength.

As it is well known, the first two types of intervention are intended to improve the structural response of the building: type a) by ensuring "rigid floor" action, type b) by connecting loadbearing and shear walls in order to prevent out of plane failures. A type b) intervention of course can improve the overall strength of shear walls, as the strength of the existing masonry spandrel beams can be increased and the equilibrium even after shear cracks appear in the masonry piers and spandrel beams is insured. Type c) interventions can obviously increase both the in-plane shear strength and the out of plane flexural strength of masonry walls. The term "can" is used intentionally, as the effectiveness of these retrofitting techniques highly depends on the type of masonry and masonry structure they are applied to.

Even if experimental and analytical research has been carried out in the past decades on these techniques, nevertheless the effectiveness was always checked in terms of strength increase rather than on chemical, physical and mechanical compatibility with the original masonry (Modena et al., 1997a; Binda et al., 1997). Few research was carried out in this direction on the effectiveness of grout injections (Tomazevic and Turnsek, 1982; Tomazevic, 1992; Binda et al., 1993; Binda et al., 1994; Modena and Bettio, 1994; Bettio et al., 1996; Laefer et al., 1996; Valluzzi et al., 2004) and of jacketing (Modena and Bettio, 1994; Modena et al., 1997b). The conclusions recommended a careful approach and suggested a previous knowledge of the masonry wall morphology and of the masonry characteristics, since some types of walls could be not injectable. Similar conclusions were reached for jacketing; where connectors through the wall of the opposite two reinforcing nets (especially for multiple leaf stone masonry) could not be realised, the system was failing (Figure 2).

The failures due to inadequate application of repair interventions are the most difficult to interpret. The questions to be answered are: what actually

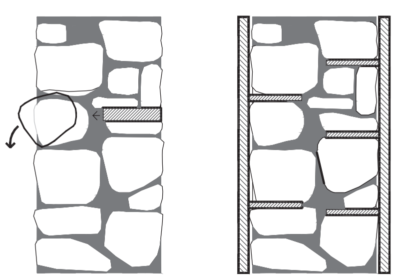


Figure 2. Difficulty in the application of jacketing to multiple leaf stone masonry.

caused the failures and how did they develop and how serious were their consequences to the overall response of the building.

In this context a further problem has been defined, that is the modality of intervention on buildings repaired in the past with unsuccessful techniques. Up to now, the question was often solved by the complete demolition of the building and the volume reconstruction in concrete (Figure 3).

In the following, a critical review is made of some retrofitting techniques.

3.1 Concrete ties and roof and floor substitution

Concrete ties are usually inserted where timber floors and roofs are substituted by mixed concrete and clay block structures. In these cases a concrete tie is built at every floor. The tie is positioned along the four sides of the structure as a connection floor to walls. In an existing building while the roof concrete tie can be positioned on the whole thickness of the top wall, the ties at each floor can only be inserted in part of the section after partial demolition of it. In this case it is very difficult to realise a stiff connection to the existing wall. In general this connection is very difficult when the wall is made of a multiple leaf irregular stone masonry.

The damages observed more frequently were the following: (i) partial eccentric loading of the walls (Figure 4), (ii) lack or poor connection of the tie beam to the walls (Figure 5). The seismic events, then, showed that these elements cannot transmit the horizontal actions to the walls and neither can connect the two masonry leaves, of which one remains free and can rotate freely and overturn (Figure 6).

The collapse mechanism of the masonry is not for in plane shear as expected after the floor substitution, but a partial overturning mechanism of the external leaf of the wall which starts for lower values of the expected collapse coefficient. Some details visible in the upper part of the Figures 4 and 6 suggest that the intervention contributed to reduce the already weak connection between the leaves to the very critical section where the walls are connected to the floor. In fact, in those connections the confining actions of the floors are applied and most probably less uniformly distributed. Even the contribution of the new internal wall (Figure 6), perpendicular to the collapsed facade was completely missing in the collapse, possibly due to the restoration interventions.

