Title: **IDENTIFICATION OF STRENGTHENING STRATEGIES**

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INTRODUCTION

Since the beginning of structural restoration, architects and engineers have envisaged and actually applied a wide variety of repair or strengthening interventions to improve the structural response of ancient masonry structures. Some of these interventions have been specifically implemented to upgrade the capacity of ancient structures to resist earthquake. The set of possible interventions is based on alternative operations involving different mechanical devices and repair materials. They are also characterized by their different way of understanding and acting on the original masonry structure and the way they affect the integrity and the authenticity of the original materials and the structural features. The purpose of the present document is to identify and compile strengthening solutions used in practice, with real applications referred to in textbooks or technical papers.

In structural restoration, every construction constitutes a genuine problem and no general rules can be envisaged to decide about the adequacy and effectiveness of possible solutions. Because of it, the document refers in a general way the solutions actually found in the literature (or actually used in practice) without any aprioristic prejudice on their suitability and acceptability. In practice, the possible solutions must be carefully considered and their actual applicability to each specific problem must be assessed in detail. Historical investigation, inspection and monitoring and structural analysis may contribute to conclude about the actual causes of the possible structural problems, the real safety of the structure and the need for strengthening or upgrading. A careful investigation of the causes of the structural problems and the response of the structure may also help decide about the most suitable intervention.

When selecting possible repair or strengthening solutions, it is also essential to keep in mind the principles of conservation and the modern criteria for the analysis and restoration of historical structures. These criteria include the well-know requirements for minimum intervention, reversibility, non-invasiveness, durability and compatibility with the original materials and structure. Considering these principles and criteria is essential to determine a best solution among a set of alternative possibilities. Certainly, repair or strengthening normally convey a certain loss of cultural value since they normally involve a certain alteration of the original materials and structures. Because of it, any possible solution must be judged on account of its possible cost (loss of cultural value meant by its implementation) and benefit (gain in lifespan, gain in seismic performance, reduction of probability of partial or total failure, or reduction of probability of damage in fixed artistic contents or decoration…).

The repair or strengthening techniques included in this document constitute general solutions having been used in practice, in a more or less recent past. However, the fact that they have actually been used does not automatically mean that they are adequate or effective solutions sanctioned by a proven positive performance. It does not either mean the solutions comply with the restoration principles and criteria. In fact, many of the solutions used and included in the document will normally be in opposition to the conservation principles because of the large alteration that they produce in the original materials and structure, or because their large invasive, obtrusive or irreversible character.

The reader is to consider the solutions referred and carefully analyse them, taking into account the specificity of the problem to be solved (the features of the structure to be repaired or strengthened, the nature of the structural or material problems affecting it, the purpose of the strengthening or upgrading) and to conclude critically about the applicability of the solutions and the best possible option. The reader is as well to consider the compliance of the solution with the restoration principles. As mentioned, any possible solution will produce a cost and a benefit in terms of conservation of the cultural values of the construction, and it is the responsibility of the engineer or architect to choose a solution providing a satisfactory, or even the best, cost to benefit ratio.

The present document, aimed mostly at providing a compilation of possible solutions, is to be read and considered in combination with “Guidelines for the conservation of historical masonry structures in seismic areas”, a companion document also resulted from ALA/95/23/2003/077-122 project. This second document is specifically oriented at providing criteria for the selection of adequate solutions, complying with restoration principles, for the seismic upgrading of masonry historical structures. In a way, the present document provides an overview of possible interventions, while the mentioned second document is intended to contribute with criteria for the determination of suitable solutions verifying, to the possible extent, with the conservation principles and criteria for structural restoration.

The ample variety of repair or strengthening solutions used in practice can be arranged according to different criteria.

A rough distinction can be made among the traditional and the modern strengthening techniques. Traditional techniques employ the materials and building processes used originally for the construction of ancient structures. Modern techniques aim at more specific or efficient solutions using innovative materials and technologies.

Another possible differentiation is between interventions operating over a material or a structural level. Actions oriented to the material level aim at treating material pathologies derived from decay or poor mechanical properties of the masonry. Structural actions are normally linked to a defective design of the structure or to structural modifications carried out during its history.

Strengthening techniques can also be classified in terms of the material or mechanical effects they produce on the structure. Nevertheless, it is almost impossible to find a classification both comprehensive and not repetitive. Normally, the strengthening actions and their effects have an inborn complexity which is difficult to summarize univocally.

For this reason the presentation of the interventions is organized in three parts. The first one proposes a characterization of the interventions. The purpose is to allow a correlation between essential concepts, techniques and strategies for the numerical simulation of techniques. This part is oriented to theory and numerical simulation. However, this type of classification may not be very adequate for practitioners or for practical purposes. Therefore, in the second part, a classification by structural elements is proposed. In this part the application of the techniques described in Part I to specific types of members is described. In the third part, the description of the repairing and strengthening of the structure at global level is presented. Some times, a global intervention is necessary in order to correct undesirable global behaviour. This section presents the possible actions that can be used in order to modify the behaviour of the structure at “global level”.

The presentation of the possible techniques includes a short description, references to practical or real applications described in the technical literature and a short discussion on its applicability, advantages and disadvantages, and compliance with restoration principles. This discussion is only aimed at provide some hints on the possible use of the technique. The reader, or possible user, should in any case analyse the features and possibilities of the technique in detail taking into account the nature and specific challenges of the problem to be solved.

Finally, the possibility of including seismic reinforcement in a numerical analysis is considered. The numerical modelling of a specific technique of intervention is conceived as the superposition of a series of elementary actions corresponding to the categories described in the first part. This document also includes some proposals for the numerical modelling of the effects caused by such elementary actions.

1. CLASSIFICATION OF STRENGTHENING TECHNIQUES

1.1 Basic strengthening actions

Generally, the effect of any repair or strengthening technique on a structural member or an entire structure can be described as a combination of a limited number of some basic actions. The scope and effect of any specific strengthening techniques, no matter the materials or strengthening devices involved, is better understood through the identification of the basic actions that it produces on the structure. The main basic actions are:

confinement: it literally means to impede the deformation. The local form refers to techniques applied to single elements, counteracting the lateral strain and thus improving the mechanical properties of masonry. Global confining is related to the whole structure, limiting for example the deformations at floor level reaching a monolithic seismic response and avoiding the out-of-plane failure mechanism.

reinforcement: incorporating to the resisting section new material with higher mechanical properties well connected thus normally increasing its strength and stiffness.

enlargement: widening of the resisting section with the addition of new material. Normally the material used has mechanical properties similar to the original one. The improvement is due to a better stress distribution and a larger resisting area.

material substitution: removal and replacement of damaged parts of a structure. The materials used in the reconstruction may be similar to the original ones or possess better mechanical properties.

structural substitution: creation of new load bearing structure with modern materials, without the dismantling of the old one. It is used to maintain the external features of an existing building with insufficient capacity.

tying: binding together different elements or different parts of a single element. Steel bars are the most diffuse devices dealing with global tying. A wider variety of technologies is to be found in local tying.

propping: sustain, support a part of a structure with additional elements. It can be applied to damaged or intact structures that need a higher strength or stiffness. The main distinction has to be made between lateral propping (strutting) and vertical propping.

anchoring: fastening an element or a part of a structure to a firmer solid. The most diffuse form is anchoring to rock and soil. This intervention is used to improve the stability of a structure and to avoid its collapse in case of a seismic event.

improvement: general improvement of the characteristics of the resisting section when it is not due to one of the forms of intervention already mentioned.

prestressing: changing the stress field in a structure or in an element using external loads or precompression.

isolation: absorbing the seismic forces and vibrations in external devices usually placed between the proper foundation and the masonry structure.

soil stabilization: intervention focussed on the soil beneath the structure, aiming at an improvement of its bearing capacity.

cleaning: cleaning the structure, elements or parts of the structure by removing elements, materials or biological parasites.

These categories are representative of most of the strengthening effects a seismic strengthening or repairing may have on a structure.

1.2 Structural elements

For practical purposes, it is useful to classify the strengthening techniques into the application to structural elements. These last have been subdivided in the following groups:

support: these elements support the cover. They give the resistance of the structure to vertical and lateral forces. Walls and columns are the common support elements. Beams and arches are considered as part of the cover element. The most common materials used in walls are masonry (brick or stone) and earth (adobe, tapial, etc.), while columns are made with masonry, stone or wood.

cover: these elements can be classified into two types: horizontal and curved elements. Horizontal covers resist loads by bending; while curved elements resist loads by axial forces. In general, horizontal covers are made with wood beams and boards. Curved elements are arches and vaults and are made with masonry.

foundation: transmits the loads of the structure to the ground. They are continuous or discontinuous. The most common material is stone or brick masonry.

1.3 Global level

The seismic behaviour of historical structures can be improved by reducing the seismic demand or by increasing the seismic capacity of the structure, as well as a combination of both actions. The seismic demand can be reduced modifying:

mass: increasing, removing or redistributing the weight of the structure.

fundamental period of vibration: modifying the fundamental period in order to obtain less amplification of the ground accelerations

soil condition: improving the characteristics of the soil or isolating the structure from the ground motion

use of the structure: changing the use of the structure, the seismic demand can be reduced

The seismic capacity can be increased by:

strengthening structural elements: taking into considerations the actions and techniques described in sections 3 and 4.

adding structural components: providing new resisting material or structural elements to the existing structure.

Improving the connections between existing structural elements: enabling an increased overall seismic behaviour.

2. REPAIRING AND STRENGTHENING TECHNIQUES

2.1 Introduction

The present chapter includes a description of different strengthening techniques.

Each technique is presented schematically covering the subsequent topics:

- Strengthening actions: categories representative of the technique.
- Usual application: structural situation suitable for the specific intervention.
- Technique: working scheme.
- Main targets: desired impacts on the structure.
- Advantages / disadvantages: a short discussion stating the principal advantages and disadvantages of each technique
- Practical cases: examples of documented applications.

2.2 Injection

Strengthening actions: improvement.

Usual applications: Walls presenting a diffuse presence of voids, incoherence of the rubble filling material, visible cracks in the external parameters.

Technique: Injection of mortar or fluid resin through holes previously drilled in the external parameters of the wall. Normally used in stone-masonry structures.

Main targets: Filling existing cavities and internal voids and sealing possible cracks. Injection increases the continuity of the masonry and hence its mechanical properties.

Advantages/disadvantages: The injection increase the tensile and shear strength of the masonry, as well as its ductility. Injection is fully non-reversible operation and should only be carried out using injected materials with proven compatibility with the original material.

Practical cases: Bell-tower of Monza, Italy, laboratory tests performed in the Laboratory of Material Testing of the Department of Structural and Transportation Engineering of the University of Padua, Italy.

References: [1], [2], [3], [7], [9], [15], [16], [17].

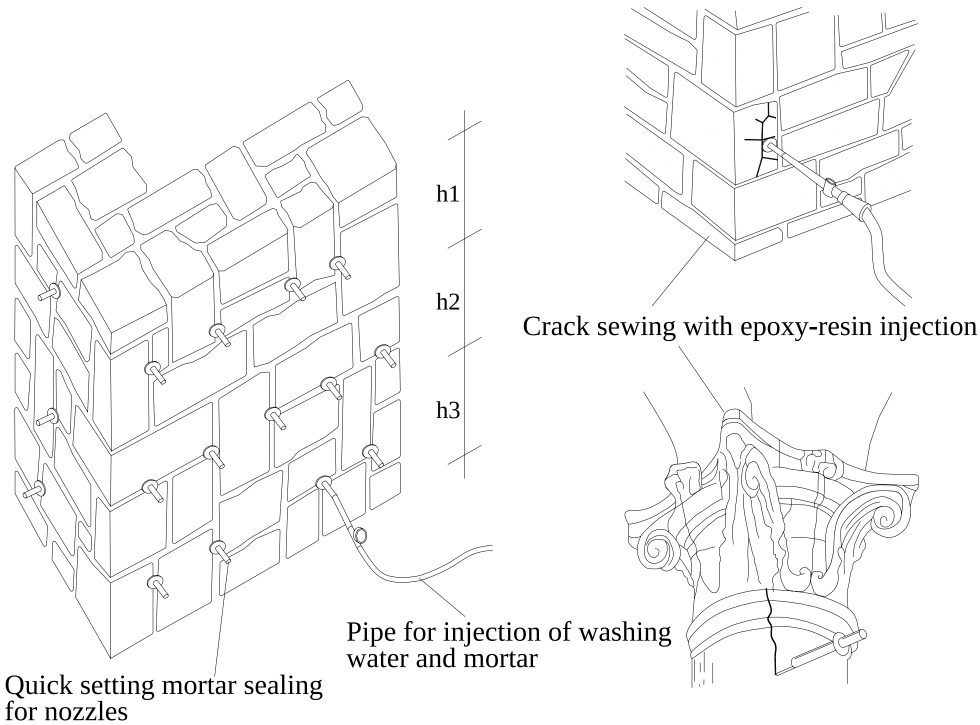


Figure 1: Walls and cracks injections

2.3 Local reconstruction “cuci-scuci”

Strengthening actions: material substitution.

Usual applications: Walls with severe but localized cracks or highly deteriorated parts.

Technique: The existing masonry pattern is locally removed where major deterioration has occurred and it is replaced with new masonry reproducing closely the mechanical properties of the original one. It is one of the first techniques applied to restoration.

Main targets: Preserving the mechanical efficiency and regaining the continuity in a masonry structure.

Advantages/disadvantages: Reversible intervention and preservation of the structure’s appearance. The relation cost-effect diminishes when the area of intervention becomes larger. Local reconstruction constitutes a historical / traditional technique and can be considered partially reversible.

Practical cases: -.

References: [3], [5], [9], [16].

