Chapter

Historic Masonry

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Abstract

Masonry is a composite material characterised by its good behaviour under dead loads and in a nonaggressive environment. However, this noble material does not satisfactorily resist seismic loads. The different types of historical masonry that have remained over time are characterised by an adequate mixture of materials with low chemical reactions that are degrading due to environmental conditions. There are numerous historical masonry construction techniques in the world, reflecting local conditions of materials and workmanship. The key to its permanence and maintenance over time despite the effects of earthquakes is the construction technology and quality of materials used. As a result of earthquake damage observation and experimental research, various technical solutions for rehabilitation and retrofit of masonry are now available. Finite element modelling has become a very useful tool to identify the damage problem in historical masonry but requires a significant contribution of parameters obtained from destructive and nondestructive tests.

Keywords: heritage, ceramic units, mortars, compatibility, modelling, strengthening

1. Introduction

Masonry is a material composed of natural or manually manufactured units joined with fresh mortar, which constitute an important inventory of existing buildings in the world from the Egyptian civilization to the present day. The most widely studied and investigated construction techniques correspond to the masonry of the Greek and Roman constructions that have remained to this day. In Africa and Asia, the oldest masonry was made of stone or earth. In America, ceramics were used as masonry in the late nineteenth century that are now part of the local cultural heritage.

The preservation of heritage buildings requires knowledge to guide technical and economic maintenance strategies [1]. Building materials degrade over time when in contact with the environment, and this is a natural and inevitable process. From the perspective of use, the main unknown behaviour is the rate of deterioration, necessary data to raise the estimated construction service life in relation to safety and/or functionality [2].

The use of masonry has significant advantages in cost, installation speed, aesthetics, durability, sound insulation, thermal insulation, fire resistance and accidental damage, energy consumption, maintenance and repair, availability of materials and local workmanship and potential recyclability. Regarding the disadvantages, we have detected the need for greater resistant area compared to reinforced concrete, the need of better foundations, problems in the insulation, the size of the openings, in the arrangement of the joints, considerations of safety and health, durability problems by presence of water and salts and currently lack of skilled labour.

The architectural function of the masonry is the envelope of the building to protect its inhabitants and their belongings from environmental agents, for example, the effect of rain. They can be constituted as walls of barriers or drainage.

Structural masonry can be classified as bearing or nonbearing. The bearing masonry resists the own weight and wind loads or earthquake and gravitational loads generated by the floors or ceilings supported on it [3].

The presence of moisture, whose origin may be the wet soil, rainfall or faulty drainage services, causes damage to old masonry. Although moisture can be measured by different techniques, the results are not repeatable. In other cases, new interventions with new materials have increased moisture problems [2].

The application of the finite element method using nonlinear constitutive models is a tool to verify the observed damages and stress states of historic masonry. But nevertheless, laboratory and field tests are necessary in order to characterise masonry materials and provide reliable data on the design parameters needed for building modelling although the number of samples to be extracted should be minimal.

1.1 Methodological evaluation of historical construction

The methodology used in the study of cases evaluates at the beginning whether the historical works have heritage values or not (**Figure 1**), defining the responsibilities before specifying the procedure [2]. All the activities involved in this task involve the interaction of different disciplines and an important responsibility of the maintenance management of the heritage.

Figure 2 presents the different steps of the procedures followed for the rehabilitation of historic buildings, applying safety criteria stated in the regulations and conservation criteria of the International Council on Monuments and Sites (ICOMOS) charts [4]. In this evaluation, the impact of the durability of the materials and the environmental sustainability with the built environment must be incorporated in addition to the safety in the structure.

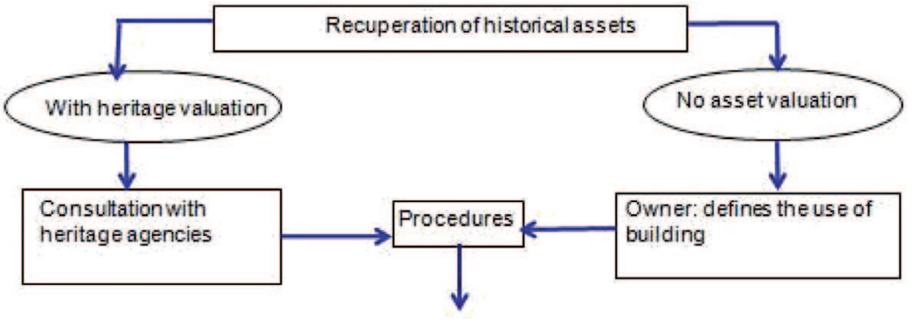

Figure 1.
Basic criteria for recovery of historical works.

