ISSN: 0871-7869

Rehabilitation and strengthening of old masonry buildings

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- Março de 2013 -

Relatório ICIST
DTC nº 02/2013

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Introduction

Men with mainly four materials built the oldest constructions and these materials lasted thousands of years for construction purposes. These were earth (from which bricks come from, for instance), stone, wood and natural plants fibres. With these four elements men was able to build spectacular constructions some of which are still standing nowadays. Later in the XVIII century, with the beginning of the industrial revolution in England, the iron is burnt with coal and its impurities decrease giving rise to cast iron, to be built in great quantities. While the iron from Nature is very brittle, the cast iron is resisting well to compression, although bad to tension, and can be used as a structural resisting element working in compression. With fewer impurities, later on, we have the forged iron/steel and later the steel, where carbon is mixed with iron is small quantities to make it become more malleable. The forged steel and the steel are used mainly in tension due to the phenomena of buckling. Steel structures are common nowadays although not in great quantity in Portugal when compared to England. The last great change occurring in construction materials was the introduction of concrete. In Portugal it started in the 40's only by introducing some concrete elements, reinforced with steel, to build floors and some columns such how it is found in *Placa* buildings. Later on, in the 60's complete reinforced concrete buildings were built in Portugal and this is the most common practice, nowadays, to build new buildings.

The old masonry buildings in Lisbon that still stand nowadays are called pre-*Pombalinos*, *Pombalinos*, *Gaioleiros* and *Placa* buildings. They were built with stone and/or bricks, sometimes lime, and wood, (*Placa* buildings also with a few reinforced concrete structural elements). Foundations were built with a large masonry footing sometimes settled on a base of wooden piles (*Pombalino* buildings). On the ground floor one can find masonry walls, some made of stone masonry others of brick masonry. It is also possible to find arches made of masonry very common on the ground floor of *Pombalino* buildings. The floors and the roof are made with wood joists, except for *Placa* buildings as previously referred.

The strengthening of old masonry buildings is an important issue since these buildings constitute the historical centres of many cities and thus deserve attention from the state authorities for preservation purposes.

When strengthening an old building, one must focus first on understanding how it is working, assessing its performance for gravity and seismic loads. Then, the problems and/or pathologies must be encountered and only then one can start prescribing the necessary solutions for the rehabilitation or strengthening.

Old masonry buildings have common pathologies that are mainly related to their age. For instance the wood can be damaged due to the changes and exposure to humidity. It can have fungus attack or insect attack. On the other hand the masonry can be also damaged. In case of the masonry the most important pathologies have structural origin and can be translated into desegregation, crushing, fracture and cracking. The most common causes are related with foundation settlements, movements of thermal origin, horizontal thrusts transmitted by inclined roofs or arches, the existence of concentrated and high loads (generally associated with adaptation of the building to new usages) and earthquakes which have a considerable influence in a material that is both heavy and brittle.

The ageing of the masonry and in particular its desegregation depends in a great deal of the way the masonry is protected by coating; the cracking or the loss of these coatings, expose the masonry to the action of the atmospheric agents being especially relevant the action of the wind transporting sands and dust that give rise to erosion.

The foundation settlements are usually associated with the construction of additional floors and/or the execution of excavations in the adjacent areas of the building and have has a result the decompression and dragging of the soil. The changes of the ground water flows are also important.

The iron was used in old buildings mainly for small elements such as nails, screws and elements with anchor shape. These were used to connect wood elements between each other, connect masonry walls between each other and also connect wood floors with masonry walls. The main problem for this material is its corrosion given the lack of maintenance because of the inaccessibility of the elements. The risk of oxidation is, in first place, the loss of useful cross-section of the elements and, secondly, the effect of destruction caused by the increase of the volume of the iron elements that may cause the rupture of the masonry.

The existing pathologies should be tackled. On the other hand, the structural system of the building may be assessed and improved whenever necessary. One reason for improving the structural system of a given building may be, for instance, the objective of changing its use or merely an adaptation to nowadays usages and facilities. For instance the introduction of toilets, the introduction of elevators, air conditioning, the widen up of rooms, etc.

Moreover, one can think of improving the structural system for earthquake resisting purposes. It is then very important to understand very well the original behaviour of the structure. It is always essential to improve the connections between the structural elements, e.g., between the floors and walls (and frontal walls with walls in *Pombalino* buildings) and between the roof and the top of the walls. In this way these structural elements will not separate when the earthquake strikes and will behave together. It is usually also important in any building to strengthen its floors given the wooden floors are flexible in plan(while the masonry is rigid) and thus they do not transmit forces between parallel walls. The whole structure should behave like a box where all the structural elements are having similar displacements and moving together. The foundations may be improved also.

In the following lines it is presented separately structural interventions, firstly related to the foundations; then, structural interventions herein called Local and, finally, structural interventions that are affecting the whole building (Global) behaviour.

Structural interventions related to the foundations

a) Improvement of the ground soil by Jet-Grouting

This technology was first developed in the 70s but later it had a large expansion on the 80s. It was introduced in Portugal in the beginning of the 90s due to the construction of the metropolitan in Lisbon. It consists in the disaggregation of a volume of soil, internally in the ground without previous excavation, mixing it with cement grout introduced in high pressure (values between 200 and 800 bar) and velocity in the order of 250 m/s. This results in a material with mechanical characteristics with higher values then the previous ones for the soil and with less permeability (Fig. 1).