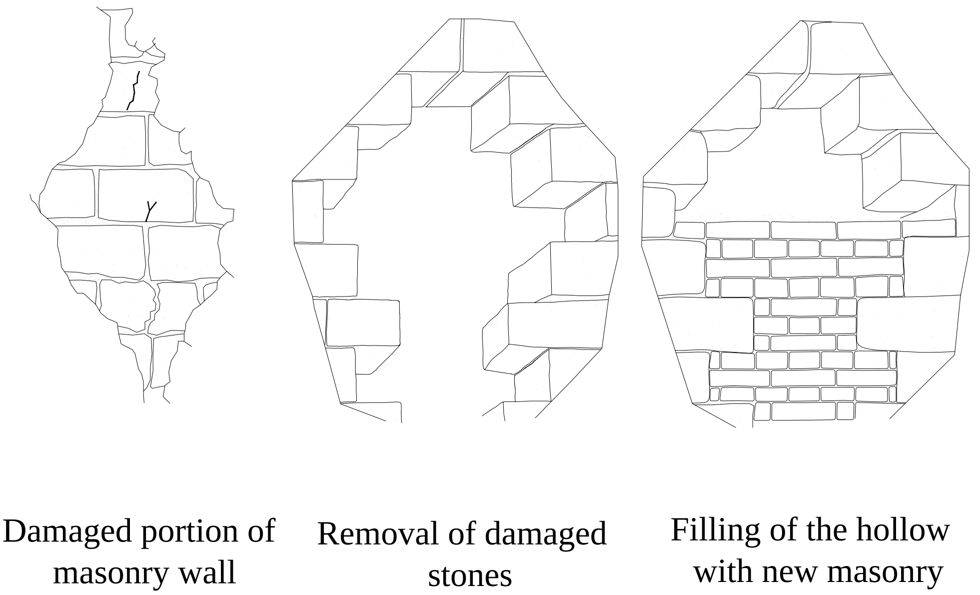


Figure 2: Steps in "cuci-scuci" intervention

2.4 External reinforcement

Strengthening actions: reinforcement.

Usual applications: Old and new masonry structures needing earthquake protection and higher mechanical properties.

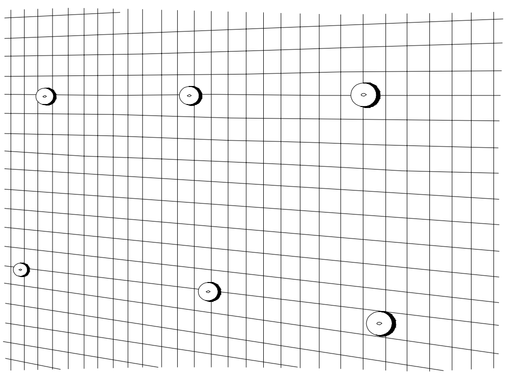
Technique: Application of high-performance materials (i.e. FRP, steel, wood, plastic) on the external parameters of the wall, locally (i.e. strips) or to the whole surface of the structure (i.e. grid reinforcement). The connection with the masonry parameter is normally obtained with the use of epoxy resins or mortar. An effective use of this technique requires certain regularity in the masonry surface. In arches and vaults a reinforcement can be applied between the extrados and an additional masonry layer.

Main targets: Increasing ductility and obtaining a more resistant structure adding a material that can resist tensile stresses.

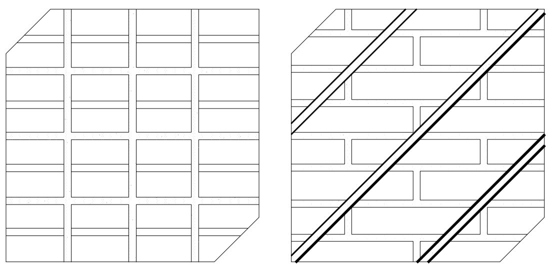
Advantages/disadvantages: It may increase the strength of the element in an effective way. The effectiveness depends largely on its continuity and end connections. Reinforcement by means of ductile metals (steel, titanium) produces also an increase of ductility. External reinforcement is normally irreversible (as its recovery from the wall will normally cause the peeling off of the brick or stone surfaces) but non-invasive.

Practical cases: Adobe houses in Yacango, Peru. Town Hall of Assisi. Laboratory tests performed in the Laboratory of Material Testing of the Department of Structural and Transportation Engineering of the University of Padova, Italy.

References: [2], [4], [6], [13], [18], [27].



Polymerie grid reinforcement



FRP strips reinforcement

Figure 3: Examples of innovative material reinforcement ([4] fig. 4.38, [2] fig. 3.9)

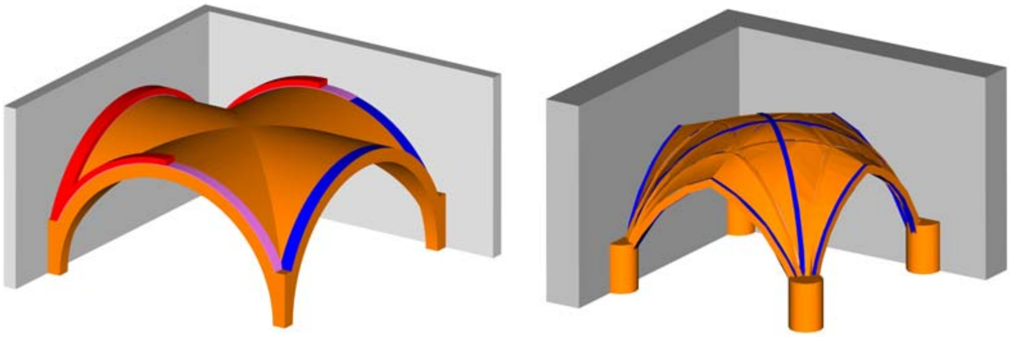


Figure 4: Example of FRP strips use in masonry vaults reinforcement ([3] fig. VO6)

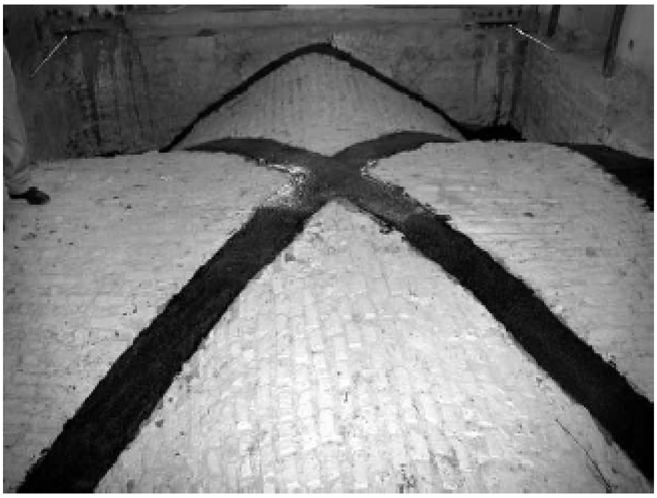


Figure 5: Strengthening intervention of cross vaults in the Town Hall of Assisi ([27] fig. 20)

2.5 Stitching

Strengthening actions: reinforcement, tying.

Usual applications: Masonry elements needing higher cohesion and mechanical characteristics without a visible modification.

Technique: Reinforced injections. Holes are drilled in the element and filled with bars and mortar.

Main targets: Increasing the mechanical properties and the ductility of the element.

Advantages/disadvantages: It is a versatile and quick upgrading technique. Stitching acts improving or reinforcing the material or structural member. Reinforced injections are severely invasive and fully irreversible. Moreover, reinforced injections will cause some deterioration to the wall or stone in which the perforations are executed and, in principle, should never be applied when the walls or stones with fixed artistic contents (paintings, carving, artistic treatments or decorations). Lime mortar should be normally used for reinforced injections. The use of Portland mortar should normally be disregarded because of incompatibility problems with the surrounding stone or masonry. Epoxy resin may also generate some compatibility problems. Stitching may have inadequate side effects due to the fact that, while improving the overall strength and ductility of the member, it may also increase the likeliness of cracking and damaging in the units (stones or bricks) due to soil settlements, earthquakes or other actions.

Practical cases: -.

References: [32]

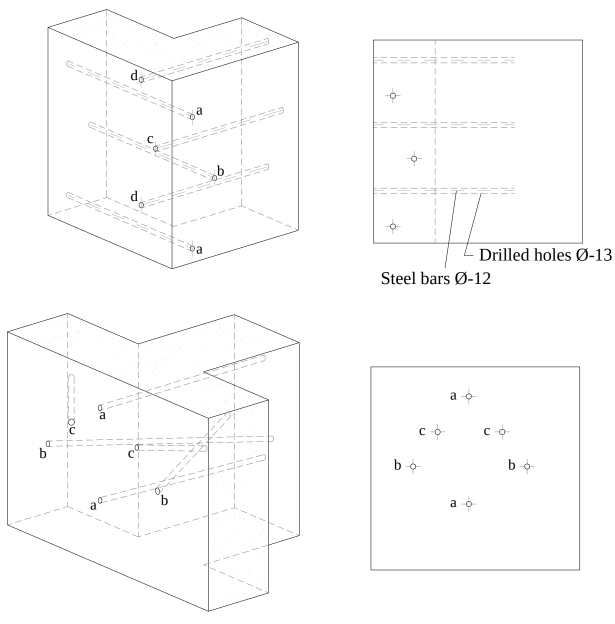


Figure 6: Example of FRP strips use in masonry vaults reinforcement

2.6 Repointing and reinforced repointing

Strengthening actions: improvement, reinforcement (reinforced repointing only).

Usual applications: Masonry walls presenting visibly deteriorated joints or mortar in poor conditions.

Technique: Partial removal and substitution of deteriorate joint mortar with new mortar with better mechanical properties and durability. Reinforced repointing is indicated for masonry walls with regular horizontal joints and consists of laying reinforcement bars in the mortar matrix. Usually applied in combination with other interventions.

Main targets: Increase the compressive and shear strength in small thickness masonry. It is normally more effective as a way of reducing the deformation. Reinforced repointing has also a confining effect on the walls.

Advantages/disadvantages: It is a versatile and quick upgrading technique. Repointing can be considered partially reversible and consistent with traditional / historical maintenance or repair practices.

Practical cases: Santa Sofia Church in Padua, Italy.

References: [2], [11], [12], [17].

Figure 7: Steps for reinforced repointing intervention ([2] p. 443, fig. 3.24)

2.7 Tie bars

Strengthening actions: tying.

Usual applications: Masonry structures with poor interconnection between intersecting walls, arches or vaults suffering damage relate to ductile failure.

Technique: Steel bars anchored with plates or other devices to the structure. They are working in tension and have different practical applications all aiming at improving the seismic response of the structure.

Main targets: Improving the overall structural behavior by ensuring seismic cooperation between structural elements.

Advantages/disadvantages: Increase the seismic resistance of existing masonry with such minor changes to the original structure. It is reversible. Tie bars are used to improving the overall structural behaviour by ensuring seismic cooperation between structural elements. Tie bars are non-invasive and can be easily removed. Moreover, they are normally very efficient in their tying action (provided that their anchorage is maintained in good condition).

Practical cases: Bell-tower of S. Giustina, Padua, Italy, Bell-tower of Nanto, Vicenza, Italy.

References: [3], [9], [12], [16].

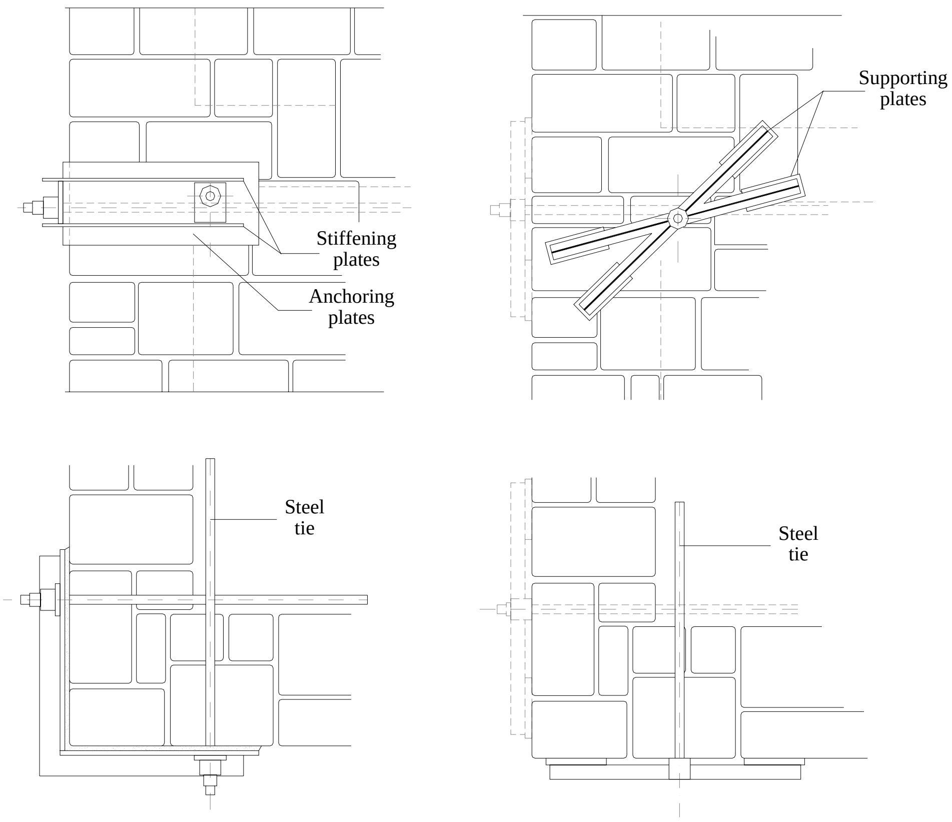


Figure 8: Examples of anchoring of steel ties on intersecting walls

2.8 Local tying

Strengthening actions: tying.

Usual applications: Parts of an element or of a structure with poor connection and presenting risk of partial failure.

Technique: Fastening of confining parts with different devices (pins, cramps).

Main targets: Developing a micro-continuity in the structure thus improving structural monolithic nature and strength.

Advantages/disadvantages: Simple and effective technique allowing the increase of the resistance of the element. It modifies the original appearance. It is reversible.

Practical cases: Coliseum in Rome, Italy.

References: [31], [32]

Figure 9: Example of anchoring with steel ties on a part of Coliseum, Rome, Italy

2.9 Discrete confinement in piers

Strengthening actions: confinement.

Usual applications: Piers suffering too high compressive force.

Technique: Application of steel rings in critical sections of the pier.

Main targets: Obtaining a punctual confinement where needed thus improving the compressive strength of the pier.

Advantages/disadvantages: Simple and effective technique. Increase the resistance of the element. It modifies the original appearance. It is a full historical and traditional, non-invasive and reversible technique characterized by its large effectiveness. Generally this technique does not increase to a significant extent the overall seismic response of a building.

Practical cases: -.

References: -.

Figure 10: Local confinement for critical sections of a pier

2.10 Element substitution

Strengthening actions: material substitution.

Usual applications: Structural element deteriorated or not suited for its load bearing function.

Technique: Overall substitution of the structural element. The materials and technologies used can be similar to the original ones or can be intended to modify its behaviour and mechanical properties. A typical example is overall substitution of floors and roofs.