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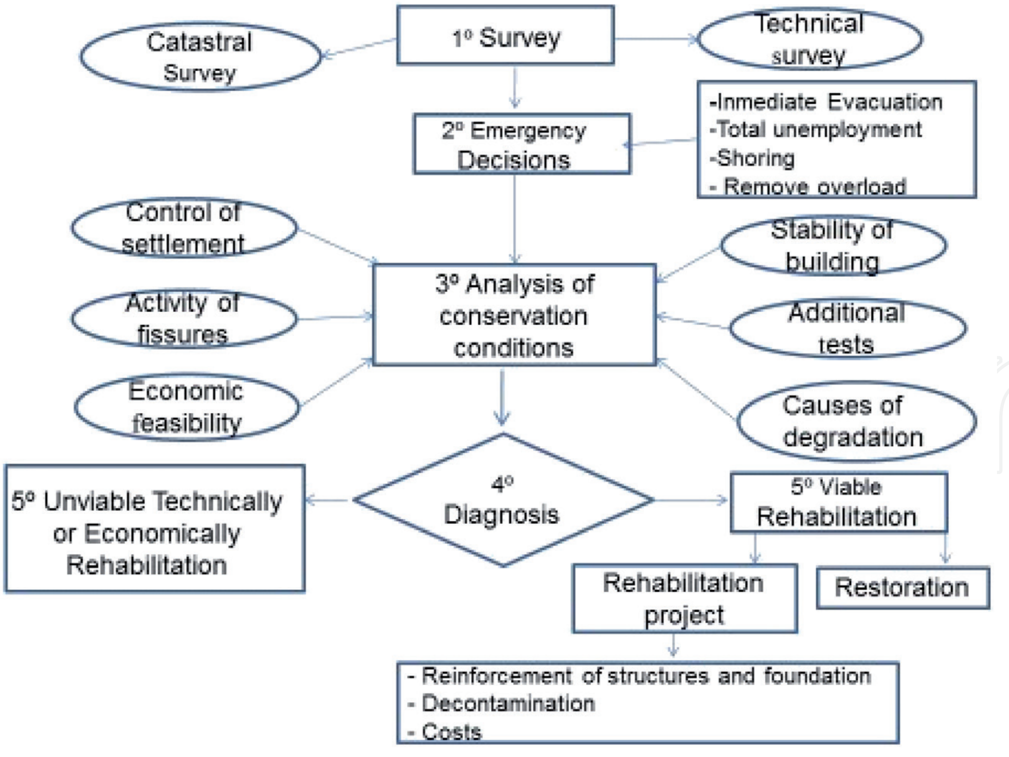


Figure 2.
Procedures of study of heritage construction.

2. Masonry materials

2.1 Historic masonry units

2.1.1 Natural stone

Stone has been used from earliest times. Stone as a material is geographically widespread. Its use in structures is often confined to local materials from a nearby quarry. Load bearing stonework was used up to about the late nineteenth century, but many earlier structures were built of rubble or brick faced with stone ashlar. Since about the year 1900, stone has been mostly used as facade to cheaper masonry or as cladding for other materials.

Stone masonry construction may be of ashlar, squared/coursed rubble, random rubble, etc. Composite rubble/ashlar walls have often been used. It cannot be assumed that a pier or wall with ashlar facing is of solid construction through its entire section; often the core will be of very weak material [5].

2.1.2 Bricks and blocks

Bricks are the oldest man-made building material. Examples of sun-dried clay bricks (adobe) date back to 8000 BC, and fire bricks were used by 2500 BC. Clay bricks were traditionally made locally. Urban buildings of the late nineteenth century and early twentieth century were made of masonry of fired ceramic bricks [5]. In the transition to the use of steel, concrete constructions appear, which employ hybrid metal profiles for supporting floor slabs or as bridges and columns within the masonry to withstand earthquakes known as sidero-brick [6]. Since 1930 the use of reinforced concrete in the world is widespread, leaving the brick masonry walls for minors or cladding in reinforced concrete structures or termination of facades.

Although features may be more reliable as a dating aid, brickwork may sometimes be approximately dated by the brick size. However, there are regional variations which may be greater than those relating to age [5]. Bricks can be fired clay, calcium-silicate or concrete.

Figure 3 shows different placement patterns of solid bricks: stretcher bond, header bond, English bond and Flemish bond, which have different applications in construction (walls, landscaping, pavements).

These patterns allow to identify the time of construction but not the elements of metallic union that were placed from the middle of the nineteenth century in the form of flat strips every four or six courses. Its presence is detected by the slight but regular cracking in these joints due to the increase in volume due to iron corrosion.

The walls with inner cavities are later than 1850 for thicknesses close to 0.40 m and preponderance from 1930 to thicknesses of 0.45 m. These walls generally have a common brick course, an air layer of 0.05 m and a course of decorative purposes or tightness control.

The first uses of concrete blocks are at the beginning of the twentieth century with an important growth due to the demand of houses before World War II. Since World War II, the use of concrete blockwork increased dramatically because of the promotion of cavity walls and the need for improved thermal insulation, which was achieved by the use of lightweight concrete blocks for the inner skin.

Block sizes vary from 390 × 190 × 60 mm to 590 × 215 × 250 mm. The blocks may be solid, cellular or hollow. Densities vary in the range 475 kg/m^3 (autoclaved aerated) to 2000 kg/m^3 (normal aggregate).

2.2 Historical binders

The mortars present in the historic masonry of buildings are typically composed by simple or hydraulic limes. There are two kinds of binders, aerial or hydraulic, depending on the mechanism of hardening [7].

They can be subdivided into simple mortars, hydraulic mortars and composite mortars. The binder can be cement, lime or mix of both. In the past, same mortars contained ash to give a dark colour.

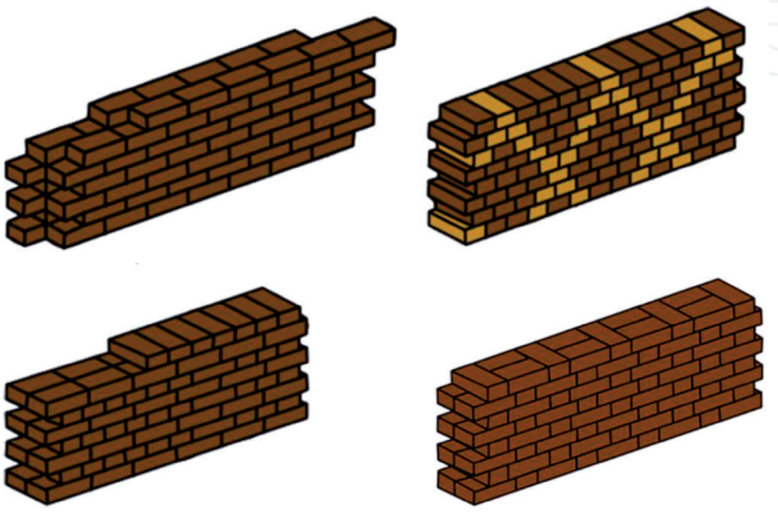


Figure 3.
Common solid brickwork bonds: stretcher (up, left), header (up, right), English (down, left) and Flemish (down, right) bonds [5].

