A CLASSIFICATION OF STRUCTURES AND MASONRIES FOR THE ADEQUATE CHOICE OF REPAIR

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Abstract
The research emphasises the necessity of a deep knowledge of the wall morphology and of the components, of their characteristics and of the eventual state of damage and its causes, when approaching the modelling of an historic stone masonry structure. A classification of historic masonry buildings together with a classification of single and multiple leaf masonry sections according to the number of leaves and their connections as a result of a long term investigation carried out in different Italian Regions will be presented. It will also be shown how without this knowledge incompatible techniques for repair can be adopted which can cause damages under seismic events.

1. INTRODUCTION
An extensive research has been carried out by the authors within the frame of National contracts supporting the study of vulnerability of historic centres in Italy [1]. Buildings and dwellings of these centres were not declared as monuments and for a long time were considered as “minor” architectures; hence to them the preservation principles were not applied. This caused the application of heavy repair techniques which turned out to be incompatible with the original structures and materials causing high damages under the last earthquakes [2].

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 [3].

The worst defect for a masonry wall is to show no monolithic behaviour in the lateral direction; this can happen for instance when the wall is made by small pebbles or by two external leaves even well ordered but not mutually connected, sometime containing a rubble infill. This causes the wall to become more brittle particularly when external forces act in the horizontal direction. The same problem can happen under vertical loads if they act eccentrically [4].

A systematic survey of the buildings allow the authors to classify their typology according also to their structural behaviour under in-plane and out-of-plane actions during seismic events; this is a way to avoid the application of inappropriate mathematical models to verify their safety state and to choose appropriate repair techniques.

The investigation on masonry textures also allow to classify the wall morphology. It is worth to remark that textures appearing regular on the external surface of a wall often correspond disordered arrangement in the section (Fig. 1). Therefore, a correct analysis of the mechanical behaviour of existing masonry structures, especially when multi-leaf walls are present, can not disregard the proper investigation of the arrangement of materials in the thickness of the wall itself.

![Regular texture](image1.png) ![Irregular courses](image2.png)

**Figure 1: Masonry textures and sections**

A classification of historic masonry walls has also been carried out in different Italian Regions according to the construction technique. The wall sections were carefully surveyed and subdivided as single and multiple leaf masonry sections according not only to the number of leaves but also to the connections between the leaves. In the meantime the masonry elements
(stones, bricks, mortars) were characterised in laboratory and the masonry were tested on site by flat-jack and sonic tests.

A Data Base has been also prepared containing the masonry prospects and sections and their characteristics.

2. BUILDING TYPOLOGIES

The mathematical models used to detect the load carrying capacity of the masonry constructions should take into account the many different types of structures which are representative of the building function: houses (isolated, in rows, etc.), palaces, churches, towers, castles, fortifications, etc.

Each type has its own behaviour under the external actions. Frequently they suffer from structural damages typical of the special typology. For example a crack pattern denoting damage under compression is typical of heavy structures as towers, bell towers, fortified walls, church pillars, etc. When this type of damage is present, the vulnerability of the building to synergetic external actions can be high. The lack of maintenance can also increase the vulnerability level of the structure causing damages to the timber structural elements as floors and roofs; in these cases the structure can partially or totally collapse under events like earthquakes or floods. Also other elements as vaults and arches can show damages due to lack of maintenance.

The mechanisms of damage and failure under horizontal actions are different for different type of structures. According to their behaviour it is possible to distinguish: isolated buildings, row houses, complex agglomerates of houses frequently found in historic centres, with a complex volumetric evolution [5].

A classification of the main types of masonry structures is proposed in Fig. 2. According to the complexity of the structure and also of its eventual evolution in time the model must simulate the right structural behaviour. Each of the classes needs appropriate models for calculation. Input data necessary to the model can only come from a careful investigation on site aimed to know the geometry, the technique of construction, the evolution of the structure along the time, the crack pattern survey and the damage survey; a laboratory investigation is also needed to characterise the materials. The choice of the appropriate analytical models strongly
depends on the level of knowledge, on the complexity of the structure and on the types of actions acting on it.

3. UNSUCCESSFUL REPAIR CAUSED BY LACK OF KNOWLEDGE

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 have confirmed the need of improving the knowledge of the seismic response of old masonry buildings and the need of reliable retrofitting techniques. The 1997 earthquake was not so much destructive to leave only ruins. The damages caused to non repaired and repaired buildings could be used to learn a better approach to modelling and retrofitting of stone masonry structures [5]. The effects of the event have shown that in several cases the adopted structural models were not adequate and the retrofitting techniques had not provided the expected effects. The earthquake stressed, in fact, the
cases of incompatibility between the existing damaged structure and the way the repair technique were applied. Most of the failures were due to lack of knowledge of the materials and of the construction details and this caused a wrong choice of the technique of repair but they were also due to a poor application of the technique caused by lack of skill [1], [2], [6], [7].