Main targets: Recover the original function of the element, correct eventual design faults, modify the seismic response.

Advantages/disadvantages: Preservation of the structure's appearance. Irreversible intervention.

Practical cases: Tarazona Cathedral, Spain.

References: -.

Figure 11: Removal of a pier of Tarazona Cathedral, Spain

2.11 Structural substitution

Strengthening actions: structural substitution.

Usual applications: Masonry structures or elements in good / bad condition but judged not adequate to resist the imposed loads.

Technique: Creation of a new structure substituting structurally the old one, which is not dismantled and continues having its aesthetical function.

Main targets: Recover the functionality of a structure maintaining its historical and cultural value, modifying an erroneous design.

Advantages/disadvantages: In principle, this type of operation does not comply with the modern understanding of conservation or upgrading of cultural heritage structures. However, structural substitution may be designed to ensure full reversibility and non-invasiveness and can be considered as an extreme possibility for very severely damaged or seismically weak structures whose upgrading by other means would require the use of other more invasive and transforming procedures.

Practical cases: "Mole Antonelliana", Turin, Italy.

References: -.

Figure 12: R.C. structure substituting the original one in the "Mole Antonelliana", Turin, Italy

2.12 Dismantling and remounting

Strengthening actions: material substitution, improvement.

Usual applications: Masonry element or structures containing parts that have to be removed, substituted or repaired, if a local intervention is not feasible.

Technique: Accurate and complete dismantling of an element or a structure to repair, extract or substitute part of the components and successive remounting reproducing accurately the original organization and shape.

Main targets: Recover the functionality of a structure maintaining its historical and cultural value, modifying an erroneous design.

Advantages/disadvantages: The purpose is to recover the functionality of a structure while maintaining its historical and cultural appearance. Dismantling and reassembling should only be undertaken when required by the nature of the materials and structure and/or when conservation by other means is more damaging.

Practical cases: Towers of the façade of Barcelona cathedral, columns of the Mexico City Cathedral

References: [21]

Figure 13: Substitution of individual blocks of a pillar in the Mexico City Cathedral [21]

2.13 Continuous confinement (jacketing)

Strengthening actions: confinement.

Usual applications: Elements suffering too high compressive force, excessive lateral deformation or formed by parts poorly connected.

Technique: Application of self-supporting reinforced concrete cover surrounding the structural element and resisting lateral strain.

Main targets: Obtaining a continuous confinement thus improving the strength and stiffness of masonry.

Advantages/disadvantages: The target is to obtain a continuous confinement and thus improving the strength and stiffness of the masonry. The jacketing can also act as enlargement (i.e. it can provide additional resisting section). Due to the need to connect the original and the added wythes or parts, jacketing can be hardly reversible. On the other hand, jacketing is obtrusive since it requires hiding the original masonry and paraments behind the new material. The effectiveness of the intervention is guaranteed just in case of the application of jacketing on both sides of the wall, with diffuse connections. Significant increase in terms of stiffness.

Practical cases: -.

References: [1], [2], [8], [9], [10], [14].

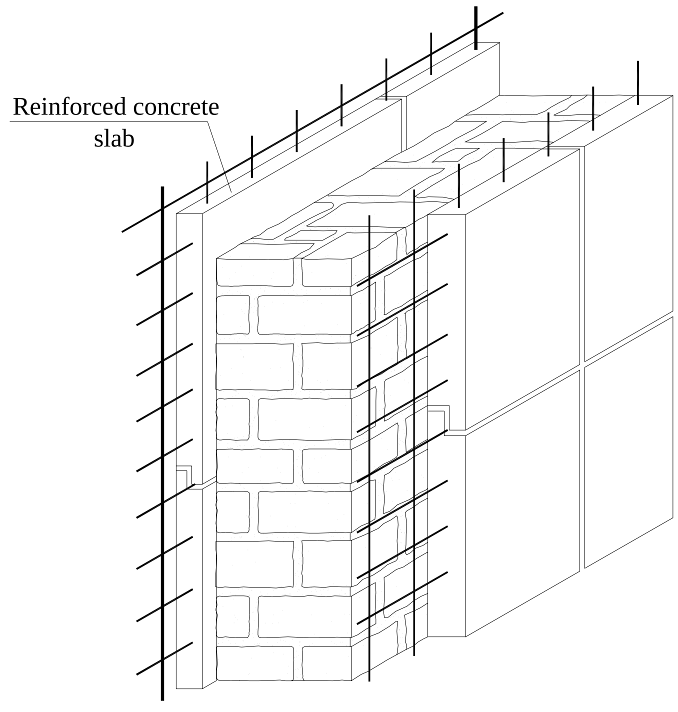


Figure 14: Reinforced concrete jacketing of a wall

2.14 Enlargement

Strengthening actions: enlargement.

Usual applications: Masonry elements in good condition subjected to a too high stress field.

Technique: Enlargement of the sections of structural members by the addition of new material compatible with the original one and well connected to it.

Main targets: Distributing the load to a larger resisting section, thus reducing the stress field.

Advantages/disadvantages: Provide additional resisting section. It is not reversible and difficult to repair in the future. The aim of enlargement is at distributing the load to a larger resisting section, thus reducing the intensity of the stresses carried by the masonry elements. The life span is reduced if concrete is used for the enlargement. The reversibility of the technique will depend on the possibility of dismantling the added parts without causing harm to the original material.

Practical cases: Two four-storey old buildings in Jelenia Gora, Poland.

References: [1], [2], [8], [9], [10], [14].

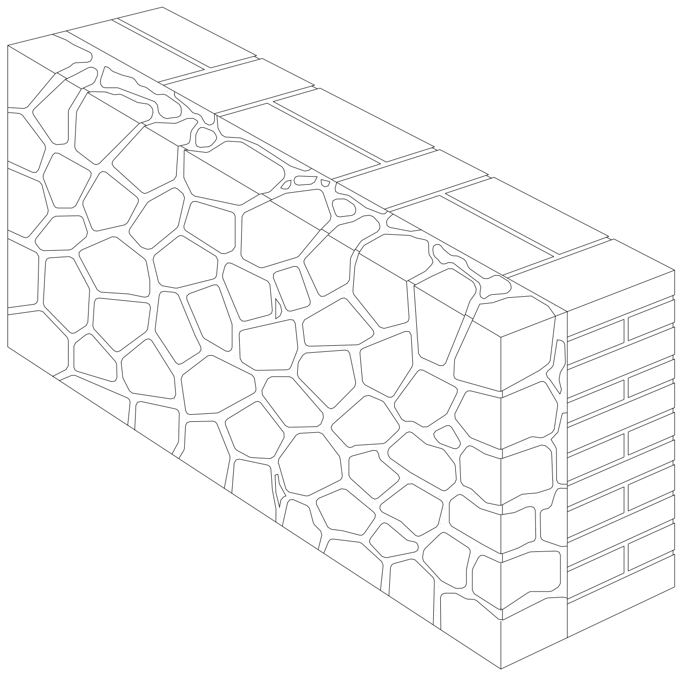


Figure 15: Example of enlargement of a wall

2.15 Buttressing

Strengthening actions: propping.

Usual applications: Structures having a low resistance to lateral forces or motion, arches or vaults experiencing span increasing.

Technique: Using massive elements made of concrete or masonry to prop a structure on a side. Buttresses resist lateral forces and deformations essentially with their weight.

Main targets: Impeding failure mechanisms related with lateral deformations, carrying horizontal forces.

Advantages/disadvantages: Buttressing may be useful for structures having a low resistance to lateral forces or motion, including arches or vaults. It must be noted that, while buttresses originally built as part of the entire construction may be very efficient, similar elements added after the construction, once the structure (in particular, the original walls) are already loaded, may show very limited efficiency. This is due to the fact that buttresses built as reinforcing elements after the construction of the building will not benefit from receiving part of the vertical load of vaults and roofs, already taken by the walls, which will limit their capacity to counteract lateral forces. Furthermore, the structure will need to deform to significant extent in order to mobilise the new buttress. The separation of later added buttresses from the walls of the building due to differential soil settlements is not uncommon.

Practical cases: -.

References: [25]

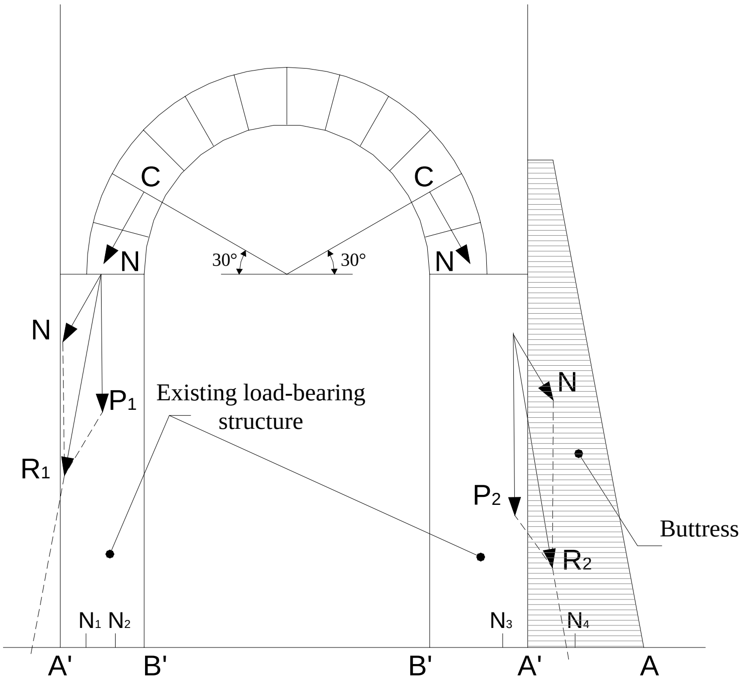


Figure 16: Regaining the stability of the vault bringing back the thrust line inside the vault thickness

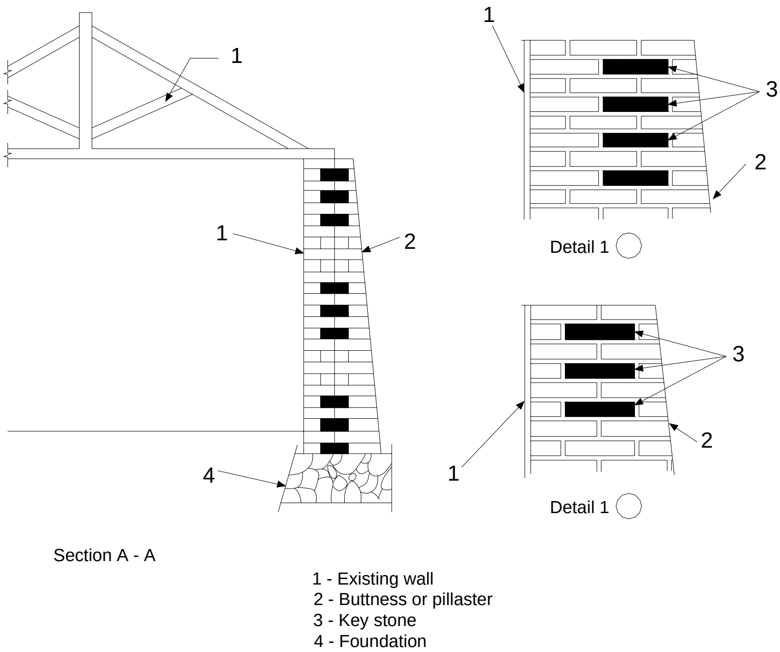


Figure 17: Strengthening long walls by buttresses [25]

2.16 Discrete confinement in walls

Strengthening actions: confinement.

Usual applications: Multi-leaf masonry walls with no sufficient connection between different layers.

Technique: Application of punctual confinement to the wall, either with transversal steel bars, anchored to plates or other steel devices at both sides of the wall, or with reinforced concrete elements cast in transversal holes drilled through the whole thickness of the wall.

Main targets: Impeding the separation between different layers, thus improving the mechanical properties of the wall.

Advantages/disadvantages: A mechanical anchored steel bar is a reversible technique, simple and easy to collocate. It acts impeding the separation between different layers of the stone or material, thus improving the mechanical properties of the wall. It is also useful to improve multi-leaf masonry walls with no sufficient connection between different wythes. If the holes are not injected, the technique can be considered mostly non-invasive and reversible.

Practical cases: Laboratory tests performed in the Laboratory of Material Testing of the Department of Structural and Transportation Engineering of the University of Padua, Italy, laboratory tests performed in the Laboratory of Material Testing of the Department of Structural and Geotechnical Engineering of the University of Genoa, Italy.

References: [1], [3], [17].

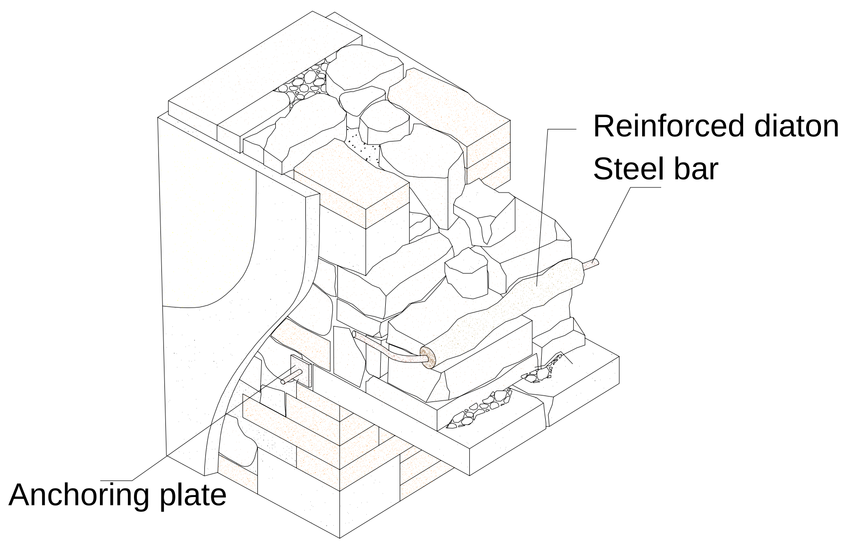


Figure 18: Local confinement examples for multi-layer walls ([3] fig. MU6, [1] fig. 131)

2.17 Strutting

Strengthening actions: propping.

Usual applications: Damaged structures or elements risking collapse, or not able to carry out their load-bearing function.

Technique: Using members designed to resist a compressive load, used to sustain a structure. Struts can work vertical or inclined.

Main targets: Inclined struts increase the lateral stiffness of the structure and are used to counteract the out-of-plane mechanism. Vertical struts carry vertical load thus discharging the original structure.