The function of the mortar is to hold together the masonry units and compensate its dimensional tolerances. Also the purpose of mortar is to transfer the gravitational force uniformly through the brickwork, the tying effect being achieved by friction and the staggered pattern of the bricks.

Pure lime mortars, containing no clay or silt, are hardened by carbonation of calcium hydroxide. This can take many years, depending on the porosity of the stone or brick and on the thickness of the wall.

In the case of mortars made from hydraulic lime, where the limestone is ground and fired with some clay or silt, the lime reacts with water for initial strength gain, supplemented subsequently by carbonation of any free lime.

Pure lime mortars (lime-sand) are relatively weak and flexible. Pure cement mortars (cement-sand) may be stronger and stiffer than the stone or brick. If the mortar is too strong, any cracks in the masonry from whatever cause may therefore go through the stones or bricks rather than follow the joints.

Cement-lime mortars (cement-lime-sand) have intermediate strengths; the greater the proportion of cement, the stronger the mortar. Small additions of cement to lime mortars increase the strength marginally but reduce the permeability significantly. This can result in frost damage in porous stone or brick.

Mortar joints are eroded by rain running down faces of walls. This effect is aggravated by chemical breakdown of the binder, because of the acidity of the rainwater. The resistance to this weathering increases with the total proportion of binder to sand. Sulphates, from whatever source, can cause the expansion and disintegration of mortar. Some bricks contain sulphates which may be leached out into the mortar.

The strength of the mortar influences the strength of the masonry in compression, tension and flexure but not to a great degree.

Lime-sand mortars were traditionally used. They were able to accommodate movement, both from the bricks themselves and from the structure as a whole. It was considered a good practice that the mortar should never be stronger than the brick. This must be taken into account when specifying the repair mortar.

Strong cement-rich mortars tend to shrink, which can lead to poor bonding and water ingress into the wall.

The compressive strength of mortar in existing joints cannot be measured directly. The ratios of cement/lime/sand can be established by chemical analysis of mortar samples taken from the joints.

3. Historical masonry construction techniques

The basic method of construction has barely changed in several thousand years: the units are placed one above the other in such a way that they form an intertwined assembly in at least two horizontal directions. Sometimes order is achieved in the third dimension. Most of the time, an intermediate layer of mortar is used to save small to large inaccuracies between units and make the walls waterproof, airtight and soundproof.

There are four main techniques for achieving stable masonry [8]:

1. Irregularly shaped and sized but generally laminar pieces are selected and placed by hand in an interlocking mass (e.g. dry stone walls, see **Figure 4**).

2. Medium to large blocks are made or cut very precisely to one or a small range of interlocking sizes and assembled to a basic grid pattern either without mortar or with very thin joints (e.g. ashlars or thin-joint).

(a) (b) (c)

Figure 4.
Photographs of Mendoza, Argentina: (a) prehispanic stone walls (Uspallata), (b) stone bridge (Luján de Cuyo), (c) Jesús Nazareno church (Guaymallén).

(a) (b) (c)

Figure 5.
Photographs of historical masonry heritage of Mendoza, Argentina: (a) provincial Museum of Fine Arts (Luján de Cuyo), (b) Caro wine vault (Godoy Cruz), (c) Arizu winery (Godoy Cruz).

3. Small-to-medium units are made to normal precision in few sizes and assembled to a basic grid pattern, and the inaccuracies are taken up by use of a packing material such as mortar (e.g. normal brickwork, see **Figure 5**).

4. Irregularly shaped and sized pieces are both packed apart and bonded together with adherent mortar (e.g. random rubble walls).

4. Seismic behaviour of historic masonry

The behaviour of historical masonry to permanent vertical loads has been satisfactory. A different approach to heritage building occurs when there is a seismic-risk region. The way in which a structure is damaged during an earthquake is strongly influenced by its proximity to the area of fault rupture.

Under the great demands on acceleration and displacement of the seismic events studied, only the conjunction updated with new design procedure regulations, a regular good structural design, static redundancy and proper implementation will allow structures to survive strong earthquakes [2].

By definition, "repair" refers to the post-earthquake repair of damage, caused by seismic ground motion that does not increase the seismic resistance of a structure beyond its pre-earthquake state.

"Strengthening", "seismic strengthening", or "seismic upgrading", however, comprises technical interventions in the structural system of a building that improve its seismic resistance by increasing strength and ductility. According to the proposed terminology, strengthening a building before an earthquake is called "rehabilitation", whereas strengthening after the earthquake is called "retrofit" [9].

The law procedure and how to decide the appropriate methods are different in each country. However, the practice between safety and historical preservation is almost the same in all countries that have some preservation regulations, but the problems are exacerbated when the effect of seismic actions is added. The California Historical Construction Code [10] has joined the vision regarding heritage aspects and safety. It includes the subject of use and occupation; protection against fire; escape routes and accessibility; structural requirements, materials and old methods of construction; requirements of mechanical and electrical installations; and drains, whenever the building merits the identification of heritage value.

In the United States, the bearing walls of unreinforced masonry (URM) correspond to before 1933 with two courses of bricks joined at their upper end. When the interior was filled with rubble, it was stiffened elastically and modified the behaviour of the frames where the masonry is inserted.