The advantages of this technique are: it can be applied in all types of soil (as long as they contain small sized material and are not subjected to seepage); it can be applied in difficult closed areas and it does not give chance to significant vibrations.

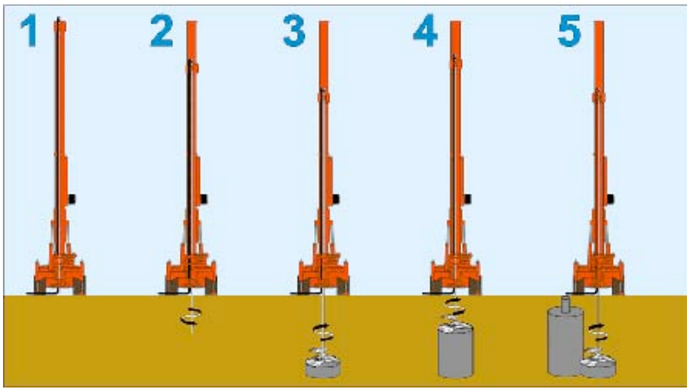


Fig. 1 The fases of jet–grouting [Lourenço, Lectures UM]

b) Improving the behaviour of foundations by enlargement and/or consolidation

As explained by Appleton [2003], the superficial foundation can be enlarged with concrete as is depicted in Fig. 2. The connection between foundation and concrete is made through connectors (“Grampo de ligação”). There is the need to excavate until the bottom of the foundation to place the formwork (“Cofragem”).

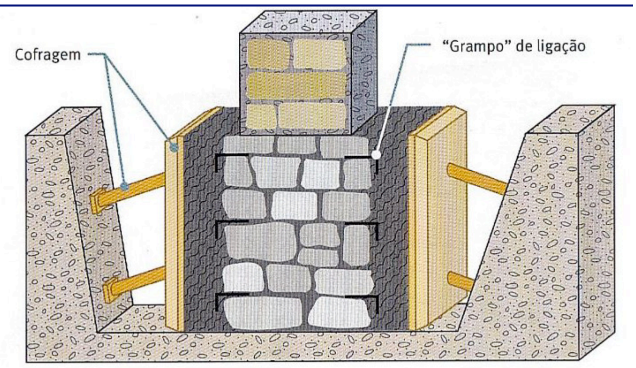


Fig. 2 Enlargement of the foundation [Appleton, 2003]

Additionally, the foundation may be improved by filling the gaps between blocks with mortar, as can be seen in Fig. 3. Visibly, there is the need to excavate until the bottom of the foundation ("Vala escavada") to perform these tasks. One uses tubes for injection ("Tubos de injecção") for the inner holes and then closes cracks at the face of the masonry ("Selagem das juntas").

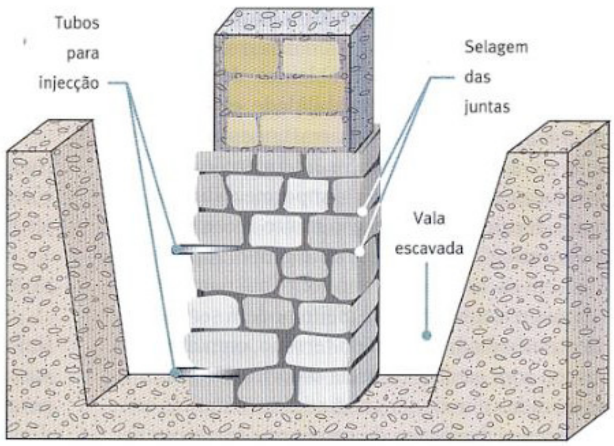
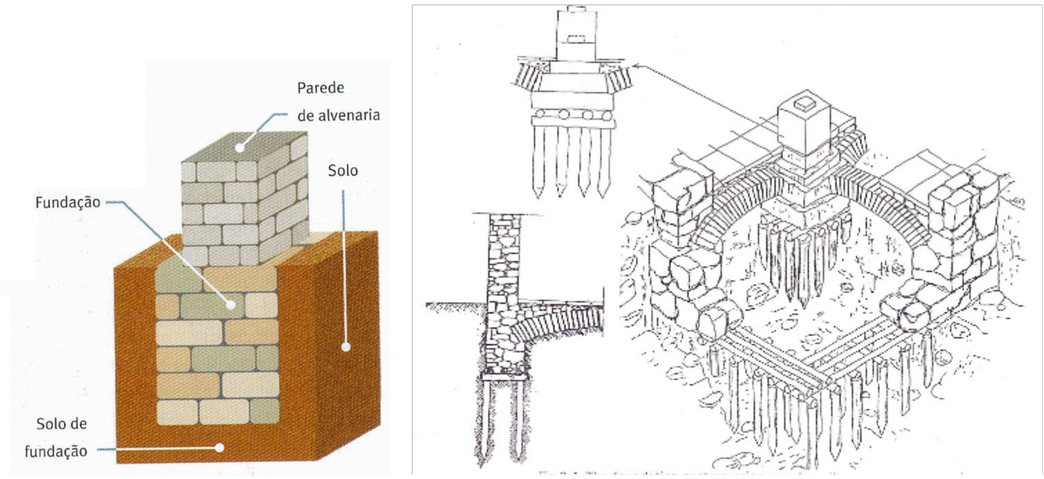