Advantages/disadvantages: Struts are efficient as a device to stop or control possible movements or out-of plumbing of vertical elements, can be considered non-invasive and fully reversible.

Practical cases: -.

References: [3].

Figure 19: Strut arches connecting two buildings

2.18 Precompression

Strengthening actions: prestressing.

Usual applications: Elements presenting damages due to tensile stresses.

Technique: Providing controlled counteracting compressive stresses. A side effect is the increase of the stiffness of the element. The force may come from steel bars or cables working in tension or from dead loads superimposed to the structure.

Main targets: Avoiding or closing cracking.

Advantages/disadvantages:

Practical cases: -.

References: [2].

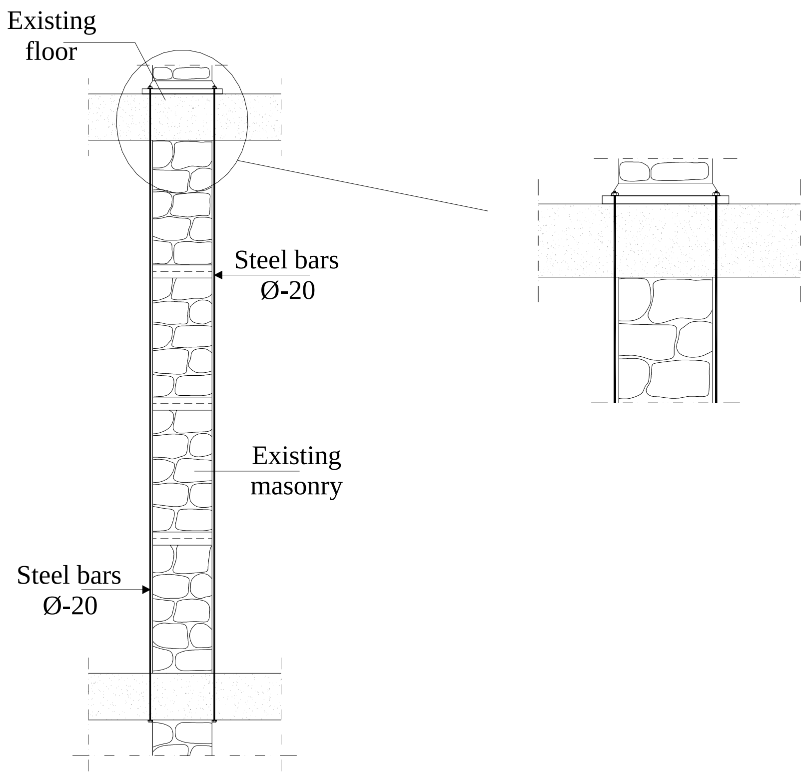


Figure 20: Steel bars precompression in a wall ([2] p. 341, fig. 13)

2.19 Self-supporting steel frames

Strengthening actions: reinforcement, improvement, structural substitution.

Usual applications: Old and new masonry structures needing earthquake protection.

Technique: Self-supporting steel frames along building walls, it is used when it is not feasible a R.C. jacketing intervention.

Main targets: Increase stiffness and ultimate shear force, avoiding brittle failure of walls.

Advantages/disadvantages: If the frames are embedded in the original masonries, the solution becomes fully invasive and irreversible, and may cause a significant loss in cultural heritage, as shown in figure 21. Very complex definition of the resisting elements to horizontal forces.

Practical cases: Six-story building in Wroclaw (Poland).

References: [10]

Figure 21: Steel frame structure substituting the load bearing wall

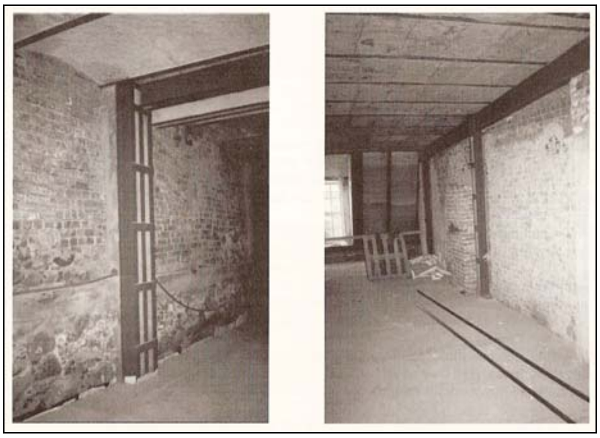


Figure 22: Steel frame structure substituting R.C. jacketing in a six-storey building in Wroclaw (Poland)

2.20 Frictional contact

Strengthening actions: prestressing.

Usual applications: Structures presenting loose parts or elements.

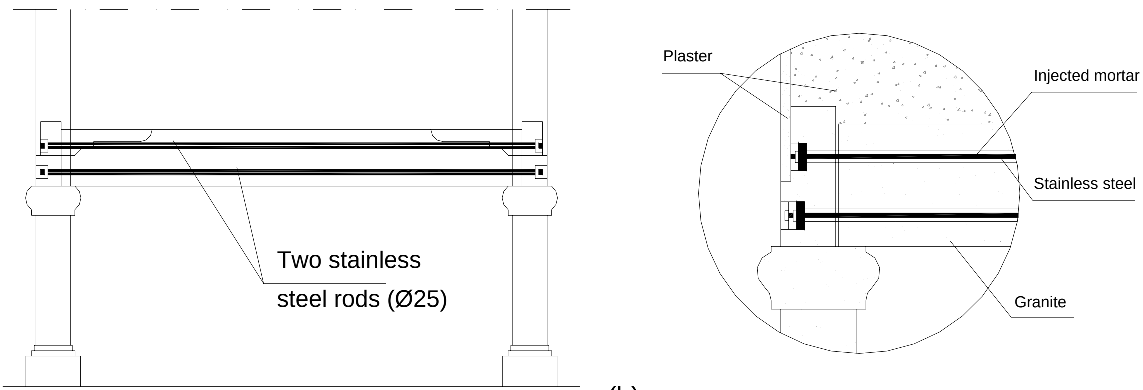
Technique: Providing compressive stresses perpendicular to the contact surfaces of confining elements.

Main targets: Using frictional forces across different members as a way to mechanically tie the two parts.

Advantages/disadvantages: -.

Practical cases: Chimney in the main kitchen of the Monastery of Arouca, Portugal.

References: [31]



(a) (b)

Figure 23: Strengthening of the chimney: (a) Front view, (b) detail [31]

2.21 Anchoring

Strengthening actions: anchoring.

Usual applications: Load bearing structures with stability problems.

Technique: Anchoring an element, with steel bars passing trough it, to rock, soil or to a firmer structure.

Main targets: Improving the stability of the structure, limiting eventual deformations.

Advantages/disadvantages: -.

Practical cases: Outeiro Church, Portugal

References: [29]

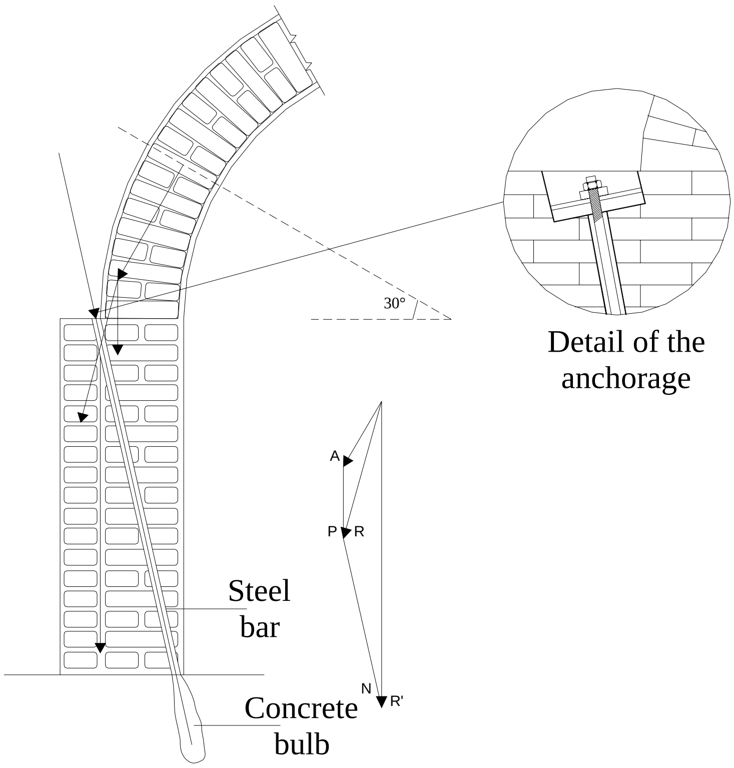


Figure 24: Example of anchoring of a vault

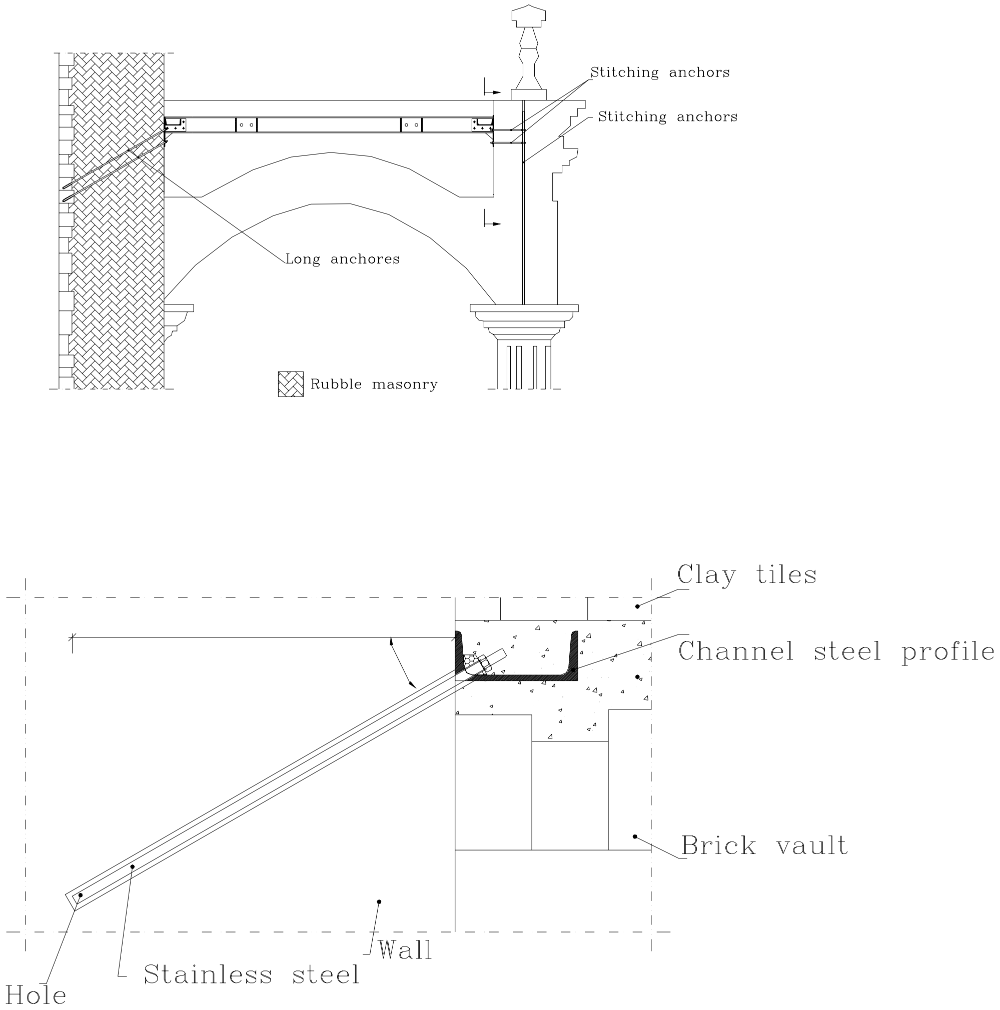


Figure 25: Example of anchoring in Outeiro church, Portugal [29]

2.22 Seismic isolation

Strengthening actions: isolation.

Usual applications: For building of primary importance, which functionality should not be affected by seismic action, seismic isolation is generally considered the most appropriate choice.

Technique: Absorbing and dissipating the seismic forces and vibration with devices placed between the foundation and the structure itself. These devices can consist of:

- elastometric materials (steel plates in an elastometric matrix);
- elastometric materials reinforced with a lead core;
- combination of elastometric materials and frictional plates of steel-bronze;
- frictional plates with very low frictional coefficient coupled with neoprene rubber or steel springs;
- assemblies of spiral springs coupled with viscous dampers;
- seismic base isolation using frictional plates with very low frictional coefficient coupled with different types of dissipative tools (piezoelectric, electrostrictive and magnetostrictive materials, memory shape alloys, viscous, electrorheological and magnetorheological fluids).

Main targets: Absorbing the seismic vibration and avoiding major damages to the building.

Advantages/disadvantages: This technique is effective when the fundamental period of the base-isolated building results substantially greater than both the predominant period of the ground motion and the fixed base equivalent period of the building. It is not suitable for structures located on very soft soils.

Practical cases: -.

References: [1], [23].

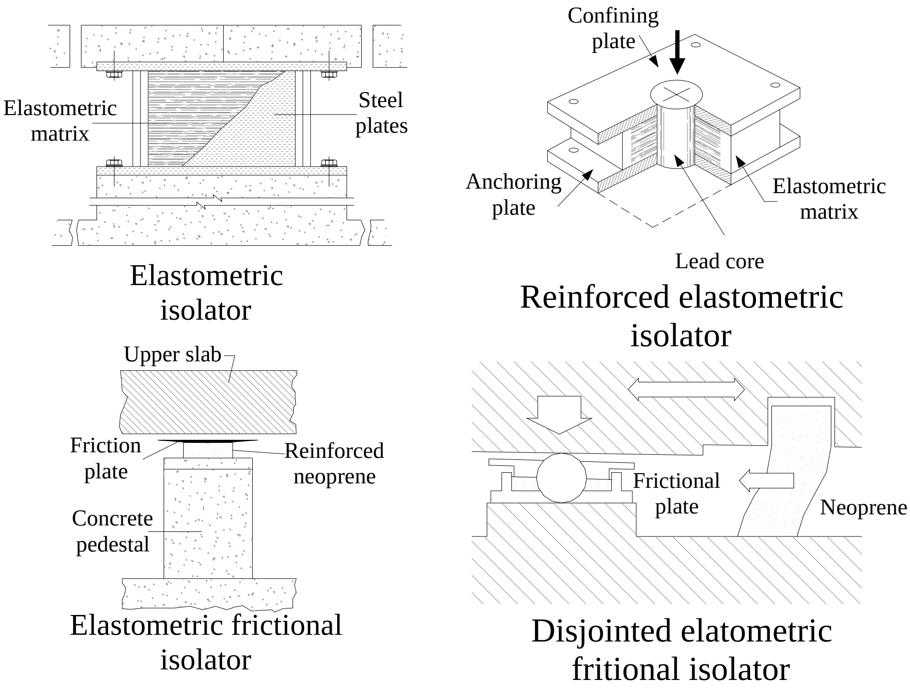


Figure 26: Different types of seismic isolator ([5] fig. 396-399)

2.23 Recovering original levels

Strengthening actions: cleaning.