The behaviour of horizontal diaphragms in historic masonry is often deficient because they are not sufficiently connected to transfer the horizontal seismic forces to the resistant side walls. They are usually made of wood, supported by beams anchored in wall inserts, which are affected by deformations outside the plane of the loaded wall, which can lead to the overturning of the wall and the collapse of the building [3].

The Long Beach earthquake (California, 1933) showed the bad behaviour of this masonry, causing the prohibition to use it in school buildings. The UBC of 1943 established that the masonry had to meet the same criteria of design of the reinforced concrete of that time, appearing the armed masonry.

The Santiago (Chile) and City of México (1985); Izmit, Turkey, and Quindío, Colombia (1999); Pisco, Perú (2007); L'Aquila, Italy (2009); Lorca, Spain (2011); Kathmandú, Nepal (2015); and Manabí, Ecuador (2016) earthquakes have shown that nonengineering masonry buildings have suffered significant damage, especially the masonry constructions in adobe and in stone [3, 11, 12].

4.1 Masonry laboratory tests

The tests of historic masonry specimens obtained from existing structures are scarce. However, there are several investigations carried out in small-scale replicas of URM or in different scales carried out in the United States, Italy and Yugoslavia in the last 25 years [3, 9].

There are in situ testing techniques to measure the compressive strength of the masonry, which produce some damage and require special equipment. The experimental static tests can be applied: flat-jack test and pull out. Ultrasonic, geo-radar, acoustic emission, static monitoring, thermography, X-ray diffraction can be used as non-destructive tests; which sometimes are not justified for masonry routine evaluations that have less thickness than the historic masonry.

The dynamic tests can be ambient vibration testing, even to register a long-term dynamic monitoring.

5. Historic masonry durability

From the point of view of durability, the walls as an open system are in contact with other contiguous structures that take part in the dynamics of the overall behaviour. Even when any infiltration can be successfully eliminated, contact with the ground or with adjacent walls provides moisture sources by capillarity. Virtually all walls contain soluble salts, either dispersed within porous materials or locally concentrated. They can be present as efflorescence that form different aggregates of crystals with various shapes and located on the surface, such as sub-springs that form crystalline aggregates below the surface, and as solutes in aqueous solutions on and inside the walls.

Figure 6.
Evolution of the mortar compatibility process during rehabilitation of school building [2].

The main known salts produced in the walls are carbonates, sulphates, chlorides, nitrates, oxalates and sodium, potassium, calcium, magnesium and ammonia. The different salt species, precipitated from multicomponent systems, vary considerably depending on the materials present, but the type of salt found can, therefore, very often give indications of their origin.

Both the plasters and the paint layer of the walls are typically open structures with high porosity (their pores can easily be intercommunicated). This means that there is a large surface exposed to the degradation agents and there is easy permeability to fluids in contact with it both liquids (solutions of salts diluted in the wall) and gases (atmospheric pollutants and water vapour) [13].

5.1 Material's compatibility

In masonry it is required that the chemical compatibility between the mortar of replacement and the old mortar, the physical compatibility in relation to the process of solubility of salts and water of transport and the structural compatibility where the resistance of the new mortar must be similar to that of the masonry historical in order to avoid damages by the use of mortars with Portland cement.

As far as mortars are complex systems, different approaches can be used for their characterisation. Nowadays, the reconstruction of the original composition is quite complex and requires the application of various and complementary techniques. In addition, the technological culture of making lime mortars has been lost, although from the economic point of view they would be of lower cost [7]. The need for mortar compatibility has led to the design of specific products to avoid damage by chemical reactions as shown in **Figure 6** [2].

6. Masonry modelling

The directed behaviour of the geomaterials (shear as a function of compressive strength) requires computational models that allow capturing the different failure modes and, without losing precision, represent them in a simple way. In accordance with this, there are several modelling techniques; the micro-models consist of the modelling of the masonry units and the mortar as continuous elements, while the masonry-mortar interface is represented by means of discontinuous elements. As the macro-models, these are phenomenological models in which masonry units, mortar and interface are represented as a composite by means of a continuous element. The technique to be used is based on the level of accuracy and simplicity desired [14].

Phenomenological models allow focusing on the overall response of the structure at a lower computational cost. For this to happen, it is necessary to establish a constitutive model whose response is representative of the behaviour of the composites. The constitutive model of Drucker-Prager [15, 16] allows to represent the behaviour of the masonry as an elasto-plastic material with a strong dependence on the acting pressure. The low number of variables to define makes this model attractive. In turn, the characterisation of these variables can be carried out in a simple way through a diagonal compression test in laboratory or application of flat-jack in situ.

To obtain the modelling parameters of the masonry, laboratory tests are carried out in a 1:1 scale on specimens of different thickness [15]. With the experimental results achieved, a finite element model is formulated using the Abaqus software [16] whose parameters allow to obtain a behaviour similar to that observed during the tests.