In this technique it is important to realise an effective connection between the tie beam and the masonry. In the case of the tie beam at the roof level, which can rest on the whole section of the wall, the connection is difficult because it should be realised by vertical metal connectors inserted in the wall from the top. Once again, this connection is seldom possible in a multiple leaf stone masonry. Furthermore the stiffness of the concrete roof can be too high compared to the one of the existing wall and the roof can hammer the wall and cause a partial collapse (Figure 7).

Figure 3. The building repaired in the 80s and partially failed, has been demolished and an r.c. structure rebuilt.

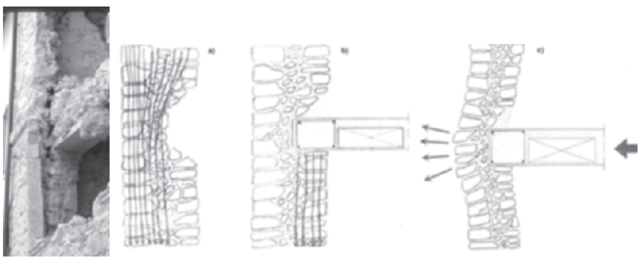


Figure 4. Effect of eccentric loading due to r.c. tie beam positioning and failure of the tie beam insertion at each floor under vertical and horizontal actions (Borri and De Maria, 2004)

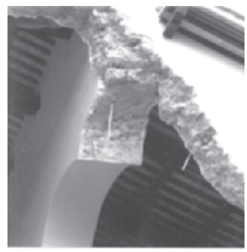


Figure 5. Difficult connection between the roof tie beam and the wall.

Figure 6. Out-of-plane collapse of a wall with r.c. tie beams.

Figure 7. Roof hammering the masonry walls.

3.2 Wall and pier jacketing

The aim of the technique is to better connect the different leaves of a wall in damaged conditions producing a new section constituted by the old one increased by the two jacketed reinforced parts. The idea behind it is to have a thicker section, to increase compressive, tensile and shear strength and ductility (Modena et al., 1997b). The same technique has also been applied to connect load-bearing and shear walls and also large cracks, as well. The technique consists in positioning a reinforcing net (ϕ= 6 to 8mm) on both faces of a wall, connecting the two nets with frequent steel connectors and applying on the two faces a cement mortar based rendering, which constitutes a sort of slab. The masonry panel, then, acquires high strength and stiffness, which is not always a positive point when considering the overall behaviour of the building.

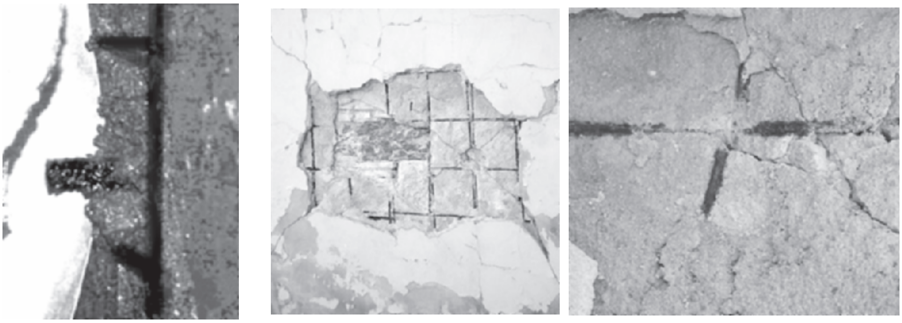
This technique was extensively applied particularly to irregular multiple leaf stone-walls in Italy and it is recommended by the Italian Code. Nevertheless, its execution on site is not very easy due to the inhomogeneity of the walls, to the cost and difficulty of connecting the two faces of the wall (Figure 2). In fact, it is possible to observe frequently local failures of jacketed walls, almost always very clearly connected to poor detailing. Examples are shown in Figures 8(a,b), representing failures respectively due to insufficient steel.

The most widespread mistakes made on site are described in the following together with the consequent damages: (i) lack of connection between the nets in orthogonal walls and in correspondence to the floors; they cause discontinuities between the walls (Figure 8a), (ii) lack of overlapping between two different sheets of the net (Figure 8c), (iii) absence of steel transversal connectors (Figure 8d), (iv) use of too short connectors (Figure 9), (v) lack of uniformity of distribution of the repaired areas in the structure; this can cause torsion stresses due to non uniform distribution of the stiffness.