Usual applications: Buildings with differential settlements or constructed in different periods.

Technique: Remove layers of soil or different materials that cover parts of the structure.

Main targets: Recover architectural elements as well as reduce the weight of the building.

Advantages/disadvantages: -.

Practical cases: Mining Palace, Mexico city

References: [22]

Figure 27: Recovering the original levels, Mining Palace, Mexico city [22]

2.24 Removing “parasite” elements

Strengthening actions: cleaning.

Usual applications: Buildings with differential settlements or constructed in different periods.

Technique: Remove non original elements that were added in different periods.

Main targets: recovering architectural elements and spaces.

Advantages/disadvantages: It is necessary to understand the historical context of the element that could be removed. Some times, the element became in a part of the history of the element. Some non structural elements can become in the time as structural element and removing them can cause some injury to the structure.

Practical cases: Inquisition Palace, Mexico city

References: [22]

Figure 28: Removing parasite elements, Inquisition Palace, Mexico city [22]

3. REPAIRING AND STRENGTHENING OF STRUCTURAL ELEMENTS

3.1 Support elements - Reinforcement of multi-leaf elements

Strengthening actions: reinforcement, improvement.

Usual applications: Columns or walls made with multi-leaf elements.

Technique: Possible choice between different techniques:

- transverse connections with steel ties, reinforced diatons;
- deep repointing and reinforced repointing with transversal connection ties;
- grout injection.

Main targets: Avoiding the internal fracture of the multi-leaf walls and reducing the transverse deformation. Homogenization of the behavior of the walls filling the voids and reintegrating loose material, increasing the resistance without important changes in the deformability.

Advantages/disadvantages: Transverse connections are a reversible intervention. The injection increase the resistance of the masonry but it is not a reversible intervention.

Practical cases: -.

References: [1], [3], [2], [7], [9], [11], [12], [15], [16], [17].

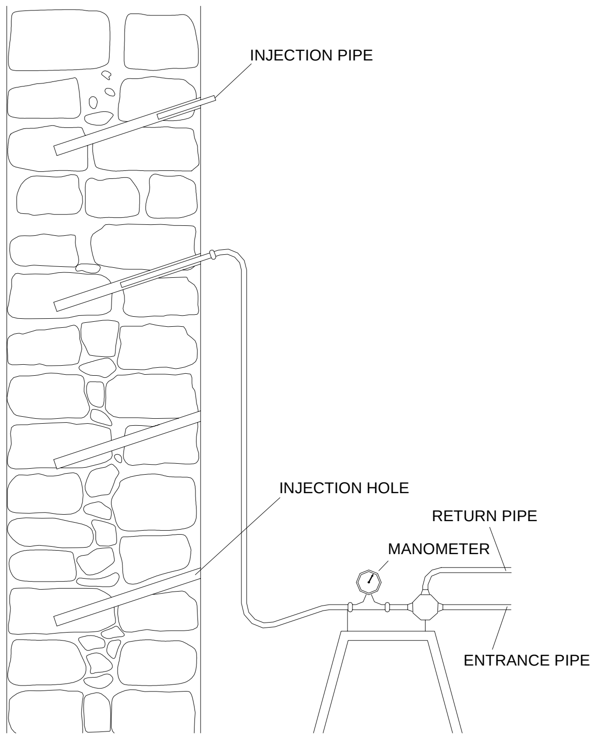


Figure 29: Working scheme for pressure mortar injection

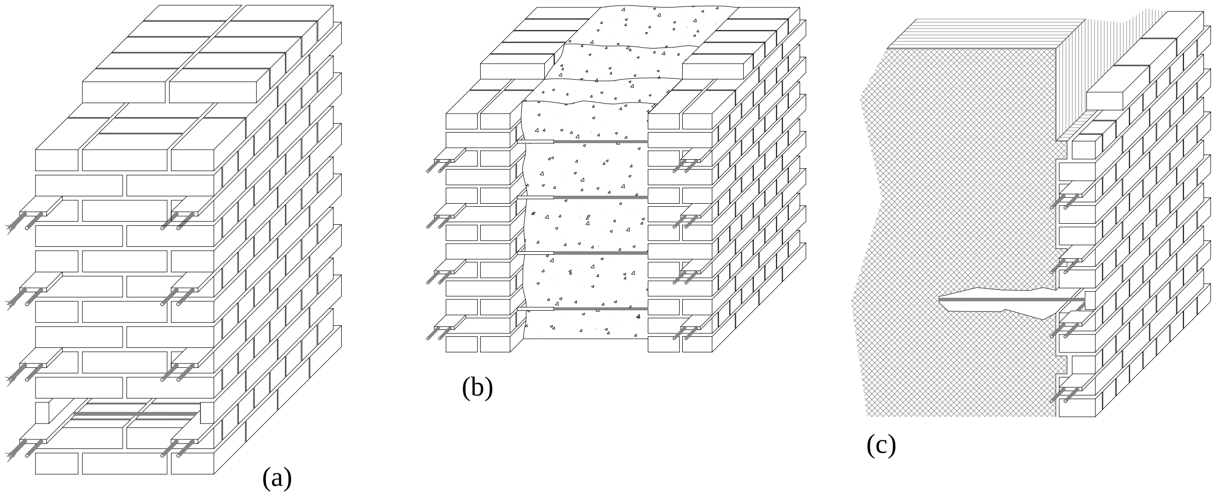


Figure 30: Examples of applications of deep rejointing: (a) one layer loading bearing wall, (b) multi-leaf with external loading bearing layers, (c) multi-leaf masonry wall with non-structural external layer

3.2 Support elements – Damaged walls with diffuse cracked pattern

Strengthening actions: reinforcement, improvement.

Usual applications: Damaged walls with diffuse crack pattern, walls of poor manufacture with high flexural or compression stresses.

Technique: Possible choice between different techniques:

- Jacketing;
- external reinforced with high-performance materials.

Main targets: Increasing the in-plane shear strength, out-of-plane flexural strength and stiffness of the wall (due to the increase of the resisting section and the confining effect of the concrete slabs), sewing cracks (local intervention), improved corner connections.

Advantages/disadvantages: Effective strengthening technique. It increases the resistance and ductility of the element. The effectiveness depends largely on its continuity and end connections.

Practical cases: Adobe houses in Yacango, Peru.

References: [2], [4], [6], [13], [18], [27].

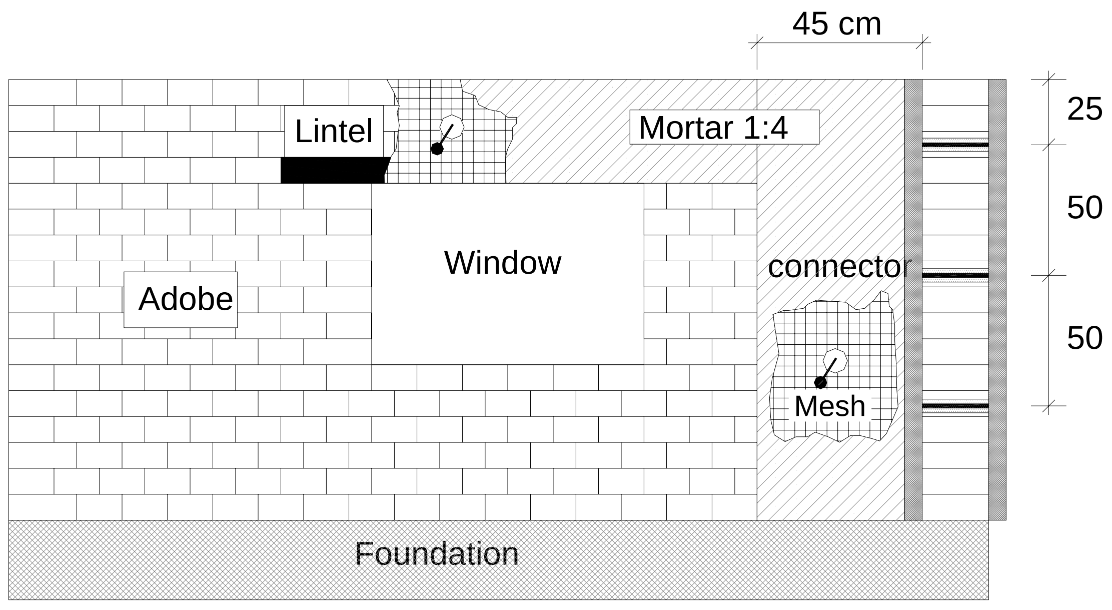


Figure 31: Example of adobe wall reinforced with wire mesh ([18] fig. 19)

3.3 Support elements – Connection between elements

Strengthening actions: reinforcement, improvement, tying.

Usual applications: Old and new masonry structures needing earthquake protection, monuments requiring a temporary and reversible reinforcement while better analyzed.

Technique: Possible choice between different techniques:

- tie bars;
- stitching;
- local tying.

Main targets: Connections between intersecting walls with steel ties placed at different levels.

Advantages/disadvantages: Improving the overall structural behavior by ensuring seismic cooperation between the walls, creation of horizontal strips of confined masonry.

Practical cases: Bell-tower of S. Giustina (Padua, Italy), Bell-tower of Nanto (Vicenza, Italy).

References: [3], [9], [12], [16].

3.4 Support elements - Reinforcement of openings

Strengthening actions: reinforcement, improvement.

Usual applications: Old masonry structures with bad framing of the openings.

Technique: Reinforce doors and windows with R.C. or steel frameworks.

Main targets: Avoiding the collapse of the wall due to the presence of the openings, protecting possible exits also in non structural walls.

Advantages/disadvantages: The mechanical properties of the reinforced concrete frame and the steel frame are not compatible with masonry. The concrete frame will tend to attract more loads, while the steel frame will provide resistance after the masonry has cracked. Additional strengthening for the top and bottom portions of the wall is sometimes required to transfer the lateral loads. Only the steel frame is a reversible technique.

Practical cases: -.

References: [1], [3], [9]

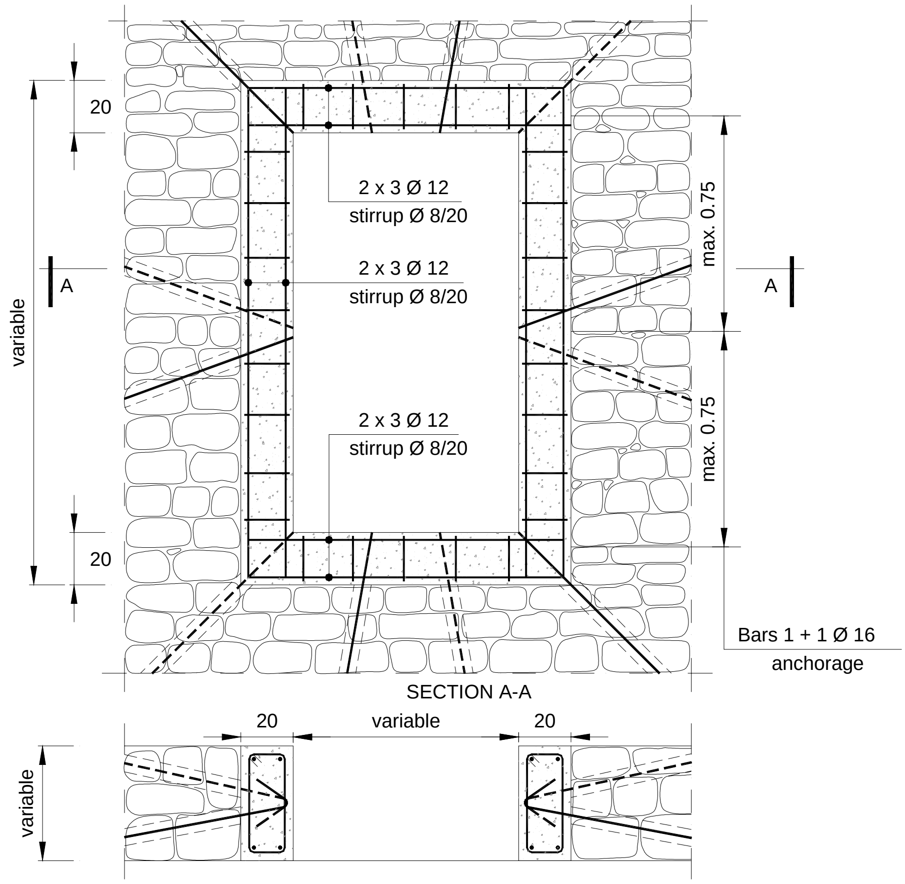


Figure 32: R.C. window framework

3.5 Cover elements - Reinforced concrete and masonry edge-beams

Strengthening actions: confinement, tying.

Usual applications: Masonry buildings with poor connections between intersecting walls, improving the diaphragmatic action of roof and floors, risk of out-of-plane seismic mechanism. Roofs discharging unbalanced thrusts on the walls.

Technique: Creating a ring of beams in the thickness of the existing masonry wall at the roof and floors level. Important details are the connection with the floor beams and the existing walls. Possibilities are the use of reinforced concrete or reinforced masonry beams, at the roof level. Another solution is a steel profiles edge-beam ring.

Main targets: Obtaining a stiffer seismic response of the whole structure, thus using better its strength resources, and avoiding out-of-plane mechanism. Counteracting roof thrusts.

Advantages/disadvantages: It is a relatively costly and time-consuming technique. It may contribute to reduce the stresses in the masonry.

Practical cases: -.

References: [1], [3].