Fig. 3 Consolidation of the foundation [Appleton, 2003]

c) Strengthening of the foundation by using micro piles isolated or in group or in row

The foundation layout present in most of the old masonry buildings is drawn in Fig. 4 a). In Fig. 4 b) one can see the foundation typical of a *Pombalino* building in downtown. This typology of buildings is mainly set on an alluvium filled valley with a weak layer of material over the bedrock. The small wood piles (average 1.5 m long) used in these buildings are meant for consolidation of the topmost layer of soil and cannot be seen as having the same behaviour as nowadays RC piles (which are usually longer, working by point resistance and lateral friction).



a) b)

Fig. 4 a) Common foundations of old masonry buildings; b) Foundations of *Pombalino* buildings

Using micro piles to strengthen a foundation is a solution reasonably used in Portugal in monuments or common buildings. It is for increasing loads in the structure, which lead to increasing loads in the soil, or to deal with settlement problems. The micro piles consolidate the shallower layers of soil and also mobilize the deepest layers of soil.

They are composed of a RC heading, a steel casing with 8, 10 or 12 meters long usually to be filled with a cement grout under pressure. Inside the casing there may be steel rods. Finally, at the bottom there is usually a bulb of cement.

To be noticed that the piles are only under pressure when there is an additional load in the structure. When they are built they do not receive any load.

In Fig. 5 one can see in a) the machine to drill the holes and in b) the micro piles casing to be filled with cement grout.

a) b)

Fig. 5 a) Machine to drill the holes, b) micro piles casing to be filled with cement grout [photos by Appleton, 2011]

Local interventions for structural improvement

a) Injections in cracks

The injections in cracks, internal or at the face, of a masonry wall are a solution of strengthening that is irreversible. They are, however, used frequently because they preserve the original aspect of the exterior of the wall. It is particularly indicated for the rehabilitation of the masonry that has internal cracks connected between them.

For this solution a cimenticious based grout is used or a hydraulic based grout or others such as organic resins based grout. This solution is based on the injection in holes previously made with injection tubes ("tubos de injecção") and spread throughout the wall, to fill with the grout the internal cracks. For the external cracks the coating should be removed previously ("remoção de reboco") and the injection tubes may be used also. Fig. 6 shows these considerations.

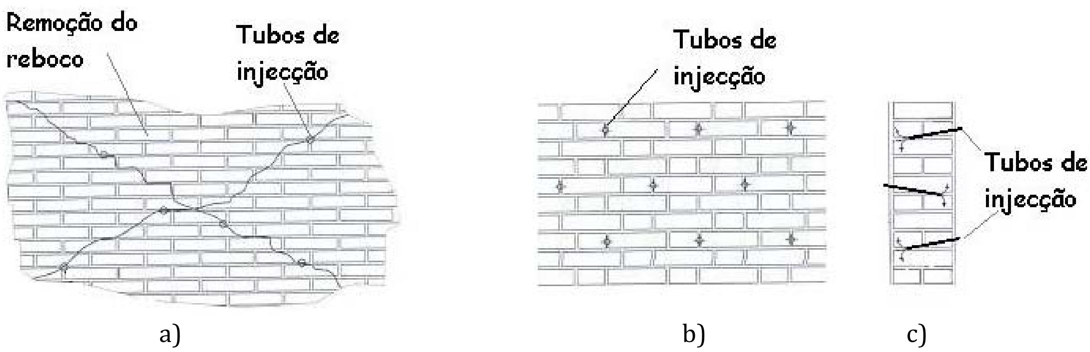


Fig. 6 (a) injection in external/face diagonal crack; (b) injection for the internal cracks; (c) side view [Roque, 2002]

The aggregate grading of the grout depends on the size of the cracks but it can be used a grout without the sand. This technique shows improvements in the mechanical characteristics of the masonry. It seems a better application in stone masonry. To deliver a specific injection grout one must carry on in-situ and laboratory tests to refine the grout. Depending on the used process, there are several solutions for the injections:

1. **Injection under pressure**: it is frequently used in masonry. To avoid structural failure of the wall (that can be in very bad conditions), the holes are done from bottom to top and from side to centre.
2. **Injection trough gravity:** it is used to highly damaged walls.
3. **Injection trough vacuum:** it is used in small interventions, mainly architectural, statues, etc. The grout is very fluid (for instance resins can be used) [Valluzzi, M., 2000].