Some failures of application of modern repair techniques are discussed in the following.

3.1 Substitution of timber floors and use of concrete tie beams.

Concrete ties, floors and roofs were frequently adopted to substitute timber floors and roofs. The tie is positioned along the four sides of the structure as a connection floor to walls. In an existing building, the ties at each floor can only be inserted in a limited part of the wall 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 even more difficult when the wall is made of a multiple leaf irregular stone masonry. Fig. 3 shows the effects of the tie insertion under an earthquake.

The damages observed more frequently were the following: (i) partial eccentric loading of the walls (Fig. 3) [6], (ii) lack or poor connection of the tie beam to the walls [8].

The seismic events, then, showed that these elements cannot transmit the horizontal actions to the walls, neither can connect the two masonry leaves, of which one remains free and can rotate freely and overturn [7]. In Figure 4 the flux of stresses is qualitatively represented: a) after excavation, b) after positioning of the tie beam, c) under out of plane action.

Figure 3: Failure of the tie beam insertion at each floor under vertical and horizontal actions [6].

Figure 4: Failure of the repair under out of plane actions.
The most frequent 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.

3.2 Grout injection.

Repair and retrofitting of the masonry walls is extensively performed by grout injections, which for years have been considered as a suitable technique to restore the homogeneity, uniformity of strength and continuity of masonry walls.

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: (i) the morphology of the wall section, (ii) the materials constituting the wall and their composition in order to avoid chemical and physical incompatibility with the grout, (iii) the crack distribution, (iv) the size, percentage and distribution of voids [8], [9].

The main problems connected to the grout injection can be summarised as follows: a) the 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 makes 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 presence of silty or clayey materials but also of any type of loose materials (in Fig. 5 a failed injection is shown); f) the need for sufficiently low injection pressure to avoid either air trapping within the cracks and fine voids or even wall disruption.

Multiple leaf walls can be made with very poor mortars and stones but have very low percentage of voids (a wall with less than 4% of voids is not injectable) and have internal filling with loose material, which is not injectable [9]. Figs 6, 7 show two of the cases where injection was very poor.
New grouts with specific properties such as a low salt content and an ultrafine size of the aggregate and the improvement of the technology of injection such as the injection pressure or the distance between the injectors, in function of the masonry characteristics, have brought in the last years to better results.

### 3.3 Wall and pier jacketing

The aim of the technique is to connect better 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 and to increase compressive, tensile and shear strength and ductility [10]. The same technique has also been applied to connect load-bearing and shear walls and 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.

This technique was largely applied particularly to irregular multiple leaf stone-walls in Italy and it was 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 8 shows how the technique can be wrongly applied in case of...
4. MASONRY MORPHOLOGY

When considering the mechanical and more generally the physical behaviour of masonry structures it should not only be remembered that masonry is a non homogeneous material, but that there are many types of masonries. In fact the differences are not only given by the use of materials according to the local possibilities (stones, bricks, earth, various types of mortars, etc.) but also due to various construction technologies. Furthermore when modelling the behaviour of a masonry structure the complexity of its geometry and volumes makes difficult the choice of an appropriate model [5].

Therefore, given the great number of existing masonries, a systematic study of the mechanical behaviour of brick- and stonework masonry should begin from an extensive investigation of the different geometry and building techniques taking into account the number of leaves often constituting a wall and the kind of constraints which may or may not be present between the leaves themselves. In fact the ancient building techniques and particularly those adopted in the poorer architecture still need to be carefully investigated.

An extensive research was carried out and is still in progress in different Italian regions [8], studying brick and stonework walls of buildings, the internal cross sections of which could be inspected; the operation can be more easily conducted in those areas where the buildings were damaged by the earthquake and have not yet been repaired [11].
The geometrical survey consists of a graphic and photographic procedure which includes taking a picture with a camera having the lens of 50 mm, using a tripod in order to ensure the parallelism between the plane of the picture and that of the wall section. The metric survey of the walls is then graphically reproduced on a PC, so that it is possible to calculate the percentage of voids, bricks (stones) and mortar (Fig. 9).

A Data Base was produced containing more than 300 masonry sections from various Italian Regions (Lombardia, Friuli, Liguria, Basilicata, Trentino, Toscana, Umbria, Sicily) [3]. The survey of the wall sections allowed to define some important parameters like: (i) the percentage distribution of stones, mortar, voids which allows to make comparisons between the percentage of materials and voids for the different Regions (Fig. 10); (ii) the ratio between the dimensions of the different layers and that between the dimension of each layer and the whole cross section; the dimension and distribution of voids in the cross section. These parameters, together with the chemical, physical and mechanical properties of the materials give the possibility of better describing the masonry and constitute a fundamental basis for the mathematical modelling and for the appropriate choice of repair techniques.

