ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Md. Rashadul Islam

Inventory of FRP strengthening methods in masonry structures

University of Minho

UNIVERSITAT POLITÈCNICA DE CATALUNYA

Education and Culture

Erasmus Mundus

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Spain, July 2008

Inventory of FRP strengthening methods in masonry structures

By Md. Rashadul Islam

Supervisor: Assoc. Professor Climent Molins

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TECHNICAL UNIVERSITY OF CATALONIA, SPAIN

Satellite Participant: INSTITUTE OF THEORETICAL AND APPLIED MECHANICS, CZECH REPUBLIC

ABSTRACT

Masonry structures are prone to extensive damage followed by failure and collapse when subjected to loads resulting from wind, earthquake and other natural or man-made events. Recent earthquakes and terrorist acts have clearly demonstrated that the development of effective and affordable strategies for the strengthening of masonry is urgently needed. As a response to these challenges, fiber-reinforced polymer (FRP) composites may offer technically and economically viable solutions. In the context of work undertaken worldwide, this paper presents an overview of research studies and field applications of masonry strengthening with FRP composites as conducted in the last few decades. In particular, the thesis covers material forms and installation techniques, namely: externally bonded laminates, near surface mounted bars, and post-tensioning; experimental test programs dealing with the out-of-plane and in-plane behavior of walls, columns and arches with discussion of failure modes, field validation, and durability analysis and applications including historical structures. Without providing full details, an effort has been made to address issues related to design so that practicing engineers can immediately appreciate the potential of this technology and understand the key parameters affecting performance and the areas that need further experimentations.

DECLARATION

I hereby declare that this paper is solely published in partial fulfillment for the requirements of the degree of Advanced Masters of Structural Analysis of Historical Construction. No part of this paper is being concurrently submitted or published in any other purpose and all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that as required by this rules and conduct, I have fully cited and referenced all materials and result that are not original to this work.

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(Md. Rashadul Islam)

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Nomenclature

FRP: Fiber Reinforced Polymer

CFRP: Carbon Fiber Reinforced Polymer

GFRP: Glass Fiber Reinforced Polymer

AFRP: Aramid Fiber Reinforced Polymer

NSM: Near Surface Mounted

URM: Unreinforced Masonry Structures

EBR: Externally Bonded Reinforcement

EU: European Union

IRA: Initial Rate of Absorption

1 Chapter 1: Introduction

1.1 Overview

One of the main problems connected with preserving and maintenance of historic buildings and existing dwellings is the need for strengthening and retrofitting of the masonry parts of the structures. For design purposes masonry is considered as homogeneous material but in reality it shows very complex heterogeneous characteristics. Aggressive environment and some natural calamities can cause extensive damage to unreinforced masonry (URM) structures. Many older masonry structures currently in use were designed and constructed with little or no consideration of these aggressive factors. In addition, recent changes in seismic requirements have left many URM buildings in need of strengthening (Vanessa E. Grillo, 2003). In many cases, these natural effects were not considered in ancient time. Since the advent of modern reinforced masonry construction, URM structures have been viewed as a significant liability when considering strengthening.

Significant research has been done on strengthening masonry components and their connections resulting in strengthening methods based on traditional materials, such as steel and concrete. These traditional techniques often add extra load to structures and make it more risky. In general, these options ignore the contribution of the URM components to the lateral capacity. Furthermore, they are quite expensive and pose significant inconvenience for the building occupants during installation. Significant progress has been made in identifying URM behavior under extreme loads and recognizing the contribution of URM components to both strength and ductility of the building system. The application of fiber reinforced polymers (FRP) for strengthening of masonry structures is relatively limited. The application of FRP materials is very beneficial having in mind its easy installation, low self weight, high strength and ability to preserve the initial shape of the wall. Their light weight means that they do not alter the mass of a structure and thus the inertial forces from seismic excitation. This thesis is an effort to collect the outcomes of almost all researches that have been done on FRP application for masonry structures, its advantages and disadvantages and also some examples of application,

1.2 Scope of the study

This thesis includes all recent research for strengthening masonry structures and examples of application. The ideas and research outcome of almost one hundred of researches have been accumulated here which will be a good help guide for any real problem. Almost all old building and historical structures are made with masonry. Due to recent change in seismic code and some other causes all historical structures need to be retrofitted (Vanessa E. Grillo, 2003). Also a lot of new buildings, bridges and pavements are being constructed with FRP. This study will be a good guide for both new as well as old structures. Also this study can be a good bibliography for the upcoming researchers.

1.3 Objectives

The sole objective of the thesis is to find out the researches that have already been done in strengthening of masonry structures.

- Find out and discuss the failure mechanism of un-strengthened and FRP strengthened masonry walls, columns, arches and vaults.
- Discuss the possible ways of application of NSM (Near surface mounted) and EBR (Externally bonded reinforcement) FRP materials. Also the behaviour of epoxy resin will be focused.
- Both flexure and shear strengthening phenomenon will be analysed.
- The better application geometry and configuration and possible outcome will be extracted from past and recent experiments.
- The effectiveness of different FRP layouts subjected to different actions (gravitational force, seismic force) will be critically analysed.
- The areas where further research is needed will be localised.

1.4 Methodology

To carry on this bibliographic research a lot of research papers from scientific journals particularly ‘’Journal of Composites for Construction’’ and ‘’Construction and Building Materials’’ had been studied. Their principal outcome has been extracted and arranged in logical sequence. Also some of their experimental results have been more elaborately described and good possibilities are focused. In some cases, it is seen that different researchers did their study in a particular field and got same type of result. Those outcomes are highly marked.

1.5 Organization of the thesis

This paper consists of six chapters.

Chapter one comprises of general and formal requirements of the thesis. The background, scope and objectives of this paper have been discussed.

Chapter two consists of the state of the art. A brief literature related to masonry strengthening techniques, the way of doing these, design targets and real examples and also the properties of FRP, its design issues and application methodologies with real examples have been discussed with appropriate figures and references.

Chapter three is also state of the art organized by three different typologies (walls, columns and arches) of the FRP application on masonry structures strengthening. The potential for application of the materials, application procedures, possible failure modes and the benefits and application of walls, columns, arches and vaults have been analyzed. Also some limitations of FRP application such as creep problem, freeze-thaw cycling and temperature effects have been discussed.

The discussion and limitations of current and previous researches have been presented on chapter four. Also a lot of valuable suggestions regarding application type, materials selection, the most efficient lay out and materials and benefits and limitations have been presented.

Chapter five is the brief and concise conclusion and recommendation for further studies. All the references with year of publication and other necessary information are listed in chapter six.

2 Chapter 2: Literature review

2.1 Introduction

Masonry structures are the oldest structures ever made. Due to lack of scientific and modern knowledge they were really built as per the available knowledge, experiences and empirical evidences. With passage of time it needed restoration and strengthening as many of the structures became the cultural heritage and got a good social value. At the beginning of restoration process a lot of strengthening techniques had been suggested by the experts. Some of them might have improved the structural performance very much and became popular. Also depending on the structures, site and local availability of materials many strengthening techniques developed and used in different locations of the world. Recently FRP became the most popular material for strengthening as it overcomes a lot of disadvantages of other techniques. FRP can be applied to almost all type of structures though every structure is unique.

At the time of selecting possible repair or strengthening solutions, it is also essential to consider the principles of conservation and the modern criteria for the analysis and restoration of historical structures. These criteria are minimum intervention, reversibility, non-invasiveness, durability and compatibility with the original materials and structure. Cost should be considered also though it is not within the criteria. Generally considering these principles and criteria the best solution is found out among a set of alternative possibilities or a combination of different techniques.

2.2 Necessity of strengthening

Masonry structures were built on ancient times when no appropriate theory and good knowledge were available. People usually built their houses according to the available knowledge and experience. So many buildings which still exist do not satisfy the present guidelines. Also the recent worldwide earthquakes make people more conscious about the safety of life and property. Some of the famous building which becomes valuable in terms of culture and history demand longer service life.

It is also a common issue that the place which was residential area some years ago now becomes industrial area, so people will usually want to change to use of their previous building. Sometimes there may be mistake while construction. So lot of reasons may be claimed for strengthening existing buildings. It is summarised as follows

- To eliminate structural problems or distress which results from unusual loading or exposure conditions, inadequate design, or poor construction practices. Distress may be caused by overloads, fire, flood, foundation settlement, deterioration resulting from abrasion, fatigue effects, chemical attack, weathering, inadequate maintenance, etc.
- To be conform to current codes and standards.
- To allow the feasibility of changing the use of a structure to accommodate a different use from the present one.
- Durability problems due to poor or inappropriate construction materials.
- Design or construction errors.
- Aggressive environments not properly understood during the design stages.
- Increased life-span demands made on ageing infrastructure.
- Exceptional or accidental loading.
- Varying life span of different structural or non-structural components.

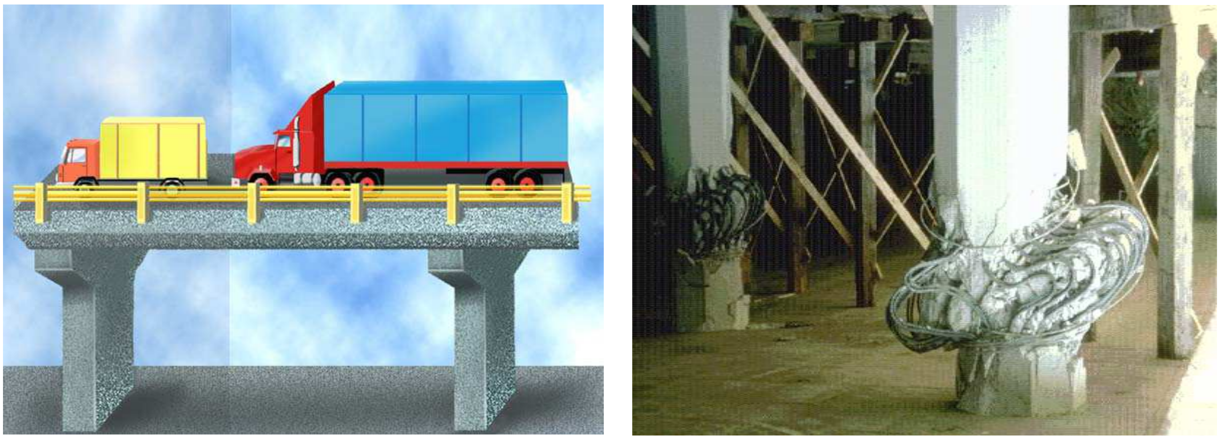
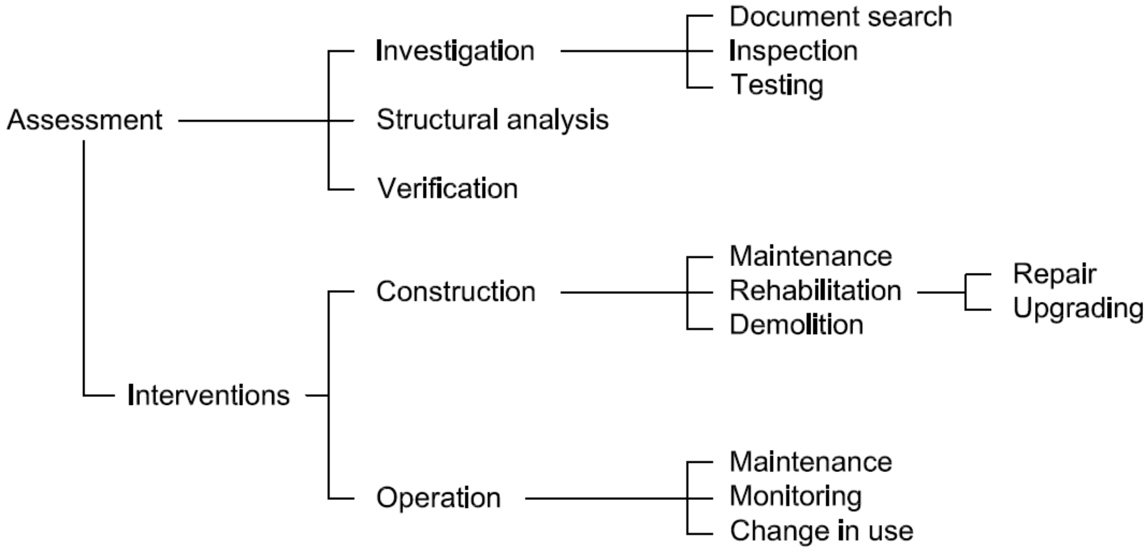


Figure 2.1: The reasons of strengthening structures (John Busel, David White, 2003)

The above virtual figure shows that at early stage (say, 50 years ago) the vehicle were small in size, like the first one but now due to large demand the bridge piers need to be retrofitted to support the heavy load. Also increasing service life is an important factor for strengthening structures. We generally will want that our national or international monuments last very long days.

Assessment of existing structures requires following the following tree diagram-



(J. S. Cruz 2008)

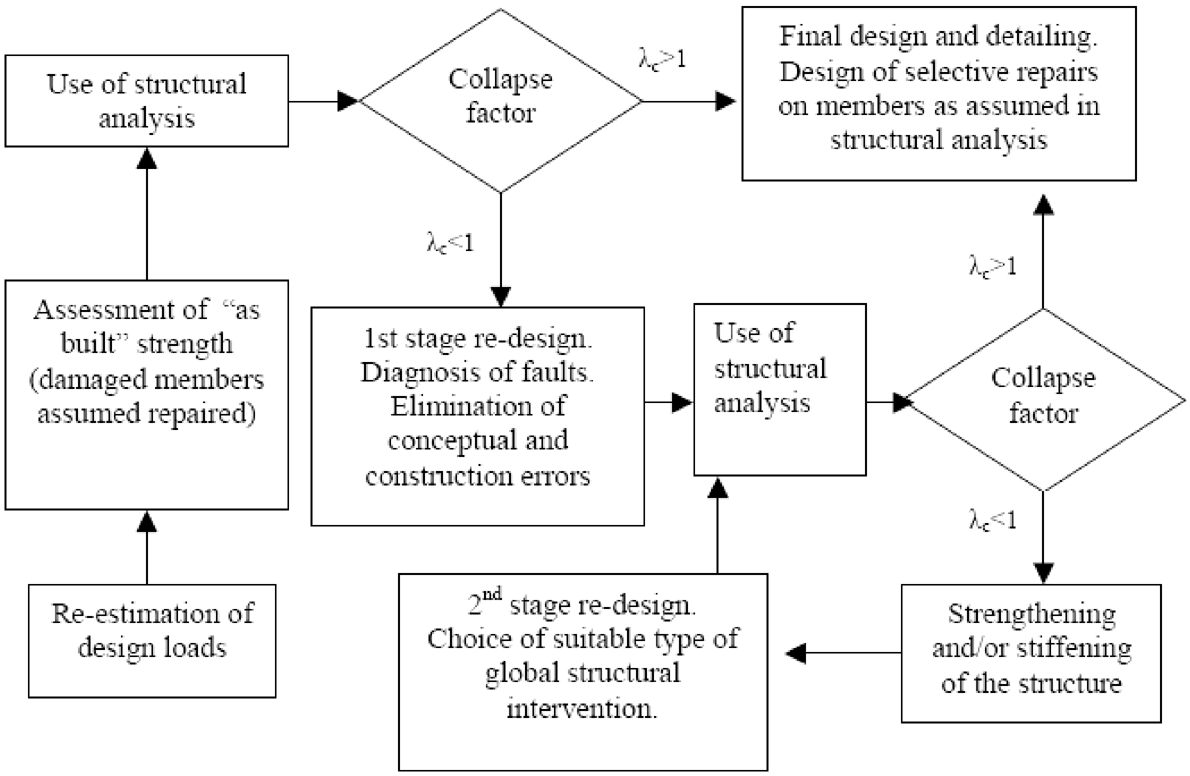
Repairing/strengthening means to increase one or more than one of the following parameters

- Tensile capacity
- Shear capacity
- Flexural capacity
- Compressive capacity
- Member stability
- Ductility
- Strength or stiffness or both

2.3 Design of Structural Repair and Strengthening

Structural damage is very often not identified as such, and cosmetic repairs are undertaken to conceal the obvious defects. Hence, the strategy for repair should involve the actual redesign of the structural requirements so as to achieve an acceptable level of safety. The first stage in restoring structural ability to resist expected forces is to ensure that any conceptual and construction errors are rectified. This process may involve correcting abrupt changes in stiffness, irregularities in plan between stiffness and mass, as well as addressing poor detailing, use of inferior materials etc. The elimination of such errors does not necessarily precede any further interventions, but is assumed to take place so that a preliminary analysis can identify the critical members and extent of structural deficiency.

A usual flowchart for the redesign (Sika Limited, 2003) of structures is given below:



According to the flow chart the redesign starts with re-estimation of design loads followed by structural analysis. If the available strength capacity is above the required capacity (collapse factor, λ_c > 1) then the design will be final otherwise it will have to be modified. Strengthening is required when the available geometry or section, even after strengthening, can not offer the required resistance.

It is obvious that before strengthening the structures the required or desired resistance must be anticipated. Some part of the resistance can be attained through repair action. The rest of the resistance is generally achieved through proper strengthening design. Repair action is always helpful for the strengthening action. Sometimes, the repair activities may be compulsory.

The Figure 2.2 is a schematic representation of the required (V_B), available (V_C) and residual (V_D) resistance respectively.

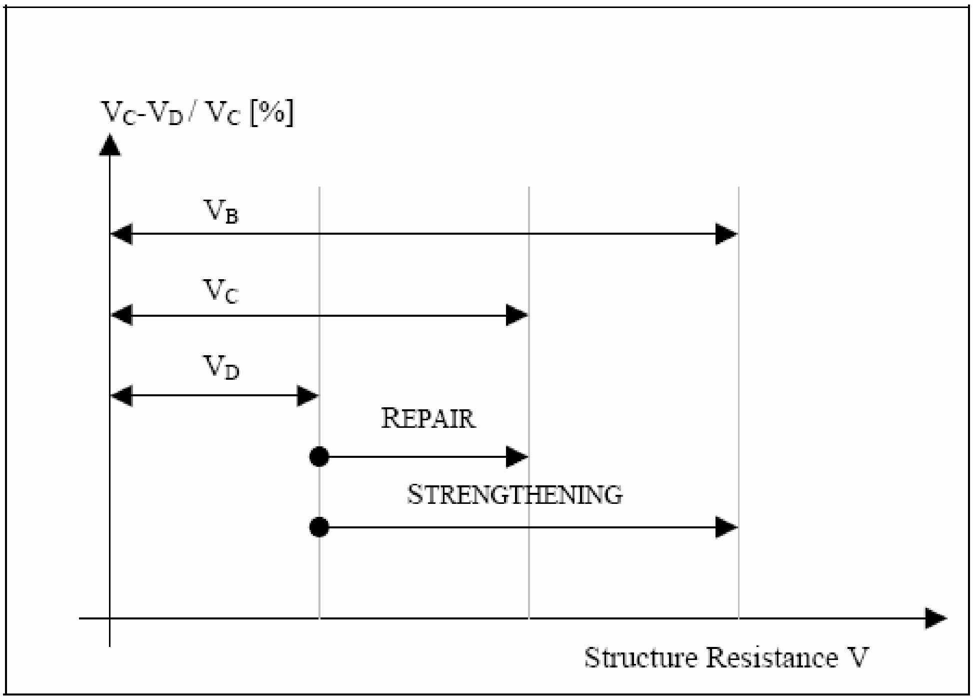


Figure 2.2: Schematic representation of V_B, V_C, V_D. (Sika Limited, 2003)

2.4 Different Strengthening Techniques

A wide variety of intervention techniques can be considered for strengthening and repair of masonry structures that have undergone damages due to overload, ground settlement, temperature variation, natural calamities like wind, earthquake etc. A rough distinction can be made among the traditional and the modern ones. Traditional techniques employ the materials and building processes used originally for the construction of ancient structures. Modern techniques aim at more efficient solutions using innovative materials and technologies.

This present chapter aims at presentation of strengthening techniques of masonry using literature analysis. A lot of laboratory techniques using traditional and modern materials have been performed. Also each specific problem has a particular solution which seems to be the best for that. And also each problem leads to specific invention of techniques for strengthening.

2.4.1 Strengthening actions

The effects an intervention (EU-India cross cultural program, October 2006) may have on a structure have been divided in the following groups:

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 monolithical 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 was 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.

2.4.2 Repairing and strengthening techniques

Repairing and strengthening of masonry structure presents an extensive variety of practical application and is continuously evolving. In this paper only the most representative and used ones are considered. Details of these techniques can be found on "Identification of strengthening techniques, EU-India cross cultural program, October 2006"

a) Injection

- **Strengthening actions:** Improvement.
- **Usual applications**: walls presenting a diffuse presence of voids in the inner part of the walls, 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. In Figure 2.3 it is shown clearly.
- **Main targets:** filling existing cavities and internal voids and sealing possible cracks. Injection increases the continuity of the masonry and hence its mechanical properties.
- **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 (EU-India cross cultural program, 2006).

Figure 2.3: Grouting injections. (da Porto F. et al. 2003)

b) 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. Figure 2.4 shows step by step the procedure of doing this.

- **Main targets:** preserving the mechanical efficiency and regaining the continuity in a masonry structure.

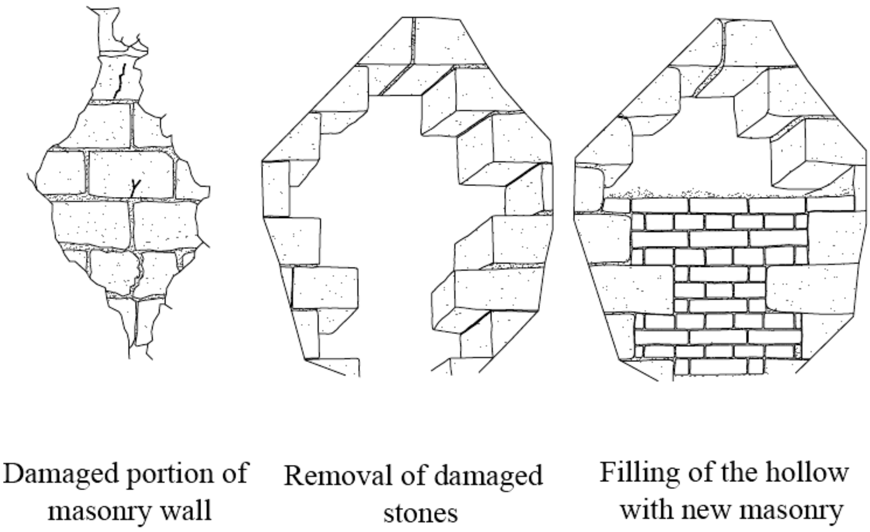


Figure 2.4: Steps in "cuci-scuci" intervention. (EU-India cross program, 2006)

c) **External reinforcement**

- **Strengthening actions**: reinforcement.
- **Usual applications**: old and new masonry structures needing earthquake protection and higher mechanical properties. Arches and vaults suffering crashing or cracks associated to intense compressive stress.
- **Technique:** application of high-performance materials (i.e. FRP, steel, wood, plastic) on the external sides 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 reinforcement can be applied between the extrados and an additional masonry layer (Figure 2.5).
- **Main targets:** increasing ductility and obtaining a more resistant structure adding a material that can resist tension.

Figure 2.5: Bridge strengthened with external steel strips (Lorenzo Jurina)

d) 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. Figure 2.6 show how strips are used in masonry vaults reinforcement
- **Main targets:** increasing the mechanical properties and the ductility of the element.

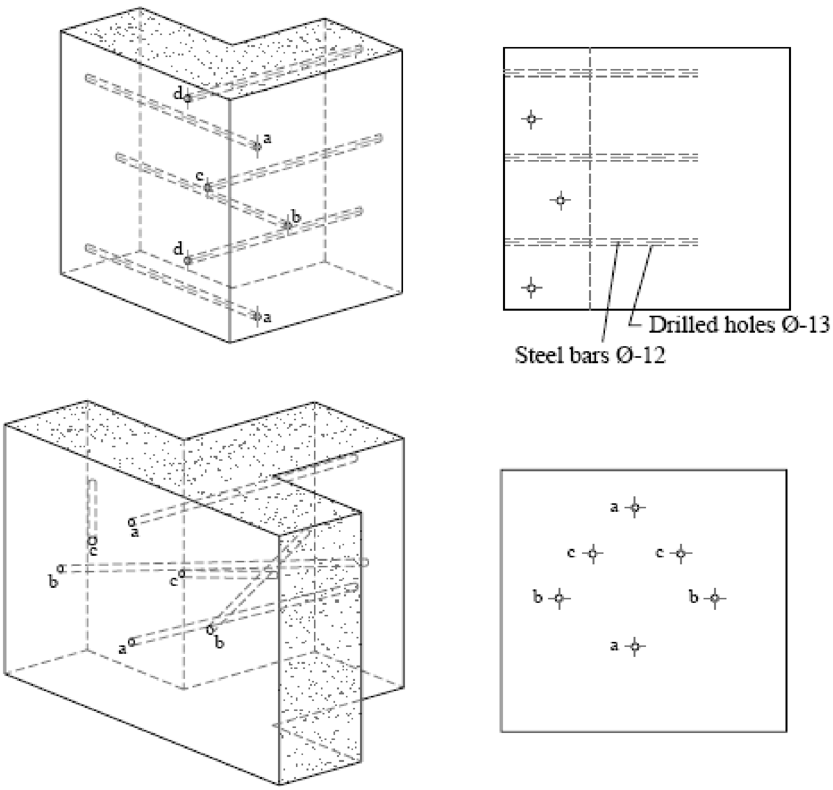


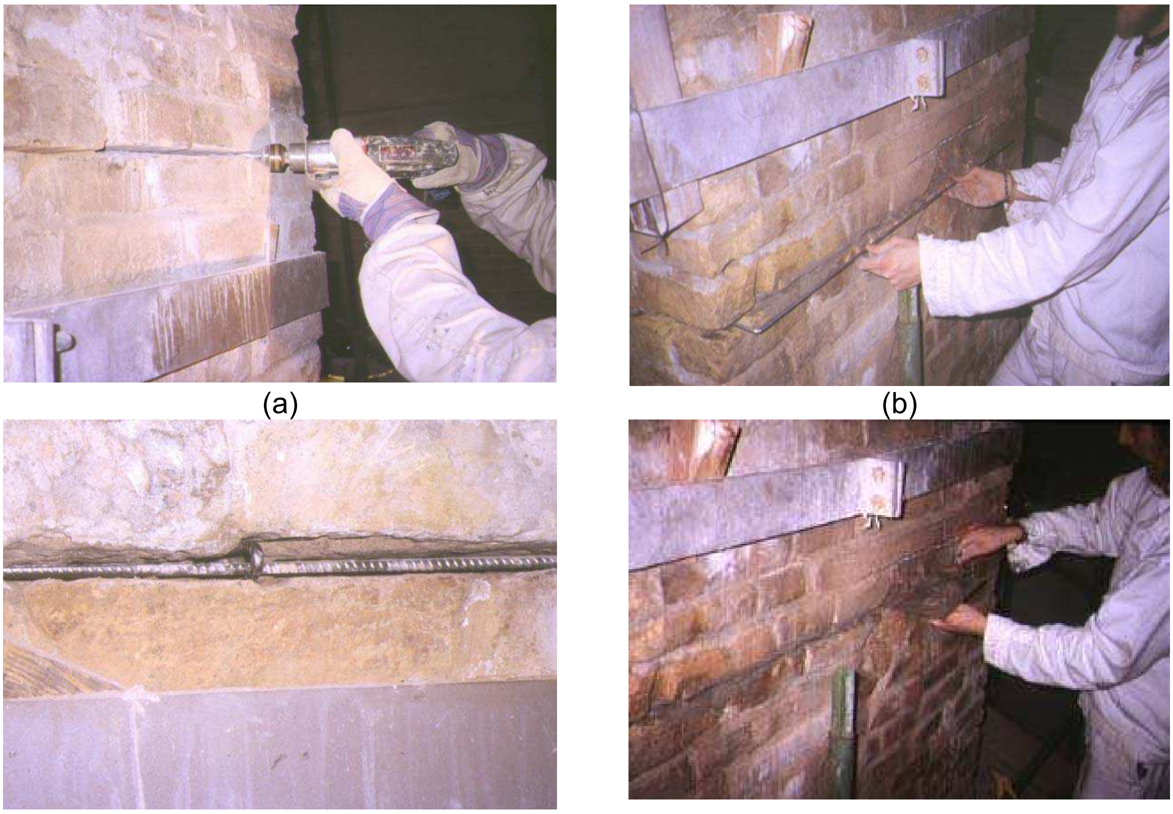
Figure 2.6: FRP strips used in masonry vaults reinforcement. (EU-India cross program, 2006)

e) 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 monolithism and strength.

f) Repointing and reinforced repointing

- **Strengthening actions:** Improvement, reinforcement (reinforced repointing only).
- **Usual applications**: masonry walls presenting visibly deteriorated joints or mortar in poor conditions.