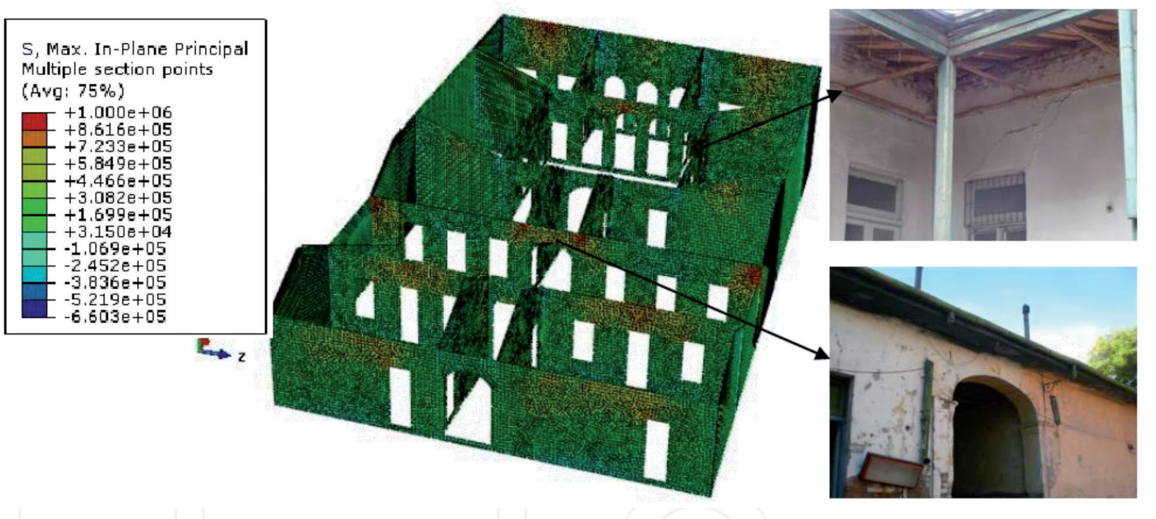


Figure 7.
Comparison of stress state modelling and building damage status [17].

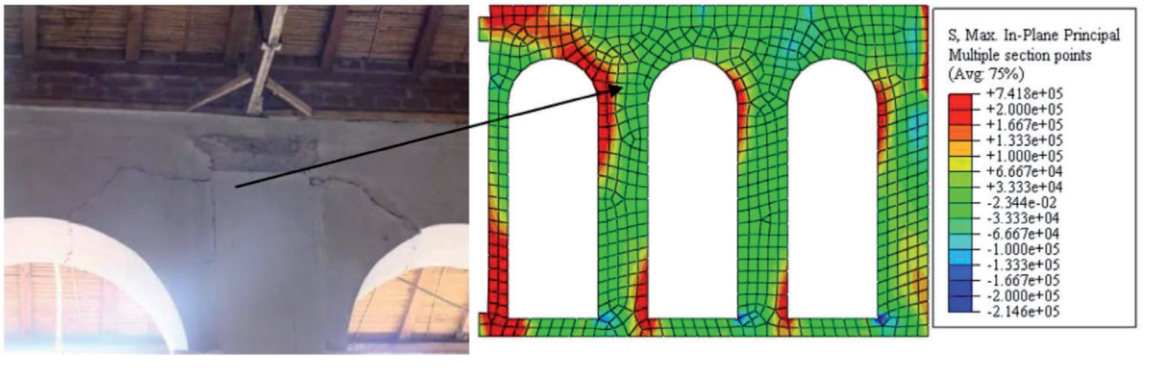


Figure 8.
Comparison between stress state modelling and building damage status [17].

Based on the model generated and calibrated, the building geometry and the state of applicants loads are simulated, the results of which are compared with the real damage evidenced in the structures analysed. The analysis of the results from

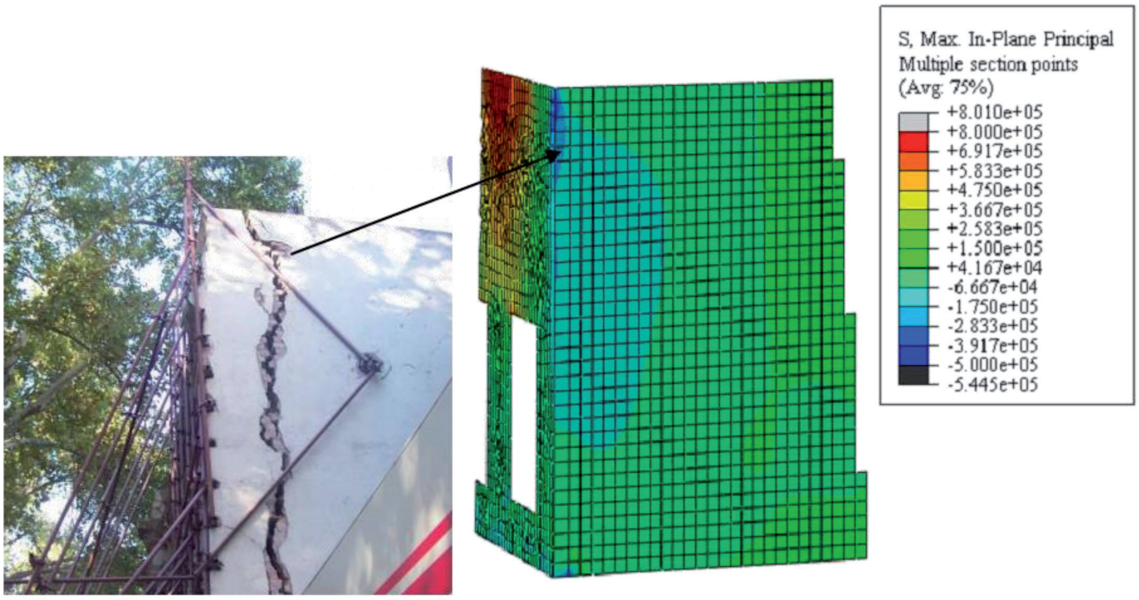


Figure 9.
Simulation of facade damage due to inefficient foundation [17].