In old structures, the inorganic grouts, non-cimenticious, like hydraulic limes, should be preferred because of compatibility issues with the already existing mortars. The organic mortars (polyester or epoxy), more fluid, should only be used when there are needs for higher resistance, hopefully without compromising the compatibility between the materials [Roque, 2002].

b) Strengthening roof diaphragms with plywood

To stiffen and strengthen the roof diaphragm (which may be originally made only by a single layer of boards nailed to the joists), one can adopt an intervention that is compatible with the original timber structure, by adding multilayer spruce plywood panels, which are lighter and easier to apply to an inclined plane in comparison to a reinforced concrete slab, although providing a significant stiffness increase. One example of intervention [Magenes et al., 2012], Fig. 7, consists in adding 3 layers of plywood, each 21 mm thick, glued with polyurethane glue and connected to the purlins by means of chemically anchored, 10 mm diameter threaded steel bars. After having drilled and cleaned the hole, a two-component epoxy mixture is inserted in the hole and then the bar is introduced and rotated to distribute the resin. Bars were placed at a constant spacing of 30 cm and penetrated into the purlins to connect the upper plank layers with the roof structure.

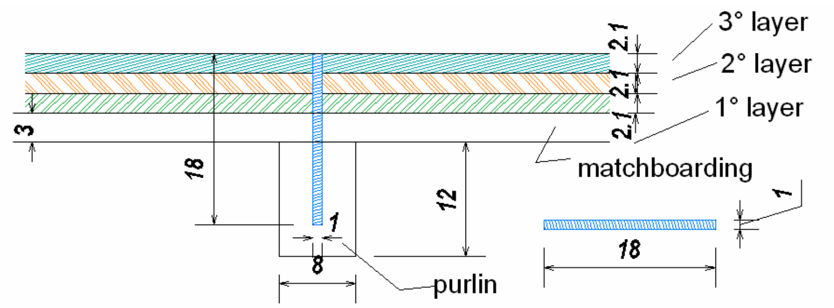


Fig. 7 Scheme of the intervention on the roof diaphragm, consisting in the application of multilayer panels and chemically anchored steel connectors. [Magenes et al, 2012]

To improve the diaphragm behaviour of the roof, continuous steel plates (80 mm wide and 5 mm thick) were connected all along the perimeter to the roof, to favour the development of a strut and tie mechanism. The roof is then completed by adding plain roofing tiles nailed to the multilayer spruce plywood panels.

c) Transversal anchorage in walls

The application of transversal anchorage in walls aims to connect better the two layers of the wall avoiding their separation from the interior core, as can be seen in Fig. 8. The interior core is usually constituted by rubble of low quality. The application of such technique may include, or not, binding material such as grout (cement, lime).

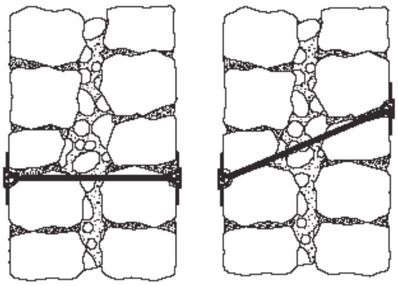


Fig. 8 Face to face connector in wall of two layers [Cóias, 2007]

d) Strengthening masonry column with jacketing

In similarity with the case of strengthening the masonry walls with reinforced cement coating, the masonry piers can be strengthened with reinforced concrete as an outside layer. The steels rods are placed in the perimeter of the pier and then the concrete is poured covering the steel rods. The rods should be anchored to the base foundation of the pier.

e) Repair of damaged wood elements

These are repair techniques and not strengthening solutions. The reduced existence of pieces of natural wood of considerable dimension nowadays makes it difficult to substitute complete pieces of damaged wood with natural wood elements. In this way one can find several substitutes of wood. The damaged wood elements may be replaced by glued laminated wood, for instance. The damaged wood elements can be replaced also with epoxy resin mortar and this mortar has similar mechanical characteristics to the wood to be reconstructed. In this technique, it is advisable that the connection between existing wood and mortar be enforced by mechanical connectors. It is necessary also that there is enough protection of the mortar against fire given the susceptibility of this material to high temperatures. In Fig. 9 a) it is depicted rotten wood joists and in Fig. 9 b) more rotten wood elements.

a)

b)

Fig. 9 a) Rotten wood joists at the connection to the wall; b) Rotten wood elements [Cruz, 2012]

Global interventions for structural improvement

a) Strengthening of masonry walls with reinforced cement coating

In this case (Fig. 10 a) and b)) one places thin (less than 10 cm) layers of coatings of cement reinforced with steel (or glass fiber or plastic meshes, see section d)) on masonry walls. The coating increases the walls strength and ductility. It can be placed in the outside or in the inside or both, depending on the most accessible areas.

To enable the behaviour of both elements (existing and new) to work together one places steel connectors on the wall.

It is thought that a wall of rubble (stone) masonry with 0.60 m of thickness reinforced with two layers of cement coating with steel meshes and with 0.10 m thickness in total, may have increased its strength in compression and shear of 3 to 6 times its original strength, at least [Appleton, 2009].

a)

b)

Fig. 10 a) Masonry wall from the inside with steel mesh, b) spraying of the cement grout into the wall [fotos by Appleton, 2011]

b) Strengthening of masonry walls with polypropylene meshing

Polypropylene meshing uses common polypropylene packaging straps (PP-bands) to form a mesh, which is used to encase masonry walls (Fig. 11 a)), preventing both collapse and the escape of debris during earthquakes. PP-bands are used for packaging all over the world and are therefore cheap and readily available while the retrofitting technique itself is simple enough to be suitable for local builders. PP-meshing has been applied in Nepal, Pakistan and more recently in China. This method is most readily applicable in terms of low-cost upgrading of traditional structures to limit damage caused by normal earthquakes and give occupants a good chance of escape in an once-in-a-lifetime large earthquake. Non-engineered masonry is widespread throughout the developing world and replacement of all such dwellings is both unfeasible and undesirable, given that they are often the embodiment of local culture and tradition. It is therefore often more feasible to consider low-cost retrofitting of such buildings. Experiments and advanced numerical simulations have shown that PP-band mesh can dramatically increase the seismic capacity of adobe/masonry houses [P. Mayorka and K. Meguro, 2008].