(a) (b) (c) (d)

Figure 2.7: steps for reinforced repointing intervention (Valluzzi, Binda, Modena, 2004)

- **Technique**: partial removal and substitution of deteriorate joint mortar with new mortar with better mechanical properties and durability. Reinforced rejointing is indicated for masonry walls with regular horizontal joints and consists in laying reinforcement bars in the mortar matrix. Usually applied in combination with other interventions. In Figure 2.7 it is illustrated carefully step by step.

- **Main targets:** increase the compressive and shear strength in small thickness masonry, normally more effective for the reduction of the deformation. Reinforced repointing has also a confining effect on the walls and help the transmigration of the tractions from the brick to the steel.
- **Practical cases:** Santa Sofia Church in Padua, Italy.

g) 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 traction and have different practical applications all aiming at a monolithic response of the structure. In Figure 2.8 it is illustrated carefully.
- **Main targets:** improving the overall structural behavior by ensuring seismic cooperation between structural elements.
- **Practical cases:** Bell-tower of S. Giustina, Padua, Italy, Bell-tower of Nanto, Vicenza, Italy.

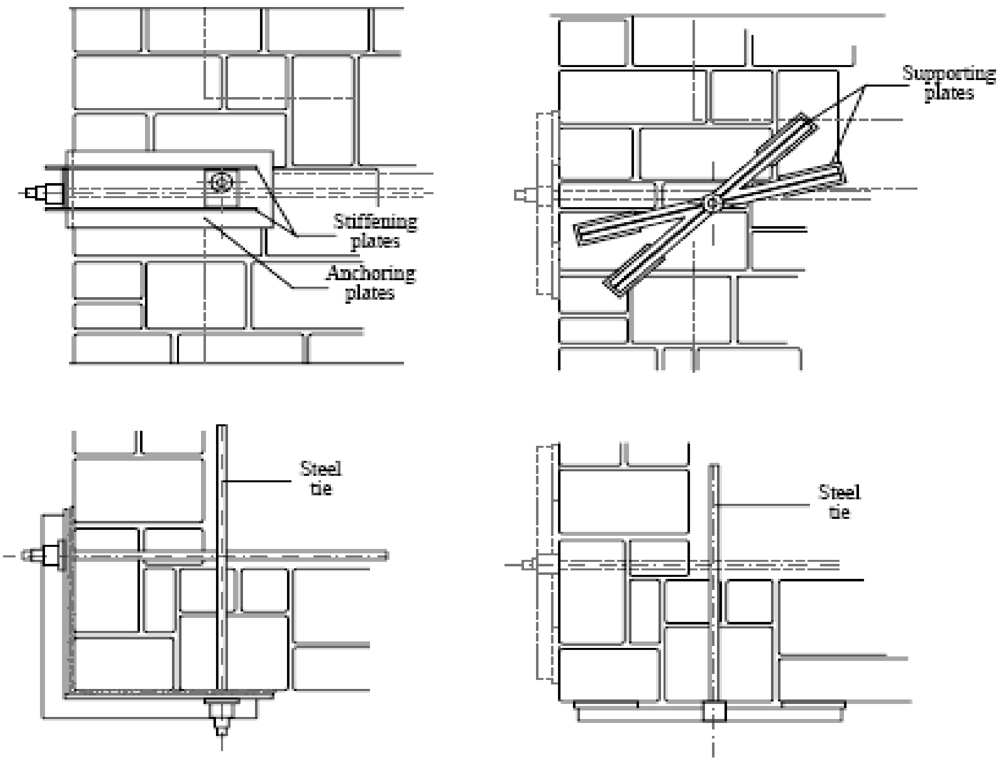


Figure 2.8: Examples of anchoring of steel ties on intersecting walls. (EU-India cross program, 2006)

h) Structural substitution

- **Strengthening actions:** Structural substitution.
- **Usual applications:** masonry structures or elements in good conditions but judged not adequate to resist the imposed loads. In Figure 2.9 shows R.C. structure is substituted the original one in the "Mole Antonelliana", Turin,
- **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.
- **Practical cases:** "Mole Antonelliana", Turin, Italy.

Figure 2.9: R.C. structure substituting the original one in the "Mole Antonelliana", Turin, Italy. (EU-India cross program, 2006)

i) 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. Figure 2.10 shows Tarazona Cathedral, Spain as the example of it.
- **Main targets:** recuperate the original function of the element, correct eventual design faults, and modify the seismic response.

Figure 2.10: Removal of a pier of Tarazona Cathedral, Spain. (EU-India cross program, 2006)

j) 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.
- **Practical cases:** Towers of the façade of Barcelona cathedral.

k) 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 reinforce concrete cover surrounding the structural element and resisting lateral strain. In Figure 2.11 it is illustrated carefully.
- **Main targets:** obtaining a continuous confinement thus improving the strength of masonry and a monolithic behaviour of the element.

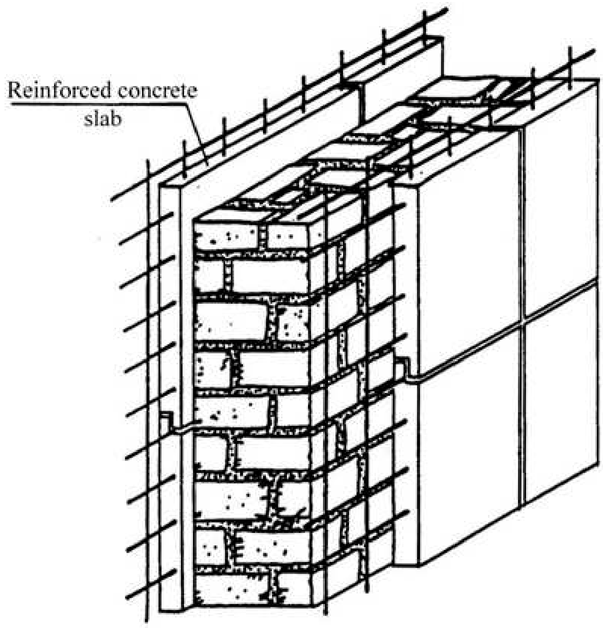


Figure 2.11: reinforced concrete jacketing of a wall. (EU-India cross program, 2006)

I) 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. Figure 2.12 shows the application of steel confinement.
- **Main targets:** obtaining a punctual confinement where needed thus improving the compressive strength of the pier.

Figure 2.12: Local confinement for critical sections of a pier. (EU-India cross program, 2006)

m) 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. In Figure 2.13 it is illustrated with good label.
- **Main targets:** impeding the separation between different layers, thus improving the mechanical properties of the wall.
- **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.

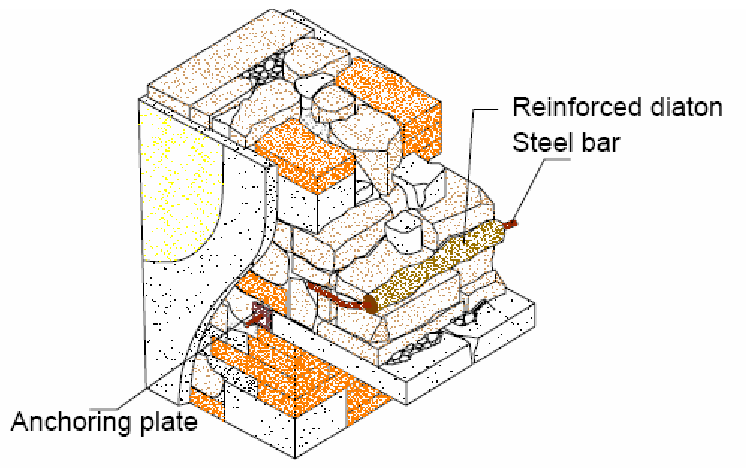


Figure 2.13: Local confinement for multi-layer walls (EU-India cross program, 2006)

n) Reinforced concrete and masonry edge-beams

- **Strengthening actions**: confinement, tying.
- **Usual applications:** masonry buildings with poor connections between intersecting walls, floors not constituting a rigid diaphragm and risk of out-of-plane seismic mechanism. Roofs discharging unbalanced thrusts on the walls.
- **Technique:** casting a ring of reinforced concrete beams in the thickness of the existing masonry wall at floor level. Important details are the connection with the floor beams and the existing walls. Another solution is a reinforced masonry edge-beam

ring. In Figure 2.14 it is illustrated that roof is confined with reinforce concrete edge-beam.

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

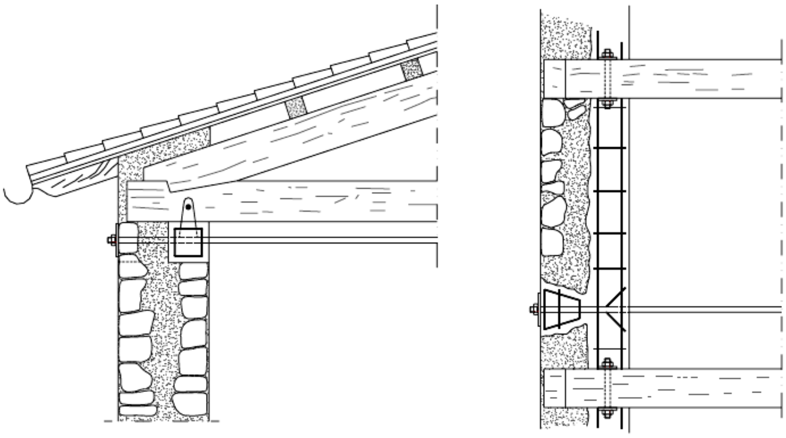


Figure 2.14: Roof confining reinforce concrete edge-beam. (EU-India cross program, 2006)

o) Enlargement

- **Strengthening actions:** Enlargement.
- **Usual applications:** masonry elements in good conditions 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. In Figure 2.15 it is illustrated carefully.

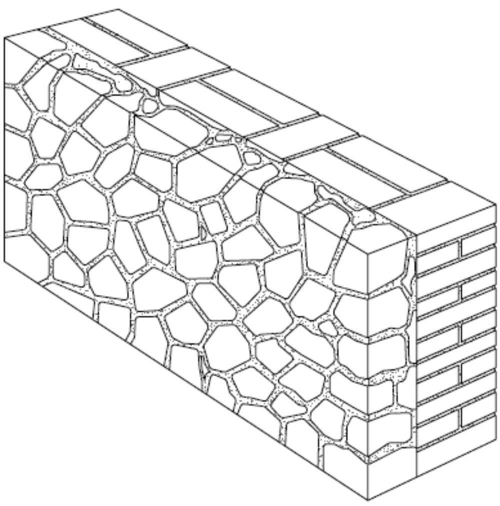


Figure 2.15: Enlargement of a wall (EU-India cross program, 2006)

- **Main targets:** distributing the load to a larger resisting section, thus reducing the stress field.
- **Practical cases:** two four-storey old buildings in Jelenia Gora, Poland.

p) 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.

In Figure 2.16 the thrust line is being brought back inside the vault thickness

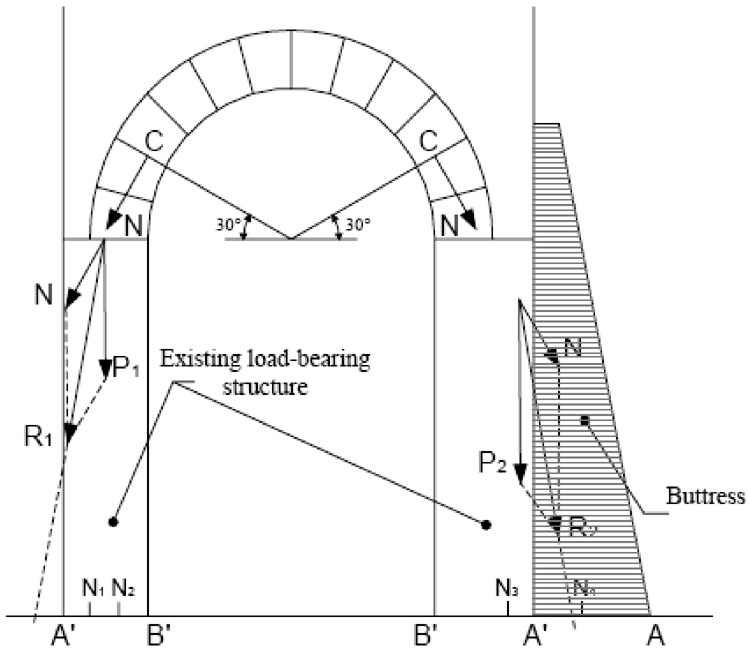


Figure 2.16: Regaining the stability of the vault (EU-India cross program, 2006)

q) Suspension

- **Strengthening actions:** propping.
- **Usual applications:** structures needing support, in the case technical or aesthetical reasons impede considering a propping artefact beneath the element that needs it.

- **Technique:** active connection of the original structure with an upper one carrying part of the load.
- **Main targets:** stabilizing and discharging the original structure.
- **Practical cases:** temporary intervention to sustain the dome of the “Basilica di Assisi”.

r) 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.

s) 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. Figure 2.17 shows a real example in Italy.

Figure 2.17: Strut arches connecting two buildings. (EU-India cross program, 2006)

t) Pre-compression

- **Strengthening actions:** loading.
- **Usual applications:** elements presenting damages due to traction.
- **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. Figure 2.18 shows steel bars precompression in a wall
- **Main targets:** avoiding or closing cracking.

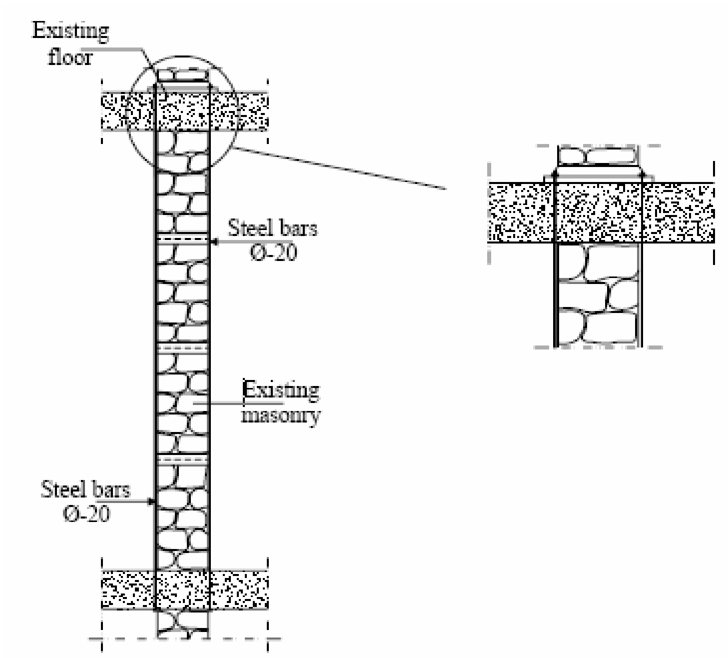


Figure 2.18: steel bars precompression in a wall (EU-India cross program, 2006)

u) 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. Figure 2.19 shows anchoring of a vault
- **Main targets:** improving the stability of the structure, limiting eventual deformations.

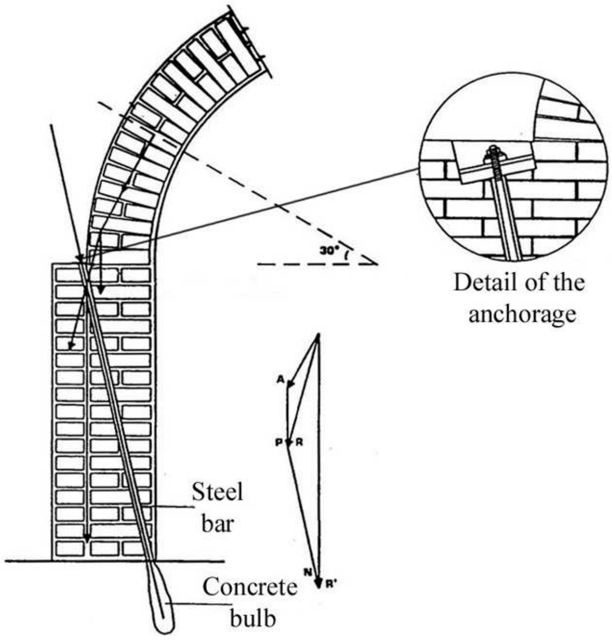


Figure 2.19: Anchoring of a vault. (EU-India cross program)

v) Direct interventions on foundations

- **Strengthening actions:** enlargement, reinforcement, improvement.
- **Usual applications:** damaged, poorly dimensioned foundations or foundations with insufficient interconnection between element and bad load distribution. Figure 2.20 shows concrete reinforcement of an existing foundation.

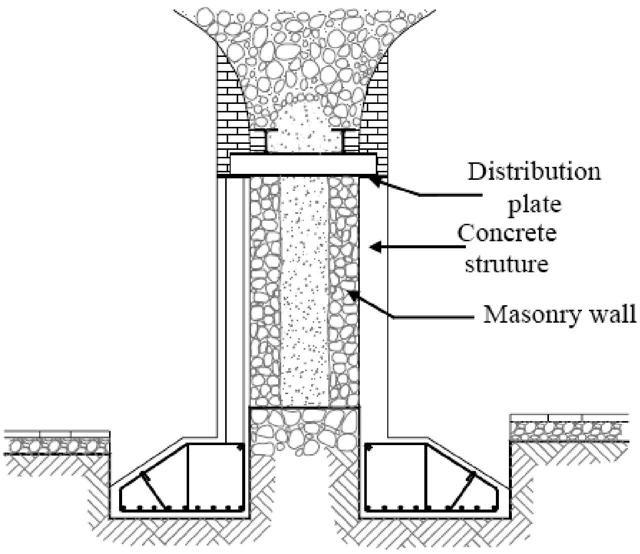


Figure 2.20: Concrete reinforcement of an existing foundation (EU-India cross program, 2006)

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

w) 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-paling:** 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-paling, 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.
- **Practical cases:** "Palazzo de la Mercanzia", Bologna, Italy, "Università degli Studi di Parma", Parma, Italy, a historical building in Lisbon, Portugal.

x) Seismic isolation

- **Strengthening actions:** foundations
- **Usual applications:** building of primary importance, which functionality should not be affected by seismic action, seismic isolation is 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, electroreological and magnetoreological fluids).

- **Main targets:** absorbing the seismic vibration and avoiding major damages to the building. Different types of seismic isolator have been shown in Figure 2.21.

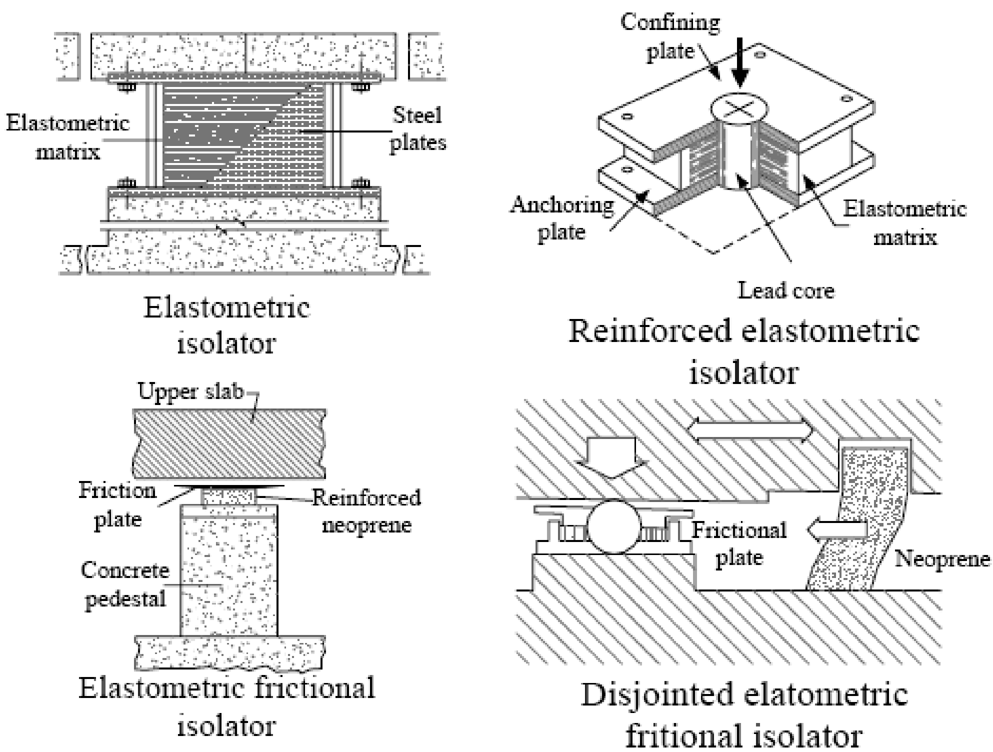


Figure 2.21: Different types of seismic isolator (EU-India cross program, 2006)

y) Improving the buttresses

If we improve the buttresses the structure can be able to undergo the more horizontal loads, because one of the failure modes of arches is related to the collapse of bearing wall. Figure 2.22 shows the performance of these phenomena.

Figure 2.22: The adobe arch of the with improved buttresses (Lorenzo Jurina, 2002)

z) Tying

One of the best techniques for protecting the arches is inserting the tie between springers. It reduces the lateral thrust to the piers. Figure 2.23 shows the using the two steel bar as tie in Real Collegio in Lucca, Italy.

Figure 2.23: Real Collegio in Lucca, Italy. (EU-India cross program, 2006)

2.4.3 Strengthening Masonry Foundations

Foundation is the most vital part of the structure. Even though every part of the structures are well designed and are good condition may fail due to foundation problem. And it is very difficult to repair. In determining whether or not the foundation can resist the horizontal forces that are transferred to it, it is necessary to investigate foundations in terms of type, material, condition, and embedment. Residential foundation systems can be divided into six general categories:

- No foundation
- Partial foundation
- Post and pier throughout
- Perimeter footing with interior posts
- Continuous perimeter and interior footings
- Continuous footings with a slab floor on grade.

With no foundation, or too small a partial foundation, the horizontal forces in the building cannot be transferred safely into the ground. There is a similar discontinuity in the load path with a post and pier foundation. You will learn more about post and pier systems in the next section, Retrofitting Post and Pier Type Houses.

2.4.3.1 Foundation decay

There are two concerns for the foundation condition: deterioration and cracking.

a. **Deterioration:** Deterioration of the foundation wall is normally visible to the naked eye. Before beginning work, a visual inspection of the foundation walls can find excessive concrete or masonry cracking and weathering. Mortar in reinforced masonry should be well pointed and tooled. Existing concrete should be smooth and without separation or exposure of stone aggregates. Poorly finished and consolidated concrete frequently suffers later from excessive weathering. If parging or repointing cannot repair the wall, a full foundation retrofit is required.

b. **Foundation Cracking:** When concrete foundation walls are constructed without expansion joints, hairline crackling will normally occur. Cracks that are wider at the top than at the bottom are often caused by soil settlement. When the crack is wider at the bottom than at the top, there is likely problem with expansive soil. Figure 2.24 shows crack in masonry foundation.

Figure 2.24: Crack in Masonry Foundation (California seismic society, 2005)

The presence of expansive soils or foundation settlement indicates the need for professional advice. Geotechnical engineers specialize in solving these problems. Depending on the size of the crack, concrete cracking can be repaired with various epoxy or cementitious mortars. These products require special inspection and careful quality control by the approved applicator. These products should be used only under the qualified advice of an engineer or architect.

2.4.3.2 Problems associated with differential settlement

Uneven (differential) settlement can be a major structural problem in small residential buildings, although serious settlement problems are relatively uncommon. Many signs of masonry distress are incorrectly diagnosed as settlement-related when in fact they are due to moisture and thermal movements. Indications of differential settlement are vertical distortion or cracking of masonry walls, warped interior and exterior openings, sloped floors, and sticking doors and windows. Settlement most often occurs early in the life of a building or when there is a dramatic change in underground conditions (Figure 2.25). Often such settlement is associated with improper foundation design, particularly inadequate footers and foundation walls.

- Soil consolidation under the footings
- Soil shrinkage due to the loss of moisture to nearby trees or large plants
- Soil swelling due to inadequate or blocked surface or house drainage
- Soil heaving due to frost or excessive root growth
- Gradual downward drift of clay soils on slopes
- Changes in water table level
- Soil erosion around footers from poor surface drainage, faulty drains, leaking water mains or other underground water movements

(occasionally, underground water may scour away earth along only one side of a footer, causing its rotation and the subsequent buckling or displacement of the foundation wall above)

- Soil compaction or movement due to vibration from heavy equipment, vehicular traffic, or blasting, or from ground tremors (earthquakes).

Gradual differential settlement over a long period of time may produce no masonry cracking at all, particularly in walls with older and softer bricks and high lime mortars; the wall will elastically deform instead. More rapid settlements, however, produce cracks that taper, being largest at one end and diminishing to a hairline at the other, depending on the direction and location of settlement below the wall.

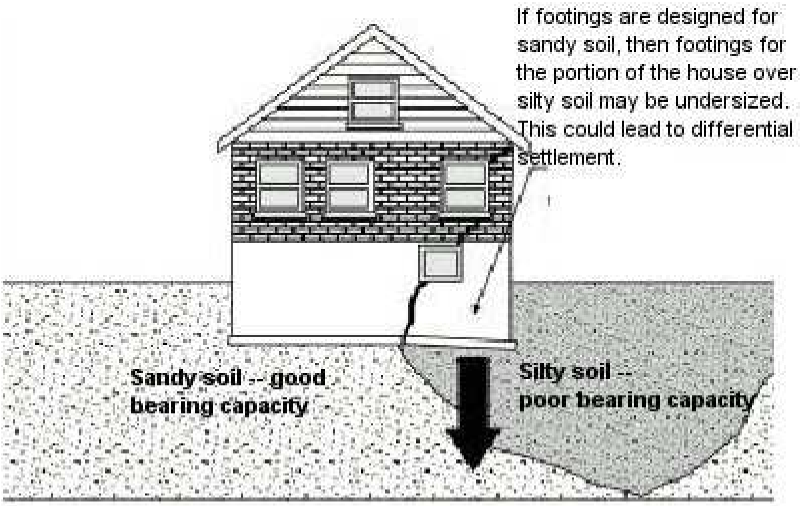


Figure 2.25: Differential settlement caused by variable soil (California seismic society, 2005)

Cracking is most likely to occur at corners and adjacent to openings, and usually follows a rough diagonal along mortar joints (although individual masonry units may be split). Settlement cracks (as opposed to the similar-appearing shrinkage cracks that are especially prevalent in concrete block) may extend through contiguous building elements such as floor slabs, masonry walls above the foundation, and interior plaster work. Tapering cracks, or cracks that are nearly vertical and whose edges do not line up, may occur at the joints of projecting bay windows, porches, and additions. These cracks indicate differential settlement due to inadequate foundations or piers under the projecting element.