Furthermore, a low durability of the technique was often observed, due to insufficient thickness of the steel cover with consequent steel corrosion (Figures 9b,c). This problem is of a great importance in building where capillary rise and diffuse moisture are widely recognisable.

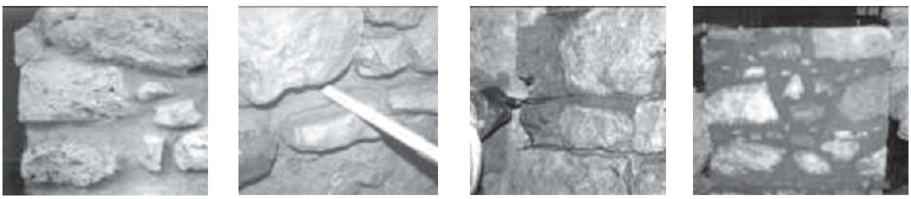
(a) (b) (c) (d)

Figure 8. (a) Failure due to insufficient steel mesh overlapping and (b) insufficient transversal ties confining action; (c) lack of connection between nets; (d) absence of connectors.



(a) (b) (c)

Figure 9. (a) Too short connectors; (b), (c) corrosion of the steel net in a jacketed wall.



(a) (b) (c) (d)

Figure 10. (a) Joint after cleaning, *(b)* detail of the joint depth, *(c)* first layer of repointing, *(d)* after intervention.

A proposal for a confining technique for the walls was made by Binda et al. (2005), (Corradi et al. 2005), based on deep re-pointing of the wall carried out on both sides (Figure 10). Tests were carried out on site and gave encouraging results, particularly when the technique is applied together with grout injection.

3.3 Grout injection

Repair and retrofitting of masonry is extensively performed by grout injection, which for years have been regarded as a suitable technique to restore the homogeneity, uniformity of strength and continuity of masonry walls. Research has been carried out in these last years on the effectiveness of the technique. Testing on small-scale models under horizontal loads has also been performed in order to study the response of masonry repaired by injection of grouts, and compare it to other techniques (Tomazevic and Turnsek, 1982; Tomazevic, 1992).

In general, the aims of the technique are: (i) to fill large and small voids and cracks increasing the continuity of the masonry and hence its strength, (ii) to fill the gaps between two or more leaves of a wall, when they are badly connected. The aim can be fulfilled only knowing with good precision the morphology of the wall section, the materials constituting the wall and their composition in order to avoid chemical and physical incompatibility with the grout, the crack distribution, the size, percentage and distribution of voids (Binda et al., 1997; Binda et al., 1993; Binda et al., 1994; Laefer et al., 1996; Valluzzi et al., 2004).

As known, the success of the injection technique can be limited when badly applied, due to the masonry morphology, to the desegregation and sedimentation of the grouts, to the mix characteristics (grain size distribution) and to the operative technique.

The main problems related to grout injection can be summarized as follows: a) lack of knowledge on the size distribution of voids in the wall, b) the difficulty of the grout to penetrate into thin cracks (2-3 mm), even if microfine binders are used, c) the presence in the wall, of fine and large size voids, which make difficult choosing the most suitable grain size of the grout (injecting large size voids with a fine grained mix can in fact induce segregation), d) the segregation and shrinkage of the grout due to the high rate of absorption of the material to be consolidated, e) the difficulty of grout penetration, especially in the presence of silty or clayey materials, f) the need for sufficiently low injection pressure to avoid either air being trapped within the cracks and fine voids or even wall disruption.

Therefore, the effectiveness of a repair by grout injection depends not only on the characteristic of the mix used, but also on its mechanical properties and on the injection technique adopted and once again on the knowledge of the wall type. The injectability of the grout is influenced also by its compatibility with the masonry to be repaired. The technical improvements of the last years have lead to the development of new grouts with specific properties, such as a low salt content and an ultra fine size of aggregate, and have also shown how to optimise the injection methodology, such as the injection pressure or the distance between the injectors, in relation to the masonry characteristics. Multiple leaf walls can be made with very poor mortars and stones but have very low percentage of voids (less than 4% of voids are not injectable) and have internal filling with loose material, which is not injectable. Figures 11 and 12 show two of the cases where injection was clearly proved to be very poor.