This is mainly achieved by increasing the structural ductility and energy dissipation capacities. Under moderate ground motions, PP-band meshes provide enough seismic resistance to guaranty limited and controlled cracking of the retrofitted structures. Under extremely strong ground motions, they are expected to prevent or delay the collapse, thus, increasing the rates of survival. This method is good for one-storey buildings and can be used for a maximum of two storeys. To protect the Polypropylene from ultra violate rays, mud plaster is used on the outside, providing adequate cover to ensure the durability of the material [Shrestha et al. 2012].

To enable the behaviour of both elements (existing and new) to work together one places anchorages throughout the wall (Fig. 11 b)).

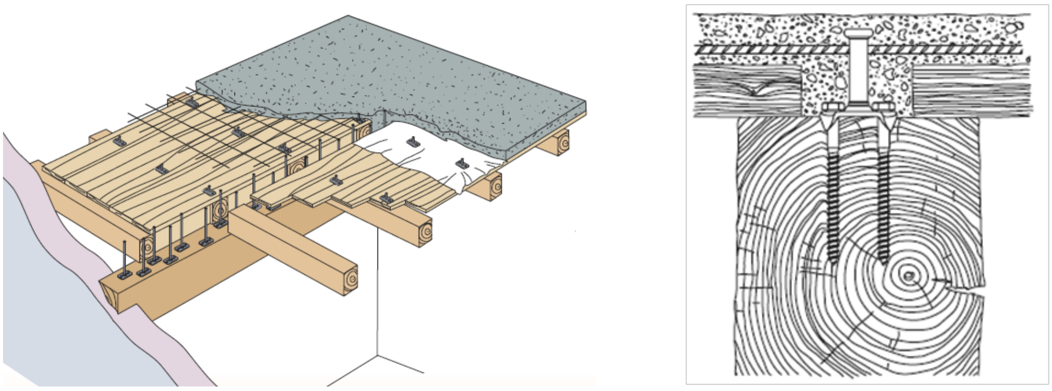
a) b)

Fig. 11 Implementation of PP band method of retrofitting in Kathmandu Valley (a) and anchorage throughout the wall (b) [Shrestha et al. 2012]

c) Strengthening of floors and improving the connection floor/wall

Traditional masonry buildings have timber floors, and they are typically flexible. The increase of the in-plane stiffness of floors is an evident and most effective method of improving the seismic behaviour of old masonry structures. This is mainly because the increase of in-plane stiffness of floors enables the structure behaves like a box, i.e. enables the horizontal forces to be redistributed between the different vertical structural elements, and then the horizontal forces of failing walls can be redistributed to the adjacent remaining walls. A significant role in the stability of the entire building is assigned to the floors. These structures are required, in addition to an adequate performance level, a remarkable rigidity and an efficient connection to the supporting walls, especially in what concerns seismic actions. For this reason, by strengthen a floor, on has an opportunity to improve the behaviour and efficiency of the entire structure.

A technique well spread for the in-plane reinforcement of wooden floors, consists on placing over the existing floor a concrete slab, usually reinforced with a metallic net, and anchored to the existent floor by pins or connectors fixed on the top edge of the beams, which cross the planking and are embedded in the concrete slab and connected to the metallic net, see Fig. 12 a) and b).



(a) (b)

Fig. 12 a) Example of the reinforcement of a wooden floor with a cooperating reinforced-concrete slab, (www.tecnaria.com); b) Basic connectors Tecnaria (www.tecnaria.com)

The structural particularity of this type of intervention is the connection between wood and concrete, designed to transmit shear forces parallel to the structure, between the beams and slab. There is almost no advantage in overlaying the slab without linking it to the pre-existent structure, because the two structures would work independently. Finally, it should be noted that this reinforcement technique, developed in the last 20 years, allows to significantly increase the floor's in-plane bending stiffness, however, it leads to a weight gain for the floor, resulting in increase of the seismic actions. Thus, it is important to limit the concrete thickness to 5 to 10 cm. The technique is also not reversible.

Another possible technique is the idea of including on the floor a horizontal bracing composed of steel ties and arranged in crosses (Fig. 13) and this technique has been developed for many decades. Care is taken to improve the connection between the floor and the masonry wall with L-shaped steel plates (Fig. 13). On the contrary to the previous technique this one does not increase significantly the mass of the floors and is reversible.

Fig. 13 In-plane stiffening with metallic diagonals and reinforcement of connection floor-wall (*Pombalino* building) [photo from Edifer]

In the Fig. 14 one can see a photograph of the connection with L-shaped steel plates between wooden floor and masonry wall.