2.4.3.3 Problems associated with masonry piers

Figure 2.26: Overstressed Masonry Foundation (California seismic society, 2005)

Masonry piers are often used to support internal loads on small residential buildings or to support projecting building elements such as bay windows, porches, and additions. Piers often settle differentially and over a long period of time (particularly when they are exposed to the weather) they tend to deteriorate. Common problems are:

- Settlement or rotation of the pier footing, which causes a lowering or tilting of the pier and subsequent loss of bearing capacity. Wood frame structures adjust to this condition by flexing and redistributing their loads or by sagging.
- Frost heaving of the footing or pier, a condition caused by the lack of an adequate footing or one of insufficient depth. This will result in raising or tilting the pier, and in structural movement above it similar to that caused by settlement of the footing.
- Physical deterioration of the pier due to exposure, poor construction, or overstressing. Above-ground piers exposed to the weather are subject to freeze-thaw cycles and subsequent physical damage.
- Loss of bearing of beams, joists, or floors due to the above conditions or due to movements of the structure itself.

Piers should be examined for plumpness, signs of settlement, condition, and their adequacy in accepting bearing loads. Check their width to height ratio, which should not exceed 1:10. Those that are deficient should be repaired or replaced. When appearance is not a factor (as is often the case), piers can be supplemented by the addition of adjacent supports.

2.4.3.4 Cracking associated with drying shrinkage

The shrinkage of concrete block walls as they dry in place often results in patterns of cracking similar to that caused by differential settlement: tapering cracks that widen as they move diagonally upward. These cracks usually form during the buildings first year, and in existing buildings will appear as old cracks and exhibit no further movement. Although such cracks are often mistaken for settlement cracks, shrinkage cracks usually occur in the middle one-third of the wall and the footer beneath them remains intact. If the wall is unsound, its structural integrity sometimes can be restored by pressure-injecting concrete epoxy grout into the cracks or by adding pilasters.

2.4.3.5 Sweeping or horizontal cracking

The sweeping or horizontal cracking of brick or concrete block foundation walls may be caused by improper backfilling, vibration from the movement of heavy equipment or vehicles close to the wall, or by the swelling or freezing and heaving of water saturated soils adjacent to the wall. Like drying shrinkage, sweeping or horizontal cracking may have occurred during the original construction and been compensated for at that time.

2.4.3.6 Foundation Retrofit

Several options exist to retrofit the buildings footings and foundation walls which are listed below:

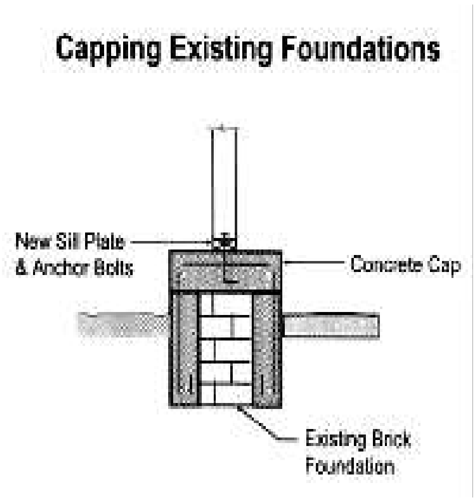


Figure 2.27: Capping of Foundation (California seismic society, 2005)

a) **Capping:** It means that concrete is placed over or alongside the existing foundation wall. “Capping” of an existing un-reinforced masonry foundation refers to the addition of concrete (or shotcrete or gunite) on the top of, on one side of, or on the top and both sides of an existing foundation (Figure 2.27). There are limitations and inherent risks that should be considered before undertaking foundation capping. In addition, when foundation capping is being undertaken as part of voluntary earthquake retrofit, the priority of foundation capping relative to other retrofit needs should be considered.

b) **Replacement:** It involves shoring up the building and putting in a complete or partial perimeter footing and stem wall. This method is frequently used to reset houses that fell off their foundation during an earthquake but remained intact Shoring can be omitted when replacement is done in small sections at a time. The latter technique is popular for occupied structures. For unreinforced masonry foundation the most common approach is to replace all or part of the existing foundation with a poured reinforced concrete foundation.

c) **Parallel systems:** These are systems of new structural elements that create a parallel horizontal force-resisting system at the foundation level. These systems are designed by an engineer or architect. The new structural elements are typically located near the exterior walls. A sample system using large concrete columns is shown in Figure 2.28. Capping is popular when owners wish to maintain the appearance of masonry foundation walls.

Figure 2.28: Parallel System of Foundation Repair (California seismic society, 2005)

All these strengthening techniques, its target and application has been summarised in Table 2.1. Due to lack of information some real examples are missing.

Table 2.1: Strengthening techniques of masonry structures

Name	Where	How	Target	Application
Injection	Thick wall	Injecting mortar or fluid resin through holes	Filling existing cavities and voids, sealing possible cracks	-
Cuci- Scuci	Walls with severe but localized cracks	Replace deteriorated portion with compatible materials	Preserving and regaining mechanical efficiency	-
External reinforcement	Needing earthquake protection and higher mechanical properties	Application of high-performance materials	Increasing ductility and resistance	Adobe houses in Yacango, Peru. Town Hall of Assisi.
Stitching	Needing higher cohesion and mechanical characteristics without a visible modification	Reinforcement, tying.	Increasing the mechanical properties and ductility	-
Repointing and reinforced repointing	Deteriorated joints or mortar in poor conditions	Partial removal and substitution of deteriorate joint mortar with new one	Increase the compressive and shear strength	Santa Sofia Church in Padua, Italy.
Tie bars	Poor interconnection between intersecting walls, arches or vaults	Tying.	Improving the overall structural behavior	Bell-tower of S. Giustina, Padua, Italy, Bell-tower of Nanto, Vicenza, Italy
Precompression	Elements presenting tensile damages	Providing counteracting compressive stresses	Avoiding or closing cracking.	-

Table 2.1 continued

Name	Where	How	Target	Application
Local tying	Element or of a structure with poor connection	Fastening of confining parts	Developing a micro-continuity in the structure	Coliseum in Rome, Italy
Discrete confinement in piers	Piers suffering too high compressive force.	Application of steel rings	Obtaining a punctual confinement	--
Element substitution	Structural element deteriorated	Overall substitution of the element	Recover the original function of the element	Tarazona Cathedral, Spain.
Structural substitution	Elements in good / bad condition but judged not adequate	Creation of a new structure substituting the old one	Recover the functionality	"Mole Antonelliana", Turin, Italy.
Dismantling and remounting	Parts to be removed, substituted or repaired	Accurate and complete dismantling	Recover the functionality of a structure	Towers of the façade of Barcelona cathedral
Jacketing	Elements suffering too high compressive force,	Application of self-supporting reinforced concrete cover	Improving the strength and stiffness	--

Table 2.1 continued

Name	Where	How	Target	Application
Discrete confinement	Multi-leaf masonry walls with no sufficient connection	Punctual confinement to the wall	Impeding the separation of different layers	-
Strutting	Damaged structures or elements risking collapse	Using compressive members	Increase the lateral stiffness	-
Anchoring	Load bearing structures with stability problems	Anchoring an element	Improving the stability of the structure	Outeiro Church, Portugal
Seismic isolation	Building of primary importance	Devices placed between the foundation and the structure itself	Absorbing the seismic vibration	-
Cover elements-masonry edge-beams	Roofs discharging unbalanced thrusts on the walls	Creating a ring of beams	Obtaining a stiffer seismic response of the structure	Costly and time-consuming

Table 2.1 continued

Name	Where	How	Target	Application
Foundations - Direct interventions	Damaged, poorly dimensioned foundations or foundations	Widening, connecting, repairing and reinforcing	Better load distribution and improvement	"Ospedale degli Innocenti" Florence, Italy
Enlargement	Elements in good condition subjected to a too high stress	Enlargement of the sections	Distributing load to a larger section	Two four-storey old buildings in Jelenia Gora, Poland.
Buttressing	Structures having a low resistance to lateral forces	Using massive elements	Impeding failure mechanisms	-
Foundations - beneath the foundation	Foundations on not consolidated soil	Micro piling, jet grouting	Transferring the load, improving soil properties	"Palazzo della Mercanzia", Bologna, Italy
Soil stabilization	Buildings with differential settlements	Control piles, under excavation, jet-grouting, Micro-piling	Control differential settlements	Inquisition Palace and Cathedral of Mexico city,

2.5 FRP materials

Continuous fiber-reinforced materials with polymeric matrix (FRP) can be considered as composite, heterogeneous, and anisotropic materials with a prevalent linear elastic behavior up to failure. They are widely used for strengthening of civil structures as the traditional techniques pose some disadvantage such as

- Difficulty in manipulating heavy steel plates at the construction site
- Deterioration of the bond at the steel-concrete interface caused by the corrosion of steel
- Need for scaffolding and temporary support or loading
- Proper formation of joints due to the limited delivery lengths of the steel plates.
- It is labour intensive (Figure 2.29)
- It often causes disruption of occupancy
- In many cases it provides RC elements with undesirable weight and increased stiffness

Figure 2.29: Benefit of FRP application over steel member (John Busel, David White, 2003)

The use of FRP successfully solves the above problems. In addition, it has the good reputation to

- Increases out-of-plane flexural strength
- Increases in-plane shear strength
- Increases stiffness at service loads
- Results in monolithic action of all units
- Converts masonry from a weak/brittle material to a strong/ductile material

- Strengthening of entire wall can be accomplished by treating only a fraction of wall surface area
- Adds very little weight to the wall
- Increases wall thickness by less than ¼ in. (5mm)
- Limited access requirements
- Costs less than conventional methods
- Lightweight (1/4 to 1/5 of steel), good mechanical properties, corrosion-resistant, etc.

Composites for structural strengthening are available in several geometries from laminates used for strengthening of members with regular surface to bidirectional fabrics easily adaptable to the shape of the member to be strengthened (Figure 2.30). Composites are also suitable for applications where the aesthetic of the original structures needs to be preserved (buildings of historic or artistic interest) or where strengthening with traditional techniques cannot be effectively employed.

Figure 2. 30: Different FRP materials (CNR-DT 200/2004)

2.5.1 Characteristics of composites and their constituents

Composite materials exhibit the following characteristics:

- They are made of two or more materials (phases) of different nature and “macroscopically” distinguishable.
- At least two phases have physical and mechanical properties quite different from each other, such to provide FRP material with different properties than those of its constituents.

Fiber-reinforced composites with polymeric matrix satisfy both of the above characteristics. In fact, they are made out of both organic polymeric matrix and reinforcing fibers. Carbon fibers may exhibit values of Young's modulus of elasticity much larger than those of typical construction materials. Therefore, they are more effective from a structural point of view. Potential problems with other materials used as support need to be carefully evaluated by designers and practitioners. The matrix may be considered as an isotropic material, while the reinforcing phase, with the exception of glass fiber, is an anisotropic material (different properties in different directions). The defining characteristics of FRP materials are as follows:

- Geometry: shape and dimensions.
- Fiber orientation: the orientation with respect to the symmetry axes of the material; when random, the composite characteristics are similar to an isotropic material ("quasi-isotropic"). In all other cases the composite can be considered as an anisotropic material.
- Fibre concentration: volume fraction, distribution (dispersion).

Therefore, composites are in most cases a non-homogeneous and anisotropic material

Table 2.2: Characteristics of composites and their constituents (CNR-DT 200/2004)

	Young's modulus E	Tensile strength σ_r	Strain at failure ε_r	Coefficient of thermal expansion α	Density ρ
	[GPa]	[MPa]	[%]	$[10^{-6}\ °C^{-1}]$	$[g/cm^3]$
E-glass	70 – 80	2000 – 3500	3.5 – 4.5	5 – 5.4	2.5 – 2.6
S-glass	85 – 90	3500 – 4800	4.5 – 5.5	1.6 – 2.9	2.46 – 2.49
Carbon (high modulus)	390 – 760	2400 – 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon (high strength)	240 – 280	4100 – 5100	1.6 – 1.73	-0.6 – -0.9	1.75
Aramid	62 – 180	3600 – 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 – 3.6	40 – 82	1.4 – 5.2	30 – 54	1.10 – 1.25
Steel	206	250 – 400 (yield) 350 – 600 (failure)	20 – 30	10.4	7.8

To summarize FRP properties, it is convenient to recognize fiber-reinforced composites in two categories, regardless of their production technology:

• Single-layer (lamina)

• Multi-layer (laminates)

Laminates are materials composed of stacked layers (the lamina) whose thickness is usually of some tenths of a millimeter. In the simplest case, fibers are embedded only in the lamina's plane (there are no fibers arranged orthogonally to that plane). The size of laminates is intermediate between those of the fibers and those of engineering structures. There is also a special class of multi-layer composites, so-called hybrid laminates, where each single lamina is made out of both different fibers (*e.g.,* epoxy matrix composites with carbon and aramid fibers to get a stiff and tough composite) or different materials (*e.g.*, composites with alternate layers of epoxy resin with aramid and aluminum fibers). The main advantage of laminates is represented by the greater freedom of fiber arrangement. Due to the anisotropic characteristics of FRP material, their mechanical properties depend on the choice of the reference system. The main axes are usually chosen to be concurring with the symmetry axes of the material (natural axes). The case of a unidirectional FRP material is illustrated in the Figure 2.31.

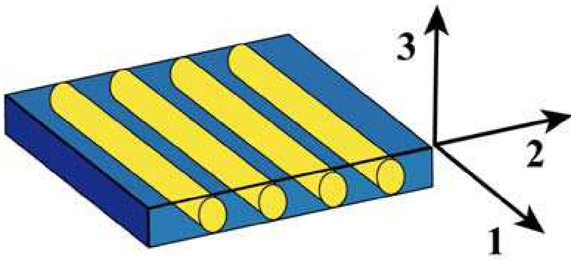


Figure 2.31: unidirectional FRP material (CNR-DT 200/2004)

Composite materials can be stronger and stiffer (carbon FRP) than traditional construction materials. As a result, composites may become very attractive when the weight of the structure becomes an issue. FRP tensile strength and Young's modulus of elasticity can be up to four and two times that of traditional materials, respectively. This means that a composite material structure may weigh nearly half of a traditional construction material structure of equal stiffness or less.

2.5.2 Types of fiber

The most common fibers used in composites are glass, carbon, and aramid. Their unique mono-dimensional geometry, in addition to being particularly suitable for the realization of composites, provides FRP laminates with stiffness and strength higher than those of three-dimensional FRP shapes. Fibers are made of very thin continuous filaments, and therefore, are quite difficult to be individually manipulated. For this reason, they are commercially available in different shapes. A brief description of the most used is summarized as follows (Figure 2.32):

- Monofilament: basic filament with a diameter of about 10 μm.
- Tow: untwisted bundle of continuous filaments.
- Yarn: assemblage of twisted filaments and fibers formed into a continuous length that is suitable for use in weaving textile materials.
- Roving: a number of yarn or tows collected into a parallel bundle with little or no twist.

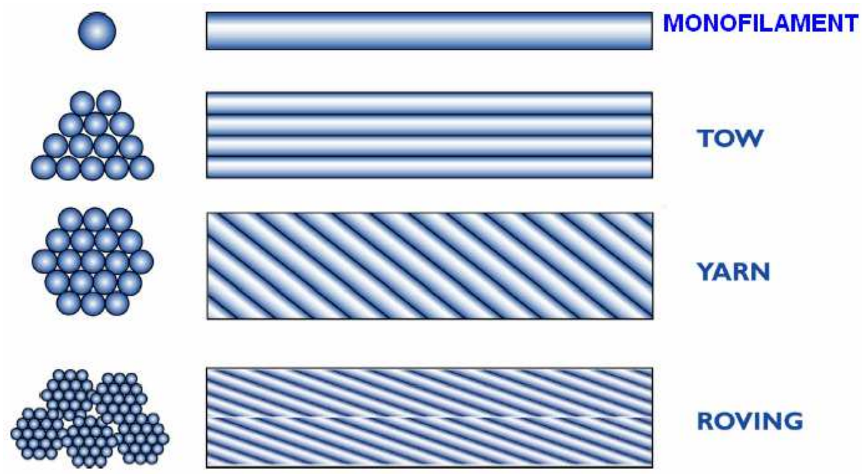


Figure 2.32: Different types of fibers (CNR-DT 200/2004)

Glass fibers

These are fibers commonly used in the naval and industrial fields to produce composites of medium-high performance. Their peculiar characteristic is their high strength. Glass fibers typically have a Young modulus of elasticity (~70 GPa) lower than carbon or aramid fibers and their abrasion resistance is relatively poor; therefore, caution in their manipulation is required (Figure 2.33). In addition, they are prone to creep and have a low fatigue strength. To enhance the bond between fibers and matrix, as well as to protect the fibers itself against alkaline agents and moisture, fibers undergo sizing treatments acting as coupling agents. Such treatments are useful to enhance durability and fatigue performance (static and dynamic) of the composite material. FRP composites based on fiber glass are usually denoted as GFRP.

Carbon fibers

Carbon fibers are used for their high performance and are characterized by high Young modulus of elasticity as well as high strength (Figure 2.33). They have an intrinsically brittle failure behavior with a relatively low energy absorption; nevertheless, their failure strength are larger compared to glass and aramid fibers. Carbon fibers are less sensitive to creep rupture and fatigue and show a slight reduction of the long-term tensile strength. FRP composites based on carbon fibers are usually denoted as CFRP.

Aramid fibers

Aramid fibers are organic fibers, made of aromatic polyamides in an extremely oriented form. First introduced in 1971, they are characterized by high toughness. Their Young modulus of elasticity and tensile strength are intermediate between glass and carbon fibers. Their compressive strength is typically around 1/8 of their tensile strength. Due to the anisotropy of the fiber structure, compression loads promote a localized yielding of the fibers resulting in fiber instability and formation of kinks. Aramid fibers may degrade after extensive exposure to sunlight, losing up to 50 % of their tensile strength. In addition, they may be sensitive to moisture. Their creep behavior is similar to that of glass fibers, even though their failure strength and fatigue behaviour is higher than GFRP. FRP composites based on aramid fibers are usually denoted as AFRP.

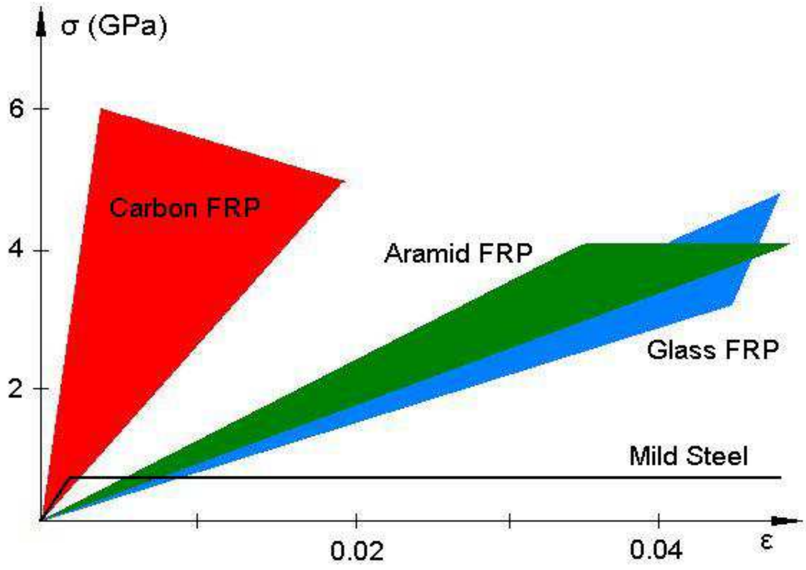


Figure 2.33: Stress-strain diagrams for some available fibers (Sika Limited, 2003)

Matrices

Thermoset resins are the most commonly used matrices for production of FRP materials. They are usually available in a partially polymerized state with fluid or pasty consistency at room temperature. When mixed with a proper reagent, they polymerize to become a solid, vitreous material. The reaction can be accelerated by adjusting the temperature. Thermoset resin have several advantages, including low viscosity that allows for a relative easy fiber impregnation, good adhesive properties, room temperature polymerization characteristics, good resistance to chemical agents, absence of melting temperature, etc.

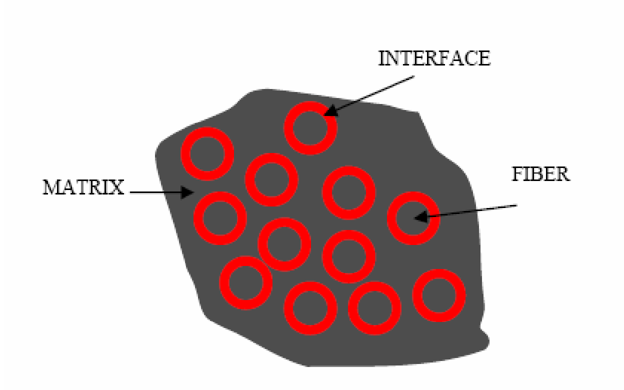


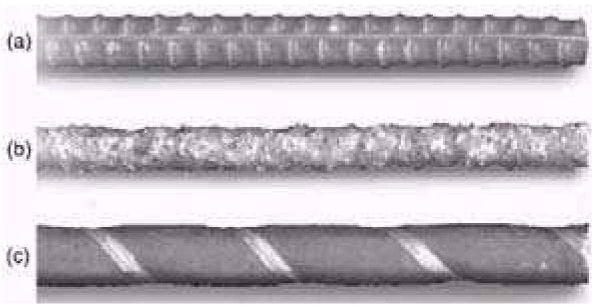
Figure 2.34 : FRP phases (Ricamato M, 2007)

Disadvantages are limited range of operating temperatures, with the upper bound limit given by the glass transition temperature, poor toughness with respect to fracture ("brittle" behavior), and sensitivity to moisture during field applications. The most common thermosetting resins for civil engineering are the epoxy resin. Polyester or vinyl ester resins are also used.

Epoxy resins

Epoxy resins are characterized by a good resistance to moisture, chemical agents, and have excellent adhesive properties. They are suitable for production of composite material in the civil engineering field. The maximum operating temperature depends both on formulation and reticulation temperature. For operating temperatures higher than 60 °C, the resin should be suitably selected by taking into account the variations of its mechanical properties. There are usually no significant restrictions for the minimum operating temperature.

***Internal Reinforcement*:**



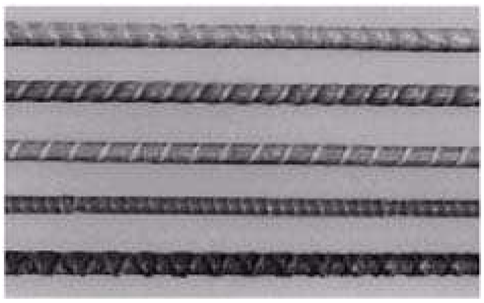


Figure 2.35: Surface treatment of the FRP bars

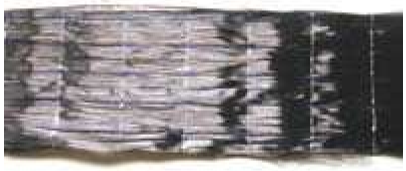
Rupture of CFRP bars (carbon fiber)   Rupture of GFRP bars (glass fiber)

Figure 2.36: Different types of internal reinforcement (CNR-DT 200/2004)

Polyester resins

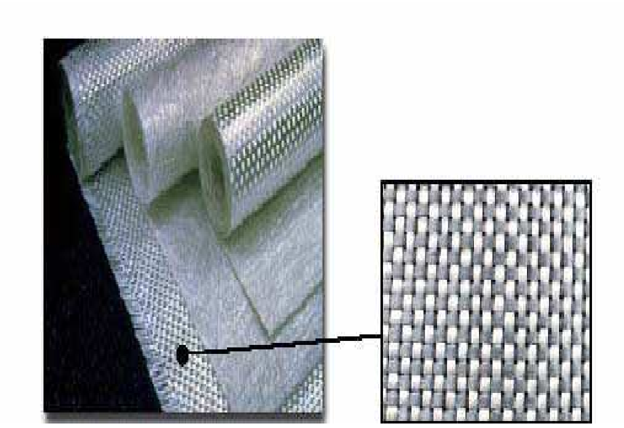
Polyester resins have a lower viscosity compared to epoxy resins, are very versatile, and highly reactive. Their mechanical strength and adhesive properties are typically lower than those of epoxy resins.

FRP sheets/laminates (externally bonded reinforcement)

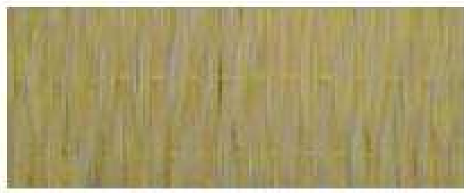


CFRP fibers (CNR-DT 200/2004)

CFRP fibers impregnated with epoxy resin (CNR-DT 200/2004)



Glass fibers



Aramid fiber

Figure 2.37: Different types of external reinforcement (Ricamato M, 2007)

Adhesives and bonding principles

The implementation of FRP-based structural strengthening (*e.g.,* pultruded laminate) equires the use of adhesives. The type of surface treatment to be carried out prior to FRP application is important for the correct use of adhesives. An adhesive is a material quite often of a polymeric nature capable of creating a link between at least two surfaces and able to share loads. There are many types of natural and synthetic adhesives (elastomers, thermoplastics, and mono- or bi-component thermosetting resins); the most suitable adhesives for composite materials are based on epoxy resins.

Several advantages include the possibility of connecting different materials, providing greater stiffness, uniform distribution of loads, and avoiding holes dangerous for stress concentrations. On the other hand, adhesives are sensitive to environmental conditions, such as moisture, and are not appropriate when exposed to high temperatures (fire resistance).

The efficiency of adhesion depends on many factors, such as:

- surface treatment,
- chemical composition and viscosity of the adhesive,
- application technique,
- hardening or cross-linking process of the adhesive itself.

Adhesion mechanisms primary consist of interlocking of the adhesive with the surface of the support with formation of chemical bonds between polymer and support. As a result, adhesive strength may be enhanced by surface treatments that improve interfacial properties of the support by increasing the roughness of the surface to be strengthened.

2.5.3 FRP strengthening systems

FRP systems suitable for external strengthening of structures may be classified as follows:

• ***Pre-cured systems***:

Manufactured in various shapes by pultrusion or lamination, pre-cured systems are directly bonded to the structural member to be strengthened.

• ***Wet lay-up systems***:

Manufactured with fibers lying in one or more directions as FRP sheets or fabrics and impregnated with resin at the job site to the support.

• ***Prepreg systems***:

Manufactured with unidirectional or multidirectional fiber sheets or fabrics preimpregnated at the manufacturing plant with partially polymerized resin. They may be bonded to the member to be strengthened with (or without) the use of additional resins.

Mechanical properties of FRP strengthening systems

In FRP materials, fibers provide both loading carrying capacity and stiffness to the composite while the matrix is necessary to ensure sharing of the load among fibers and to protect the fibers themselves from the environment. Most FRP materials are made of fibers with high strength and stiffness, while their strain at failure is lower than that of the matrix. The Figure 2.38 shows the stress-strain relationship for fiber, matrix, and the resulting FRP material.