Injectability tests proposed (Binda, et al., 1993) can be carried out in the laboratory on materials sampled from the internal part of walls. The sampled material can be inserted in cylinders and be injected in laboratory (Figure 13). Compressive and splitting tests on the injected cylinders in laboratory can be carried out on the cylinders after the time necessary to reach the hardening of the grout.

The methodology used for testing the injectability of the material is presented in Figure14. The sequence of operations in laboratory is shown in Figure 15 while Figure 16 presents a comparison between cylinders filled with different materials and injected with different grouts.

Figure 11. Poor results of applied injecttion.

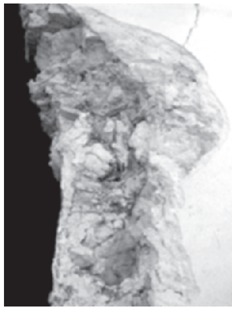


Figure 12. Only some spots were injected in the case of this wall with very low percentage of voids.

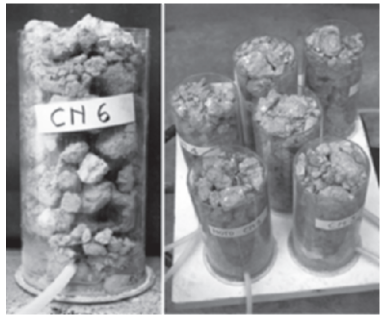


Figure 13. Cylinders can be filled with the materials sampled on site in order to evaluate the masonry injectability.

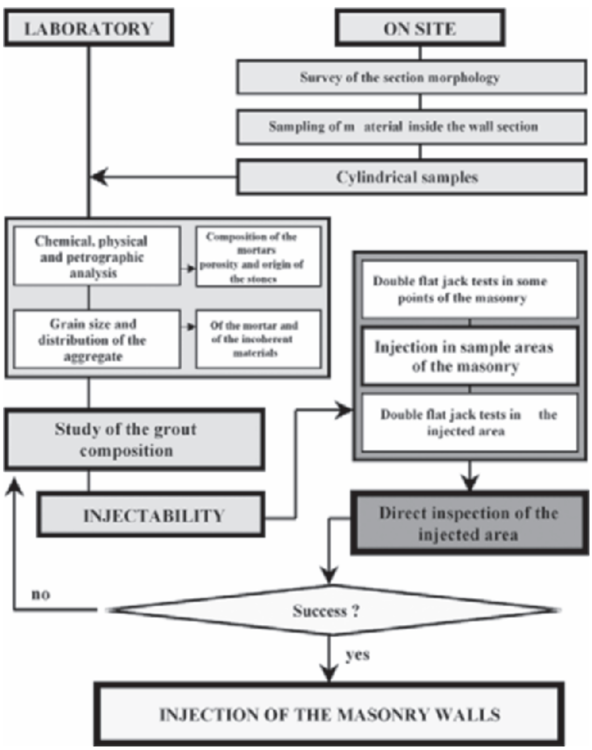


Figure 14. Methodology used for testing the injectability of the masonry

Figure 15. Phases of the injection in laboratory.

Injectability tests can be carried out directly on site on sampled area, locally dismantling the masonry. Non destructive tests as sonic tests can also be carried out on site, before and after injection in order to detect the penetration and diffusion of the grout.

4. OLD AND TRADITIONAL RETROFITTING AND REPAIR TECHNIQUES

Even if the scientific knowledge reached much lower levels as today, the mitigation of the earthquake effects by improving the structural behaviour and studying better details was certainly tried. Special techniques were suggested since the past centuries for repairing the damaged buildings and retrofit the structures. In the following a brief description of the techniques is reported referred to the different structural elements.