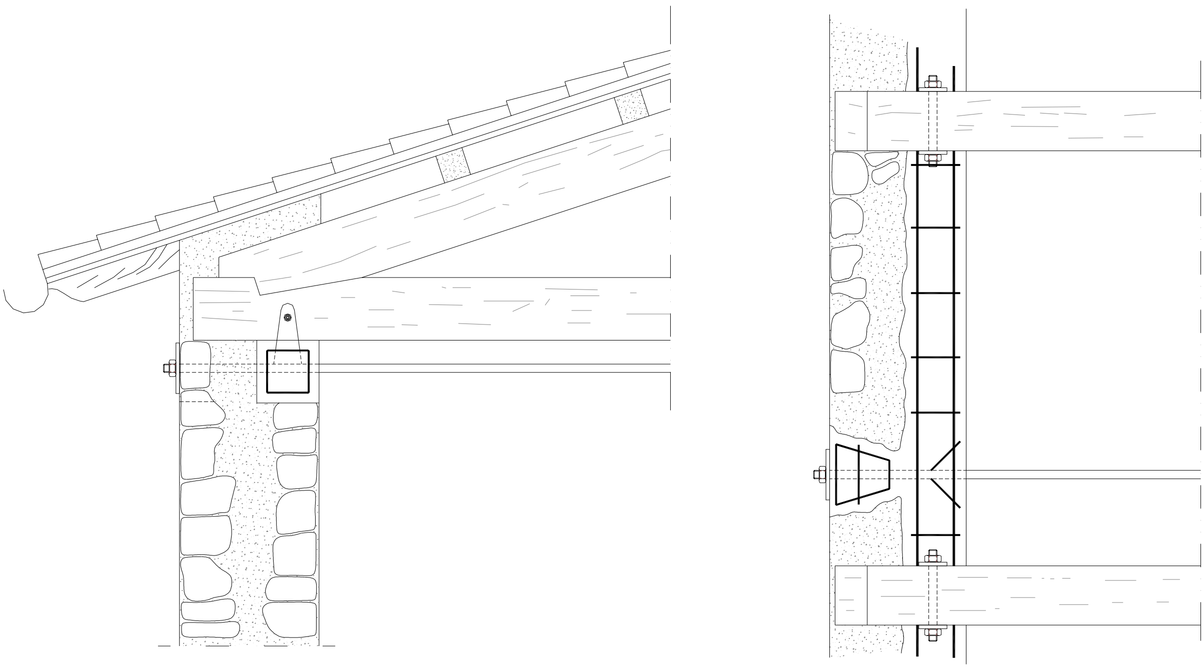


Figure 33: Roof confining reinforcement concrete edge-beam

3.6 Cover elements - Reinforcement of wooden floors

Strengthening actions: reinforcement, improvement.

Usual applications: Wooden floors of old masonry structures.

Technique: Possible choice between different techniques:

- substitution or strengthening of the existing beams;
- providing increased connection with the walls;
- stiffening of the floor with a rigid R.C. tie-beams structure at floor level;
- steel ties;
- anchoring of roof beams on the perimetral walls;
- reparation and substitution of purlins;
- connection between roofing elements.

Main targets: Achieving a better seismic global response of the structure and avoiding the collapse of the floor during the earthquake.

Advantages/disadvantages: -.

Practical cases: Cathedral of Porto, Portugal

References: [1], [2], [3], [30]

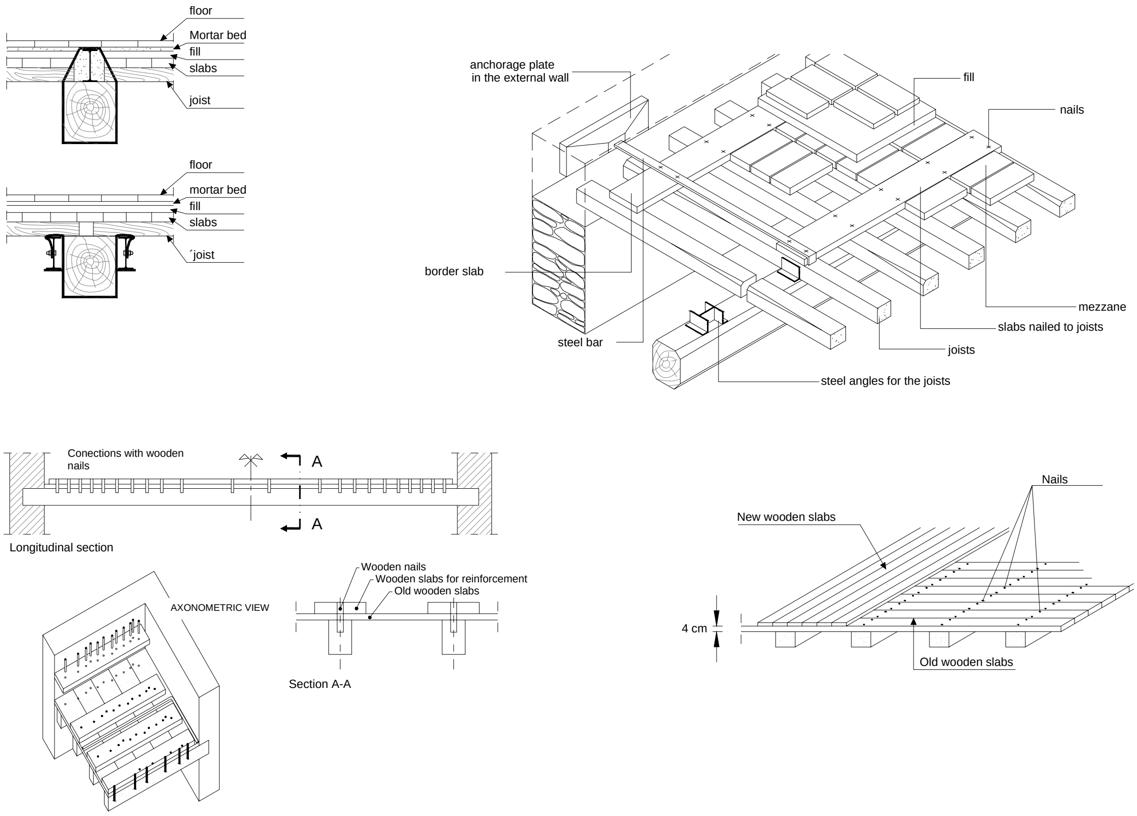


Figure 34: Different types of reinforcement of wooden floors

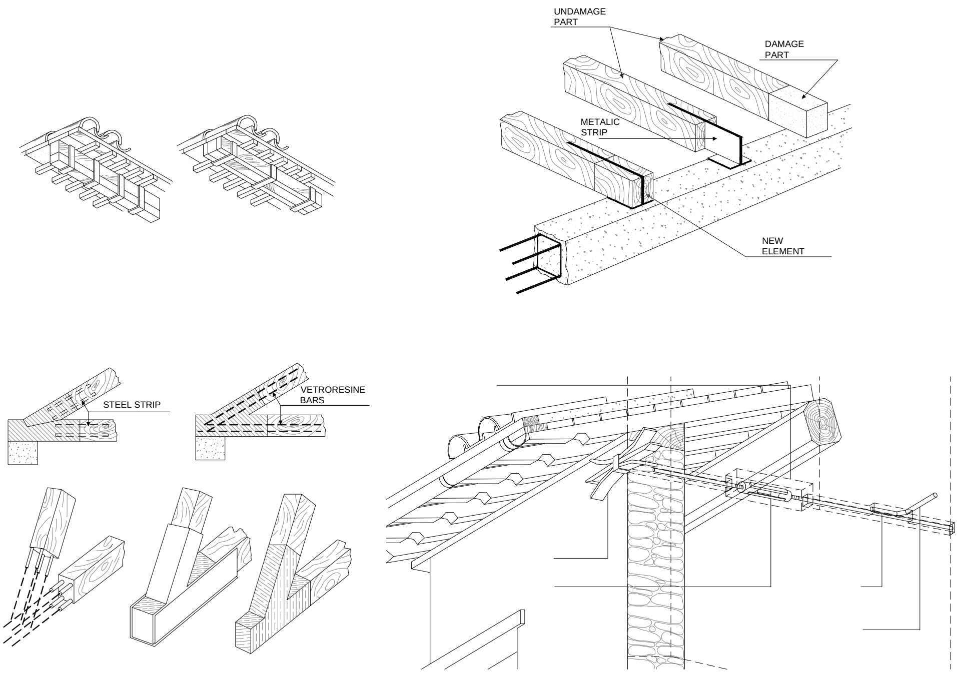


Figure 35: Some examples of repairing and strengthening of existing wooden roofs

3.7 Cover elements - Reinforcement of arches and vaults

Strengthening actions: reinforcement, tying, propping, improvement.

Usual applications: Arches and vaults suffering damage related to ductile failures.

Technique: Different interventions are available:

- ties connecting the springings;
- ties located at the tympanum of the arch;
- enlarging the section of the arch / vault or the section of the buttresses;
- use of FRPS strips in different positions;
- adding weight on top or anchoring of the buttresses;
- supporting the original structure with an upper one carrying part of the load.

Main targets: Regaining the stability of the arch / vault bringing back the thrust line inside the vault thickness and avoiding the opening of the springers.

Advantages/disadvantages: Depends on the strengthening technique. In general, the techniques reduce the masonry stresses. Lighter interventions are generally to be preferred since they do not comport a remarkable increase of the seismic action.

Practical cases: temporary intervention to sustain the dome of the “Basilica di Assisi”.

References: [1], [2], [3], [22], [25], [26], [28]

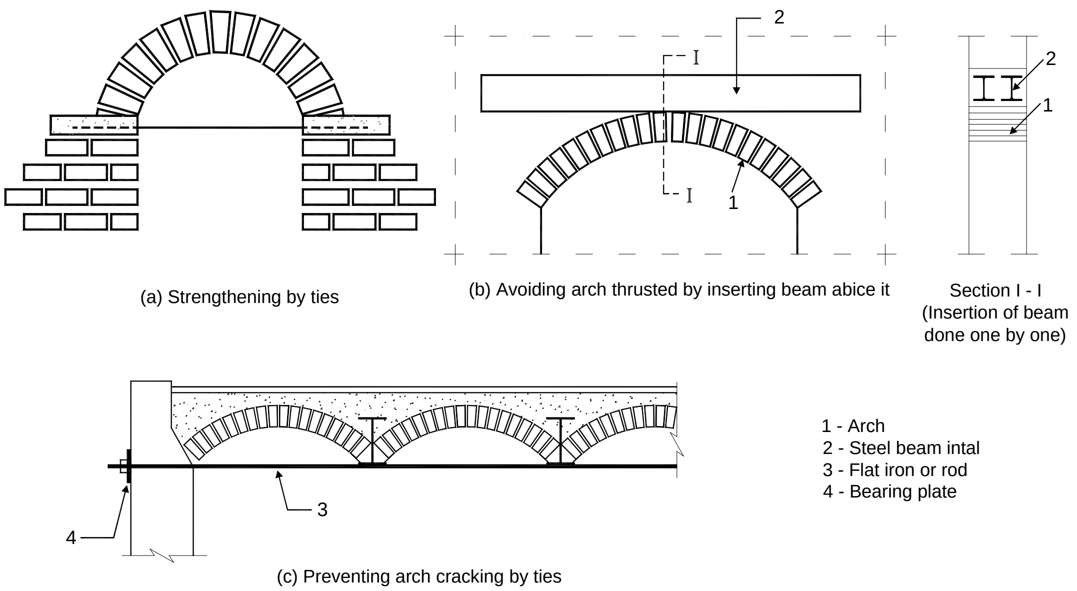


Figure 36: Different techniques of strengthening an arch [26]

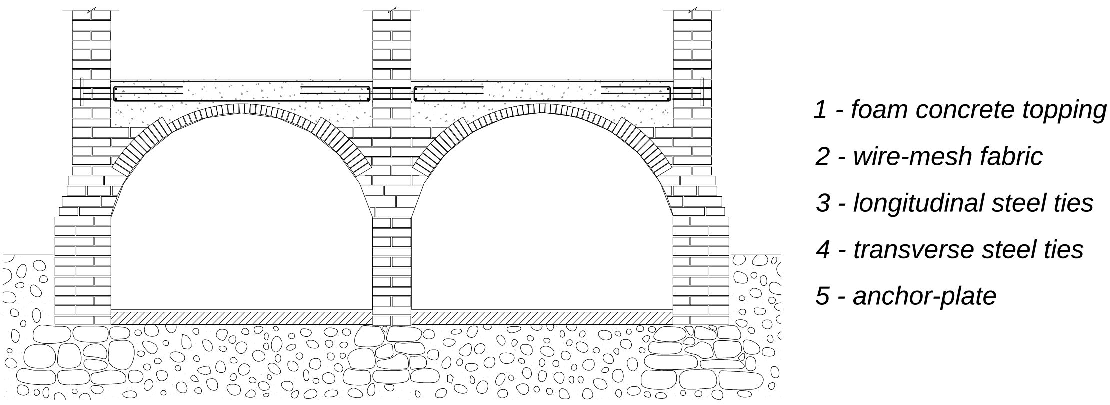


Figure 37: Strengthening of masonry vaults with foam-concrete topping [28]

3.8 Foundations - Direct interventions

Strengthening actions: enlargement, reinforcement, improvement.

Usual applications: Damaged, poorly dimensioned foundations or foundations with insufficient interconnection between element and bad load distribution.

Technique: Widening, connecting, repairing and reinforcing the original foundation with the technologies seen for the other parts of a structure.

Main targets: Better load distribution and improvement of the mechanical properties of the foundation structure.

Advantages/disadvantages: Used to restore or improve condition of existing foundation. Effectiveness depends on proper identification of originating factor and on good knowledge of geotechnical conditions.

Practical cases: "Ospedale degli Innocenti" Florence, Italy.

References: [1], [23], [25].