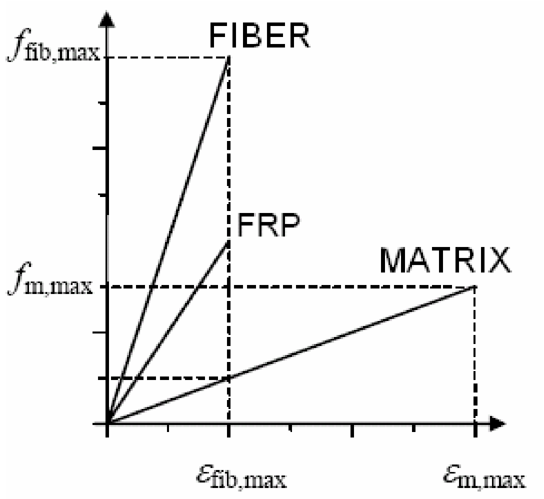


Figure 2.38: stress-strain relationship for fiber, matrix (CNR-DT 200/2004)

The Table 2.3 summarizes mechanical properties of a pre-cured laminate compared to the average values of the corresponding fibers. The values of Young modulus of elasticity, E_f, and ultimate strength at failure, f_f, of the laminate are lower than those of the fiber itself, while the ultimate tensile strain is of the same order of magnitude for both materials.

Table 2.3: Mechanical properties of pre-cured laminate (CNR-DT 200/2004)

Pre-cured systems	Modulus of elasticity [GPa]		Ultimate strength [MPa]		Ultimate strain [%]	
	FRP E_f	Fiber E_{fib}	FRP f_f	Fiber f_{fib}	FRP ε_{fu}	Fiber $\varepsilon_{fib,u}$
CFRP (low modulus)	160	210-230	2800	3500-4800	1.6	1.4-2.0
CFRP (high modulus)	300	350-500	1500	2500-3100	0.5	0.4-0.9

Pre-cured systems

Pre-cured composites are characterized by a unidirectional disposition of fibers. Reliable values of FRP mechanical properties shall be obtained with experimental testing to ensure determination of appropriate statistical parameters accounting for the adopted manufacturing process as well. In case of pre-cured systems, manufacturers typically provide mechanical characteristics referred to the laminate cross-section having a well specified size.

Wet lay-up systems

In case of wet lay-up systems (Figure 2.39), final thickness of the FRP laminate can not be estimated in a deterministic fashion. Therefore, it is recommended to refer to both mechanical and geometrical properties of dry fabric according to the technical data sheets provided by FRP manufacturer.

Pre-impregnated systems

Pre-impregnated (prepreg) systems are impregnated directly at the manufacturer plant and delivered in rolls. Resin may receive pre-polymerization treatments. A pre-impregnated system is a thin sheet (0.15 mm typical thickness), flexible and moderately sticky, with detaching film (silicon paper or similar) applied on the surfaces to preserve the system itself from external contamination. Storing shall be performed under controlled moisture and temperature conditions.

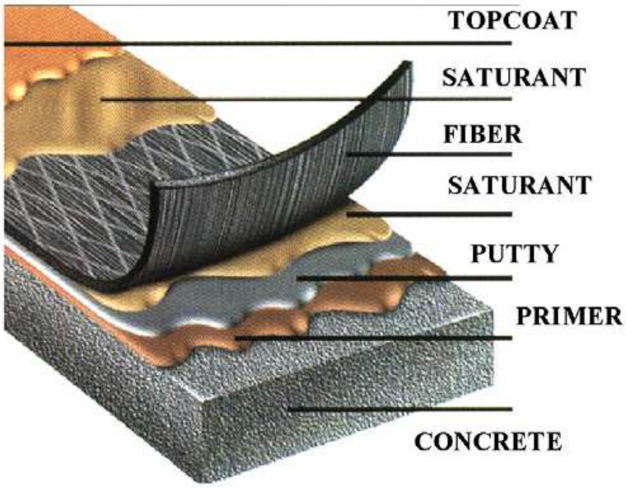


Figure 2.39: Wet lay up system (CNR-DT 200/2004)

Quality control

The qualification process of FRP systems and the necessary experimental tests developed by the manufacturer shall be aimed to complete the following:

- Ensure quality of products and compliance with published specified values.
- Provide a statistically significant number of experimental results for physical and mechanical characteristics to be used for design.
- Provide, when possible, data on experimental tests related to long-term behavior of the FRP system.

Qualification tests regard physical and mechanical properties (stiffness and strength) of composite materials, regardless of their particular application. Both mechanical and physical qualification tests shall be carried out by a certified laboratory provided with the necessary equipment and experience in the characterization of composite materials. Suitable safety factors should be employed on the basis of the adopted manufacturing technique.

2.5.4 General principle of strengthening design and partial factors

Design with FRP composites shall be carried out both in terms of serviceability limit state (SLS) and ultimate limit state (ULS), as defined by the current building code. Structures and structural members strengthened with FRP shall be designed to have design strength, R_d, at all sections at least equal to the required strength, E_d, calculated for the factored load and forces in such combinations as stipulated in the current building code. The following inequality shall be met: $E_d \leq R_d$.

The design values are obtained from the characteristic values through appropriate partial factors different for each limit state as indicated in the current building code.

Properties of FRP materials

Properties of FRP materials to be used for strengthening existing structures shall be determined through standardized laboratory tests. Properties of the existing materials in the structure to be strengthened shall be obtained both on-site or laboratory tests and, when available, from any additional source of information (original documents of the project, further documentation obtained subsequently, etc) Strength and strain properties of FRP materials used for strengthening, as well as those of existing materials (unless otherwise indicated in the current building code) are described by the corresponding characteristic values.

Partial factors

A. Partial factors, γ_m for FRP materials

For ultimate limit states, values to be assigned to the partial factors, γ_m, indicated by γ_f for FRP materials, are suggested in the following Table 2.4 as a function of the FRP failure mode:

Table 2.4: Partial factors (CNR-DT 200/2004)

Failure mode	Partial factor	Type A application(1)	Type B application(2)
FRP rupture	γ_f	1.10	1.25
FRP delamination	$\gamma_{f,d}$	1.20	1.50
(1) Certified strengthening systems. (2) Uncertified strengthening systems			

For serviceability limit states, a value of $\gamma_m = \gamma_f$ 1.0 is assigned to all partial factors, except where otherwise indicated.

B. Partial factors γ_{Rd} for resistance models

For ULS, values to be assigned to the partial factors γ_{Rd} are reported in the following Table.

Table 2.5: Partial factors for resistance models (CNR-DT 200/2004)

Resistance model	γ_{Rd}
Bending / Combined bending and axial load	1.00
Shear / Torsion	1.20
Confinement	1.10

2.5.5 Special design problems and relevant conversion factors

Hereafter, some reference values to be assigned to the conversion factor η, that affects both durability and behavior of FRP materials are reported.

Environmental conversion factor, η_a

Mechanical properties (*e.g.,* tensile strength, ultimate strain, and Young modulus of elasticity) of FRP systems degrade under specific environmental conditions such as alkaline environment, moisture, extreme temperatures, thermal cycles, freeze and thaw cycles, and ultraviolet radiations (UV).

a) Effects of alkaline environment.

The water contained in the pores of concrete may cause degradation of the resin and the interface between FRP and support. The damage of the resin due to alkaline environment is typically more dangerous than that due to moisture. The resin shall complete its curing process prior to being exposed to alkaline environment.

b) Effects of moisture.

The main effects of moisture absorption concern the resin; they can be summarized as follows: plasticization, reduction of glass transition temperature, and strength and stiffness (the latter less significant). The absorption of moisture depends on the type of resin, the composition and quality of the laminate, the thickness, the curing conditions, the resin-fiber interface, and the working conditions. In a marine environment, where osmotic effects may cause the presence of air pockets in the resin, it is suggested to use protective coatings.

c) Effects of extreme temperatures and thermal cycles.

The primary effects of temperature concern the viscous response of both resin and composite. As the temperature rises, the Young modulus of elasticity of the resin lowers. If the temperature exceeds the glass transition temperature, the performance of FRP materials significantly decreases. In general, thermal cycles do not have harmful effects on FRP; however, they may cause micro-fractures in systems with high modulus resins. For typical temperature in civil infrastructures, undesired performance can be avoided by choosing a system where the glass transition temperature is always higher than the maximum operating temperature of the structure or component being strengthened.

d) Effects of freeze and thaw cycles.

In general, exposure to freeze and thaw cycles does not have an impact on FRP performance, whereas it lowers the performance of the resin as well as the fiber-resin interface. For temperatures below 0 °C, polymeric-based resin systems may improve their performance by developing higher strength and stiffness. The effects of the degradation induced by freeze and thaw cycles may be magnified by the presence of moisture.

e) Effects of ultraviolet radiations (UV).

Ultraviolet radiations rarely degrade the mechanical performance of FRP-based systems, although this may cause some resins to have a certain degree of brittleness and surface erosion. In general, the most harmful effect linked to UV exposure is the penetration of moisture and other aggressive agents through the damaged surface. FRP-based systems may be protected from such damages by adding fillers to the resin or by providing appropriate coatings. The following Table 2.6 summarizes the values for the environmental conversion factor, η_a, depending upon fiber/resin type and exposure conditions.

Table 2.6: Environmental conversion factor, η_a (CNR-DT 200/2004)

Exposure conditions	Type of fiber / resin	η_a
Internal	Glass / Epoxy	0.75
	Aramid / Epoxy	0.85
	Carbon / Epoxy	0.95
External	Glass / Epoxy	0.65
	Aramid / Epoxy	0.75
	Carbon / Epoxy	0.85
Aggressive environment	Glass / Epoxy	0.50
	Aramid / Epoxy	0.70
	Carbon / Epoxy	0.85

Conversion factors for long-term effects η_l

Mechanical properties (*e.g.,* tensile strength, ultimate strain, and Young modulus of elasticity) of FRP-based systems degrade due to creep, relaxation, and fatigue.

a) Effects of creep and relaxation

For FRP-based systems, creep and relaxation depend on both properties of resins and fibers. Typically, thermosetting resins are less viscous than thermo-plastic resins. Since the presence of fibers lowers the resin creep, such phenomena are more pronounced when the load is applied transversely to the fibers or when the composite has a low volume ratio of fibers. Creep may be reduced by ensuring low serviceability stresses. CFRP, AFRP, and GFRP systems are the least, moderately, and most prone to creep rupture, respectively.

b) Fatigue effects.

The performance of FRP systems under fatigue conditions need to be taken into consideration as well. Such performance depends on the matrix composition and, moderately, on the type of fiber. In unidirectional composites, fibers usually have few defects; therefore, they can effectively delay the formation of cracks. The propagation of cracks is also prevented by the action of adjacent fibers.

c) Impact and explosive loading

The behavior of FRP systems subjected to impact or explosive loading is not completely understood yet. First indications suggest choosing AFRP (more resistant to impact) and/or GFRP systems rather than CFRP.

d) Vandalism

FRP composite materials are particularly sensitive to cuts and incisions produced by cutting tools. Particular protection systems need to be carried out for FRP strengthened members open to the public where vandalism could be an issue.

To avoid failure of FRP strengthened members under continuous stress or cyclic loading, values of the conversion factor for long term effects, η_l , are suggested in the following Table.

Table 2.7: Conversion factors for long term effects (CNR-DT 200/2004)

Loading mode	Type of fiber / resin	η_l
Continuous (creep and relaxation)	Glass / Epoxy	0.30
	Aramid / Epoxy	0.50
	Carbon / Epoxy	0.80
Cyclic (fatigue)	All	0.50

e) Strengthening limitation in case of fire

FRP materials are particularly sensitive to high temperatures that may take place during fire. When the room temperature exceeds the glass transition temperature of the resin (or the melting temperature in the case of semi-crystalline materials), both strength and stiffness of the installed FRP system are reduced. In case of FRP applied as external reinforcement to concrete or masonry members, exposure to high temperature produces a fast degradation of the bond between the FRP system and the support.

2.5.6 Installation Guidelines for FRP Panels

Fiber glass Reinforced Plastics Panels should only be installed over solid wall surfaces (gypsum board, concrete board, wood, cinder block, etc.). Wall surfaces should be clean, flat, dry and smooth. Uneven wall surfaces should be corrected for best results. FRP Panels will form to the contour of the wall surface when attached.

Inspection, Storage and Preparation

FRP Panels should be inspected promptly upon receipt and stored in a dry area with a temperature of 55° or more for a period of 48 hours for best results. Before installation FRP panels should be unwrapped and removed from the pallet, then carefully stacked on a flat, dry surface.

Tools

FRP panels should also be cut using power circular saws with carbide or masonry blades. FRP panels may be drilled for fastening with a metal drill bit. A masonry bit should be used when drilling in concrete, if required. Always protective eye lenses should be worn when cutting fiber glass plastic panels.

Expansion & Contraction

All brands of FRP Panels will expand and contract due to changes in temperature and environment. It is important to allow a 1/8" gap at the ceiling and panel base. A 1/16" gap should be allowed between panels and division bars. If face mounted mouldings. more space should be allowed for expansion and contraction of FRP panels longer than 8' and in areas with high fluctuations in temperature. Pre-drilled holes for FRP panels should be slightly larger than the diameter of fastener shank to allow for normal expansion and contraction.

Moldings & Sealants

The use of trim moldings and silicone sealant with FRP liner panels is recommended by the experts to achieve a moisture resistant installation. Moldings should be cut to size and place silicone sealant into channel of moldings during installation and placed on panels before fastening, if required.

Fasteners

In high moisture areas or certain situations, fibreglass plastic panels should be installed with non-corroding fasteners. Plastic pin rivets, chrome pin rivets, on piece nylon rivets, stainless nails or screws are generally recommend (Figure 2.40). Fasteners should be installed to fit snug, but should not be over tightened. The proper length and width of rivet fastener should be carefully selected for the covered project substrate. "Nydrives" may be used to fasten FRP panels to wood, metal, drywall, concrete, insulation and more.

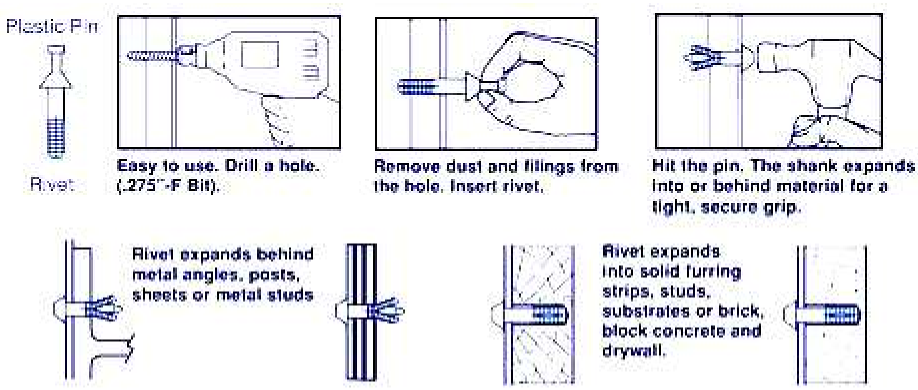


Figure 2.40: Different steps of fastening

Adhesives

The use of a FRP formulated adhesive is highly recommended when installing panels to all types of substrates. Adhesive should be applied to the entire back side of the FRP panel about 1/4" (6.4 mm) thick, using the manufactures suggested size trowel. After applying adhesive, it is imperative to secure the FRP panels with an adjustable rolling tool to properly "set" the FRP panel and substrate.

Fastening/Fastener Layout

- First FRP panel installed should be set true with a plumb line.
- During installation plumb line should be checked.
- The edges of FRP panels should not fastened until mouldings are in place.
- FRP panel / fastener layout / solid wall:
    - FRP panel at center should be fasten and worked outward.
    - Fasteners based upon 16" center
    - Fasteners should be staggered on opposite FRP panel edges and next to division bar for flat seam.
    - Liner panels should be pre-drilled for fastener installation using a guide panel.

Molding Installations

- Vinyl or aluminium mouldings can be used in the above diagram.
- Vinyl mouldings should not be used for exterior applications.
- Vinyl mouldings are DA and USDA accepted. Aluminium mouldings should not be used where FDA and USDA acceptance is required.
- Mouldings should be cut as needed for proper fit.
- Mouldings should be placed on panels before fastening edges, if required.

3 Chapter Three: Application of FRP to strengthen masonry members

3.1 General

Existing unreinforced masonry (URM) buildings, many of which have historical and cultural importance, constitute a significant portion of the world's building inventory. Recent earthquakes have repeatedly shown the vulnerability of URM buildings (ElGawady et al, 2006). Moreover, based on modern design codes most of the existing URM buildings need to be retrofitted. For example, in Switzerland, a recent research carried out on a target area in Basel shows that from 45 to 80% of the existing URM buildings, based on construction details, will experience heavy damage or destruction during a moderate earthquake event (Lang K, 2002). This brought to light the urgent need to improve and develop better methods of retrofitting for existing structurally inadequate URM buildings. Conventional retrofitting techniques (e.g. steel jacketing, grout injection, shotcrete etc.) have several disadvantages such as available space reduction, architectural impact, heavy mass addition, corrosion potential etc. During the last decade or so on, fiber reinforced polymers (FRPs) offered a promising alternative solution for retrofitting of masonry structures. FRPs present several well-known advantages such as high strength to weight ratio, ease of application, and high resistance to corrosion over existing conventional techniques. The application of FRP on masonry members namely walls, columns and arches are discussed below with experimental evidences and real experiences.

3.2 Walls

Wall is the principal component of the masonry structures. The design approach to successfully retrofitting an under-reinforced masonry building is to analyze the response of the structure for different actions and then find ways to strengthen the weak links in the existing system without drastically changing the building or creating collapse mechanisms. Typical weak links include in-plane failure of the masonry, out-of-plane wall failure, and connections between the walls and the flooring.

a) In-plane failure

In-plane resistance of unreinforced masonry walls is based on mortar strength and brick proportions. If the forces are strong enough to exceed the in-plane strength capacity of the wall, a shear failure will occur. This failure mode is characterized by brittle tensile cracking through the mortar and the masonry unit and a sudden loss of lateral load capacity. The most common type of strengthening for in-plane resistance is the filling of the voids in the blocks.

This procedure is time consuming and often not feasible. Other proven techniques include the addition of shotcrete or steel bracing or FRP diagonal bracing.

b) Out-of-plane failure

Seismic or wind loadings induce out-of-plane bending of walls between the restraining floors. Analysis of the failure modes must take into account many different factors, such as boundary conditions, wall compressive strengths, joint tensile strengths, wall stiffness, and applied loadings. Walls will typically remain stable under dead load and after cracking if they are within the specified height-to-thickness ratio. If the slenderness ratio is exceeded, the wall needs bracing by either a horizontal brace or vertical columns. Parapets, chimneys, and similar elements extending above the topmost line of restraint are most vulnerable to out-of-plane forces.

c) Connections

Out of plane loads cause walls to push against and pull away from the floors that they are connected to. Failure to have a secure connection between the two elements can cause failure by falling brick as well as floor collapse. This type of problem can be corrected and work can be performed while the building is occupied. Restraint of out-of-plane bending and tension ties between the walls and the floors are required to reduce the risk of collapse. For these applications, a sheet or fabric reinforcement is the most effective.

3.2.1 Flexure Strengthening

3.2.1.1 NSM FRP bar

FRP bars can be used as a strengthening material to increase the flexural capacity of URM walls. The successful use of NSM bars for improving the flexural capacity of RC members led to extending their potential use for the strengthening of URM walls. The use of NSM FRP bars is attractive since their application does not require any surface preparation work and requires minimal installation time. Fiber-reinforced polymer (FRP) materials may be a means of preventing or lessening the effects of this overloading. Application of NSM FRP bars does not require any surface preparation work, preserves appearance and requires minimal installation time compared to FRP laminates. Another advantage is the feasibility of anchoring these bars into members adjacent to the one to be strengthened (i.e., columns and beams).

Strengthening Procedure

The NSM technique consists of the installation of FRP reinforcing bars in slots grooved in the masonry surface. An advantageous aspect of this method is that it does not require sand blasting and puttying. The strengthening procedure can be summarized as:

1. Grooving of slots having a width of approximately one half times the bar diameter and cleaning of surface,
2. Application of embedding paste (epoxy-based or cementitious-based paste) (see Figure 3.1a), The groove is first half filled with a paste, a bar is then placed into the groove and lightly pressed to force the paste to flow around the bar.
3. Encapsulation of the bars in the joint (see Figure 3.1b), the groove is then filled with more paste and the surface is leveled.
4. Finishing and coating for environmental action.

If hollow masonry units are present, special care must be taken to avoid that the groove depth exceeds the thickness of the masonry unit shell, and that local fracture of the masonry occurs. In addition, if an epoxy-based paste is used, strips of masking tape or other similar adhesive tape can be attached at each edge of the groove to avoid staining of the masonry surface (see Figure 3.1).

(a) Application of Embedding Paste

(b) Encapsulation of FRP Bar

Figure 3.1: Installation of NSM FRP Bars (Nanni and Gastavo, 2002)

Depending on the kind of embedding material, cementitious-based or epoxy-based, a mortar gun can be used for tuck pointing or an epoxy gun can be used. The guns can be hand, air or electric powered, being the latter two, the most efficient in terms of efficiency. Figure 3.2a illustrates the application of an epoxy-based paste using an air powered gun. Figure 3.2b shows the application of a cementitious-based paste with an electric powered gun.

(a) Air Powered Gun

(b) Electric Powered Gun

Figure 3.2. Guns for Installation of Embedding Paste (Nanni and Gastavo, 2002)

Test evidence

The increase of strength mainly depends on the number of bar applied in each unit section. It is observed that increments of 4 and 14 times the original masonry capacity are achieved for Walls with 24 inches and 12 inches displacement of the #3 GFRP bars (0.25in diameter), respectively (Nanni and Gastavo, 2002). Also it is clear from another test of them that masonry walls strengthened with NSM FRP bars exhibit similar performance to walls strengthened with FRP laminates. Another research by Turco et al, (2006) depending on the amount of FRP, increases ranging from 4 to 26 times the original masonry out of plane capacity can be achieved for concrete block masonry and the ultimate strain in walls which fails by debonding was 0.8–1.4% which represents about 43–78% of the ultimate allowed bar strain.

Modes of failure

The walls after strengthened exhibits three different modes of failure (Galati et al, 2006):

1. debonding
2. flexural failure and
3. shear failure at the supports.

(i) FRP debonding

This is the most frequent mode of failure. Initial flexural cracks are primarily located at the mortar joints. A cracking noise during the test reveals a progressive cracking of the embedding paste. Since the tensile stresses at the mortar joints are being taken by the FRP reinforcement, a redistribution of stresses occurs. As a consequence, cracks develop in the masonry units

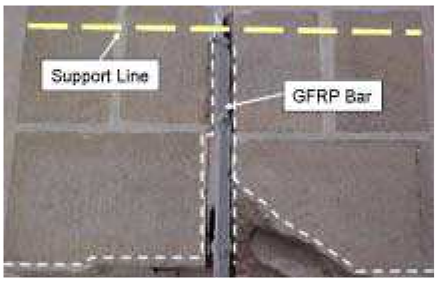


Figure 3.3. Debonding Failure (Nanni and Gastavo, 2002).

oriented at 45° or in the head mortar joints. (Figure 3.3). Due to the smoothness of the rectangular bars, some of the specimens reinforced with rectangular bars debond due to sliding inside the epoxy. For specimens having a deep groove, debonding is caused by splitting of the embedding material.

(ii) Flexural failure

After developing flexural cracks primarily located at the mortar joints, a wall fails by either rupture of the FRP reinforcement or by the masonry crushing. FRP rupture occurs at mid-span.

(iii) Shear failure

Cracking starts with the development of fine vertical cracks at the maximum bending region. Thereafter, flexural-shear failure is observed at an orientation angle at approximately 45°. In the flexural flexural-shear mode, shear forces transmitted over the crack causes a differential displacement in the shear plane, which results in FRP debonding. It can be observed that the strength and stiffness of the FRP strengthened walls increase dramatically when comparing them to a URM specimen. For some of the specimens utilizing carbon or glass FRP rectangular bars, a higher ductility is observed when compared with the specimens reinforced with circular bars. In fact, for these specimens the failure is due to the sliding of the bars inside the groove. In these cases, after the failure, the wall can still carry load because of the friction between the rectangular bar and the epoxy paste. An interesting observation can be underlined for specimens built with a stack pattern bond type. There is not a considerable reduction in the out-of-plane performance by placing the bar in the vertical joints or when it crosses the masonry blocks (Galati et al, 2006).

3.2.1.2 Strengthening with FRP laminates

Strengthening of masonry structures through concrete jacketing is quite effective, as it increases the strength, the stiffness and the ductility of masonry; however, this technique suffers from the following disadvantages.

- The heavy jackets add considerable mass to the structure, which is sometimes impossible to carry down to the ground level (e.g. in the case of building facades with arches). Moreover, this extra weight usually modifies the dynamic response characteristics of the structure, which may result in increased dynamic loads. important aesthetics requirements and /or reduce the free space.
- It is labor intensive, resulting in major obstruction of occupancy.
- The thickness added by the jackets may violate the architectural requirements.

These disadvantages have led researchers and, subsequently, some practitioners to the idea of strengthening masonry with epoxy-bonded laminates or fabrics made of FRP. The URM walls can be either load-bearing or non-load-bearing (infill) walls, mainly constructed with solid and hollow clay or concrete brick/blocks. Due to weak anchorage to adjacent concrete members (load-bearing walls); or due to the absence of anchorage (infill walls), these walls may fail and collapse under out-of-plane loads generated by seismic forces. In URM walls, failure due to out-of-plane bending causes the majority of the material damages and loss of human life. Therefore, the development of effective strengthening techniques needs to be addressed.

Test evidence

For masonry walls strengthened with FRP laminates, research results have shown that debonding of the FRP laminate from the masonry substrate is the controlling mechanism of failure (Hamilton III et al. 1999). This has been evident in masonry walls strengthened to resist either in-plane or out-of-plane loads. This implies that the effective strain of the laminate is a function of the amount of strengthening. For walls strengthened to increase the out of- plane capacity, it has been suggested [Velazquez et al, (2000)] to fix the effective strain to a value of 0.004 for design purposes. On the other hand, debonding may have a direct relationship with the porosity of the masonry unit, which can be characterized by the initial rate of absorption (IRA) test. The technique can significantly improve both the strength and the ductility of the tested specimens (Al-Saidy et al. 1996). While the ultimate tensile strain for glass fiber is 0.03 for fabric glass, 0.04 for grid glass, and 0.028 for aramid woven have been concluded and suggested by Lang K, (2002).

The test results indicats that a load-carrying capacity of the cracked wall increass by about 80% of the original wall when repaired with carbon fiber tow sheets (Hartley et al. 1996). The tall wall specimen displacement reaches a drift ratio of approximately 1.6%. Most investigations have shown that for walls subjected to in-plane loads, the shear capacity of the walls is notably enhanced when strengthened with FRP laminates (Hamilton III and Dolan, 2001).

In addition, the strengthened walls have a more ductile behavior. Other investigations on the out-of-plane behavior of URM walls strengthened with FRP laminates demonstrate that the flexural capacity of the strengthened walls can be dramatically increased (Hamilton III and Holberg, 1999). In addition, FRP laminates offer solutions for the strengthening of masonry walls potentially subject to overloading caused by natural hazards such as high wind pressures and earthquakes, and also to high pressures caused by blast waves (Muszynsky, L.C. 1998)

GFRP sheets are capable of transferring the masonry wall from one consisted form of individual blocks to a piece of wall with full integrity. Bonding of GFRP sheets to the tension side of walls subjected to out-of-plane loading can greatly enhance the flexural capacity and ductility of the masonry walls. However, the resistance is a function of the geometry of the wall and the properties of the FRP sheets. The failure load of the strengthened concrete hollow masonry specimens can be increased significantly (can reach 10 times) over the control one for out-of-plane samples and about 1.4 to 5 times for in-plane samples for FRP composites of two layers, depending on the direction of the applied load (Sameer et al 2001). Yousef and Tarek, (2005) found that for plane seismic loading displacement capacity can be increased upto 3 times for concrete block masonry with GFRP sheet.