4.1 Foundations

The suggested way for mitigating the seismic effects was, since Plinius in the "Historia naturalis", to enlarge the dimension of the contact between the foundation and the soil. The same suggestions were given by Scamozzi (Scamozzi, 1615). Geometrical rules (plan dimension of the foundation equal to 1/6 of the height of the building) were given in 1783 by Sarti. Underpinning with brick or stone-masonry in order to reach lower strongest layers of the soil was also used in the past centuries. Leonardo da Vinci also mentioned reversed arch foundation and enlargement of the foundations. Actually this technique is still used today, were concrete beams are used. In 1909 M. Viscardini (Barucci, 1990) was proposing something similar to the base isolator

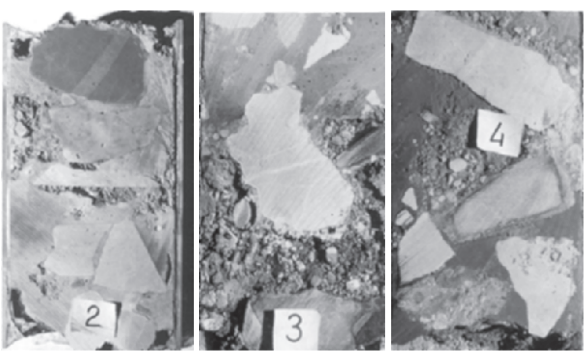


Figure 16. Comparison among cylinders filled with different materials and injected with different grouts in a laboratory.

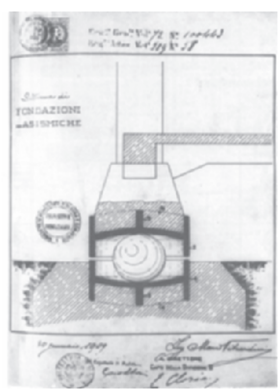


Figure 17. Design of foundations in seismic areas (1909).

(Figure 17). Similar proposals were made by C. Pesenti and others, as to insert between the foundations and the soil a layer of highly elastic material obtained by injection of wood or lead.

4.2 Walls

The use of steel or timber tie rods to connect wall to wall and wall to floor was known since the Byzantine times (Saint Demetrius in Thessaloniki, Aghia Sophia in Istanbul, 4th and 5th century). Their use continued in the Gothic architecture not only for seismic protection but also for collect the thrust of arches and vaults. In the 15th century, systems of rods were applied in seismic areas for restoring verticality of out of plane walls. Tie rods in seismic areas were suggested systematically through the 17th, 18th and 19th century (Milizia, 1554; Rondelet, 1832). This technique was also applied in Calabria in 1878 after an earthquake. In Umbria it was prescribed by the Recommendations published by the municipality of Norcia and in Sicily at the beginning of the 20th century (Archivio Storico, 1861) (Figure 18).

Another system largely adopted in Umbria was the use of buttresses against the existing walls (Figure 19).

Repointing and reconstruction of partially collapsed walls was also frequently adopted in the past; the same applies for the technique of adding a new leaf to increase the thickness of the wall.

A way of retrofitting the whole structure was the use of shear frames against the load-bearing and the shear walls (Figure 20) (Barucci, 1990). At the beginning of the 20th century reinforced masonry was also introduced in seismic areas (Genovese, 1915). In order to avoid hammering between two adjacent buildings a separation joint was realised by demolishing and reconstructing the end wall (Figure 21).

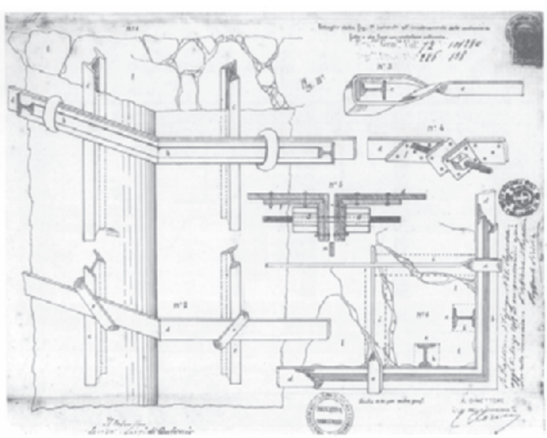


Figure 18. Connection wall to wall by tie rods (1909)

Figure 19. Addition of buttresses

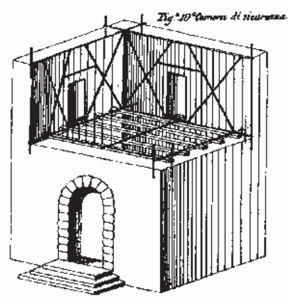


Figure 20. Timber framed walls (1876).

