REPAIR AND STRENGTHENING OF HISTORIC MASONRY BUILDINGS IN SEISMIC AREAS

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SUMMARY

The 1997 Umbria - Marche earthquake offered a unique opportunity to verify the knowledge on seismic response and on retrofitting strategies of historic masonry structures which have been developed during the last twenty years. Severe damages were in fact suffered also by those buildings that had already been, and in some cases were still being, repaired and strengthened - after the effects of the previous 1979 earthquake - according to the most updated expertise in this field, as it is expressed by the national recommendations. The study of the actual efficiency of current techniques for repairing and strengthening historic masonry is particularly dealt with in the paper. To this scope, the authors are carrying out extensive surveys on damaged buildings in order to accurately analyze the observed failure mechanisms. The crucial problems of the structure and materials incompatibility that frequently occurred are particularly taken into account.

1. INTRODUCTION

Relevant damages have been surveyed in stone-masonry buildings after the Umbria-Marche earthquake (1997-98), even where retrofitting techniques have been applied after the previous 1979 earthquake. The observations confirmed the need of improving the knowledge of the seismic response of old masonry buildings and of the reliability of retrofitting techniques.

To this scope a detailed Data-base is being built, which contains overall geometrical data (plan, views, etc.), masonry data, representation of the structural system, retrofitting history, detailed description of the damage, and mechanical interpretation of the damage or collapse process [1] of a number of buildings. The masonry of the buildings was investigated and classified with reference to its internal composition, its construction characteristics (i.e., by determining the layout of the section) and to the chemical, physical and mechanical characterization of the components and of the masonry itself, performed by site and laboratory tests.
The study is leading to a catalogue or abacus of the main failure mechanisms, which will be used to set up reliable mechanical models for interpreting the observed damage and forecasting the expected collapse modes. Here the collected data and observations are used to critically consider the effectiveness of some techniques (both "traditional" and "new") for repairing and retrofitting a defined class of masonries: the multiple leaf stone masonries.

2. FAILURE MECHANISMS AND OF REPAIRED AND UNREPAIRED BUILDINGS

The so called "minor" architecture is mainly constituted by stone buildings with timber roofs and floors. The construction typologies vary from isolated to row buildings, from the house built on a flat area to the one made on a steep mountain slope. The majority of this patrimony is characterised by a rural origin and therefore by a poor level of material choice and construction technique, but worth of being preserved as it is an important part of the historic centre.
Failure mechanisms are here discussed based on surveys carried out on two historic centers which have different characteristics and are representative of many historic centers of Umbria.
Two typologies of buildings can be considered as representative of the two centers: (i) stone-masonry buildings with walls made of irregular stones (mainly calcareous with some few blocks of travertine), having the wall section made by two partially connected leaves (interested by partial reconstruction after subsequent earthquakes), and timber floors and roofs; (ii) stone-masonry buildings as in (i), already repaired with partial or total reconstruction of the damaged walls (also using different materials as bricks, tuff blocks, etc), and having floors and roofs remade with concrete beams and hollow clay blocks.
In both cases, the internal partitions and the floor height are rather irregular. Due to the soil slope the number of floors can increase downhillup to seven.

2.1. Isolated buildings (Montesanto)

In the case of isolated buildings four main mechanisms were identified for non repaired or badly repaired structures:

1. Out of plane of loadbearing walls with local or total collapse of the facades or of the corners, or large deformation of the walls. This mechanism is due to the lack of connection between orthogonal walls (Fig. 1) and between walls and floors or roofs (e.g absence of tie rods) and to the presence of large openings (Fig. 2).
2. Out of plane mechanisms with local or large failures of the upper part of the walls and collapses of parapets, cornices and spandrels. Large diffused cracks appear where beams are settled, and local collapses occur due to the high stresses caused by the hammering. Due to the thrust of the roof and to the absence of connection between the roof and the masonry (also due to the masonry heterogeneity) the detachment of concrete ring beams was also observed (Fig. 3).

3. Wall disconnection and leaf separation with local or global failures. The presence of inhomogeneities in the wall, the lack of connection between the leaves of multiple leaf walls (Fig. 4), the filling of openings without good connection between the old and the new parts or the use of different types of materials can be the causes of such mechanism.
4. In plane mechanisms due to shear stresses with diagonal cracks of piers and walls at the different floors. They are mainly due to: bad positioned openings, differential stiffness of the walls between openings, presence of weak lintels (Fig. 5).

Fig. 1: Failure of a building corner

Fig. 2: Out of plane collapse of a bearing wall

Fig. 3: Partial collapse due to the thrust of the roof and bad connection tie beam-wall

Fig. 4: Separation of the two leaves of a wall

Fig. 5: Shear failure of a wall

2.2. Row houses (Roccanolfi)

An accurate study is still ongoing in the case of Roccanolfi, in order to better define and understand the typical mechanisms of large blocks of houses where the buildings are attached together forming a sort of curtain and built on steep slopes of the soil. To this aim groups of buildings were identified as building blocks. The damage of each block has been studied and surveyed, also adopting axonometric representations which can better show the different levels of the soil**.** This study allowed to stress out the typical mechanisms of failure of the cases when

buildings are tied together along the streets and in differential levels.
In all the blocks, the first and the last building are badly damaged by local collapses and large cracks (Fig. 6). When the collapses occur in the internal part of the blocks they always interest the non repaired buildings adiacent to the repaired ones (Fig. 7). In the central part of the building curtains with the presence of decayed floors and roofs large continuous deformations and out of plumb of the walls were detected. Moreover, due to the hammering of the two blocks cracks and damages appear where vaulted passages connect two blocks of buildings . This phenomenon is more clear when only one of the blocks was repaired.