![Figure 9: Form representing the wall section and the void calculation](image1)

![Figure 10: Percentage of mortar vs. percentage of stones referred to the area of the cross section of stonework walls in various Italian regions](image2)
5. THE BEHAVIOUR OF MULTIPLE LEAF STONE-MASONRY WALLS

It is clear that there is a real need of classification of the most common different types of sections, since the behaviour of masonry highly depends on the technique of construction which is shown from the prospects, but better from the sections. This was clearly emphasised by the ancient treaties (e.g. Rondelet and Breymann treaties), where the masonry was classified considering both the aspects. In fact the prospect is not revealing how the masonry section is built and to the same type of prospect there may correspond different types of sections (Fig.1) [12].

The first results of the before mentioned investigation showed the presence of four main types of sections in stone masonry: a) single leaf or solid, b) two leaves without connection, c) two leaves with connection, d) three leaves (Fig. 11). The systematic investigation on the morphology of masonry sections on the Italian territory was started in the early nineties by L. Binda and her collaborators [8], [13], as a necessity to define some guidelines for repair by grout injection, following studies on mortars and grout for repair [8], [9] and more recently modelling the multiple leaf walls behaviour [14].

Contemporarily Giuffrè carried out in the early '90s [4] the first studies about the mechanical behaviour of the stonework masonry typologies based on visual inspection to recognise characteristics of the "rule of art". The studies were part of a more general analysis on the vulnerability of some historical centres like Ortigia, Palermo [4], [15]. In each case the
local masonry typologies and materials were carefully studied and reported in an abacus. The presence of some characteristics, like the connection elements called diatons, can be a discriminating parameter for the evaluation of the mechanical behaviour of the wall.

Other parameters can be: dimension of the elements, shape and workability of the stones, masonry texture, mortar quality, mortar quantity, presence of wedges, presence of clear horizontal courses, presence of diatons, characteristic of the section. Each masonry behaviour is then qualitatively evaluated.

Giuffrè [4], [15] proposed a classification based on a parameter which indicates the ratio of the distance “d” between two subsequent diatons to the thickness “s” of the masonry wall. The parameter is representative of the bending resistance of the wall.

The study of the masonry section can have different aims with respect to diagnosis and repair. One of the most delicate parts of the study concerns the structural analysis with numerical methods to which a detailed survey of the wall and building geometry can provide important input data.

The study carried out by L. Binda and others [3], [8], [13] led from the initial simple classification of Figure 11 to a subsequent more refined classification based on the number of different leaves and on the type of constraint between them (Fig. 12). Whereas the first kind of classification allows to evaluate the injectability of the wall, the second one allows to formulate important hypothesis on the mechanical behaviour of the masonry. Figure 13 represents the connection between the walls surveyed by L. Binda and the mechanical models of Giuffrè [16]

6. CHARACTERIZATION OF THE SECTION MORPHOLOGY

The described damages (sec. 3) enhance the necessity of a deep knowledge of masonry morphology before planning the structural intervention [17].

The usual approach to characterise the masonry section requires drilling cores. Nevertheless, the results are frequently very poor. Coring should be done with a rotary driller using a diamond cutting edge. This operation is rather simple but has limits. The drilled core is usually very decohesioned (Fig. 14) so it is almost impossible to detect the quality of the original
Figure 12: Classification of stone masonries [3]

Figure 13: Qualitative behaviour of a single and multiple leaf stone masonry

Figure 14: Drilling core phases

Figure 15: Core reconstruction

materials. The mortars are powdered by the invasivity of the operation and removed by the water use to cool the driller. Inside the boreholes
additional investigations can be made by the use of borescopy. A small camera may be inserted into the borehole allowing a detailed study of its surface and try a reconstruction of the wall section. The coring results often show an apparent absence of mortar (Fig. 15). This fact is frequently the origin of the exaggerate use of grout injection. Furthermore no information is given on the organisation of the masonry texture in the section. It should in fact be remembered that borescopy can only give a general stratigraphy of the section. In order to understand the morphology of a masonry wall it is much more important a direct inspection. When possible it can be performed by removing few bricks or stones, surveying photographically and drawing the section of the wall.

7. CONCLUSION

As in the case of conservation of monumental buildings, compatible repair techniques and materials have to be applied even to dwellings.

The knowledge of the structure typology, of the masonry morphology and of the material chemical, physical and mechanical properties, is necessary through an onsite and laboratory investigation carried out on each building.

The repair and retrofitting techniques have to be properly chosen according to the structure and material characteristics. There is not one single technique for the masonry or for the structural elements, but only the most appropriate choice for every structure or masonry typology. The proposed classification of masonry sections has the aim of showing the differences of brick and stone masonries constructed in different times and sites. When implementing constitutive laws for the structural analysis of masonry structures these differences should be taken into account, because they produce certainly different mechanical behaviour of the masonry elements. Even if at the end homogenised models will be applied, it will not be possible to have a unique generally valid model. The model has to be previously adjusted to the masonry morphology.

5. References