The strengthened specimens are capable of supporting out-of-plane loads of a magnitude of up to 32 times the weight of the tested wall. At failure, the deflection of each wall is as much as 2.5% of the wall height (Ehasani et al. 1999).The failure of the out-of-plane strengthened walls is initiated around the mid-span and started by the development of shear crack that propagates across the width of the wall, which causes debonding of the GFRP laminates across the width of the wall (Yousef and Tarek, 2005).

The FRP laminates can be applied in two ways

1. unidirectional laminates covering the entire wall (0°) and
2. cross-ply laminates (0°/90°).

Wall strengthening with two unidirectional layers of carbon sheet (thickness 0.584 mm each) shows strain at failure is 0.71%. This strain is 57% of the rupture strain of the carbon/epoxy composite system. The ultimate load capacity of this red brick masonry specimen can be 12 times the capacity of the as-built specimen (Ayman, 2007). The ultimate failure mode is a combination of a compressive failure of the bricks followed by a cohesive failure of the carbon epoxy laminates as shown in Figure 3.4.

Figure 3.4. Combined failure mode of brick- compression failure and laminate cohesive failure (Ayman, 2007).

A total of three unidirectional plies of E-glass/epoxy (thickness 1.143 mm each) are similar to the retrofitted specimen with two unidirectional layers CFRP system. For this case the ultimate capacity of this wall is 11.54 times the out-of-plane ultimate capacity of the control, unstrengthened wall specimen. The strain at failure of the mid-height surface laminate is 1.07% which translates to about 48% of the experimentally obtained rupture strain of the E-glass/epoxy FRP composite system (Ayman, 2007).

Figure 3.5: An example of grid pattern application of FRP (Sika Limited, 2003)

Although the E-glass/epoxy inherently exhibits lower stiffness properties compared to carbon/ epoxy-type laminates, the average stiffness increase in the linear range of this wall, as compared to the as-built specimen, is about 60% higher. (Ayman, 2007).

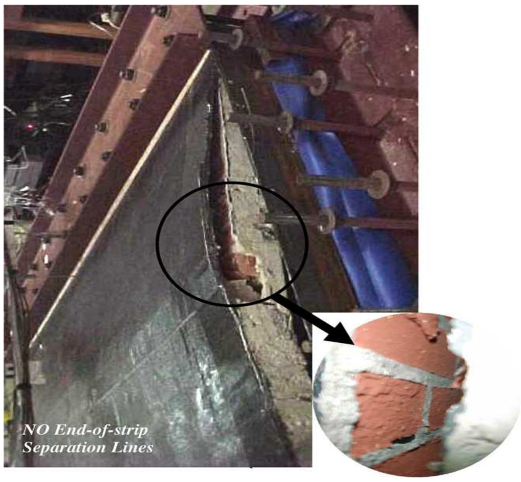
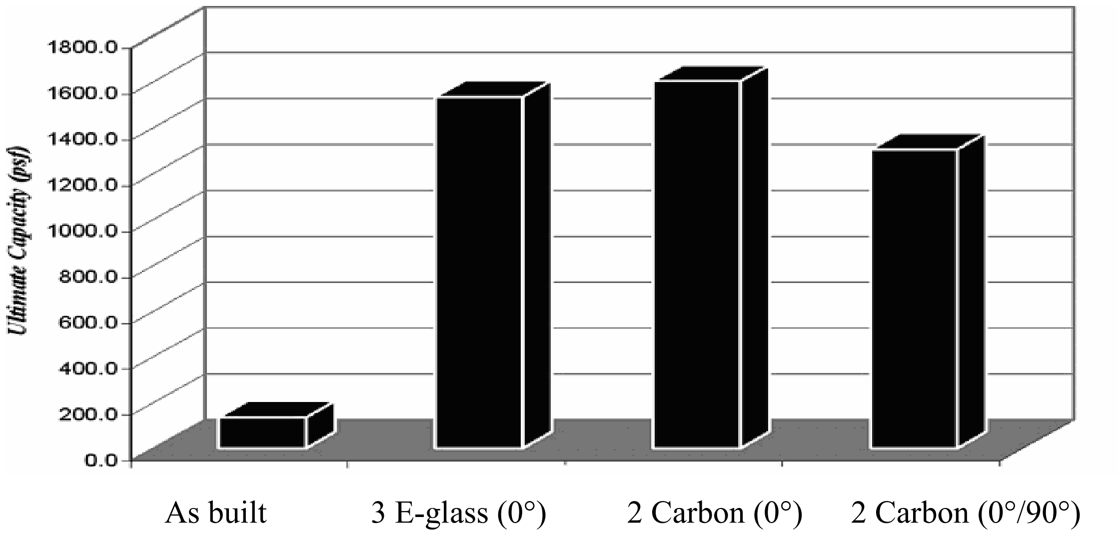


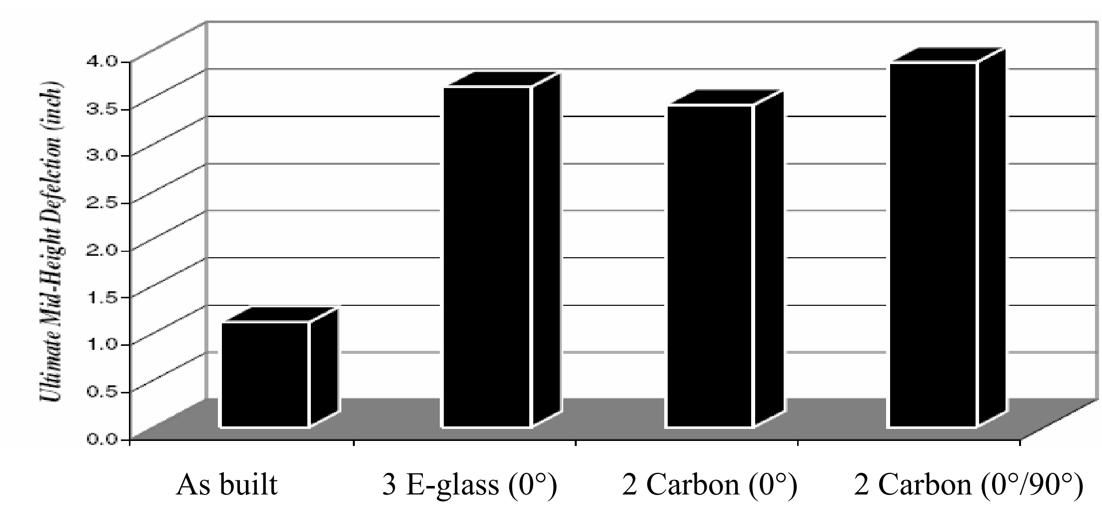
Figure 3.6: Ultimate failure mode of the cross-ply (Ayman, 2007).

The results of this study confirm the effectiveness of both the E-glass/epoxy and carbon/epoxy FRP composite strengthening systems in upgrading the out-of-plane flexural structural performance of unreinforced brick walls. The coupling effect of in-plane and out of-plane reinforcements is shown to have positive effects on both the out-of plane capacity and the ductility of the retrofitted wall specimen. Furthermore, due to the suppressing action provided by the orthogonal ply (applied in the direction parallel to the support), end-of-strip longitudinal separation observed in unidirectional reinforced wall, is eliminated.

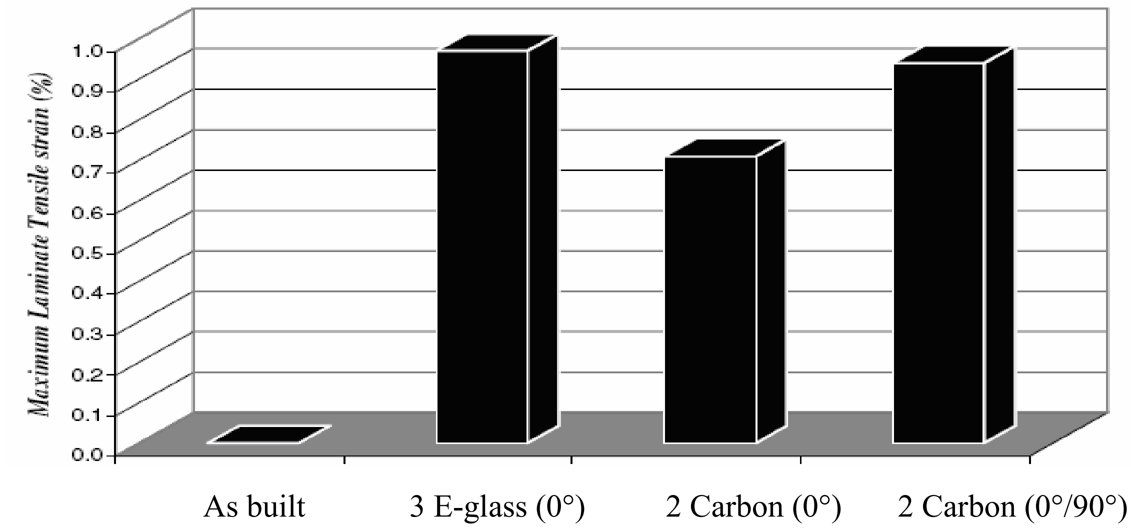
The contribution of the 90-ply is effective and is considered to be a contributing factor in determining the ultimate failure mode of this specimen. Figure 3.6 shows a typical failure mode of FRP strengthened wall with cross ply laminates. The cross-ply actually acts as a cross-support which forces the 0-degree laminated strips to deform as a single wide laminate. This prevents the 0-degree separation between the unidirectional laminates that is observed in specimen strengthened with two plies of unidirectional carbon/epoxy composites. The ultimate capacity is about 81% of specimen with two unidirectional layers system and 9.22 times the strength of the as-built specimen. The strain at failure of this specimen is 1%, which is about 83% of the measured rupture strain of the carbon/epoxy system. This is another indication of the merit of using the cross-ply is that it succeeds in increasing the efficiency of the external FRP composite reinforcement system (the ultimate strain is 16.9% higher than specimen with two unidirectional layers system) (Ayman, 2007). Figures 3.7 compare the performance of unidirectional layers and 90° ply for ultimate capacity, mid height deflection and maximum tensile strain.



Ultimate capacity for all wall specimens.



Mid-height deflection at ultimate for all wall specimens.



Mid-span tensile strains at ultimate load

Figure 3.7: Comparison of different parameters of the four kinds of specimens (Ayman, 2007.)

Based on these observations, it is recommended that in order to achieve optimal out-of-plane performance of strengthened brick walls, cross-ply lamination schedule should be used. This will be satisfied in the case where both out-of-plane and in-plane composite reinforcements are provided. However, if only out-of-plane reinforcement is required, it is recommended to add a lighter orthogonal ply (about 10– 15%) of the major flexural composite reinforcement demand (Ayman, 2007). Additional research is needed in order to accurately determine the optimum percentage of orthogonal polymer composites reinforcements.

3.2.1.3 Post tensioning

Post-tensioning can be used to close or control cracking in damaged structures or to increase the cracking moment of resistance in new construction. The evolution of an all-concrete-and-FRP anchor has the promise and potential of a completely metal free post-tensioning system that would avoid the issue of corrosion completely. Figure 3.8 dictates the concepts of post tensioning.

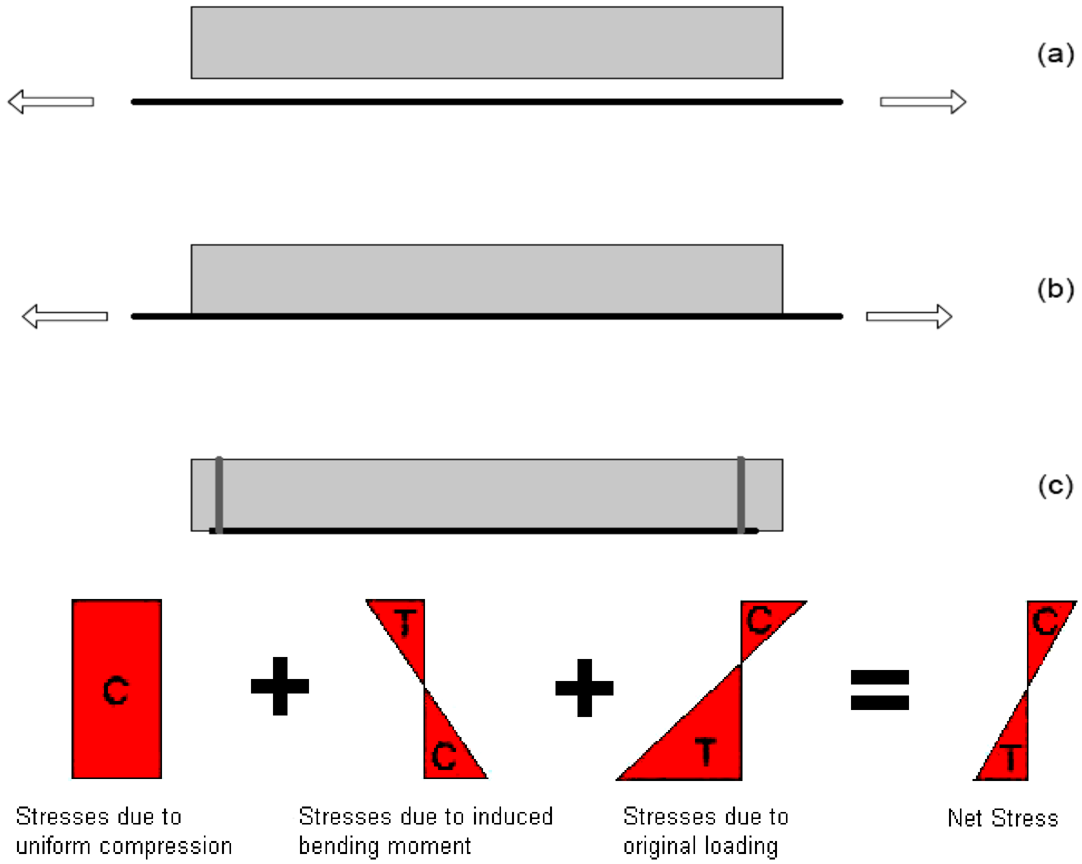


Figure 3.8: Strengthening with Prestressed FRP: (a) prestressing (b) bonding (c) end anchorage and release and finally the stress reduction (Sika Limited, 2003)

Post-tensioning has been applied successfully to a variety of masonry structural forms. The advent of advanced composite materials provided an alternative to the corrosion protection measures adopted previously. In particular, Fiber Reinforced Polymers (FRP's) have properties that are attractive for post-tensioning applications (Sayed Ahmed and Shrive, 1998). Post-tensioning of structural masonry has been advanced by recent research and is increasingly being used for new construction as well as the strengthening of existing structures [Ganz (1991)]. Post-tensioning enhances cracking loads, improves the cracking behaviour and results in an increased flexural resistance of masonry walls. Except for possible eccentricities of the tendons relative to the (deflected) wall axis post-tensioning forces do not contribute to the instability of the wall but they do contribute to the wall's flexural stiffness (Mojsilovi, and Marti, 1994).

a) Dead end b) Live end

Figure 3.9: Applying post tension (John Busel, David White, 2003)

The glass in some GFRP's is sensitive to alkaline solutions and AFRP's are prone to creep. Despite this latter feature, an AFRP post-tensioned masonry foot bridge was designed and constructed in the U.K. (Shaw and Baldwin 1995). CFRP is better because of the high strength and durability. CFRP tendons have a propensity to rupture under shear or lateral loading. Thus the anchorages used for steel tendons cannot be used on CFRP tendons. The sharp ridges on the wedges of a standard anchorage, that is designed to dig into and grip the steel tendon, cause a carbon fiber tendon to shatter in the anchorage. Figure 3.9 shows the mechanical system of applying post tension.

The different techniques can be used to grip FRP tendons and when used with CFRP, the requirements for an anchorage established by the PTI are passed (Sayed Ahmed and Shrive 1998). However, there is some inconsistency in use on the part of others and the anchorage needs to be made more robust in terms of its performance before site use can be recommended. This anchorage is made of stainless steel and has a copper sleeve that sits over the tendon where it is to be anchored, to help relieve stress concentrations caused by the wedges. (Campbell et al. 2000).

3.2.2 Shear strengthening

3.2.2.1 NSM FRP bar

The technique denominated FRP structural repointing is basically a variant of the NSM technique. It consists of placing FRP bars in the mortar joints. Repointing is a traditional retrofitting technique commonly used in the masonry industry, which consists of replacing missing mortar in the joints. The term "structural" is added because this method does not merely consist of filling the joints as the traditional technique, but allows for restoring the integrity and/or upgrading the shear and/or flexural capacity of walls.

Strengthening Procedure

FRP structural repointing offers advantages compared to the use of FRP laminates. The method itself is simpler since the surface preparation is reduced, sandblasting and puttying is not required. In addition, the aesthetics of masonry can be preserved. In this technique, the diameter size of the FRP bars is limited by the thickness of the mortar joint, which usually is not larger than 3/8 inches. The strengthening procedure consists of: (1) cutting out part of the mortar using a grinder, (2) filling the bed joints with a epoxy-based or cementitious-based paste (see Figure 3.10a), (3) embedding the bars in the joint (see Figure 3.10b), and (4) retooling.


a) Application of Embedding Paste

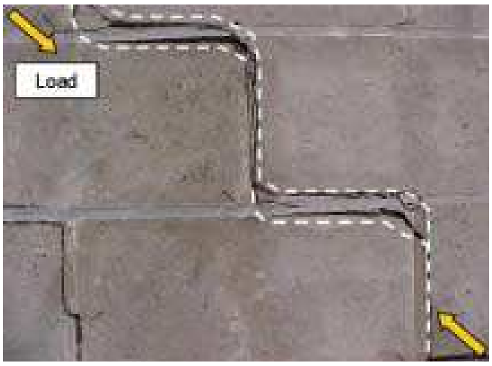

(b) Installation of GFRP Bars

Figure 3.10: Strengthening by Structural Repointing (Nanni and Gastavo,2002)

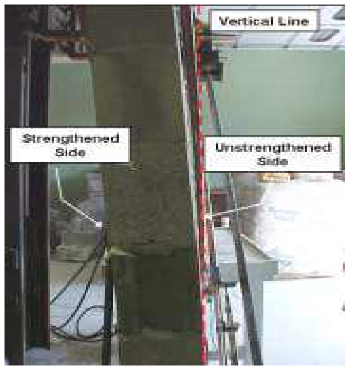
To ensure a proper bonding between the epoxy-based paste and masonry, dust must be removed from the grooves by means of an air blower prior to filling the bed joints. A masking tape or another suitable adhesive tape can be used to avoid staining. Stack bond masonry allows to install FRP bars in the vertical joints, if required (Figure 3.10b). In this case since the face shell thickness of the masonry units does not limit the grove depth, this can be deeper.

Test Evidence

The wall strengthened with GFRP bars having a diameter of 0.25in at every horizontal joint on one side the shear capacity generally increases in about 80% (Nanni and Gastavo, 2002). Another research by Turco et al, (2005) depending on the amount of FRP, increases of shear upto150% of the original concrete block masonry wall capacity can be achieved. The strengthened hollow brick masonry walls showed stability (i.e. no loose material is observed) after failure. This fact can reduce risk of injuries due to partial or total collapse of walls also subjected to out-of-plane loads. In addition, due to the reinforcement eccentricity, the wall may be tilted to the direction of the strengthened face (Figure 3.11b). In addition, due to the reinforcement eccentricity, which causes the crack growth on the unstrengthened side, to increase at a higher rate than the strengthened side



(a) Debonding of epoxy/block interface



(b) Tilting of Wall R2

Figure 3.11: Specimens after failure (Nanni and Gastavo, 2002)

It is observed that the walls strengthened with FRP bars and walls strengthened with equivalent same amount of FRP laminates (in terms of axial stiffness), has similar shear capacity; however, the pseudo-ductility is less in the laminates strengthened wall, which can be attributed to the occurrence of the sliding shear failure (Nanni and Gastavo, 2002). Remarkable increases in shear capacity and pseudo-ductility, up to 200%, can be achieved if steel is used in conjunction with FRP bars. These increments can be reached mainly if the reinforce has a symmetric shape (Grando et al, 2002). It is found that remarkable increases in shear capacity are achieved by strengthening URM walls by FRP structural repointing. So it can be concluded that NSM bar does not increase shear strength as much as flexure strength.

3.2.2.2 Strengthening with FRP laminates

Nowadays, FRPs represent a new opportunity to restoring ambit, with considerable development in URM strengthening. A key problem is represented by FRP's up-to-failure linear elastic behavior, which prevents the ductility of the system being based on the plastic behavior of the strengthening material itself; therefore, redistribution-derived theories are not applicable. Consequently, investigations on alternative mechanisms providing sufficient signals of incipient collapse are required. A certain number of FRP masonry strengthening applications have already been performed, involving either FRP bars or laminates, but few analytical or experimental research works have investigated the effectiveness and reliability of that new technology.

Test evidence

The unreinforced specimens present brittle failure due to splitting along the loaded diagonal.

(i) Single-side strengthening

Splitting failure with a clear diagonal crack pattern is obtained generally in all single-side reinforced panels, whereas ultimate load is in many cases lower than the reference. The samples exhibits a clear bending deformation during the loading phases along the unreinforced diagonal; as a consequence, the main damage is concentrated on the unreinforced side (Valluzzi et al, 2002). That bending phenomenon is caused by a noticeable difference of stiffness on the opposite sides as a result of the asymmetrical reinforcement.

Figure 3.12: Shear strengthening by CFRP plates in one side at Shariati museum in Tehran, Iran in November 2005. (Motavalli M, 2005)

Among the one-side reinforced specimens, diagonal strengthening configuration always reveals a higher effectiveness than the squared grid set-up. So, asymmetrical applications (single-side reinforcement) on masonry panel offer a limited effectiveness. Figure 3.12 is a real example of applying single sided FRP.

(ii) Double-side strengthening

In all these cases, the failure mechanism consisted in sudden loss of collaboration between reinforcement and substrate, due to either de-lamination (peeling) of the superficial part of masonry or rupture of the FRP strips. Gain in strength increased by about 50% for single of GFRP (thickness of each ply 0.11 mm) and CFRP (thickness of each ply 0.167 mm), and about 65% for double layers of GFRP and CFRP in tuff masonry walls. It is seen that reinforcement with double layers of CFRP and cross pattern led to a shear strength increase fairly close to those with single layers of CFRP and GFRP, and grid pattern. (Marcari et al, 2007).

Hollow (unreinforced) concrete masonry walls were tested, retrofitted with CFRP laminates on both sides of the walls by Gergely and Young, 2001. Three walls were tested with in-plane reverse cyclic loading and three with out-of-plane loading. The addition of the CFRP increased capacity in terms of displacement by a factor of 4 in shear and 8 in bending, but 31 times in terms of load.

In the case of cross pattern, CFRP always leads to higher gains in shear strength than GFRP. It is observed that an almost equal strength increase is given by both single and double layers of GFRP, while CFRP is more effective when double layers is used. In the latter, the shear strength increase is almost double that of single layer CFRP (Marcari et al, 2007). The strength and stiffness change with change in fiber orientation. Changing the orientation from 90° to 45° leads to a slight increase in ductility and strength. The 45° oriented fiber shows almost constant stiffness where as the 90° one decreasing stiffness and almost no stiffness at ultimate load. (Ehsani et al 1997, Valluzzi et al, 2002).

Table 3.1: CFRP vs. GFRP and cross pattern vs. grid pattern for shear strengthening

Name	CFRP (double layer)		GFRP (double layer)	
	Shear	Displacement	shear	Displacement
Grid pattern	50% (65%)	1.37%	50% (65)	69% (16%)
Cross pattern	Better (50%)	0.96%	Good	22 % (Not)

The differences between CFRP and GFRP in terms of shear strength became less significant when a grid pattern was used; however the shear strength improved when the amount of shear reinforcement increased (Marcari et al, 2007).

In terms of displacements, the CFRP reinforcement increases significantly. The single layer GFRP increases of the maximum drift by about 22%and 69% for cross and grid patterns, respectively; the double layers GFRP reinforcement almost do not change the maximum drift in the case of cross pattern, whereas an increase of about 16% is achieved with grid pattern. For both CFRP and GFRP the grid pattern is more effective than the cross pattern (Figure 3.13) in order to improve the displacement capacity of strengthened panels (Marcari et al, 2007). Similar results were found by Stratford et al, (2004).

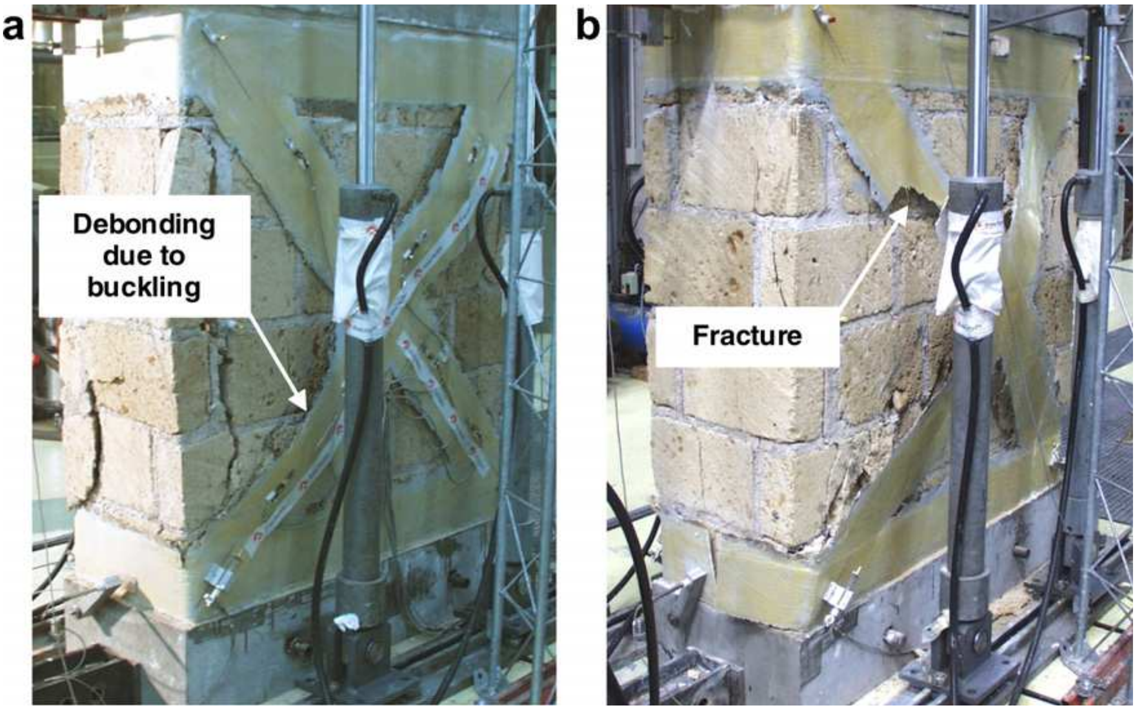


Figure 3.13: Typical photographs of the panels strengthened with cross layout (Marcari et al, 2007).

An experimental campaign indicates that, for similar effective axial stiffness, the lower Young modulus allows GFRP strips to be more compatible with the masonry substrate than CFRP, thus resulting in larger strength increases. This is consistent with the fact that tensile failure of GFRP strips is generally reached, while no tensile rupture is detected for CFRP (Marcari et al, 2007).