Figure 21. Joint cut between two houses.

4.3 Floors and roofs

These two important elements were continuously repaired against the earthquake, sometimes by substituting the highly damaged ones with stronger ones (steel beams and depressed vaults instead of timber); nevertheless a great deal of repair of the timber structures was also carried out.

Special care was given to the construction or the repair of timber roofs, with the description of all the most important details. It was considered safer to connect the roof beams to the walls and the use of trusses in order to avoid large thrusts. Some of the mentioned interventions have failed due to repeated seismic events, so it is impossible to criticise their effectiveness. Most timber ties and repair of timber floors and roofs simply failed for lack of maintenance; the same was for repointing and thick renderings when poorly made but also due to incompatibility with the substrate. The addition of a third leaf to existing walls usually failed by separation of the new leaf especially when bad connections were realised between the new and the other leaves. Steel ties, when appropriately applied, were successful everywhere; so were timber and floor roofs provided neat good connection existed between the walls and the timber elements.

5. MULTILEVEL APPROACH TO THE ANALYSIS OF THE VULNERABILITY OF STONE - MASONRY BUILDINGS

The research was supported by the Italian Department of Civil Protection, involving Universities and Cultural Property Regional Offices.

The aim of the research was to set up, for historic centres, systematic data-bases storing the information useful in order to prepare rescue plans and to design interventions for the preservation of the cultural heritage. Such information deals with: i) the technological and constructive characteristics of the surveyed buildings, ii) the material and structure properties (with particular reference to the constructive techniques and to the materials used for load-bearing masonry), iii) the materials and the techniques used for restoration before the earthquake, iv) the collapse mechanisms of the buildings and structures due to the earthquake, considering also the ones already retrofitted.

The object of the aforementioned research was not the single building, but the whole historic centre (even if small). Therefore, the strategic aim was also, besides collecting information on the effectiveness of the repair techniques adopted in the distant and recent past, 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. Hence there was the necessity of defining a "minimal" investigation program, eventually carried out by the Municipality or by the Province or Region, in order to support the designers in choosing the right analytical models for the safety definition and the appropriate intervention techniques for their projects (Binda et al., 1999; Binda et al., 2004a and 2004b).

It is possible to state that the seismic vulnerability assessment of historical buildings should consist of an articulated procedure which first of all takes advantage of two sources of information: indirect (as archives and bibliographic information, collected for reconstructing the evolution of the building from origin and its load history, also through the study of the earthquakes occurred in the past) and direct (as geometrical and photographic survey; typological analysis of the building, aimed at understanding the rules of behaviour in the process of formation and growing of the built types; stratigraphic survey, when possible, for gaining chronological information; survey of the masonry section and surface texture; survey of the crack pattern; analysis of the main structural elements including load-bearing walls, roofs, floors and vaults, staircases, and of their connections, damages, and effectiveness of past repair; laboratory characterisation of material samples; on site tests).

6. CONCLUSIONS

The recent frequent earthquakes in Italy provided an opportunity to learn from the failure mechanisms that occurred to both non retrofitted and retrofitted buildings. As in the case of conservation of monumental buildings, compatible repair techniques and materials have to be applied even to a simple dwelling. Knowledge of the structure typology and masonry morphology, of the material's chemical, physical and mechanical properties is necessary through an onsite and laboratory investigation carried out on each building.

When using new techniques and materials, experimental research has to be carried out before, not only on the mechanical behaviour but also on the physical and chemical compatibility with the existing structure and materials.

The collected data have to be documented for future interventions, possibly in the form of a data base extended to the whole historic centre.

The repair and retrofitting techniques have to be properly chosen according to the structure and material characteristics. There is not a single technique for every masonry or for every structural element, but the most appropriate for every case.

Guidelines should be available for both designers and end users describing the way of choosing the most reliable intervention.

ACNOWLEDGMENTS

The research has been partially supported within the GNDT - Framework Program 2000-2004 "Simulation of earthquakes and damage scenarios in urban areas. Vulnerability of historic centres and cultural heritage" supported by the Civil Protection Agency, Italy and by MIUR - Cofin, 2002.

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