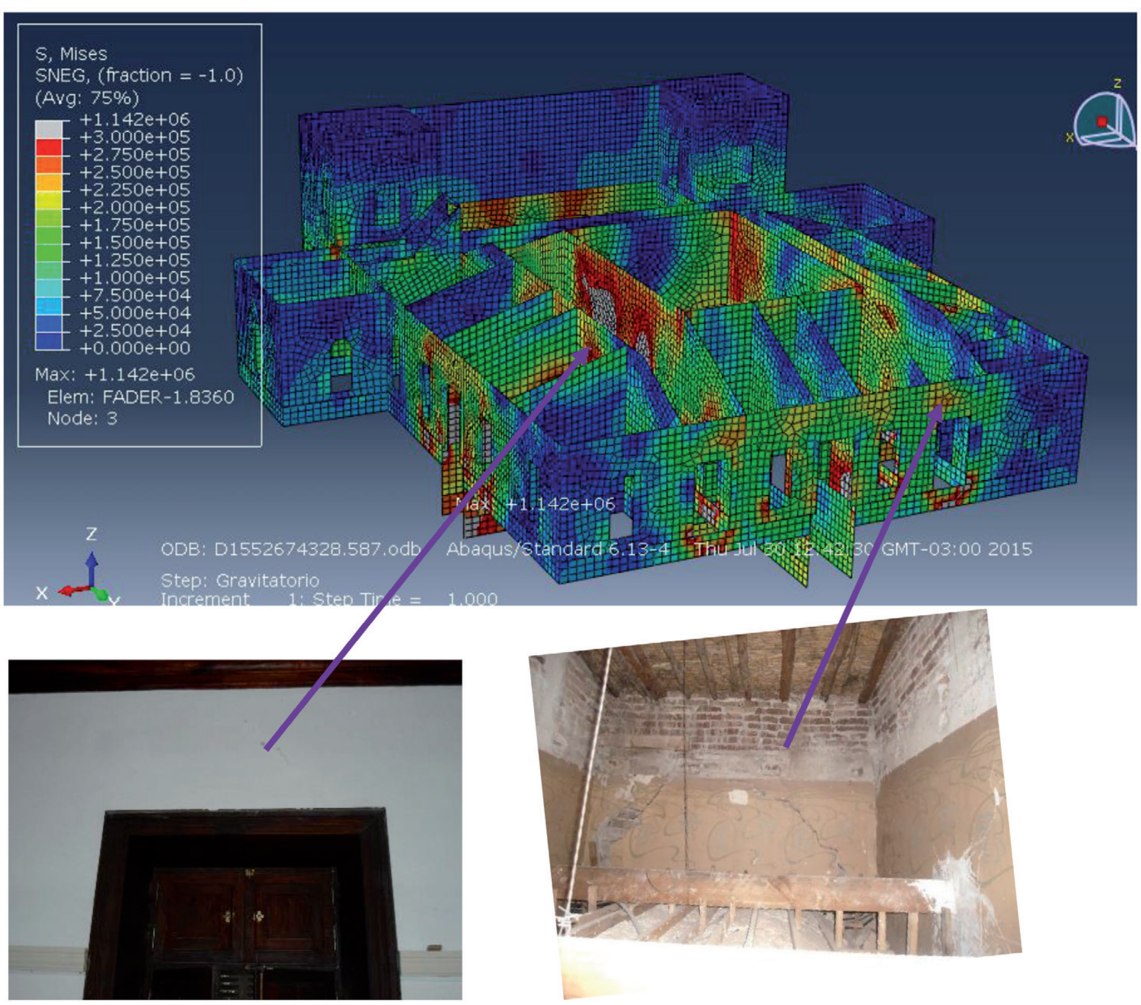


Figure 10.
Damage due settlements of different sectors [18].

the structural simulation allows a better understanding of the causes of the deterioration as well as the cracking patterns. These results have allowed us to make a proposal for its repair and subsequent rehabilitation.

Figure 7 shows the general structural model and the state of stresses of the masonry of an educational building [17]. It shows the concentration of stress associated with the wall encounters and points of application of loads, points that must be reinforced locally, while the rest of the masonry is subjected to a normal tension level below the stress maximum. In **Figure 8** we can see the result of the modelling for the damage in archs, and **Figure 9** shows the detachment of the main facade.

In the case of the museum in **Figure 10**, the stress concentration in the walls of the central nave is observed as a result of the differential settlement between this sector and the lateral ones [18].

7. Study cases

Table 1 shows the cadastral characteristics of historic masonry buildings studied in Mendoza, Argentina, from 1999 to 2015 [2].

Table 2 shows the data obtained in the evaluation of the condition of the historic masonry buildings prior to the value enhancement [2].

Table 3 shows the soil criteria and masonry modelling for different buildings studied. It is taken as a criterion modelling by finite elements for walls using the type plate element of four or eight nodes. Drucker-Prager model has been used for the simulation of material failure [15]. The foundation is modelled by elastic springs, or the soil is modelled directly, considering its rigidity (elastic), since in this type of structure soil stiffness plays a fundamental role. For the roof structure, which is generally flexible, main resistance elements such as trusses or girders (ridges, etc.) are modelled, distributing loads to these elements. The seismic action is determined by applying the methods established by the regulations as proportional forces to the mass of each node of the finite element mesh [17].

Evaluated	Saint Francis Ruins, Capital	Mitre School, Capital	Giol Chalet, Maipú	Fader House, Luján de Cuyo
Date of building	XVIII century	Late nineteenth century–1906	1910	1892 house 1905–6 paints
Date of study	1999	1999 and 2010	2012	2013
Charge heritage	National Direction Architecture Municipality of Capital	Direction of Heritage Government of Mendoza	Municipality of Maipú National Direction Architecture	Direction of Heritage National Direction Architecture
Intended use	Outdoor museum	Educational museum	Vintage museum	Fine arts museum
Archaeological and historical background	Historical and archaeological studies	Few historical and archaeological studies	Few historical studies. No archaeological studies	Few historical studies. No archaeological studies

Table 1.
Data on the buildings studied.