Fig. 14 Photo of the connection with L-shaped steel plates between wooden floor and masonry wall

d) Strengthening with composite materials (CFRP and GFRP)

It is possible to strengthen with composite materials such as carbon or glass fibres reinforced polymers piers and spandrels within walls and/or columns of masonry. But the application of such method on masonry is still scarcely found. The strengthening improves flexural behaviour or tension and compression through increasing the confinement for instance in columns. The Carbon Fiber Reinforced Polymer (CFRP) or Glass Fiber Reinforced Polymer (GFRP) layers of material are glued with epoxy resin to the cleaned surface of masonry. The weak element is the masonry or the glued surface if the biding is not well done. There can be placed also connectors, especially on walls, so that the material is well bonded to the masonry. In Fig. 15 it is shown the application of CFRP/GFRP on a building, wall and column.

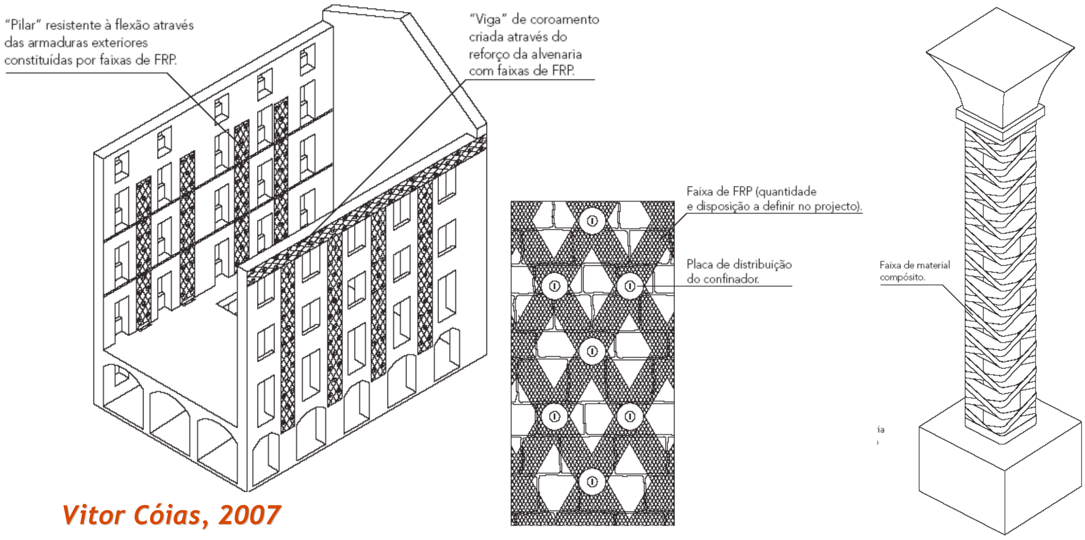


Fig. 15 Application of CFRP/GFRP on a building, wall and column [Cóias, 2007]

In Fig. 16, a wall specimen to be tested was retrofitted with two layers of Carbon Fiber Reinforced Polymer (CFRP) sheets, one in each direction, covering the entire surface of the wall. CFRP sheets are applied in only one side of the specimen. The first layer had fiber orientation parallel to bed joints and the second layer had fibers oriented 900 with the horizontal. They were applied on one side of the wall, while the other side remained with exposed block masonry. CFRP was applied using the wet layup procedure. The wall surface was first prepared prior to the application of CFRP. The preparation involved; i) surface cleaning by wire brush, followed by air pressure to remove loose mortar, ii) application of putty consisting of two-component epoxy and silica fume to cover head and bed joints and to smoothen the wall surface, iii) removal of any extra putty by a plastic putty knife, iv) after curing for a day, inspection of the surface and covering any noticeable air bubbles with putty using the same plastic knife and finally v) sanding the surface by sand paper after two full days of curing.

Fig. 16 Wall to be tested in-plane of brick masonry, strengthened with CFRP [Arifuzzaman and Saatcioglu, 2012]

Once the wall surface was ready for the application of CFRP sheets, the sheets were cut to required sizes and applied on the wall surface. The application involved the following steps:

i. Application of a layer of two-component epoxy on the surface.
ii. Application of the first layer of CFRP whose fibres were parallel to the bed joint, saturated in epoxy.
iii. Removal of extra epoxy and air pockets by means of a ribbed steel roller.
iv. Application of another layer of epoxy prior to the placement of the next layer.
v. Application of the second layer of CFRP perpendicular to the bed joint after saturating it in epoxy and following step iii.

In the following wall specimen to be tested under in-plane loads, the brick masonry wall was strengthened with GFRP strips in both sides of the wall (Fig. 17).

Fig. 17 Wall to be tested in-plane, strengthened with GFRP [Kabir et al, 2012]

Furthermore, Fig. 18 shows a wall specimen to be tested under in-plane loads with the spandrels strengthened with CFRP strips (on both sides), before testing (Fig. 18 a)) and after testing (Fig. 18 b)). After testing it can be observed the debonding of the CFRP strips from the masonry face, implying a reduction in shear strength.

a) b)

Fig. 18 (a) Wall to be tested in-plane with strengthened spandrels with CFRP (b) view of strengthened spandrel after testing showing debonding of the CFRP [Amadio et al, 2012]

If a building has insuficient shear capacity in a particular direction, the capacity of existing walls can be increased instead of inserting an additional structure. In the Fig. 19 one can see the application of an additional layer of material (CFRP or GFRP) bonded to the surface of the URM wall aiming to increase its strength.