However, previous research (Hamoush et al, 1998) indicates that the out-of-plane failure of unreinforced masonry walls retrofitted by external fiber reinforcement might be controlled by the shear strength of the system at the supports. But there appears to be no significant effect of the reinforcement fiber area and the amount of fiber extension to the support on the shear strength of the wall assembly. However, the highly variable nature of the masonry shear strength may have hidden less pronounced influences, (Hamousha et al, 2002).

Another important thing is that when a single layer overlay is used, the distance of the overlay from the support has only a minor influence on the behavior of the retrofitted system. Adding more than one layer of FRP overlay increases the structural integrity of the system and appears to reduce the variation in the behavior of the retrofitted walls, especially when the overlays are extended to the supports. (Marshall et al, 1998, Hamousha et al, 2002).

3.2.2.3 Post tensioning

Post tensioning is mainly done for crack mitigation. It also contributes much in flexure strengthening. Results (Lissel and Shrive 2000) suggest that bed-reinforcement has little effect on shear strength, but can affect post peak behaviour. The problem with reinforcement in general is that when the "shear crack" develops, the reinforcement de-bonds and the strength of the reinforcement is not activated. The usual single, wide crack crossing the bed joint and associated reinforcement is very different to the multiple narrower cracks typically seen in concrete. The most recent tests performed with GFRP ties manufactured to our design (Lissel and Shrive 2001) indicate that with proper anchorage in the mortar, the strength of a tie can be activated.

3.2.3 Numerical example for flexure strengthening with laminates

A simplified analytical example is presented to predict the ultimate strength of the fiber reinforced masonry wall systems. The method is based on the following assumptions (Ayman, 2007, Hamoush et al, 2002):

(1) linear strain distribution through the full depth of the wall;
(2) small deformations;
(3) no tensile strength in the masonry blocks,
(4) no slip between the fiber reinforced composites and the masonry wall, and
(5) plane sections remained plane.

The stress–strain relationship of the fiber reinforced composite systems is generally considered to be linear elastic up to failure (refer to Figure 3.14), while the stress–strain behavior of the masonry block is modeled as idealized uniform stress block at failure.

The ultimate compression strain in the masonry blocks is assumed to be 0.0035.

The compressive strength of the masonry assembly, (f'_m) = 3.5 ksi.

The elastic modulus of the FRP composite system is 4000 ksi (27.6 GPa).

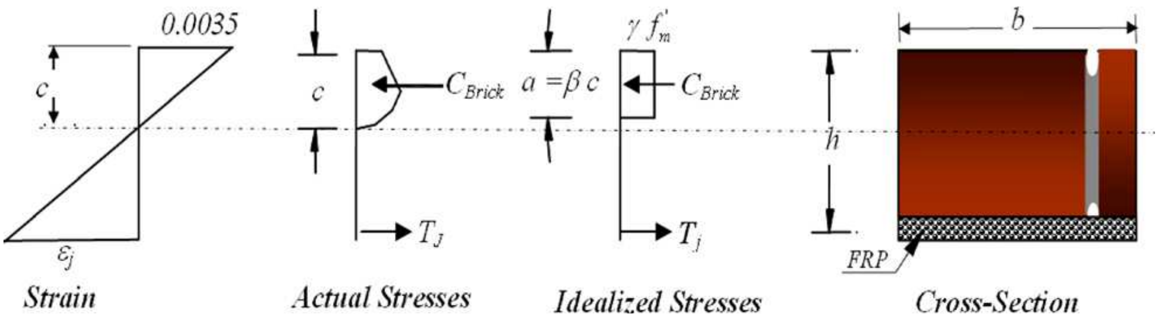


Figure 3.14: Stress and strain distribution for section analysis (Ayman, 2007)

In the following example, the proposed analytical approach is used to predict the out-of-plane capacity of a red brick wall strengthened with two unidirectional plies of carbon/epoxy composite system. Dimensions, boundary conditions, loading pattern, composite lay-up and properties are assumed reasonable value. The following are the step-by-step analytical procedures for predicting the flexural capacity of this wall.

Strengthened wall information

Wall dimensions: 2.5m x 2.5m (98.5’’ x 98.5’’).
Brick wall thickness: 101.6 mm (4’’).

CFRP ply unit thickness = t_p = 0.584 mm (0.023'').

Number of unidirectional plies = n = 2

Total thickness of CFRP laminate = t_j = t_p x n = 0.46''

CFRP on-axis tensile ultimate strain = ε_j = 1.25%

CFRP on-axis tensile modulus = E_j = 100 GPa (14.56 Msi).

CFRP on-axis tensile strength = f_{ju} = 1250 MPa (181.3 ksi). (After considering all environmental conversion factors and safety factors, it is in very much conservative side)

Boundary conditions: Fixed support, the other three edges are free

1. Calculation of neutral axis depth

h = 4'' + 0.046''/2 = 4.023 in. (102.2 mm),

a = β c = 0.88c, (Assumed β =0.88 and γ = 0.8)

C = $\gamma f_m' ab$ = 0.8 x 3.5 ksi x a x 98.5''= 275.8a,

T = $A_j f_j$ = $A_j E_j \varepsilon_j$ = 98.5'' x (2 x 0.023'') x 14560 x ε_j = 65993 ε_j

From strain compatibility:

ε_j = 0.0035(h/c - 1) = 0.01239/a - 0.0035,

T = 817/a - 231.

From equilibrium: C = T or

275.8 a = T = 817/a - 231 from which: a = 1.35'' (34.34 mm).

2. Check of CFRP allowable strain

ε_j = 0.00567,

ε_{ju} = f_{ju} / E_j = 0.0125 > ε_j ok. Thus, failure is due to masonry crushing rather than fiber fracture.

3. Calculation of ultimate moment and maximum load

M_u = ultimate flexural capacity = $\gamma f_m' ab(h - a/2) = A_j f_{ju}(h - a/2)$ or

M_u = 1240 kip-in. (147 kN m),

a) For uniform load distribution

w_u = ultimate unit load = $2 M_u / L^2$ = 0.2555 kip/in (43.49 kN/m),

P_u = ultimate load capacity = 0.2555 kip/in. x 98.5'' = 25.17 kip (112 kN),

P_u = ultimate uniform pressure = 25.17 kip/ (98.5)2 = 373.57 psf (17.88 kPa).

b) For point load

Max point load on top point = 1240 kip-in / 98.5 in = 12.59 kip (56.02 kN)

3.2.4 Real experiences

A number of buildings have been strengthened using glass or carbon FRP products supplied by QuakeWrap Inc. a leading designer, supplier, and installer of innovative Fiber Reinforced Polymer (FRP) products for the repair and strengthening of structures located in Arizona, USA. They applied FRP on walls of the following three buildings.

- One-Story CMU Block Building, Glendale, CA
- Two-Story Masonry Building, Redwood City, CA
- United Airlines Building, Oakland International Airport

a) One-Story CMU Block Building, Glendale, CA

This is the first reported application of fiber composites to strengthen an existing building and was completed in spring 1994. This one-story building had been previously retrofitted for seismic performance by addition of steel columns and tying the roof joists to the top of the walls with anchors. Nevertheless, the 12-in. wide CMU wall on the southern side of the wall cracked severely during the Northridge earthquake that occurred on January 17, 1994.

Conventional approach of shotcrete, the wall could not be utilized because the wall is located just on the edge of the property line; due to the presence of a conveyor belt hanging from the ceiling, there was limited access to shotcrete the wall from the inside. Because this was the first such field application, the city engineers were reluctant at first. But after presentation of extensive R&D data, including assurances for non-toxicity of the resins to the Fire Marshall, a construction permit was issued.

The wall was first sandblasted and cleaned with high pressure air. At the time, we had not designed and constructed an impregnator machine, so the 3-ft wide glass fabrics were saturated by hand. The fabrics were placed in vertical strips. Where steel anchor plates were present from the earlier seismic retrofit, the washers were removed and the bolts penetrated the wet fabric; the washer and nuts were immediately placed over the fabric. Figure 3.15 shows some executions.

Figure 3.15: One-Story CMU Block Building, Glendale, CA (QuakeWrap, Inc.)

To ensure proper anchorage, the fabrics were secured through blockings on the inside, at roof line. As the photos demonstrate, the finished wall was painted. The total thickness of the wall was increased by less than ¼ in. and none of the conveyor belt equipment had to be removed from the ceiling for this retrofit.

b) Redwood City, California

This two-story building is located in downtown Redwood City, south of San Francisco (Figure 3.16). The neighbouring property had excavated the lot and the owners of this building were concerned about the stability of the exposed wall during construction. The masonry wall (about 40-ft high x 70-ft long) was retrofitted with glass fabric. The contractor chose to install the fabric in horizontal strips with 6-in. overlap along the length of the wall. A crew of 3 workers finished this installation in roughly 4 days. The project was completed in August 1997.

Figure 3.16: Two-Story Masonry Building, Redwood City, CA (QuakeWrap, Inc.)

Figure 3.17: United Airlines Building, Oakland International Airport. (QuakeWrap, Inc.)

c) United Airlines Building

Glass Fiber Reinforced Polymer (GFRP) was used to strengthen the masonry walls of this building. The United Airlines maintenance facility in Oakland International Airport is a major structure with the capacity of accommodating six large aircrafts at any given time (Figure 3.17). The interior masonry walls surrounding the stairs required seismic upgrade. A major concern of the client was the cleanliness of the repair/strengthening procedure; with so many aircraft parts being exposed, dust had to be kept at a minimal level.

Glass Fiber Reinforced Polymer (GFRP) was used for this project. The entire surface areas of the walls in the vicinity of staircases were seismically strengthened using over 4,000 ft² of FRP fabric. This project was completed in November 1997.

3.3 Column

Structural enhancement of masonry elements built with natural stones is frequently needed; in particular, compressed members, as columns, are prone to brittle failure under seismic forces or static overloads. Their structural performance can be improved by adequate strengthening solutions. External confinement techniques are commonly used to strengthen compression members. This kind of intervention has shown a noticeable and growing interest through the designers' community due to the fact that it is possible to reach increments in terms of both load carrying capacity and ductility even for small area fractions of the fiber reinforced polymer FRP material. The problem of FRP confinement was extensively studied in relation to concrete columns.

A lot of researches have been done for the concrete column but at the moment only a small amount of information is available for masonry columns subjected to high compressive loads strengthened by FRP materials. Traditional techniques for rehabilitation of masonry columns by means of reinforced concrete or steel jacketing that have been largely used in the past were investigated. Recent studies furnished results on the stress–strain relationship of RC-jacketed masonry columns (Kog et al. 2001). These well-known techniques may be inadequate in the following cases:

1. For applications that should preserve architectural heritage with historical value; and
2. For masonry structures unable to bear the mass added by that kind of intervention, mainly in seismic areas where the extra weight modifies the dynamic response involving increased seismic forces.

Confinement with FRP composites presents significant advantages with respect to traditional confinement techniques: The cross-sectional dimensions of the column do not increase, which allows to comply with architectural restraints; the mass of the column does not increase, which means that the seismic behavior of the building remains unchanged; the low weight of FRP materials implies that the installation procedure is faster, easier, and less dangerous for the operator, if compared with traditional strengthening techniques.

3.3.1 Circular column

In circular column FRP is generally applied as confinement or wrapping. The fiber layer orientation is generally kept perpendicular to the column axis.

Three strengthening techniques are generally used with continuous or discontinuous CFRP sheets and using internal GFRP rebars, glued with an epoxy paste in holes drilled through the cross section. Lateral overlapping is not generally recommended. Overlapping in transverse direction is generally expected. Overlap length equal to 100 mm that is 16% of the total sheet length is good in use (Maria at al. 2007).

Table 3.2: Geometry of the specimen and also the test result (Maria et al. 2007)

Label	Construction and strengthening schemes	Peak load (kN)	Max Stress (MPa)	Ultimate Displ. (mm)	Strength Increase (%)	Strain at Peak load (%)
C-I-1	Control specimens with compact cross section	312	9.93	2.42	-	0.29
R-F-2	C-I columns confined with discontinuous CFRP jacket—two 150 mm wide strips	333	10.60	17.80	15	0.69
R-F-3	C-I columns confined with discontinuous CFRP jacket—three 100 mm wide strips	502	15.98	10.09	73	1.25
R-S-B	C-S column confined with internal GFRP rebars bar=8 mm	210	9.87	4.87	80	0.44

Continuous wrapping with one layer of CFRP of 0.150 mm thickness can increase about 93% in terms of strength for masonry wall of calcareous stone blocks (Table 3.2). Prior to test, a load equal to 60 or 80% of the ultimate load of the unstrengthened specimens has been applied on some columns. In this way it is possible to reproduce the real service conditions and the effects of overloads. Axial displacement increases about 389% that of unconfined columns. Columns confined with three 100 mm wide sheets shows higher mechanical properties (generally strength increase around 73% and strain increase 331%) with respect to the same columns confined with two 150 mm wide sheets (normally strength increase 15 % and strain increase 138%). In former case the failure is generally by tensile rupture of the composite where as in later case the failure is occurred by the expulsion of materials from the unwrapped zones, without fibers ruptures. (Maria at al. 2007).

Table 3.3: Increase of performance after strengthening (Maria at al. 2007).

Name	Axial load increase	Ultimate displacement increase	Strain at peak increase	Failure mode
Continuous wrapping	93%	285%	389%	Tensile rupture of FRP
2- 150mm CFRP sheets	15 %	635%	138%	Expulsion of materials
3- 100mm sheets	73%	316%	331%	Tensile rupture of FRP

So, for discontinuous wrapping smaller width of strips is more benefited than the same amount of materials with larger width (Table 3.3). And also high increase in ultimate strength and strain can be after strengthening; Complete FRP jacketing was much more effective than discontinuous wraps. Sika Corporation (2003) advises to keep 300mm clear gap between strips for discontinuous wrapping.

The increase in load capacity from the unwrapped cracking loads to the failure loads for the modified circular and CFRP wrapped columns averages 200% and 156% for the small and intermediate sized columns respectively. Despite the additional column area, these increases clearly highlight the effectiveness of the CFRP wrap when provided with a circular cross section to confine. (Nigel et al, 2001).

Complete wrapping generated a larger increase of compressive strength that is about 93% for all continuous wrapping specimens. Wrapping with CFRP strips two FRP strips does not take to the same increase, even if the axial strain results almost 3%, showing a relevant increase with respect to the control specimens. The ultimate load is 80% higher than the average peak load of control specimens even if the axial displacement is not significantly enhanced (Maria at al. 2007).

One interesting aspect is that damage caused by overloads applied in the pre-cracking stage before strengthening does not reduce the mechanical properties of FRP-confined columns. Presence of internal FRP rebars (passing through the core of the blocks on injecting) act as an effective confining system for cross sections composed by four blocks; strength can be increased upto 80% of the built specimen and strain can become 51% more (Maria et al. 2007). These observations indicate that the use of CFRP wrapping is effective as a technique for rehabilitating damaged masonry columns.

3.3.2 Rectangular column: Confinement

FRP jackets can significantly enhance both the strength and the deformability of masonry under axial load. Confinement effectiveness for strength, defined as the ratio of peak stress of FRP-confined masonry to that of the unconfined masonry, exceeded 3. Enhancement in deformability is much more pronounced than gain in strength, as the ultimate strain of confined masonry exceeds that of unconfined masonry by a factor of more than 30.

Under axial loading with continuous wrapping a square section column with CFRP wrapped, the average load increase can be in the order of 34%. If a circular concrete jacket is provided prior to wrapping, load increases averaging 178% due to confinement by the CFRP wrap being effective around the full perimeter of the circular cross section (Nigel et al, 2001).

Number of layers: Number of layers should have great influence on strengthening column. In most cases, particularly when the cross section aspect ratio was 1, strength and deformability increased almost linearly with the number of layers. In square section, strength increases by about 13, 40, and 110%, and ultimate strain by a factor of 10, 12.5, and 20, for one, two, and three layers of CFRP on clay brick masonry columns (Table 3.4). The respective increases in specimen with 20 mm corner rounded and Aspect ratio 1 were 40, 100, and 185% for strength and by a factor of 14, 21, and 29 for ultimate strain. In specimen with aspect ratio 1.5: 1, strength increases by 80 and 160% and ultimate strain by a factor of 2 and 10 for two and three layers of CFRP. In specimen with aspect ratio 2:1, strength increases by about 90 and 95% and ultimate strain by a factor of 2.5 and 7.5 for two and three layers of CFRP, respectively (Krevaikas and Triantafillou, 2005). So there is almost proportional relation in increase in strength and number of layers applied. But it should have a optimum solution.

Table 3.4: Effect of number of layers and aspect ratio

No of layer(s)	Aspect ratio (h/b)	Strength increase (with 20mm corner rounded) %	Strain factor (with 20mm corner rounded)
1	1	13(40)	10 (14)
2	1	40(100)	12.5 (21)
3	1	110(185)	20 (29)

Corner radius: When the corner radius is increased from 10 to 20 mm the strength increases by about 25–40% with CFRP jackets and by about 12% with the very thick GFRP jackets. Hence the beneficial effect of increasing the corner radius is verified (Krevaikas and Triantafillou, 2005)

Aspect ratio: It is very difficult to find relation between the increase in strength and aspect ratio. When two layers of CFRP are used, the reduction in confinement effectiveness when the aspect ratio becomes 2 from 1.5 is about 20–25% for strength and about 10–20% for strain (Krevaikas and Triantafillou, 2005)

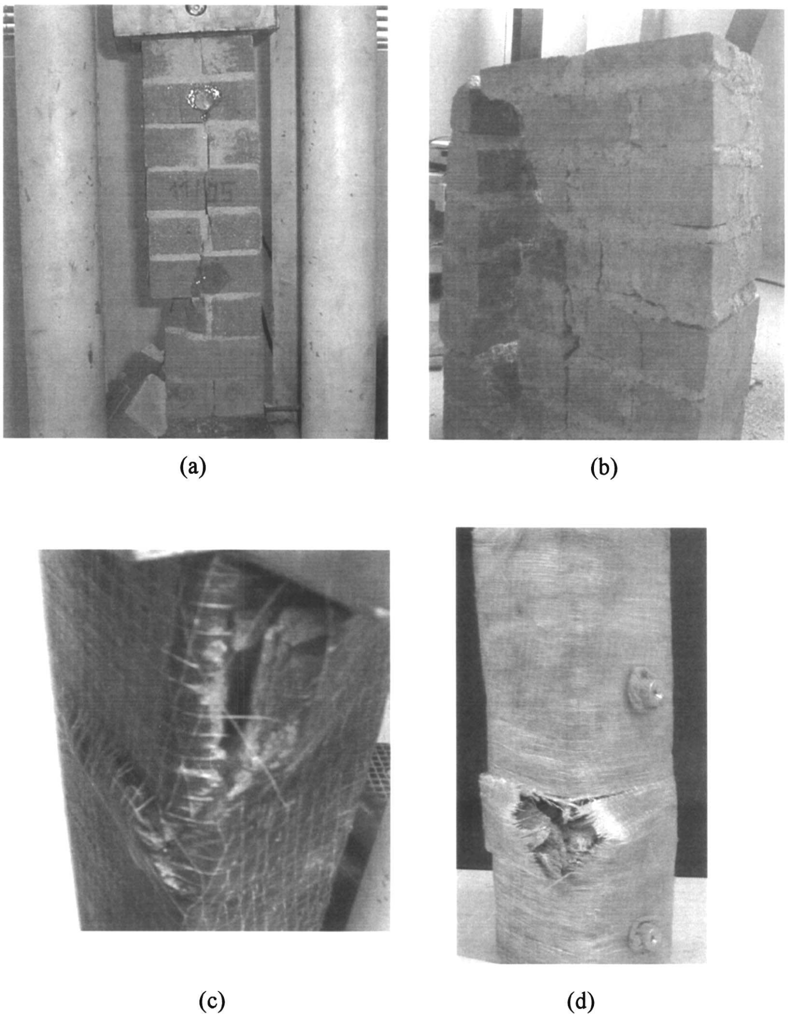


Figure 3.18: Failure modes of unconfined and FRP-confined masonry: (a) vertical cracking in specimens with square cross section; (b) vertical cracking in specimens with cross section aspect ratio 2:1; (c) fracture of CFRP at corner; and (d) fracture of GFRP at corner (Krevaikas and Triantafillou, 2005)

Type of fibers: CFRP has more modulus of elasticity and tensile strength over GFRP. As far as axial stiffness in the hoop direction is concerned, five layers of GFRP fall somewhere between two and three layers of CFRP. Yet the effectiveness of GFRP jackets with five layers is superior to that of CFRP, even compared with the three-layer CFRP jacket. This proves that the higher deformability of glass fibers, compared to carbon, makes them more effective as jacketing materials if comparisons are made for the same stiffness (Krevaikas and Triantafillou, 2005).

In general, FRP-confined masonry behaves very much like FRP-confined concrete. The confinement provided by FRP improves considerably both the load-carrying capacity and the deformability of masonry columns of rectangular cross section.

So, the gain in performance strength and deformability increases almost linearly with the average confining stress. Increasing the corner radius or decreasing the cross-section aspect ratio is beneficial to the strength and strain capacity of rectangular masonry columns. Being more deformable, glass fibers are more effective than carbon fibers if the gain in strength and deformability is compared for the same FRP hoop stiffness.

3.3.3 Rectangular column: Bed joint reinforcement

The bed joint reinforcement technique is based on the insertion of reinforcing bars in the mortar bed joints previously excavated and then refilled by a repointing material. It is particularly feasible for masonry having regular courses. For very thick columns such an intervention can be more effective if performed on both sides, which can be connected by steel ties crossing the column section.

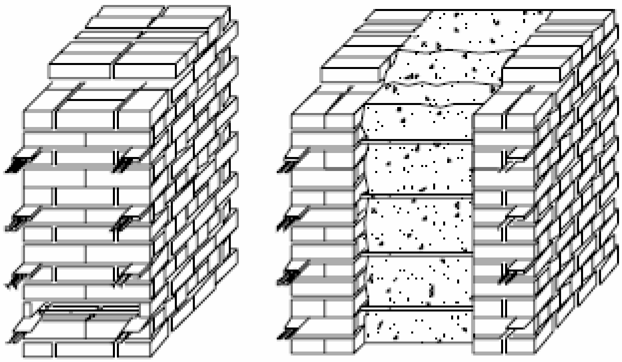


Figure 3.19: Bed joint reinforcement (Valluzzi,Disarò and Modena 2003)

The main scope of the technique is to control the dilatancy of the material under creep conditions, but other favorable effects can also be achieved: in the case of multi-leaf columns, for instance, the presence of the transversal ties could prevent the out-of-plane detachment of the external leaves; moreover, the technique can be successfully applied when the control of cracking due to differential settlements and/or thermal and moisture movements is required.

Main phases of the intervention:

a) excavation of the mortar joint ,
b) insertion of reinforcing bars (FRP or steel) in the bed joints
c) refilling by the repointing material and
d) Inserting anchorage devices

(a) excavation of the mortar joint

(b) insertion of reinforcing bars in the bed

(c) Refilling by the repointing material

(d) Inserting anchorage devices

Figure 3.20: Application of bed joint reinforcement (Valluzzi, Disarò and Modena, 2003)

Unreinforced panels:

- Diffused crack pattern on largest sides and superior detach.
- Concentrated cracks in the thick.

One-side reinforced:

- Reduced cracks on the strengthened side

Both sides reinforced:

- Lower and better diffusion of damage in the main sides

For increase flexure strength some vertical bar can be placed.

3.3.4 Numerical example of calculation of ultimate load

A very simplified and less precise example is presented with a hypothetical square column of 0.3m by 0.3m. The concept of this example is based on the research of Corradi et al, (2007). Some factors such as corner radius, effective area have been neglected for complexity. This will lead a conservative model. The fundamental parameters are as follows

f_{md} = confined masonry (strengthened specimen) compression strength = ?

f_{md0} = un-confined masonry compression strength = 12 MPa

A_m = cross-section area of masonry element = 0.3 m * 0.3 m = 0.09 m^2

N_{u0} = ultimate load capacity of un-confined masonry

N_{uc} = ultimate load capacity of confined masonry =?

k_1 = confinement coefficient = 2.0 (assumed)

f_1' = effective confinement stress = ?

CFRP thickness, t = 0.585 mm (one layer)

f_{FRP} = tensile strength of CFRP = 4600 MPa (assumed high strength fiber, its strength varies from 4100-5100 MPa), (CNR-DT 200/2004)

An element subjected to a uni-axial stress is characterized by an ultimate load capacity N_{u0} equal to

$N_{u0}=A_m * f_{md0}$ = 0.09 m^2 * 12 MPa =1.08 MN (i.e. the un-strengthened specimen can be able to resist this amount of compression load)

where A_m represents the cross-section area of the masonry element. The presence of a transversal confinement action is evidenced by an increase in the maximum strength to mono-axial compression, which is more or less proportional to the confinement stress acting on the element. Such behavior can be expressed synthetically by the following expression, which relates the strength to mono-axial compression of a confined element f_{md} to the strength of an un-confined element and the effective confinement stress, f_1' applied:

$$f_{md} = f_{md0} + k_1 * f_1' = f_{md0} + f_1$$

and therefore the load capacity N_{uc} of the confined element will be equal to

$N_{uc}=A_m * f_{md}$

The confinement coefficient k_1 can assume different values ranging from 1.9 to 4.1, according to the material and the typology of the applied reinforcement (Corradi et al, 2007).

Describing the behavior of the element under applied loads turns out to be particularly difficult and many different approaches have been tried in the past. By simple considerations of equilibrium on the confined cross-section and assuming the hypotheses of a perfect bonding between FRP and masonry, an elastic behavior of FRP up to failure, it is possible to obtain the equivalent confinement stress f_1. In particular, for a square cross-section with un-beveled edges wrapped with a sheet of thickness t and with FRP tensile strength f_{FRP} the following expression results (Corradi et al, 2007).

$$f_1 = \frac{\sqrt{2} * t * f_{FRP}}{b} * k_1$$

where k_1 is a coefficient which takes into account the increment of FRP stresses at the edges, b is the side of the square column, f_{FRP} is the tensile strength of the FRP materials.

Calculation:

Step 1: Find out basic data

f_{md0} = un-confined masonry compression strength = 12 MPa

A_m = cross-section area of masonry element = 0.3 m * 0.3 m = 0.09 m^2

k_1 = confinement coefficient = 2.0 (say)

CFRP thickness, t = 0.585 mm (one layer)

Environmental conversation factor = 0.85 (agressive environment, CNR-DT 200/2004)

f_{FRP} = tensile strength of CFRP = 4600 MPa * 0.85= 3910 MPa

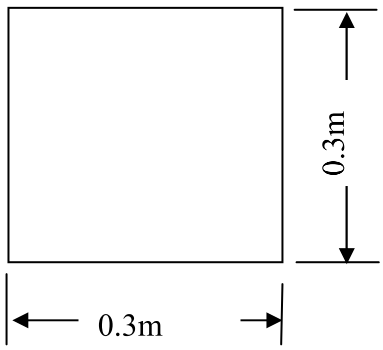


Figure 3.21: Cross-section of the hypothetical column

Step 2: Calculation of confinement stress

$$f_1 = \frac{\sqrt{2} * t * f_{FRP}}{b} * ki = 22.06 \text{ MPa}$$

Step 3: Calculation of confined masonry compression strength

f_{md} = f_{md0} + f_1 = 12 MPa + 22.06 MPa = 34.06 MPa

Step 4: Calculation of ultimate load capacity of confined masonry

N_{uc}=A_m * f_{md} = *0.09* * 34.06 =*3.0655 MN*

Result:

Increased load = *3.0655* MN – 1.08 MN = 1.985MN

% increase = 183

So, the strengthened column will be able to support additional 183% of load.