Fig. 6: Failures of end buildings in a row

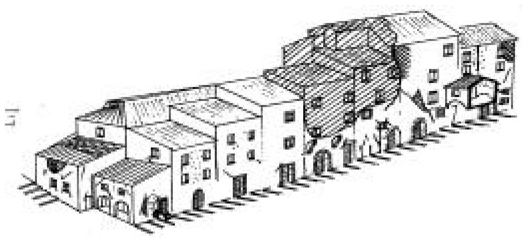

Fig. 7: Failure of center non repaired buildings in a row

3. STRUCTURE AND MATERIAL COMPATIBILITY PROBLEMS

The authors do not intend to refer to restoration and conservation theories, even if they are aware that in seismic areas it is difficult to strictly follow the principles of the different Restoration Charters (Venice, Athens, etc.). They are nevertheless convinced that repair and retrofitting techniques should always respect the original existence and that any intervention not respectful of it, can also create incompatibility with the original structure and materials. The 1997 earthquake was not so much destructive to leave only ruins, but its intensity was such that many errors and mistakes were stressed out. In fact, most of the failures were due to lack of knowledge of the materials and of building construction details, which caused a wrong choice of the repair technique and, very frequently, the poor application of it.
Therefore, it is possible to say that there are not bad techniques but only inappropriate and poor applications due to lack of knowledge and of skillness.
In the following, some critical comments will be made on the application of the most frequent modern techniques, based on the damages surveyed after the 1997 earthquake.
Grout injection. - The aims to which this technique is applied 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 materials constituting the wall and their composition (in order to avoid chemical and physical incompatibility with the grout), the crack distribution and connection, and the size, the percentage and the distribution of voids [2, 3]. Multiple leaf walls can be made with very poor mortars and stones but they have very low percentage of voids (Fig. 8) (less than 4% of voids is not injectable) and have internal filling with loose material which is not injectable [4]. *Wall and pier jacketing.* - The technique consists in the positioning of a reinforcing net (?= 6 to 8mm) on both faces of a wall, connected by frequent transversal

steel ties, and applying on the two faces a cement mortar based rendering. The aim is to improve the connection of the wall, and to increase the tensile and shear strengths and the ductility [5]. The same technique can be carried out to connect load-bearing and shear walls and to close also large cracks.
This technique was largely applied in Italy to irregular multiple leaf stone- walls and it is recommended by the Italian Code. Nevertheless, due to the inhomogeneity of the walls, to the cost and the difficulty of connecting the two faces, its execution on site is not very easy. The most diffused 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 with the floors, which cause discontinuities between the walls; (ii) lack of overlapping between two different sheets of the net (Fig. 9), (iii) absence or too spaced steel transversal connectors (Fig. 10), which can cause the separation of the reinforced layers from the wall; (iv) use of too short connectors; (v) insufficient thickness of the steel cover with consequent steel corrosion (Fig. 11); (vi) lack of uniformity of distribution of the repaired areas in the structure, which can cause torsion stresses due to the non uniform distribution of the stiffness.

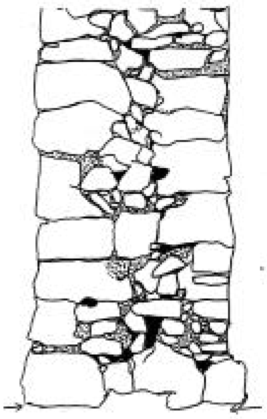
Fig. 8 Poor section with very low content of voids


Fig. 9 Lack of connection between nets


Fig. 10 Lack of connectors

Fig. 11 Corrosion of the net

Fig. 12 Eccentric loading to concrete tie positioning

Concrete ring beams and roof and floor substitution. - are usually inserted where timber floors and roofs are substituted by mixed concrete and clay block structures. In such 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. The aim is to help the structure working as a stiff box against the horizontal seismic loads. In an existing building the roof concrete tie can be performed through the whole thickness of the top wall, whereas at each floor it can only be inserted in part of the section, after partial demolition of that. Therefore, it is very difficult to release a stiff connection to the existing wall, especially when the wall is made of a multiple leaf irregular stone masonry.
The damage observed more frequently were the following: (i) partial eccentric loading of the walls (Fig. 12), (ii) lack or poor connection of the tie beam to the walls .

4. CONCLUDING REMARKS

Even if the research and the evaluation of its results are still ongoing, some concluding remarks can be drawn from the direct experience collected and monitored in the Database.

- multiple leaf stone-masonry structures are peculiar; their behaviour under seismic loads and their compatibility to repair techniques still need more knowledge to be understood; they cannot be compared even to brick or regular stone-masonry structures.
- the basic attitude of the near past to fit the real structure to reference analytical models applicable to other masonry structures implied sometimes invasive and non compatible retrofitting techniques;
- 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.

As regards compatibility problems, it is worth noting that repair techniques were used in the past centuries and the present ones are sometimes only a reproposal of them using modern materials, which can be incompatible with the existing ones. A better knowledge of the traditional techniques and new research to apply them in a modern way will be one of the major issues of the future research of the authors in this field. At present, in fact, very few research has been carried out on the behaviour of rubble and multiple leaf stone structures before choosing the appropriate repair techniques .

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