Fig. 19 Simple and visually interesting in-plane strengthening with FRPs [Ingham, 2012]

e) The use of horizontal tie-rods

Tie-rods in steel can be used in several applications of old masonry buildings. For instance, they can avoid or at least decrease the probability of out-of-plane failure. Fig. 20 a) and b) show the application of horizontal tie-rods to connect parallel walls at the level of the floors.

a) b)

Fig. 20 Using tie-rods to connect parallel walls [A. Costa, 2008]

Tie-rods can be also used in arches to absorb horizontal impulses (Fig. 21 and Fig. 22).

Fig. 21 Utilizing tie-rods to absorb horizontal impulses in arches [A. Costa, 2008]

Fig. 22 Tying of masonry vaults with tie-rods in steel (Santos, 2003)

In Fig. 23 one can see a failure of the anchorage of the tie-rod after an earthquake, because the plate was too small. In Fig. 24 it is shown the successful behaviour of the tie-rods, spaced close together.

Fig. 23 Close up of partial anchorage failure. Photograph of damage in the 2010 Darfield (Canterbury) earthquake due to deficient anchorages [Ingham, 2012]

Fig. 24 Successful anchorages spaced close together. Photograph of building after the 2010 Darfield (Canterbury) earthquake [Ingham, 2012]

Finally, in Fig. 25 one can see the utilization of tie-rods in a wooden roof.

Fig. 25 Using tie-rods in roofs [M.A. Parisi et al., 2012]

f) Retrofitting by post-tensioning

A post-tensioning retrofit is applied either by placing post-tensioning tendons into cored cavities located at the centre of the wall or by placing post-tensioning tendons externally at discrete locations. The first procedure involves coring a cavity from the top of the URM wall right through to the foundations, then placing a tendon into the cored cavity and finally the application of a post-tensioning force to the tendon. From discussions with specialized New Zealander constructors, one knows that it is possible to core a cavity up to four stories with a precision of +- 10 mm. [Ingham, 2012]. Fig. 26 a) shows the procedure of coring a cavity and Fig. 26 b) shows the bar post-tensioning.

a) b)

Fig. 26 (a) Coring operation; (b) Bar post-tensioning [Ingham, 2012]

There can be done vertical post-tensioning for piers or horizontal post-tensioning for spandrels, as suggested by Meireles [2012] for *Pombalino* buildings, or both types. The performance of post-tensioned URM walls depends upon the initial post-tensioning force, tendon type and spacing, restraint conditions and the level of confinement. Post-tensioning can either be bonded when tendons are fully restrained, by grouting the cavity or left unbounded by leaving the cavities unfilled. Because unbounded post-tensioning is reversible to some extent and has minimal impact on the architectural fabric of a building, the technique is deemed to be a desirable retrofit solution for URM buildings having important heritage value. [Ingham, 2012].

In Fig. 27 one can see in close up view a post-tensioning anchorage.

Fig. 27 Close-up view of a post-tensioning anchorage [Ahmad, 2012]

According to Ahmad [2012] some advantages of this technique for URM are:

a) Reducing cracking/deflection under service loads;
b) Significant increase in strength and ductility;
c) Keep integrity of the structure with minor changes;
d) Reversible;
e) Easy to apply.

However some disadvantages may be:

a) Not applicable to deteriorated masonry;
b) Losses due to creep and shrinkage of masonry;
c) Guiding the tendons is not simple.

Regarding the placing of post-tensioning tendons externally at discrete locations, Ma et al [2012] placed vertical and cross bracing struts at a building in the laboratory. This is to improve the shear capacity of the walls (Fig. 28).