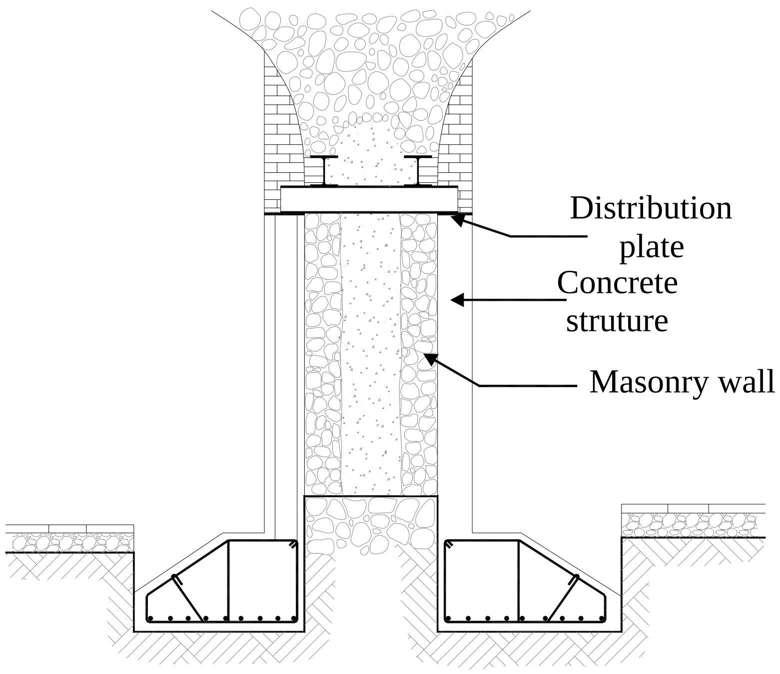


Figure 38: Example of concrete reinforcement of an existing foundation ([1] fig. 74)

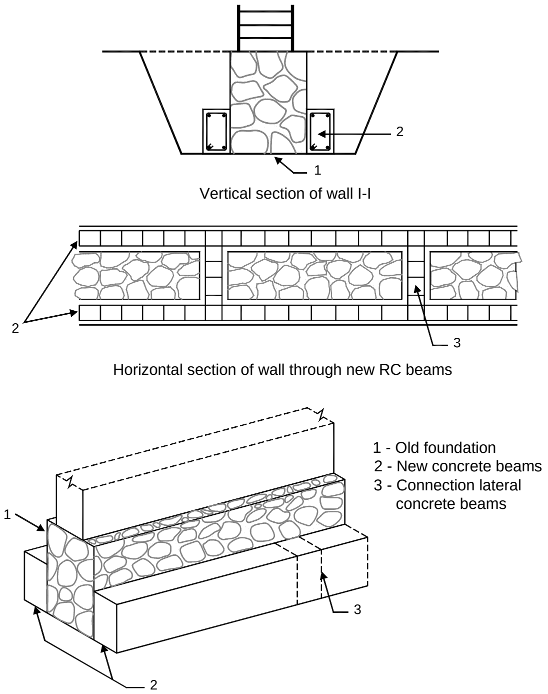


Figure 39: Improving a foundation by inserting lateral concrete beams [25]

3.9 Foundations - Interventions on the soil beneath the foundation

Strengthening actions: soil stabilization.

Usual applications: Foundations on not consolidated soil, possible sinking of the structure.

Technique: Possible choice between different techniques:

- micro-piling: concrete piles grouted into steel hollow tubes drilled below the original foundations towards a soil layer with better characteristics;
- jet-grouting: technique similar to the micro-piling, the concrete is directly grouted with high pressure in a borehole drilled in the soil, creating a mixed material column;
- wooden-pile driving: the piles are driven in the soil compacting and consolidating it.

Main targets: Transferring the load to a soil layer with better mechanical characteristics, improving the properties of the soil just beneath the foundation.

Advantages/disadvantages: Piles must first be installed or cast in place. Major structural modifications required in the monument's foundation system. The superstructure must be adapted and/or reinforced to tolerate imposed movements. Rate and magnitude of corrective vertical displacement can be accurately controlled. The jet-grouting can be difficult to implement; it is sometimes intrusive (can produce damage to archaeologically rich deposits or ancient buried structures).

Practical cases: "Palazzo della Mercanzia", Bologna, Italy, "Università degli Studi di Parma", Parma, Italy, a historical building in Lisbon, Portugal.

References: [1], [5], [20].

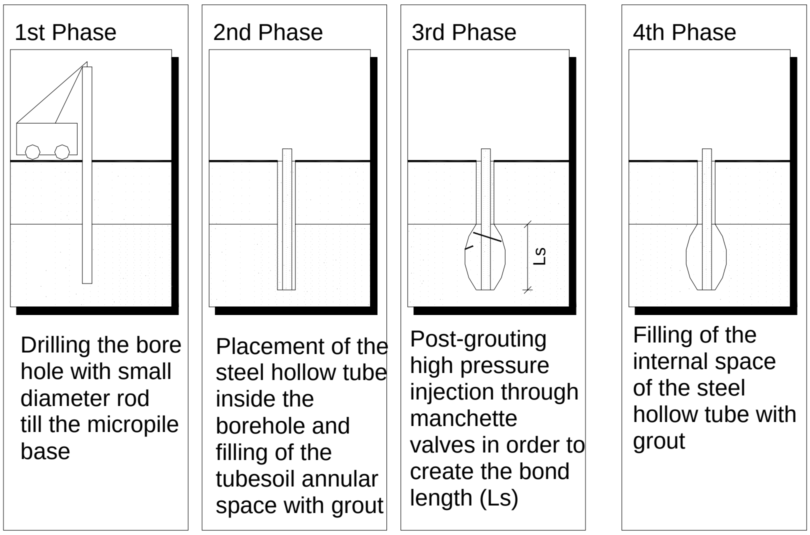


Figure 40: Micro-piling construction phases ([5] fig. 2)

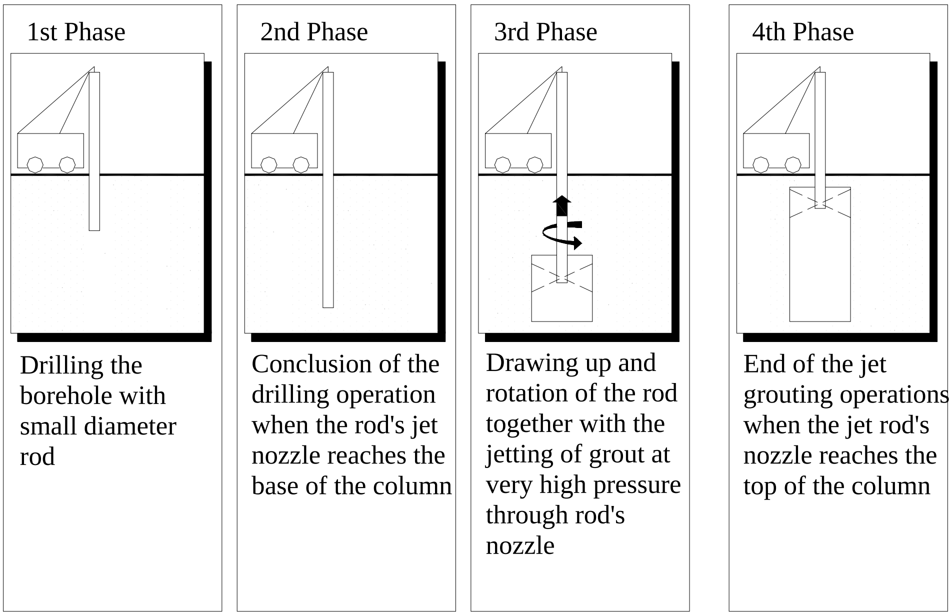


Figure 41: Jet-grouting construction phases ([5] fig. 2)

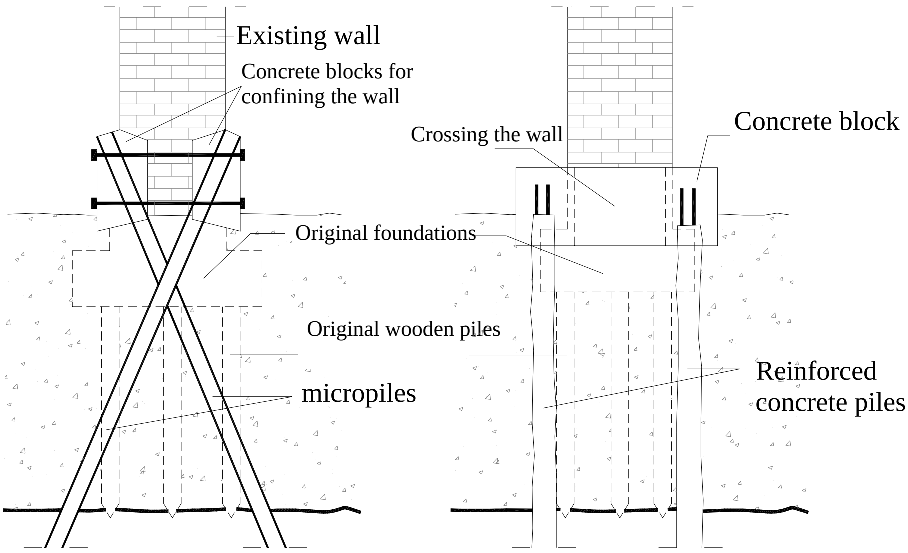


Figure 42: Reinforcement of existing foundations with insufficient or degraded wooden piles: (a) with micropiles, (b) with concrete piles [20]

3.10 Foundations - Control piles

Strengthening actions: soil stabilization.

Usual applications: Foundations with insufficient or degraded wooden piles, buildings with differential settlements.

Technique: Piles connected indirectly to the building by means of a frame.

Main targets: They may be used to regulate loads applied at the pile heads or to directly control settlements. Consolidation and compacting the soil towards the compression applied by the piles.

Advantages/disadvantages: Modifications at foundation and at the superstructure level required. Permanent maintenance required.

Practical cases: Cathedral of Mexico City

References: [23].

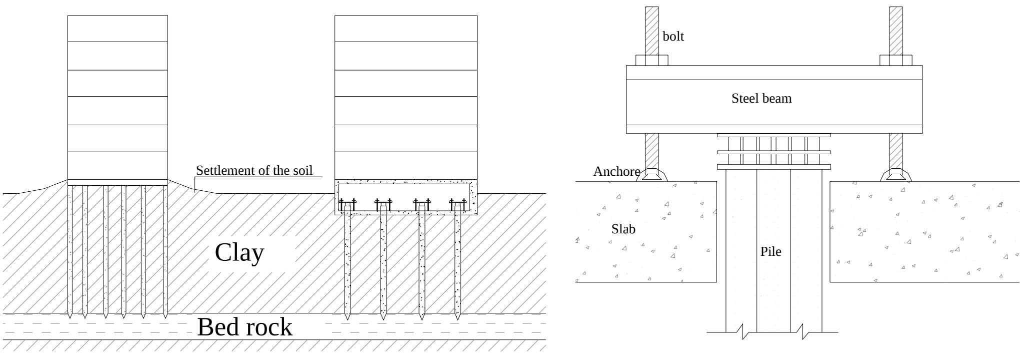


Figure 43: Control piles: (a) global behaviour of the building, with and without control piles, (b) detail of the connection between pile and structure

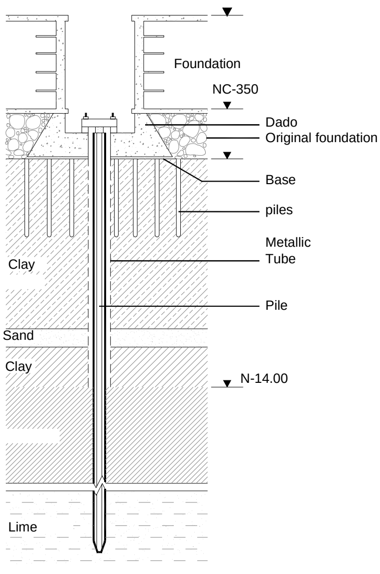


Figure 44: Detail of the control piles used in the 1970 restoration of Mexico city Cathedral [21]

4 REPAIRING AND STRENGTHENING AT GLOBAL LEVEL

4.1 Improving connections between intersecting walls

Strengthening actions: Tying, confinement.

Usual applications: Strengthen the connection or improving a weak connection between perpendicular walls.

Technique: Steel ties are positioned in the outer side of the walls and covered with plaster and protect from corrosion. Alternatively, the ties may be placed in channels cut into the masonry; the cut pieces of stone are carefully removed and after the ties are placed and protected against corrosion, they are used again to cover the ties. The ties are anchored at the ends of the walls on steel bearing plates. The ties may be prestressed and anchored on the anchor plates by means of nuts.

Main targets: Improving the seismic behaviour of the whole structure.

Advantages/disadvantages: Constitutes a very effective technique to seismically upgrade the building. Provides a very significant improvement of the seismic resistance with only a minor alteration on the original structure.

Practical cases: Constitutes a common historical and traditional strengthening technique commonly used in many countries of Europe.

References: [24], [33]

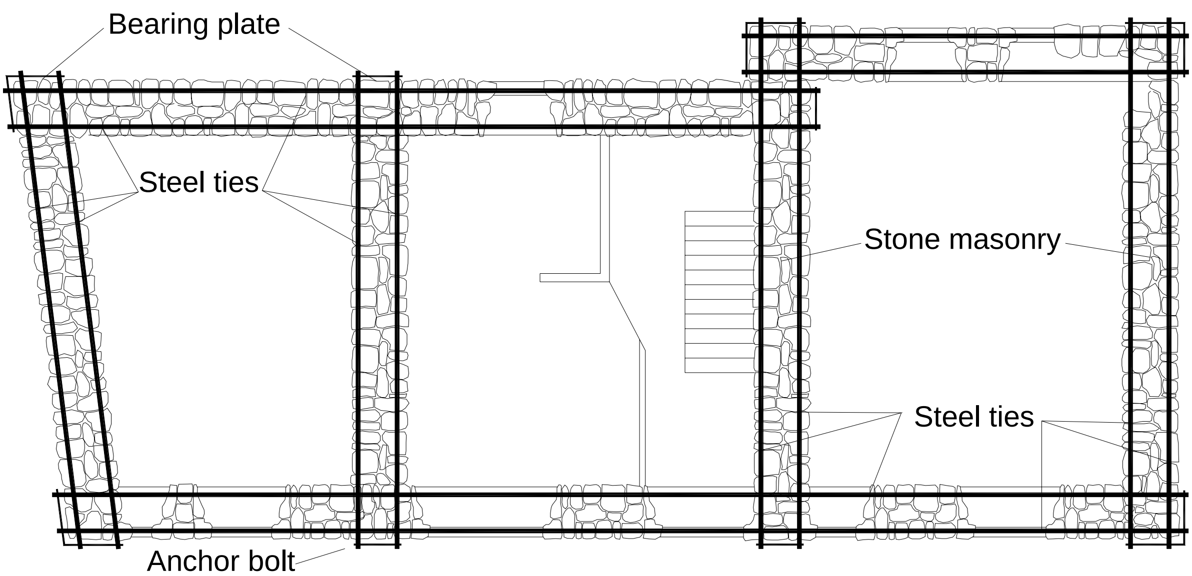


Figure 45: Distribution of ties to improve the overall seismic response in plan [33]

4.2 Improving connections between walls and horizontal diaphragms

Strengthening actions: Tying.