3.3.5 Application

Retrofitting projects such as Palazzo dei Celestini and the St. Giorgio Church (Lecce, Italy) have shown the great potential of the use of FRP materials for the structural rehabilitation of historic masonry structures (La Tegola et al. 2000). These projects have also shown the versatility of FRP materials in the retrofitting of masonry columns. In Palazzo dei Celestini, which is a building of the XVI century in natural masonry blocks, a column was in serious danger of collapse and presented wide vertical cracks that indicated imminent crushing failure. The retrofitting strategy consists of providing confinement with FRP laminates and inserting FRP rods as dowels to increase the effectiveness of confinement and to prevent the expulsion of masonry pieces under high axial loads (Figure 3.22).

Figure 3.22: Strengthening of Columns (Tumialan et al. 2001).

Laboratory tests shows an increase of above 200% in compressive strength for the columns strengthened with laminates and rods as compared to the control specimens. An increase of about 50% compared to the simply wrapped columns is reported (Tumialan et al, 2001). The short time for the repair and the preservation of the aesthetics in the above mentioned cases can be considered as an example in which the retrofitting with FRP materials is the only solution that can guarantee the desired results.

3.4 Arches and Vaults

Among the structural components in masonry buildings, arches and vaults deserve particular attention. They are very widespread in European historical centers, and their preservation as part of the cultural heritage is a very topical subject. Because of their ages or for accidental causes (such as earthquakes), these structures can suffer several types of damage, so the contribution of strengthening materials and repair techniques may be required to re-establish their performances and to prevent the brittle collapse of the masonry in possible future hazardous conditions.

3.4.1 Behavior of Arches and Vaults

The stability and the safety of curved structures under a given loading condition is strongly dependent on the geometry of the structures and on the mechanical characteristics of the constituent material. The masonry has a well-known negligible tensile strength, so the safety condition for masonry arches or vaults is achieved when the line of thrust, coincident with the funicular polygon, is kept inside of each section of the arch itself. When the resultant of the internal forces moves outside the central core, the section partialises and a phase of high deformations starts (Heyman,1982).

The consequence of that is the formation of a plastic hinge, which exhibits the crushing of a limited portion of the masonry at the compressed edge of the arch. When the number of the plastic hinges is equal to or higher than four, the structure becomes labile and the collapse occurs. Figure 3.24 shows the trend of the line of thrust and the failure pattern of an un-strengthened arch under two different loading conditions: vertical load *Q* concentrated in the middle of the arch [Figure 3.23 (a and b)] or applied to 1/4 of the span of the structure [Figure 3.23 (c and d)]. For a given arch, the latter load condition is the most unfavorable.

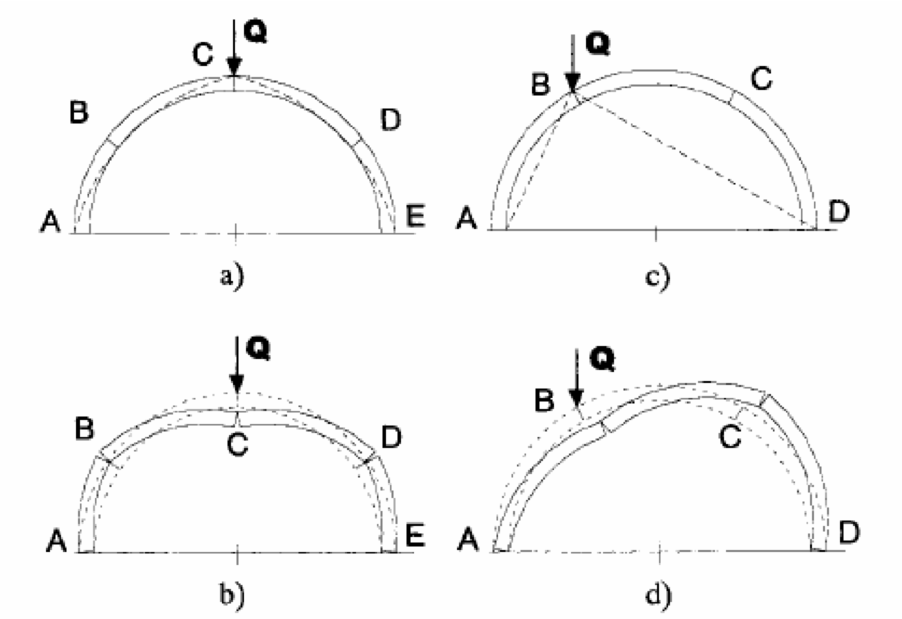


Figure 3.23: Thrust line and collapse mechanism of un-strengthened arch for vertical load applied to: (a, b) Middle of arch span; (c, d) 1/4 of arch span (Valluzzi et al, 2001)

The consequence of these assumptions is that failure of a masonry arch theoretically occurs by formation of a sufficient number of hinges transforming the arch into a mechanism, and stability under given loads depends essentially on the geometry of the structure. From the kinematics' standpoint, the effect of the FRP composites is to inhibit the formation of the hinges. At a location where the FRP sheet is bonded, no hinge can open on the opposite side of the arch thickness. Depending on the extension and location of the strengthened portions of the arch and on the loading pattern, the formation of hinges may be either altered (i.e. hinges form at different locations than in the un-strengthened arch) or completely prevented. Therefore, the capacity of the arch may be controlled by local failure mechanisms depending on material properties, such as masonry crushing, sliding of mortar joints, and FRP debonding or rupture.

From the static standpoint, the presence of the FRP reinforcement allows the line of thrust to fall outside the thickness of the arch by introducing tension resistance. The importance of this theorem lies in the fact that the thrust line found in this way need not to be the actual thrust line.

3.4.2 Mechanism of failure

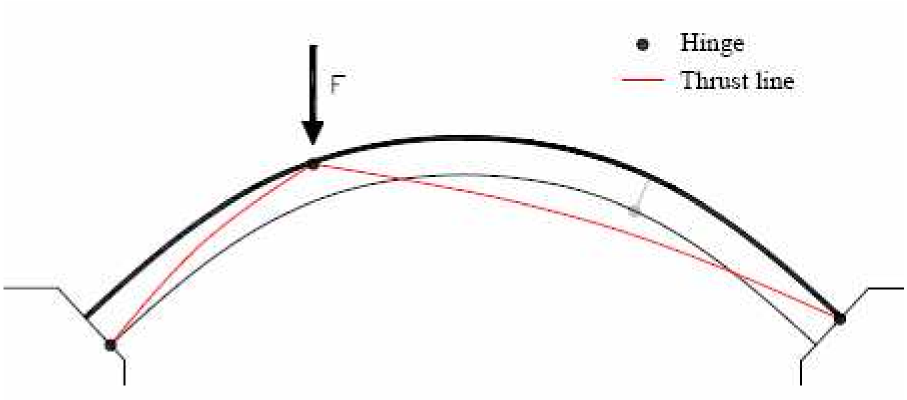
It has been seen that the application of the strengthening material modifies the static behavior of the arch by inhibiting the formation of the fourth plastic hinge. Therefore, the collapse of the structure is due to other mechanisms, which are dependent on the limits of strength of the constituent materials (original vault and reinforcement) and on the structural interactions of them at the local level. The following possible mechanisms of collapse generally happen.

- Crushing of the masonry
- Detachment of the adhesion system
- Masonry sliding due to shear stresses
- Tension rupture of the FRP reinforcement (Generally expected but very rare)
- Hinged mode (for un-strengthened arch and vaults)

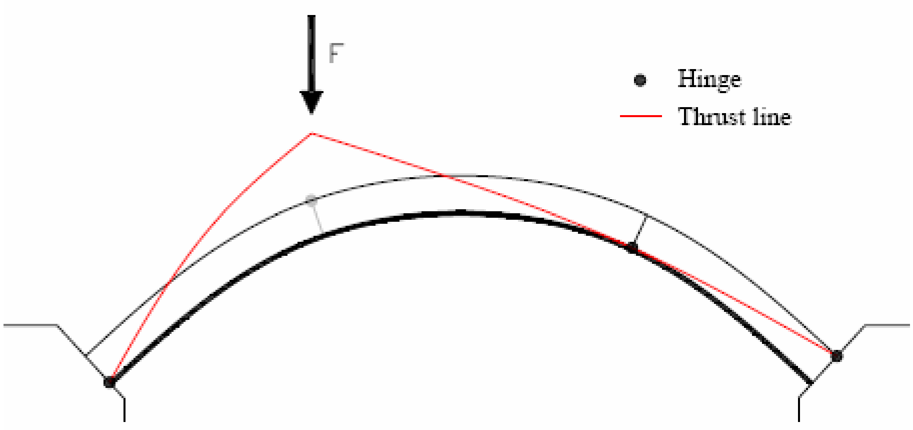
3.4.3 Strengthening

The presence of FRP strips applied at the intrados or at the extrados of the vaults alters the mechanism of formation of the plastic hinges, because the fibers can bear the stresses occurring at the tensed edges. In those sections (which are in combined compressive and bending stresses), as for concrete structures, the resistance depends on the masonry compression strength and on the fiber tensile strength. In any case, the resistant mechanism is substantially enhanced. The effects of the application of the fibers at the extrados or at the intrados of the structure are described below. In the case of external strengthening [Figure 3.24 (a)], the line of thrust can fall outside the lower edge of the vault without any structural collapse. For the case of a vertical load applied to 1/4 of the span, the hinge formation in the B position is prevented.

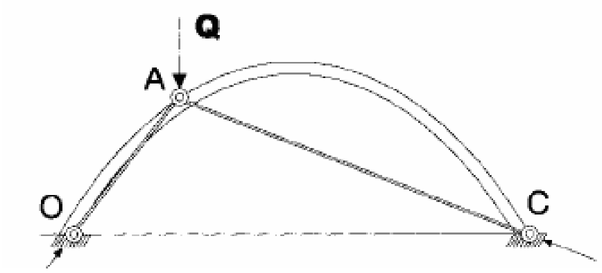
As a consequence, the vault becomes an iso-static structure (it is a three hinges arch) consisting of two curved beams strengthened on their upper sides [Figure 3.24(c)]. Such a scheme allows one to obtain the stress parameters in every section of the structure by simple geometrical and equilibrium relationships. Figure 3.25 shows how stress parameters vary along the abscissa of the vault.

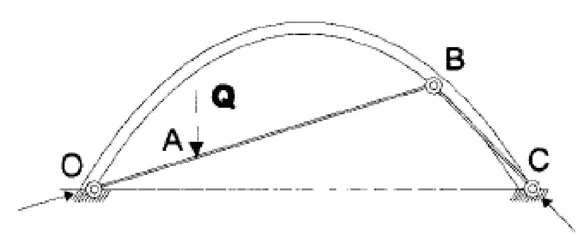


a) Thrust line for extrados strengthening



b) Thrust line for intrados strengthening





c) Static scheme for extrados strengthening d) Static scheme for intrados strengthening

Figure 3.24: strengthening of arches at extrados and intrados (Valluzzi et al, 2001)

In the case of a structure strengthened at the intrados, the distribution of the stress parameters is very different. First, as shown in Figure 3.24(b), the line of thrust falls outside the upper edge of the structure and the fibers prevent the hinge formation close to the point of application of the load. As a consequence, the external load is no longer in a nodal position, so the trend of the stress parameters along the vault is as shown in Figure 3.25 In particular, comparing the two cases, the flexural moment changes its sign and the shear stress at the springers is reduced.

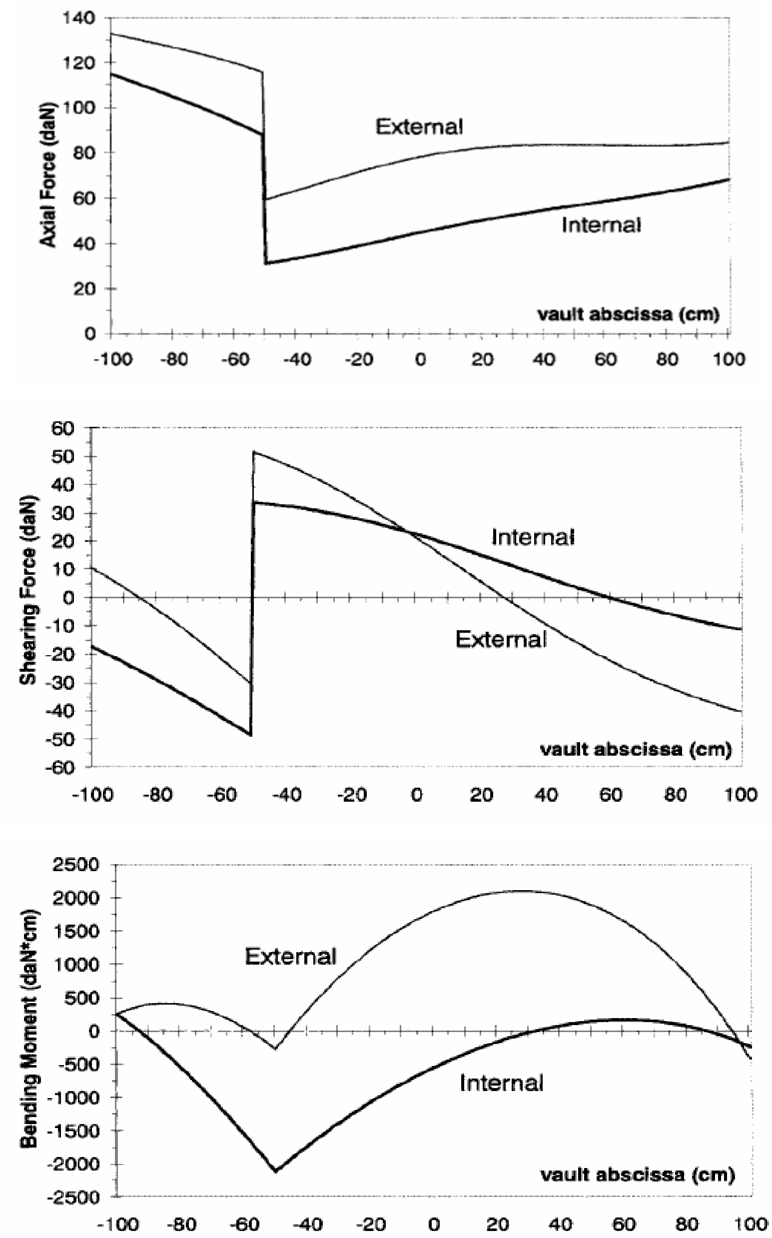


Figure 3.25: Trend of stress parameters for internal and external reinforcement after strengthening (Valluzzi et al, 2001)

Tests Evidence

a) Strengthening at Extrados

As for the vaults strengthened at their extrados, despite different fiber types being used, all specimens fail because of the sliding between brick and mortar in the first joint closest to the springer (see Figure 3.28). Moreover, the collapse occurs without any warning as the weakest point of the structure is the hinge closeness to the springer (Bati and Rovero, 2008, Valluzzi et al 2001).

Figure 3.26: Global deformation (Valluzzi et al. 2001)

Figure 3.27: Effect of excessive confinement (Valluzzi et al. 2001)

Figure 3.28: Failure mechanism detected in tests (sliding failure) (Valluzzi et al. 2001)

A solution that can avoid such a brittle type of failure and, at the same time, optimize the quantity of the applied FRP can be the increase of the surface of the reinforcement only in the proximity of the springers. The application of a larger width of the fibers strips would involve a better resistant area able to prevent the sliding. For extrados strengthening it is found that an increase of ultimate loads of 1215%, 1484% and 1808%, respectively, for 1.25, 2.5 and 5-cm-wide CFRP reinforcements (Bati and Rovero, 2008).

In real situations, the presence of a lateral fill can modify the failure mechanism of the vaults. The fill can cause the raising of the point of formation of the plastic hinge without modifying the load carrying capacity of the structure. Furthermore, it is observed that the distance between the strips and their width can influence the mechanism of failure (Blasi and Foraboschi 1994, Foraboschi and Blasi 1996).

In the case of the carbon strengthening, a secondary effect of excessive confinement has been observed, with a consequent ‘‘transversal’’ deformation (Figure 3.27). The combination of the small width of the strips and of the high modulus of elasticity of the fibers provokes an uneven distribution of stresses with concentration in the limited zone located underneath the reinforcement. Such phenomenon contributes to a decrease in the global resistance (Valluzzi et al 2001). The glass fibers, in fact, despite their lower mechanical characteristics against the carbon ones, have involved a higher increase of strength.

b) Strengthening at Intrados

As regards the cases of application of the fibers at the intrados of the vaults, the detachment of the adhesion system from the masonry in the proximity of the loaded section is detected as a mechanism of failure in the ultimate phase of loading. Anyway, the structure does not reach a state of collapse because the fibers contributed to holding the bricks together (Valluzzi et al 2001). Because the ultimate strength of the structure depends on the adhesion between fibers and masonry, it is necessary to verify the possibility of detachment of the system before its application.

Moreover, because the component perpendicular to the fibers, which is responsible for the failure, is proportional to the tension in the fibers, it should be better to employ fibers not having a high strength and, at the same time, increase the width of the strips. Comparing to the un-reinforced arch load, the collapse load exhibits an increment of 691%, 904% and 1362%, respectively, for the 1.25, 2.5 and 5-cm-wide CFRP reinforcements, (Bati and Rovero, 2008). From Figure 3.30 it is clear that or the arches with reinforcement at the intrados, the kinematic ductility decreases with an increase in the strip width, while it increases for the arches with reinforcement at the extrados.

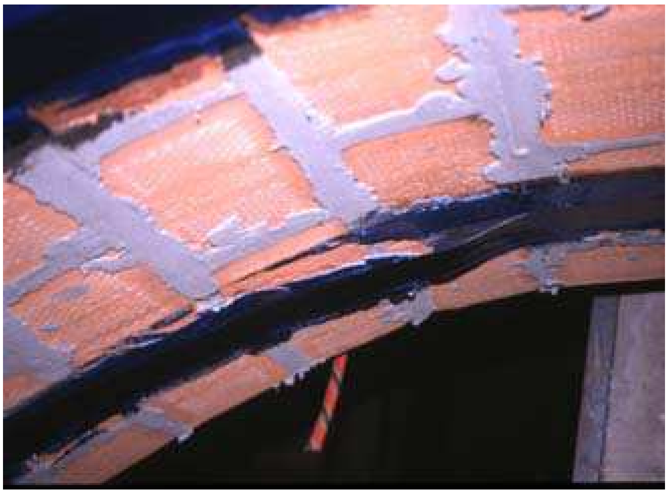
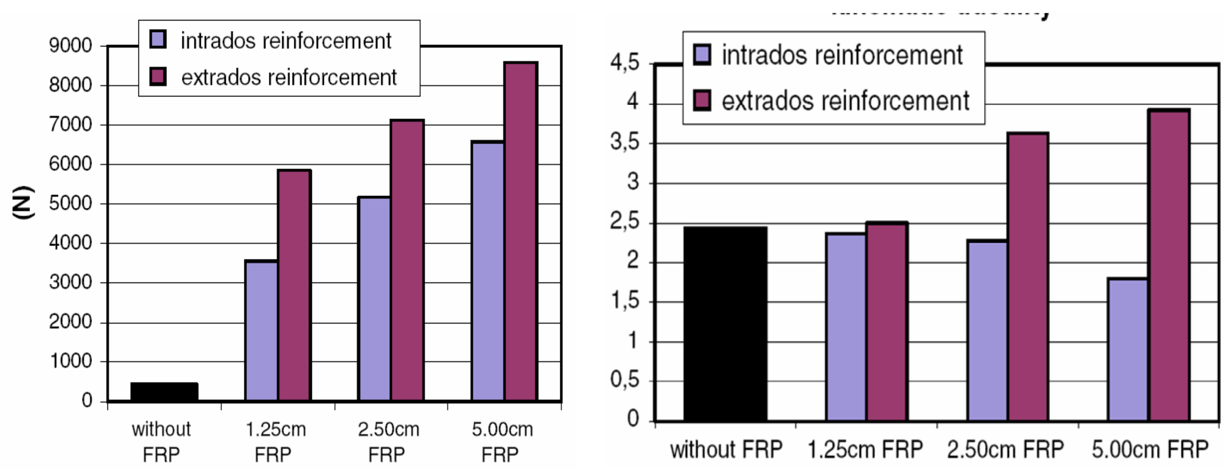


Figure 3.29: Detachment of Fibers (Valluzzi et al 2001)

Vaults strengthened at their intrados reveals a more ductile mechanism of failure because of the detachment of the fibers perpendicularly to the masonry interface but the kinematic ductility is greater for the arches strengthened at the extrados. Figure 3.29 shows the typical failure mode (detachment) of intrados strengthened vaults. The failure is located in a limited zone, so the binding action of the strips can still avoid the collapse of the structure.



Peak loads Kinematic ductility

Figure 3.30: Comparison of intrados and extrados strengthening (Bati and Rovero, 2008).

Comparing between intrados and extrados reinforcement (Figure 3.30) with the same width, points out that the extrados reinforced arches are stiffer than the intrados reinforced ones. The collapse loads of the extrados reinforced arches are greater than those of the intrados reinforced arches (Bati and Rovero, 2008).

3.4.4 Reducing lateral thrust

Fiber-reinforced polymer (FRP) composites are being increasingly used for rehabilitation and strengthening of masonry structures and, in particular, to strengthen masonry arches and vaults against their most critical failure mechanisms. The FRP reinforcement, introducing tension resistance, allows the line of thrust to fall outside the thickness of the arch. This fact has two important consequences: the capacity of the arch itself is increased, and the lateral thrust transmitted to the piers is reduced, thereby increasing the capacity of the ‘‘arch and piers’’ system. So while designing strengthening with FRP reducing lateral thrust is also should be considered.

Vaults are usually subjected to symmetric loading, as a result of the large dead-to-live load ratio. Hence, collapse of a vault typically occurs when no tie-rods or tie-beams are adopted and the piers are unable to bear the thrust of the vault.

The application of FRP reinforcement to a masonry arch allows a substantial reduction of the lateral thrust transmitted to the piers. The FRP reinforcement should be placed either at the intrados spanning an angle centered at the crown (Figure 3.31), or at the extrados spanning two angles from the abutments towards the haunches and anchored at the abutments (Lorenzis et al, 2007).

Figure 3.31: Strengthening of the vaults with FRP sheet. (a) FRP spike; (b) the spikes are inserted through the sheet into the holes; (c) picture of the vault after completion of strengthening. (Lorenzis et al, 2007)

The complete elimination of the thrust is possible when the amount of reinforcement is such that the ultimate moment of the strengthened masonry cross-section under pure bending equals the maximum moment of the external load (Paolo Foraboschi, 2004, Lorenzis et al, 2007). In this condition, the arch behaves like a beam. The amount of reduction of the minimum thrust may be limited by the insufficient extension of the reinforcement or by the possibility of sliding of the mortar joints.

Strengthening the four lateral arches of an edge vault with FRP sheet at the intrados produces a significant reduction of the thrust transmitted to the piers. The use of FRP anchor spikes is effective in preventing debonding of an FRP sheet applied at the intrados of a masonry arch. The application of FRP at the intrados can then be regarded as an effective solution. In many cases, strengthening of a vault at the extrados is unfeasible or significantly onerous, as it implies removal of floor finishes and spandrel fill.

3.4.5 Application

1. **St. Fermo Church, Verona, Italy**

Intervention on the vault of the Brenzoni chapel by means of external bonded FRP laminates,

Figure 3.32: St Fermo church, Verona, Italy

The procedure includes

a. Preparation of the surface where FRP will be applied

b. Smoothing and cleaning of the surfaces

c. Application of the FRP materials

d. UV Protection

a. Preparation of the surfaces

b. Smoothing and cleaning

c. After Application of FRP

d. UV Protection

Figure 3.33: Repair action in St. Fermo Church (Valluzzi et al 2001).

2. Villa Bruni – Padova, Italy

The vault is made of clay bricks masonry. It's a barrel vault around 13 centimetres thick, with a low rise vs span ratio. The procedures include

- Removal of the filling present on the central sector and positioning of timber frame. Application of carbon fiber laminates on the extrados of the vault lateral sectors.
- Application of the FRP on the intrados of the central zone. Figures 3.34 to 3.37 show the different steps of FRP application to the vaults.

Figure 3.34: Villa Bruni – Padova

Figure 3.35: Cracks in the vaults

Figure 3.36: Repairing action

Figure 3.37: Application of FRP

2. **San Giorgio Church, Italy**

In San Giorgio Church the arches and vaults showed a remarkable level of damage due to the settlement of the columns. The same phenomenon caused high states of stresses in the masonry walls, creating a possibility of imminent local crushing.

Figure 3.38: Strengthening of Masonry Vaults (Tumialan et al, 2001).

FRP tendons were chosen to take the drift of the arches. FRP laminates were used to bridge the existing cracks in the vaults (see Figure 3.38). As a result of the very small thickness of the laminate, no sign of intervention is visible on the surface after plastering. In this case, the FRP strengthening system was applied in the internal side of the vaults. Strengthening strategies have also involved applying FRP laminates in the external side of the vaults. This solution was necessary for the repair of San Francesco Cathedral (Assisi, Italy) after the earthquakes in 1997. This was necessary because the internal surfaces were covered by ancient frescos executed by Giotto that could not be altered. (Tumialan et al, 2001). The short time for the repair and the preservation of the aesthetics in the above mentioned cases can be considered as an example in which the retrofitting with FRP materials was the only solution that could guarantee the desired results.

3.5 Anchorage

For near surface mounted FRP method no anchorage is needed as it is inserted inside groove and plastered after pasting. But for surface reinforcing method anchorage plays a significant role for strengthening. Being FRP is a brittle materials anchorage with FRP bars is generally brittle.

3.5.1 Brittle Anchorage

The non ductile anchorage methods utilized the following three techniques

(a) Improved bonding

- walls are ground to produce a rough surface finishing

(b) Anchoring with steel bars

- Grooves of are made along the four sides of a wall with some distance from the edge.
- It should have sufficient width and depth to accommodate the desired bars
- The first layer of the FRP sheet is bonded to the wall surface.
- Steel bars are placed onto the FRP sheet and pushed into the grooves.
- Then the second layer of FRP sheet is bonded onto the first sheet, with excess epoxy placed in the grooves
- Then the steel bars are again pushed into the grooves and held firmly in place until the FRP system had hardened.
- Finally, the grooves are filled with epoxy to produce a level surface (Figure 3.39).

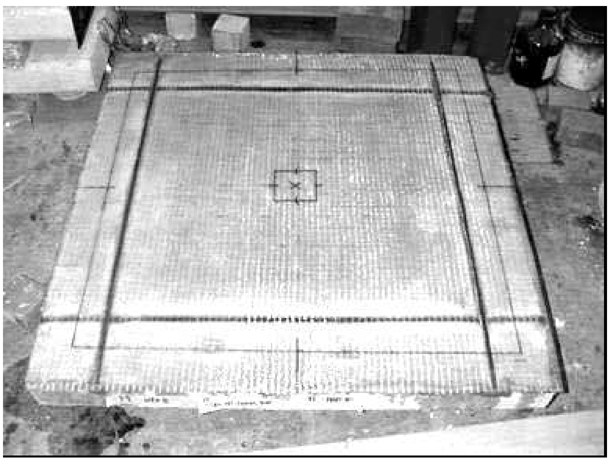


Figure 3.39: Layout of embedded steel bar anchorage system. (Tan et al, 2003)

Figure 3.40: Layout of FRP bolt anchorage system (Tan et al, 2003).

(c) Bolt anchorage system

- First bonding the first layer of FRP on to the wall surface
- Making inclined holes of 50mm deep and 10mm diameter are drilled into the wall at specific locations
- The holes are then filled completely with epoxy
- inserting of the glass fiber bolts
- the bolts are then spread out evenly and coated with epoxy before the second FRP sheet is applied
- Rollers are used to remove any trapped air bubbles in the FRP system (Figure 3.40)

Load–Deflection Behavior

The relationship between load and deflection cease to be linear near the ultimate load. After the ultimate load is reached, the load carrying capacity of the specimens is reduced drastically.