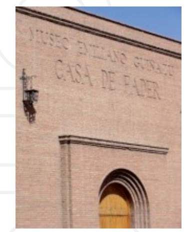
Evaluated	Saint Francis Ruins, Capital	Mitre School, Capital	Giol Chalet, Maipú	Fader House, Luján de Cuyo
Valid contributions from different epochs	1941: Put in value Maintenance Ruins Park and archaeological exploration	Maintenance (paint, flooring) 1955: Replacement of floating floors 1964: Reinforcing bases	Different uses over time (bank deposit, file, housing)	Summer house 1949: Put in value as a museum Subsequent updates of aesthetic value
Masonry type	Masonry handmade ceramic solid mortars with different types of bonding Variable thicknesses 	Handmade ceramic solid 0.55 m (head and rope) Good constructive technique 	Handmade ceramic solid 0.30 m (head) with metal profiles on walls 	Handmade ceramic solid 0.55 m (head and rope) Slab of masonry and metal beams Good constructive technique 
Main problems detected, damages and durability	1861: Destruction by earthquake Deterioration by weathering (capillarity) Cracking in critical areas Imposition of vegetation	Cracking cut eardrums 1985 earthquake Separation facade 2006 earthquake Lack of perimeter chains Settlement arches for lack of foundation bearing capacity Water drainage and sewers problems Efflorescence and soluble salts	Expansion mortar corrosion of wires and profiles on walls Reinforcement corrosion losses in storm drains Contributions of soil moisture plumbing losses Presence of soluble salts	Cracking of supporting structures, mixtures of materials, lack of soil bearing capacity Contributions of soil moisture Problems in storm drains Masonry deterioration by weathering, efflorescence and presence of salts Problems with gardens
Regional seismic risk	High (alluvial soil)	High (alluvial soil)	High (alluvial soil)	High (alluvial soil)
Causes of structural damage	Mendoza earthquake of 1861 and later	Mendoza earthquake of 1917 and later	Lack of maintenance	Several earthquakes Interventions Lack of maintenance

Table 2.
Characteristics of previous interventions, masonry and existing pathologies.

Evaluated	Saint Francis Ruins, Capital	Mitre School, Capital	Giol Chalet, Maipú	Fader House, Luján de Cuyo
Modelling soil	Triangle 15 nodes Mohr-Coulomb elastic theory Plaxis Bv	Triangle 15 nodes Mohr-Coulomb elastic theory Plaxis Bv	Elastic theory	Elastic theory Interaction with Abaqus
Modelling structure	Elastic Midlin theory Plaxis Bv	Eight nodes isoparametric nonlinear Abaqus SAP2000 linear retrofit	Linear masonry plates SAP2000 linear retrofit	Nonlinear model Drucker-Prager masonry Abaqus SAP2000 linear retrofit
Estimate safety	It supports earthquake IV MM	>80% of the original	>80% of the original	>80% of the original
Type of proposed intervention	Reversible (temporary propping) until the final consolidation project	Reversible (outer metal reinforcement chained) Irreversible in foundation	Irreversible (removal of corroded profiles) Without intervention foundation	Reversible (outer metal reinforcement chained) Irreversible in foundation
Present status	Executed	Executed	Proposed	Executed

Table 3.
Modelling and type of intervention.

8. Repair, rehabilitation and retrofit of historic masonry

A large number of historical structures do not meet safety requirements because today's requirements are more demanding than those at the time of construction and because many years have passed by since their construction and structural safety has deteriorated due to use and time. To bring these historic buildings to a level of safety standards today, it is necessary to adapt its structure. However, historical value may be lost due to intervention; therefore, new approaches are needed to achieve sufficient safety.

The San Fernando, California, earthquake of 1971 demonstrated that the adaptation of the parapets to avoid their fall was effective. The 1994 Northridge, California, earthquake showed little damage to historic reinforced masonry with respect to URM that suffered damage and collapse [3].

The structural rehabilitation of historical buildings could be done by hiding those new structural elements or exposing them. Sometimes, the exhibition of new structural elements is preferred because alterations of this type may be reversible; in the future they can be changed without losing the historical character of the building [17].

The decision to hide or expose structural elements is complex, and there is to be a consensus with the preservation professionals who are participants of the project. In high seismic-risk area, it is difficult to strictly follow the principles of the different restoration charts (Venice, Athens, etc.), and the task is a challenge of structural engineering [17, 18].

The strengthening techniques depend on the building response to the earthquake. Different response leads to different strengthening methods. Three main groups could be:

- Interventions to obtain better global response of the building (in case of building box type behaviour and a prevailing in-plane response, **Figure 11**)

- Interventions for the local mechanisms (in case of a prevailing out-of-plane response, **Figure 12**)

- Interventions on blocky structures (where the kinematic mechanisms must be prevented: obelisks, towers and also arches and vaults, **Figure 13**) [19]

In the PERPETUATE project [18], both traditional and innovative intervention techniques have been evaluated. Some of the methods that are widely used in URM structures are insertion of horizontal tie rods; insertion of anchors between structural elements; adding new walls, buttresses and foundations; changing of weak mortar in joints of existing masonry (repointing); repair of cracks; jacketing of walls with reinforced concrete; grout injections of stone masonry walls; injections of cement or epoxy-based grout into cracks; and insertion of reinforced concrete "ring" beams or moment frames and reinforced concrete slabs. Each of these mentioned methods has its own advantages and disadvantages.

Figure 11.
Reinforcement of foundations and reversible metallic structures in columns and lattice, Mitre school, 2012.