Usual applications: Stabilizing masonry walls during earthquake.

Technique: Requires the stiffening of a floor slab so that it can behave as a relatively stiff horizontal diaphragm. This can be achieved by placing a thin layer of lightweight concrete on the roof slab or by building a wooden slab in combination with the existing roof. The concrete / wooden new diaphragm must be connected to the original roof (using, for instance, screws). The diaphragm is connected to the masonry walls using reinforced injections or steel ties anchored on the wall surfaces.

Main targets: Preventing out-of-plane instability of masonry walls during earthquake by connecting them to a floor slab acting as a relatively stiff diaphragm. Improving the seismic load distribution.

Advantages/disadvantages: Construction of concrete layers on wooden historic floors, and connected to them, is not compatible with historical construction methods, is intrusive and is hardly reversible. The same can be said about connecting the diaphragms to the walls by reinforced injections. Moreover, this approach does not yield the best seismic performance and is not so effective as improving the connection between walls by means of ties.

Practical cases: -.

References: [24]

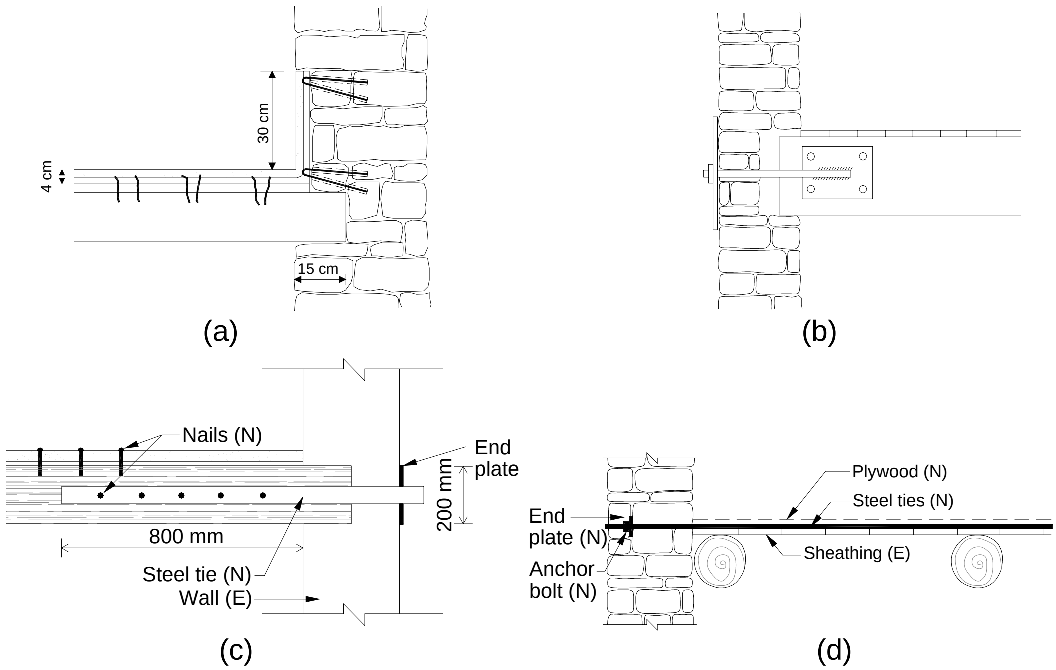


Figure 46: Alternative solutions to connect the stiff diaphragm with the masonry walls. (a) Reinforced injections. (b)-(d) Steel ties and external anchors [24]

4.3 Adding secondary lateral resisting structural system

Strengthening actions: Reinforcing, structural substitution.

Usual applications: Buildings (by means of braces), towers, masonry spires (by inner steel frame).

Technique: Adding an secondary structural resisting system consisting of a steel diagonal bracing or an inner concrete or steel frame.

Main targets: Enhance the structural integrity after the masonry has cracked or preventing the collapse. The use of pretressing ties may permit the transfer of load from the original structure to the secondary one prior to the formation of vertical cracks.

Advantages/disadvantages: Structural substitution may lead to significant problems. The mechanical properties of the original structure and the new one (which normally will consist of a steel or concrete frame) may not be compatible. The stiffer concrete frame will tend to attract more loads while the flexible steel frame will provide resistance only after the masonry has cracked. Additional strengthening of the original structure may be needed in order to preserve its integrity. However, only the steel structure will normally constitute a reversible strengthening operation.

Practical cases: -.

References: [24]

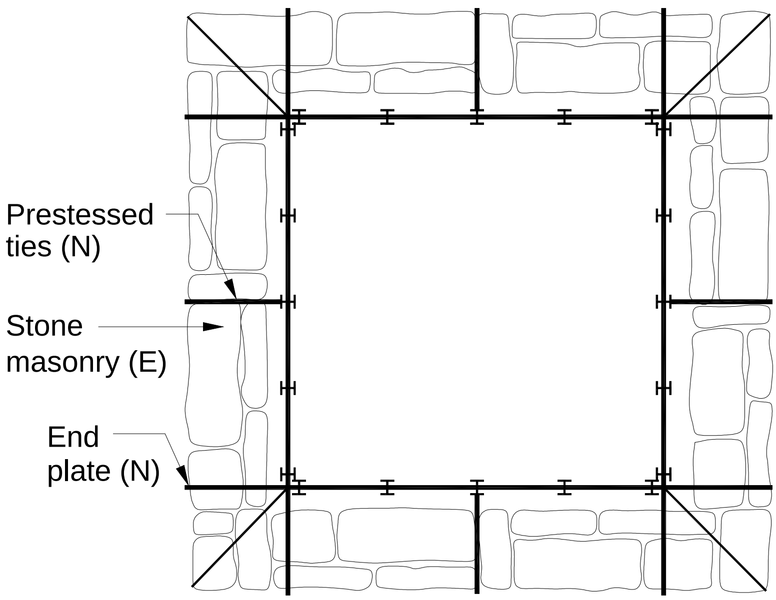


Figure 47: Steel frame (plan) for strengthening of stone masonry towers

4.4 Global confinement

Strengthening actions: Tying, confinement.

Usual applications: Buildings, churches, towers. It is used, in particular, as provisory emergency action.

Technique: Steel strands, bars or tendons, or FRP strips or tendons, are used to confine the structure and thus to stabilize the walls and to improve the connection between the different parts by generating compression and friction between them.

Main targets: Stabilize the external walls, improve the connection between parts.

Advantages/disadvantages: Is an effective technique, whose efficiency can be compared to that of improving the connection between walls by means of ties. It is fully non-invasive and reversible. The bars or tendons are normally visible; the use of small strands or tendons with reduced diameter may contribute to make them less apparent. Because of its efficiency and full reversibility, it has been used to strengthen or stabilize very deteriorated structures both as a provisory or final strengthening technique.

Practical cases: -.

References: -.

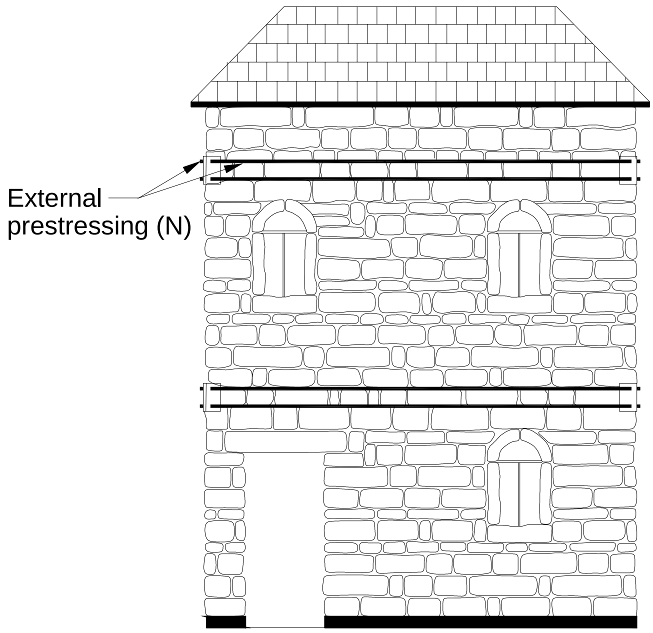


Figure 48: Confinement by means of prestrssed FRP ties [24]

4.5 Seismic isolation

Strengthening actions: isolation.

Usual applications: For building of primary importance, which functionality should not be affected by seismic action, seismic isolation is generally considered the most appropriate choice.

Technique: Absorbing and dissipating the seismic forces and vibration with devices placed between the foundation and the proper structure. Depending on the nature of the dampers can be distinguished isolation using:

- elastometric materials (steel plates in an elastometric matrix);
- elastometric materials reinforced with a lead core;
- combination of elastometric materials and frictional plates of steel-bronze;
- frictional plates with very low frictional coefficient coupled with neoprene rubber or steel springs;
- assemblies of spiral springs coupled with viscous dampers;
- seismic base isolation using frictional plates with very low frictional coefficient coupled with different types of dissipative tools (piezoelectric, electrostrictive and magnetostrictive materials, memory shape alloys, viscous, electrorheological and magnetorheological fluids).

Main targets: Absorbing the seismic vibration and avoiding major damages to the building.

Advantages/disadvantages: This technique is effective when the fundamental period of the base-isolated building results substantially greater than both the predominant period of the ground motion and the fixed base equivalent period of the building. It is not suitable for structures located on very soft soils. Seismic isolation constitutes a drastic operation which requires a significant alteration of the structure, at the level of its original foundation, and involves risky operations. Moreover, the durability of the isolating pads is limited, which may require its possible substitution in the mid or long term. In the case of ancient structures, seismic isolation should be regarded as an extreme operation to be only considered if all the possible alternatives show insufficiently effective.

Practical cases: -.

References: [1], [23].

4.6 Controlling differential settlements

Strengthening actions: soil stabilization.

Usual applications: Buildings with differential settlements.

Technique: Different actions can be taken into account as:

- control piles;
- underexcavation;
- jet-grouting;
- micro-piling.

Main targets: Try to reduce, control or avoid differential settlements.

Advantages/disadvantages: -.

Practical cases: -. Inquisition Palace, Mexico city, Cathedral of Mexico city.

References: [21], [22]

5 NUMERICAL MODELLING

Structural modelling may contribute to the validation of possible strengthening techniques by simulating their effect on an accurate numerical model of the structure. The analysis of the strengthened structure requires, in particular, the modelling of the strengthening techniques implemented. For that purpose, it may be useful to model the possible strengthening techniques by their combination of the basic actions they produce in the structure. These basic actions have been referred in section 1, while the actions produced by any strengthening technique are (tentatively) mentioned for each case in section 2. Once the basic actions are identified, they can be introduced in the numerical model as a combination of some essential numerical devices. The main numerical devices which can be used to model possible strengthening actions are:

Creation of an internal constraint: connection two or more nodes of the structure with a stiff or rigid element, thus limiting the reciprocal displacement. The strength and stiffness of the connection has to be carefully investigated. It can be used to model *confinemen*t, *tying* and *reinforcement* (seen as high resistance material well connected with the original one).

Improvement of the mechanical properties of the material: modification of the material properties of the masonry (in a macro-model) or in the joints or the blocks (in a micro-model). It can model all the techniques involving a removal and replacement of parts of a structure as well as general improvement of the material masonry. This device can be utilized to model *material substitution* and *improvement*.

Inclusion of an additional substructure: modelling of new structures interacting with the original ones. It consists simply in superposing two finite elements model. It can be used to model *structural substitution* and *propping*.

Creation of an external constraint: connection of one or more nodes of the structure to an external element or to a fixed node. It can model *anchoring*.

Application of loads: application of external nodal or distributed forces to the structure. This device can be used to model *prestressing*.

Widening of the section: increasing of the physical dimensions of the resisting section. This resource is appropriate for the numerical modelling of *enlargement*.

Modification of the seismic action: decrease or modification of the seismic forces or accelerations applied to the structure. It can be used to model *isolation* and *soil stabilization*.

Note that each device refers to one or more basic actions. Thus, any strengthening technique (such as those described in sections 3.1 to 3.12) can be described in terms of the series of actions it causes (categories mentioned in section). In turn, such actions can be modelled as a combination of the aforementioned numerical devices.

6 FINAL REMARKS

Historical structures are valuable, among other reasons, because they constitute a live document of cultural or technical knowledge from another time in history. We attribute value to historical constructions because they genuinely demonstrate the achievements of our ancestors and because they do so by providing us with a true and material testimony of their skills and mastering.

Strengthening of historical constructions is aimed at correcting their possible structural insufficiencies or at improving their structural response (for instance, their seismic response) and thus to ensure their future conservation for the benefit of future generations. However, any strengthening action on a historical construction will normally produce, by itself, some cultural losses as it will inevitably cause a certain alteration on the original materials and structural features.

Modern criteria for the restoration of historical structures aims to minimum interventions characterized by their adequate non-invasiveness, reversibility, compatibility and durability, among other requirements (see the ICOMOS/ISCARSAH Recommendations [34]). When addressing the conception and design of a possible intervention, the architect or the engineer need to consider a set of possible alternatives attaining the required level of structural upgrading and safety. Among these, the one causing the less alteration to the structure (the minimum one) should be preferred. The cost produced by the alteration, in terms of loss of cultural value, can be qualitatively measured by the grade of irreversible transformation caused to the original materials, morphology and structural features. Operations involving irreversible substitution, intrusion or obtrusion (enlargement) should be considered as producing a meaningful loss. Operations conveying a significant transformation of the material or the structure should be also considered high-cost one. Conversely, interventions based on the exploitation of the resources of the structure itself, both material and mechanical, or in the application of historical or traditional solutions consistent with the features of the structure and the historical practices (such as ties or local reconstruction following the “cuci-scuci” practice), can be considered appropriate and having almost null or limited cost. Solutions involving devices strange to the structure and the historical practices, but mostly reversible and non-invasive, can be regarded as having a limited or medium cost.

Note that a significant part of the solutions presented in the document can be, in principle, classified among the ones which might cause a significant cultural loss due to their intrusive, irreversible and highly transforming character. Nonetheless, the designer needs to be aware of all the possibilities, previous to carefully selecting the most appropriate ones for a giving specific problem.

The architect and engineer must understand that every problem constitutes a genuine case and a new challenge, and that no general rules can be formulated. The different techniques, either ancient or modern, are to be considered in detail and analysed following a cost-benefit criterion. No rule or general reasoning can actually substitute experience and judgement of the designer.

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