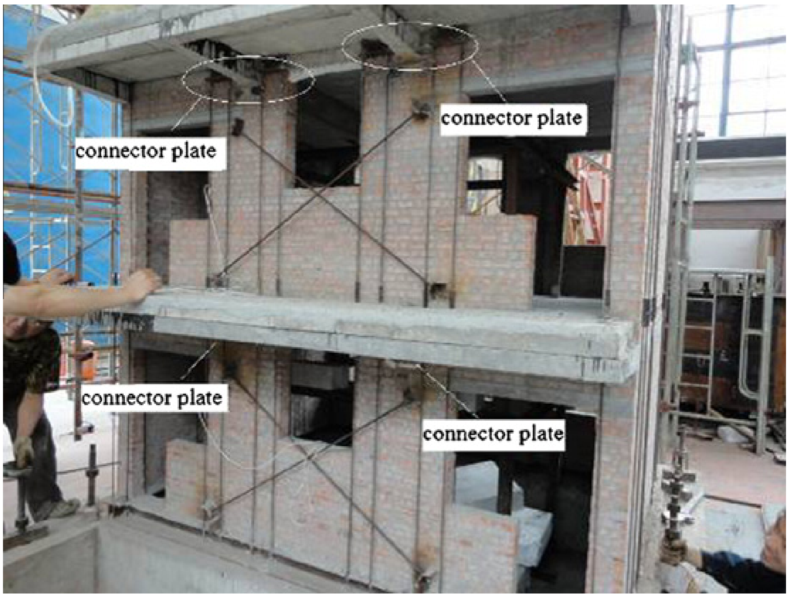


Fig. 28 Cross bracing struts at the first two storeys

f) Strengthening with ring beams

RC ring beams can be placed along the perimeter of the walls in the last floor if the roof can be temporarily removed and/or at the level of the floors. The behaviour of the different possibilities without or with ring beams for flexible or rigid diaphragms can be seen in Fig. 29 a), b) and c). Out-of-plane behaviour should always be avoided and the in-plane behaviour of the walls encouraged for a better performance of a masonry building. In this case, the situation (c) is the best situation.

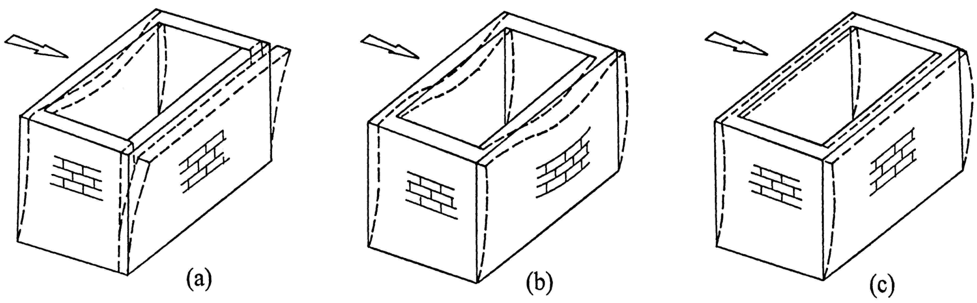


Fig. 29 Behaviour of a) Wood (flexible) diaphragm without ring beams; b) Wood diaphragm with ring beams; c) rigid diaphragm with ring beams. [Ahmad, 2012]

A reinforced concrete ring beam, 20 cm high and 32 cm wide (as the wall in Fig. 30), was cast at the roof level, on top of the perimeter façades (Fig. 30 a) and b)) in the experimental work of Magenes et al. [2012]. The reinforcement consisted in 4φ16 longitudinal bars and φ8 stirrups at a spacing of 20 cm, coherently with the prescriptions of the Italian Building Code.

a) b)

Fig. 30 Details of the reinforcement of the ring beam (left) and view of the ring beam after filling with the concrete (right) [Magenes et al, 2012]

g) Retrofitting by introducing RC shear walls

If the rigidity of the slab is sufficient then lateral strength of a building can be increased by the placement of RC shear walls. A structural engineer can rapidly calculate number of shear walls and their lengths and bars arrangement by calculation of base shear. The strength of the masonry building is neglected in the calculation of the shear walls. In the following Fig. 31 is depicted this retrofitting solution in a school building.

Fig. 31 Photo of the reinforcement of two perpendicular shear walls [Mahdizadeh et al, 2012]

h) Strengthening with RC or steel frames

The introducing of moment frames is a common strength method aiming to increase additional horizontal resistance, which can also be used as a local strengthening solution. The advantage of this system is that it is comprised of beams and columns, so is fully customizable and there is space between the vertical and horizontal elements. Moment frames allow full visual and physical access between each side of the frame and minimal spatial disruption [Ingham, 2012].

Care needs to be taken with steel frames in particular to ensure stiffness compatibility with the existing structure [Robinson and Bowman, 2000]. Steel is a ductile material but URM is not, meaning that under earthquake loads the added stiffness of the steel might not come into effect until a load is reached where the URM has already been extensively cracked. If a steel frame is erected against an existing wall, the frame needs to be fixed either directly to the URM using bolted connections into the wall or to the diaphragm [Ingham, 2012].

Steel moment frames have a high degree of reversibility as they rely on mechanical connections and relatively small ties to connect to the existing structure. Concrete frames are generally far less reversible.

Fig. 32 shows a large new moment frame of RC inside an URM building.

Fig. 32 A concrete moment frame inside the façade of a large URM building in Wellington (Dunning Thornton Consultants)

Braced frames are also a plausible solution for strengthening. The key functional difference between braced frames and moment frames is that due to the diagonal braces, braced frames prevent physical continuity between spaces on either side of the frame. Braced frames are also generally constructed of steel rather than concrete and are much more rigid than moment frames. Braced frames are a very efficient method of transferring horizontal forces but have significant setbacks and their use in façade walls is usually precluded by the presence of windows as diagonal braces crossing window openings are generally considered to be poor design. It is also difficult to get a braced frame to conform to an existing architectural character; however, they can be used to very good effect within secondary spaces and can be made to fit architecturally in some situations with careful consideration. Generally, steel braced frames have a good degree of reversibility and provide excellent strengthening when appropriately [Ingham, 2012].

Fig. 33 a) and b) show braced frames inside two different buildings.

a)

b)

Fig. 33 a) Eccentric bracing in a walkway; b) Eccentric bracing core (Dunning Thornton Consultants)

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