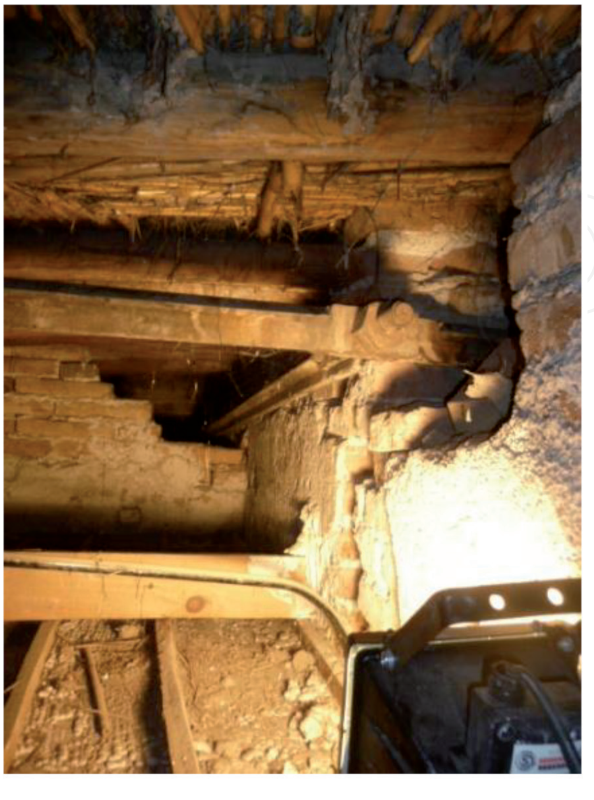


Figure 12.
Bidirectional tensors for bracing of historic masonry walls, Fader House, 2013.

Some innovative methods are strengthening brick masonry with attaching FRP fabric to the surface, restoration of stone masonry with compatible cement grouting, insertion of transversal connection in stone masonry walls, installing seismic isolation for single assets scale and installation of energy dissipation devices [18].

The choice of rehabilitation technique depends on the condition of the masonry, the availability of local workmanship and the safety requirements [4, 9, 11].

Figure 13.
Support structure of masonry blocks, Saint Francis Ruins, 2011.

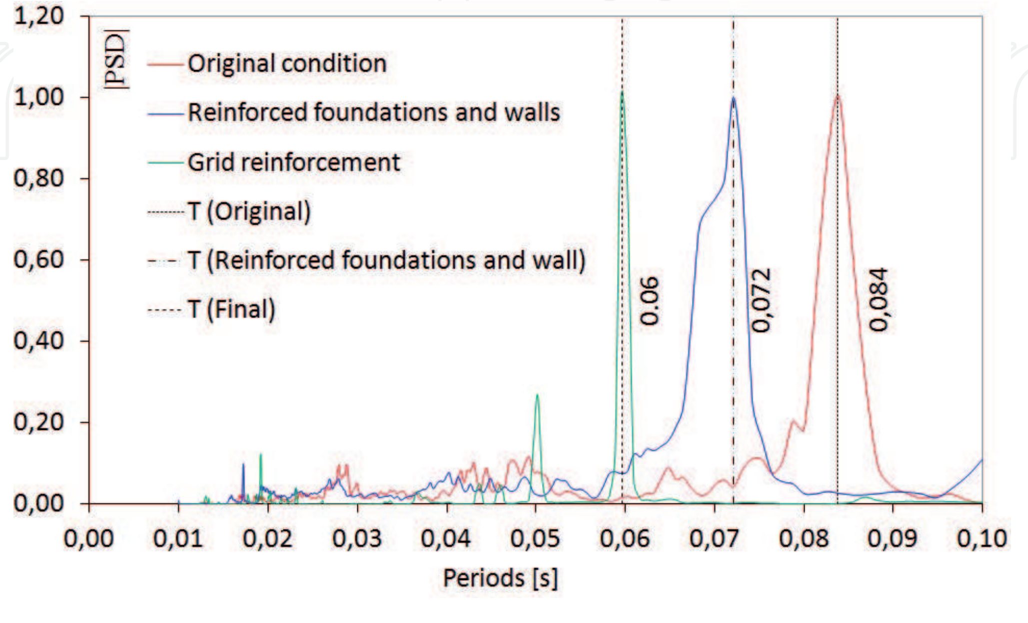


Figure 14.
Evaluation of the change of the dynamic properties of the masonry building in the different stages of the rehabilitation [20].

The effectiveness of a rehabilitation can be evaluated by system identification techniques. They measure the dynamic properties of the structure through environmental vibration before, during and after the structural reinforcement. The vibrations of low amplitude come from different sources, among them, the vehicular traffic, the micro-tremors, the wind, etc.

In the case of masonry, the parameter used to measure the efficiency of the structural reinforcement is the period of the walls measured at the top of them. Before starting the reinforcement work, the environmental vibration in the structure is measured in order to know the periods of the same with the existing level of damage. Once the foundations are consolidated and the walls reinforced, new measurements are taken, and in this way we can know the degree of recovery that the structure has had up to that stage as indicated in **Figure 14** [20].

9. Conclusions

The study of rehabilitation of masonry involves a team of specialists from historians, architects, structural engineers, geotechnical and chemical technicians, etc. That is, it cannot be considered only as a structural problem.

The seismicity of the site and the abandonment of the old buildings have caused the collapse of most of the old buildings, leading to the loss of cultural values that have been part of the local history. Therefore, the rehabilitation of old buildings should be considered a state policy, in order to preserve the few buildings that remain for the future.

It is emphasised that in the region with near-source earthquake, historic buildings that have been standing are made up of ceramic solid bricks; only very few of adobe and stone have managed to survive due to the high demand for ductility of earthquakes near-fault.

Modelling by MEF applying nonlinear constitutive models provides an effective tool for the simulation and verification of historic masonry heritage buildings, so it is necessary to research the formulation of efficient constituent models for thick masonry.

The monitoring through environmental vibration measurement has been a useful tool to evaluate the level of recovery of construction, allowing in the future to evaluate the state of conservation of the same. Model calibration is possible from frequency identification.

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