Failure Characteristics

Specimens without any anchorage generally fail prematurely. Premature failure occurs when the applied load produces high bond stresses between the FRP sheet and the masonry substrate, causing delamination of the FRP reinforcement and a flexural collapse of the wall. The delamination is due to poor bond capacity between the adhesive and the wall; hence the failure can be characterized as adhesive failure. In the case of fiber bolt anchorage system, debonding of the FRP laminates is observed at failure around the edges of the wall (Tan et al, 2003). In bolt joint anchoring, failure occurs generally by punching shear. The failure is accompanied by a loud bang, being more sudden with more layers of FRP reinforcement.

Test evidence of Surface Treatment and Anchorage Systems

It is seen that the surface grinding leads to an increase in ultimate strength of about 429% and 209% for glass and carbon FRP systems respectively. Steel bar anchorage system coupled with surface grinding resulted in an increase in ultimate strength over the control specimen of about 366% and 223% respectively for glass and carbon FRP systems. This increment is about 487% for glass and 262% for carbon FRP systems, respectively, using the glass fiber bolt anchorage system together with surface grinding (Tan et al, 2003).

The increase in strength for specimen reinforced with two layers of glass or carbon fiber sheet is about 470% as compared to about 390% for specimen reinforced with two layers of fiber glass woven roving. The load carrying capacity is further increased with the increase in the amount of FRP reinforcement. This increase is about 700, 510 and 660% for four layers of glass, carbon and woven roving reinforcement respectively (Tan et al, 2003). It is interesting to note that the increase in load carrying capacity of the specimen reinforced with four layers of carbon fiber fabrics is much lower than all the other specimens.

Effect on ductility

The ductility of a wall without any surface treatment is found to be higher than the wall with surface grinding for both types of FRP systems. Since both carbon and glass FRP are brittle materials, the application of these FRP sheets to the masonry walls will lower the ductility of the walls. The ductility of the wall with fiber bolt anchorage system is slightly higher than that of the surface ground specimens for glass FRP systems, but is slightly lower for carbon FRP systems. Steel bar anchorage system results in lowest ductility for both carbon as well as glass FRP systems (Tan et al, 2003). It can be concluded that the combination of surface grinding and fiber bolt anchorage system would result in the highest strength enhancement. Steel bar anchorage system leads to lower strength as well as the ductility of the wall due to the localized failure along the steel bar.

3.5.2 Ductile FRP Strengthening

Although FRP composites increase lateral load capacity, they do not significantly improve ductility and may actually decrease ductility if an undesirable failure mode is precipitated. This is due to the brittle nature of the composite material. Holberg and Hamilton (2002) proposed a hybrid system, consisting of bonded FRP composites in conjunction with steel. The FRP composite adds sufficient strength to the masonry allowing the steel to reach yield, thus incorporating ductility into the system. The internal connection can be a steel reinforcing bar placed in the outermost cells of the wall and fully grouted into a concrete foundation. The external connections can a steel angle- plate assembly attached to the foundation. The drift capacities of the reinforced specimens reached up to 1.7%. The lateral capacities of the strengthened specimens are nearly doubled when compared to the lateral capacity of an un-strengthened specimen (Holberg and Hamilton, 2002). The procedure includes

- Grouting reinforcing steel bars into the foundation and into the URM wall a short distance to provide a pin connection. FRP is then applied to the exterior of the wall over the grouted cell containing the reinforcing bar, creating a ‘‘lap spice’’ between the FRP and the bar. (Holberg, 2000)

- Vertical strips of carbon laminates can be adhered to the URM wall and anchored to the foundation using different anchoring techniques. One with a continuous structural steel angle anchorage retrofits on one side and a Simpson Tie anchorage on the other. The other one with a concrete fillet placed on both sides. One fillet is flat while the other is contoured. Both concrete anchorage systems are anchored through the footing and through the wall with bolts. The simpson tie approach shows much more ductility. (Laursen et al. 1995).

The ductile connection is designed to yield prior to failure of the FRP composite. Adequate strength must be provided in the masonry surrounding the dowels to ensure yielding at the pier/base interface and prevent a pull out failure. In addition to confinement of the dowels, the masonry below the pier requires strengthening against flexure and shear induced by the tensile forces in the dowels. In Figure 3.41 it is shown how the steel bars are anchored to the FRP system.

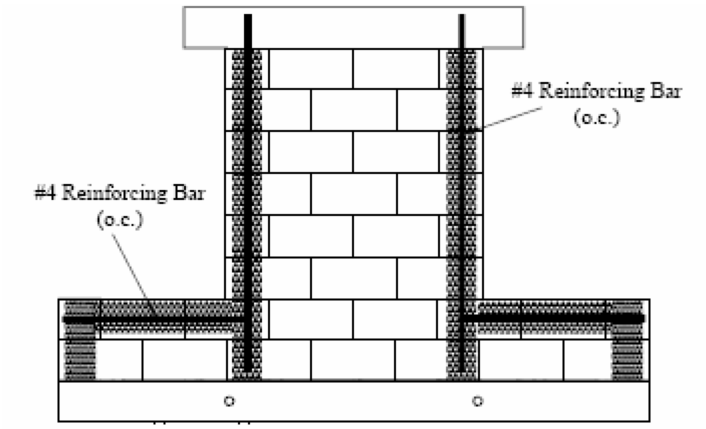


Figure 3.41: Typical reinforced structures (Vanessa E. Grillo , 2003,)

Test evidence

Improvement in the ductility, lateral capacity and energy dissipation are achieved by adding a FRP/steel strengthening system to the specimens. A drift ratio of 1.8% is possible and changes in specimen stiffness (from 10% to 20%) are observed at a drift ratio of 0.1% during testing as the specimens sustained damage through cracking, yielding and debonding of the FRP composite. Yielding is achieved for the specimens that has FRP composite sheets confining the steel reinforcement in the masonry base against bar pull out (Vanessa E. Grillo , 2003,).

3.6 Creep of masonry strengthening with FRP laminates

3.6.1 Creep of masonry

Creep is a load and time dependent inelastic strain under sustained load. Creep problems in masonry are usually associated with high compressive stresses in the lower walls of tall multi-storey buildings. Shear walls and flexural walls carry earthquake or extreme wind loads, causing no long-term stresses that might lead to creep. Basement and retaining walls, two other common uses of structural masonry, do resist sustained lateral loads from soil and ground water pressure. The flexural creep incurs from these sustained loads results in increased flexural deformations. Little information is available on the creep of flexural walls, which is likely due to the lack of problems that are encountered in typical applications. Structural masonry is generally used in bearing walls and columns where the masonry experiences axial creep due to the sustained gravity loads or prestressing.

3.6.2 Creep of composites

Individual fibers of carbon, glass and aramid do not creep significantly, but the matrix material does .The most common type of creep test is the axial tension test performed on a variety of orientations of glass, carbon and aramid fibers [Scott, Lai, Zureick 1995]. These tests have yielded very low creep values when the fiber is oriented in the direction of the applied load. The creep of laminated composites is accurately modeled using only the matrix creep data. The conclusion that is drawn from this information is that the creep of a composite system is independent of the fibers and dependent upon the matrix material and fiber orientation (Harris JS, Barbero, 1998).

3.6.3 Increased curvature and deflection

Increases in out-of-plane deflections due to creep will depend on the sustained level of stress in the materials. These sustained stresses cause an increase in strain without additional stress. In flexural members, this time-dependent increase in strain will cause the curvature to increase resulting in additional deflections.

Additional deflections caused by creep in FRP laminate are strongly influenced by the type of matrix (epoxy) used. Long-term deflections due to creep in FRP reinforced walls are 22–56% higher than those of steel reinforced walls. Experimental ultimate loads are 35–71% of the calculated ultimate load for the specimens reinforced with FRP composites (Stierwalt, H.R. Hamilton III, 2005).

It is found that the additional creep deflections due to the FRP composites are dependent primarily on the type of matrix. Consequently, these values may not be appropriate for systems other than those tested. So it obviously demands further research to identify the matrix which yields lowest creep.

3.7 Durability evaluation

FRP material used for strengthening should be durable in the environment in which it is used for the expected duration of the repair and strengthening. As the majority of the field applications relate to corrosion damage in cold climates, its performance under freeze–thaw conditions is of critical importance. As glass fibre is vulnerable in an alkaline environment, its durability in wrap applications is also a concern. But the application of FRP is a new technology. Its long term behaviour is still unknown. Before applying this issue must be considered as best as possible. It is also affected by a lot of agent listed in Table 3.5; some other agencies have been discussed in chapter two.

Table 3.5: Influencing agents (Desiderio and Feo, 2005)

No	Group of agents	Influencing agents
1	Climate agents	Main temperature, UV exposure, humidity and moisture, freeze-thaw cycles
2	Environmental agents	Chemical agents, exposure to salts, sustained loading
3	Configuration	Shape/lying, extension, presence of discontinuity
4	Technological characteristics	Application surface state, protection

This article focuses on the effects of three of the climatic agents: UV exposure and freeze-thaw cycles and temperatures for CFRP externally bonded to masonry structures.

1) Freeze-Thaw Cycling

In a FRP-interface-masonry composite system, self-equilibrating stresses develop in two cases: differential thermal expansion and contraction of the FRP, interface and masonry and when the distribution of temperature over the cross-section of the FRP is non-linear. In the longitudinal direction, CFRP laminates have a thermal expansion coefficient less then that of the substrate; even negative (Desiderio and Feo, 2005). In regions of drastic temperature changes, this can negatively affect the bond characteristics and lead to the failure of the lamina.

Here an experimental program of Desiderio and Feo, (2005) in accordance of ACI 440 2001 and its outcomes are illustrated. Specimens, made with Naples yellow tuff stones and strengthened with CFRP sheet of 65 mm width and 1.5 mm thickness, was exposed to 50 and 105 freeze-thaw cycles corresponding to 200 and 420 hours of exposure (Figure 3.42). The results are discussed in the next article.

Figures 3.42: Specimens in the climatic chamber subjected to Freeze-Thaw Cycling (Desiderio and Feo, 2005).

Figure 3.43: Specimens in the climatic chamber subjected to UV exposure (Desiderio and Feo, 2005).

2) UV exposure

Ultraviolet radiations rarely degrade the mechanical performance of FRP-based systems, although this may cause some resins to have a certain degree of brittleness and surface erosion. Thus it can affect the performance of bond capacity. In the research of Desiderio and Feo, (2005) the effect of UV on bond capacity is evaluated (Figure 3.43). The experimental values of the first results are summarized in Table 3.6.

Table 3.6: Effect of freeze-thaw cycles and UV exposure (Desiderio and Feo, 2005).

Conditioning type	No. of cycles	Ultimate stress (MPa)	Decay (%)	Failure modality
No conditioning	-	0.43	0	Tuff masonry failure
Freeze-thaw cycles	50	0.39	9	Lamina-substrate failure
UV exposure cycles	50	0.24	44	Lamina-substrate failure

The analysis of the data contained in the table shows the decrease of bond capacity in case of exposure to freeze– thaw cycles or UV. This degradation is also shown in terms of percentage decay of bond capacity with respect to control samples. It is important to note that in non-conditioned samples the failure is always on the tuff masonry, while in the conditioned ones the failure is at the lamina – substrate interface on the epoxy adhesive layer. The decay is higher for the UV exposure (44%) of the samples, the bond stress decrease by 10% for freeze-thaw cycles where as for UV exposure it becomes as high as 44%.

Most freeze–thaw tests on wrapped cylinders indicate that this exposure leads to a reduction in ultimate strength and ductility with little change in modulus. The worst deterioration is caused when the resin attained an initial equilibrium moisture gain and is then exposed to freeze–thaw cycles. In this case, after 450 cycles (daily cycle between 20°C and 188°C), the reduction in strength is 44%. Reductions are lower, 19% for carbon and 28% for glass after 300 cycles between 4°C and 188°C when initial equilibrium moisture is not considered. Exposure of GFRP-wrapped cylinders to alkaline solution (or water) at room temperatures has no effect. This contrasts with the findings for the GFRP used on the Masuhoro Bridge. However at elevated temperatures (65.58°C), exposure to alkaline solution or water is detrimental. Strength reductions are in excess of 25% after 1000 hours of exposure. (Rajan Sen, 2003)

3) Effect of high temperature

Fiber reinforced polymer (FRP) rebars are being used increasingly in construction where ordinary steel reinforcement is not suitable due to highly corrosive environments or where electromagnetic transparency of the structure is required. High temperatures, such as those due to fires or even those occurring in extremely hot climates, may decrease the properties of these rebars. The mechanical properties (especially the strength and the stiffness) of polymers are known to decrease significantly as the temperature is increased and the polymer approaches its glass transition temperature (Katz et al 1999).

The results of an experiment performed by Katz et al (1999) on concrete specimen and strengthened with four types of FRP bars of diameter around 12 mm show a severe reduction in the bond strength as the temperature is raised to 180–200°C. A reduction of 92% is seen for FRP rebars where the bond strength dropped from 13.2 to 1.1 MPa at a temperature of 250°C. The variation of strength with increasing temperature is distinct in Figure 3.44. Though this experimental is purely on concrete specimen the result will be similar to masonry specimen.

Temperature also affects the bond modulus (the slope of load vs. displacement curve), which tends to decrease as the temperature increases. The descending curve of the FRP rebars becomes more linear as the temperature increases, indicating degradation in the polymeric surface treatments that support the bond, leaving the rebar with only a friction mechanism to create a bond (Katz et al 1999).

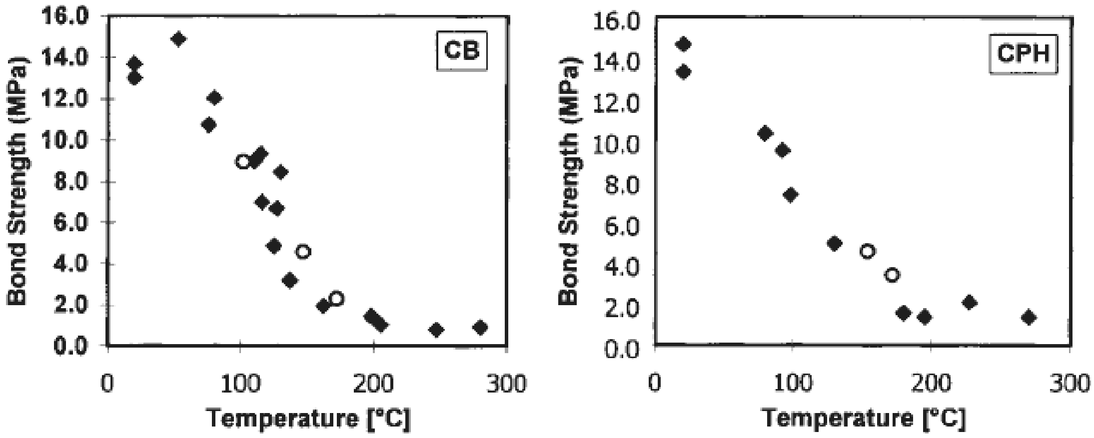


Figure 3.44: Variation of bond strength with temperature increase (Katz et al 1999)

The findings suggest that FRP is suitable in temperate regions where high temperatures and high humidity are present for only a limited time. For applications in warmer regions its use will be dictated by cost considerations. It may be justified if life-cycle costs taking into account possible degradation are lower than conventional repairs.

4) Bond behaviour

For almost all cases, where laminates is used, delamination is the great problem. For NSM bars, this problem is also available. The type of substrate has a great influence both at the ultimate and service conditions; in particular the bond performance depends not only on mechanical properties but also on other physical properties of the masonry. Therefore, considering the great variety of stones and bricks generally utilized for masonry constructions, the need of a wider investigation is needed.

The geometry of specimens has a relevant influence on experimental results. Therefore, an accurate definition of dimensions and strengthening parameters is required to avoid irregular failure and to obtain reliable experimental results. The application of transverse FRP strips does not show an improvement in terms of bond strength and strain values. However, an improvement of strain distribution along the sheet is observed (Aiello and Sciolti 2006). Further analyses are recommended in this area, considering the opportunity of increasing the transverse strips length.

The presence of transverse FRP strips seems to improve the bond performance at high load level. In particular, when transverse reinforcement is added a more effective distribution of strains over the whole length of the sheet is observed, thus reducing the decay of the bond performance near the loaded end.

4 Chapter Four: Discussion

There is great potential for the use of FRPs to strengthen and rehabilitate masonry structures for upgrading its mechanical behaviour against the possible adverse actions. The materials are light weight and very strong. The former is advantageous in not adding weight to the structure while the latter can be very advantageous if used intelligently.

An important aspect to remember that the researches have been done purely on laboratory made specimens. Actual structures are not represented perfectly by these laboratory made specimens, because the laboratory made specimen are an ideal one, and surely with good materials. But the real structures are not homogenous, different masons use different composition. And in laboratory, the specimens cannot be provided the full surroundings of the real one. Again strengthening historical structures is more crucial. The laboratory test results are not fully applicable to them. Also the application procedure for historical structures may be different upon consideration of the sites or cultural issues or architectural problems.

In addition, the surface of the old structures may not be suitable for application of FRP laminates in many cases. In that case NSM (Near Surface Mounted) bars are the only option. Each structure is unique. So, it is not possible to conclude which technique is better. It totally depends on the type of structures and their physical and mechanical condition. Also it is important to note that strengthening only by FRP may not be a good solution. Some times FRP in conjunction with other techniques may be a good solution. So, to implement any techniques of FRP applications, other techniques should also be considered.

Another important aspect is that the bond performance depends not only on mechanical properties but also on other physical properties of the masonry components. Therefore, considering the great variety of materials generally utilized for masonry constructions, the bond properties may differ drastically from masonry to masonry (Corradi et al, 2007). The long term behaviour of FRP strengthened structures is still unknown as it is still a new material. Still no authenticated design guidelines or models have been published for strengthening historical structures. Only by virtue of vast experience, it is possible to do design good intervention and best strengthening actions.

Depending on the discussion on chapter three the summary has been presented in some Tables onwards. Table 4.1 discusses the FRP using configuration and the benefits on walls. It is important to note that the reference have been cited on chapter three, to make the table simple and clear the references are not mentioned here.

Table 4.1: Potential uses and benefits of using FRP on walls

Name	Arrangement	Dimensions	Flexure increase (%)	Shear increase (%)	Ductility increase	Remarks
NSM FRP	Vertical a) 12 in c/c b) 24 in c/c	a) 0.25 inches diameter GFRP bar	a) 1400 b) 400 upto 2600	--	Significantly	De-bonding is frequent failure mode
NSM FRP	Horizontal-every joint	0.25 inches diameter GFRP bar	--	150	up to 200%	For cracked wall
CFRP sheet	One layer in tension side	--	80	--	Drift ratio of 1.6% (approx)	For tall specimen
CFRP sheet	Unidirectional 2 layers	Thickness 0.584 mm each	1200	--	Strain at failure 0.71%.	Combined failure mode
CFRP sheet	2 layers cross-ply	thickness 0.584 mm each	922	--	Strain at failure 1%	Cross-ply is better
GFRP sheet	One layer in tension side	--	Upto 1000	--	Significantly	For out of plane loading
GFRP sheet	One layer in tension side	--	150 to 500	--	Significantly	For in plane loading

Table 4.1 continued

Name	Arrangement	Dimensions	Flexure increase (%)	Shear increase (%)	Ductility	Remarks
GFRP sheet	3 unidirectional layers	Thickness 1.143 mm each	1154	--	strain at failure 1.07%	For out of plane loading
FRP laminate	Single side	--	--	limited increase	Significantly	Diagonal configuration better than square grid set-up
FRP strips	Both sides	Single layer	--	50-65 depending on density	Significantly	45° is better than 90°
CFRP sheet	Both sides	Single	800	400	Significantly	31 times the loads
CFRP sheet	--	Out-of-plane loads up to 32 times the weight of the wall			Deflection 2.5% of height	For out of plane loading
CFRP strips	Cross and grid pattern	Maximum drift 22% for cross and 69% for grid patterns				For low density FRP
GFRP strips	Cross and grid pattern	No change of maximum drift for cross pattern, 16% for grid pattern				For high density FRP

So, it is seen that the FRP bars applied 12 inches c/c (center to center) on vertical alignment yields 14 times more flexural strength. But in this case ductility increase is not as high as in case of FRP laminates. Two layers of CFRP laminates applied in cross-ply increase the flexure strength 9.22 times and yields 1% where as if applied unidirectional yields 12 times strength but ductility only 0.71%. So cross ply is better to gain ductility and strength gain is also high. Here strength is not the main criteria, as failure generally occurs by debonding and with brittle mode. So, ductility should be given a good priority.

For shear strengthening, single sided reinforcement yields no good result. The FRP bar can yield only 80% increase in shear and the one sided laminate can yield 50 to 65% increase in shear. Both sided laminates can yield 4 times shear strength. So, for increasing shear strength both sided laminates are recommended for better performance.

For strengthening circular column complete wrapping always offer the highest compressive strength. But discontinuous wrapping, sometimes, is also good for ductility. As shown in Table 4.2 a column covered 50% with three CFRP strips yields 331% increase in ultimate strain.

Table 4.2: Potential use and benefit of using FRP on columns

Circular columns				
Name	Arrangement	Thickness (mm)	Compressive load increase (%)	Strain increase (%)
CFRP	Continuous wrapping	0.150	93	389
CFRP jacket	2 discontinuous wrapping (50% of surface area)	0.150	15	138
CFRP jacket	3 discontinuous wrapping (50% of surface area)	0.150	73	331
GFRP bars	Inserted through the section	8.00 mm dia bar	80	52
Square/Rectangular columns				
CFRP sheet	Continuous wrapping	0.150	34 (178 in conjunction with concrete)	1250
CFRP sheet	Continuous wrapping 3 layers	0.150	110	200
FRP bar	Bed joint reinforcement	--	Significantly	good

Complete wrapping in conjunction with concrete cover is the best solution for both strength and ductility. But it is also important to remember that it increase the column size and corresponding weight. Also the cultural and architectural issue must be kept in mind. For square and rectangular columns strength and strain largely depends of aspect ratio, corner radius and number of layers. From Table 4.3 it is clear that number of layers has almost the exponential relationship with the strength. For square column, increasing number of layer from 1 to 2 yields strength almost 3 times and from 1 to 3 almost 9 times. Also corner rounding has a great effect. From the table it is also clear that 20mm corner rounding can increase around two times the strength of the initial strengthening. Ultimate strain is also affected by this operation. So while strengthening any square or rectangular column corner rounding is recommended, provided the architect accepts this. Meanwhile, bed joint reinforcement for column strengthening is not so interesting. In ductility increasing it has good contribution, but low contribution in increasing compressive strength.

Table 4.3: Effects of aspect ratio, number of layers and corner radius on rectangular columns (Krevaikas and Triantafillou, 2005).

No of layer(s)	Aspect ratio (h/b)	Strength increase %	Strength increase with 20mm corner rounded (%)	Strain factor	Strain factor with 20mm corner rounded
1	1:1	13	40	10	14
2	1:1	40	100	12.5	21
3	1:1	110	185	20	29
2	1.5:1	80	-	2	-
3	1.5:1	160	-	10	-
2	2:1	90	-	2.5	-
3	2:1	95	-	7.5	-

For arches, strengthening at intrados or extrados by applying FRP strips avoid the formation of the forth hinge and thus prevent collapsing. Also by applying FRP near abutments either at intrados or extrados, the lateral thrust can be prevented. Table 4.4 discuss and summarize the application and outcome of FRP application to arches and vaults. Strengthening at extrados yields greater peak loads and it is also stiffer than strengthening at intrados. But strengthening at extrados is not always possible or may be difficult. Another important thing is the width of the strips; it has a very great effect on the strength. Larger width creates more resistance and consequently increases capacity and ductility.

Table 4.4: Potential uses and benefits of using FRP on arches and vaults

Action	Arrangement	Result/Failure	Ductility	Load increase (%)
Strengthening at extrados	FRP strips are epoxy bonded	Sliding between brick and mortar in the first joint closest to the springer.	Collapse occurred without any warning	1215,1484 and 1808, respectively, for 1.25, 2.5 and 5-cm-wide CFRP reinforcement
Strengthening at intrados	FRP strips are epoxy bonded	Detachment of the adhesion system from the masonry in the proximity of the loaded section	Ductile	691, 904 and 1362, respectively, for 1.25, 2.5 and 5-cm-wide CFRP reinforcement
Intrados spanning an angle centered at the crown, or at the extrados spanning two angles from the abutments	FRP strips are epoxy bonded	The lateral thrust transmitted to the piers is reduced	Ductile	Perfect design can eliminate lateral thrust totally

Comparing between the intrados and the extrados reinforcement (with the same width) points out that the extrados reinforced arches are stiffer than the intrados reinforced ones. The collapse loads of the extrados reinforced arches were greater than those of the intrados reinforced arches.

When choosing a strengthening method, its impact on the aesthetics and activities of the building being retrofitted need to be evaluated. To be completely successful, retrofit work should be carried out with the least possible irrevocable alteration to the building appearance. Many URM buildings are part of the cultural heritage of a determined city or country. Thereby, to preserve their aesthetic and architecture is primordial. The use of NSM FRP rods is an alternative to strengthen masonry walls where aesthetics is an important issue. So, perfect method should be applied with its best consideration. Table 4.5 is a summary of different methods, its purpose and special consideration.

Table 4.5: The type of FRP, design action and special need of each technique

Strengthening method	Design action	Type of FRP	Special consideration
Wet lay up FRP sheets to the tension side of the walls	Flexure strengthening	Strips or sheet	De-bonding
Attaching prefabricated FRP to the tension side of the walls	Flexure strengthening	Strips or sheet	De-bonding
Attaching pre-stressed FRP to the tension zone of wall	Flexure strengthening	Strips	Anchorage
Vertical NSM bar	Flexure strengthening	bars	De-bonding
Horizontal NSM bar	Shear strengthening	bars	De-bonding
Wrapping schemes around the circular columns	Axial compression and ductility increase	Sheet	Confining pressure and overlapping
Wrapping schemes around the rectangular columns	Axial compression and ductility increase	Sheet	Corner rounding
Strengthening at extrados of arches and vaults	Improved ductility	Strips	Larger width
Strengthening at intrados	Improved ductility	Strips	Larger width
Intrados spanning an angle centered at the crown, or at the extrados spanning two angles from the abutments	Reduce lateral loads	Strips	Position of FRP

Any retrofit work involves a series of disruptive activities for the building occupants. Actions taken to strengthen a URM building must consider the operation of the structure both in terms of current and possible future use. Conventional strengthening may require the use of relatively heavy equipment such as welding machines, saws, etc, which can produce dust and noise that can disrupt the normal activities of the building users. The use of FRP laminates can lessen these effects. However, it is recognized that surface preparation requirements prior to the FRP installation can be disruptive. Since the surface preparation for NSM FRP rods is minimum (only grooving of the joints is required), this method would be ideal if the normal operations of the building need not be affected.

The use of new materials brings with it new failure modes and new problems which need to be recognized and addressed. These appear to have been addressed for flexural strengthening of walls and strengthening of arches.

5 Chapter Five: Conclusion and recommendation for further studies

5.1 Conclusion

There is significant potential for the application of FRP's in the masonry industry, both in new construction and for rehabilitation of old structures. FRPs can improve not just the strength capacity of the material, but also the ability to resist crack propagation and retain structural integrity and increase ductility through increased toughness. So, it is claimed that the available methods of FRP application on masonry members such as NSM bars, laminates and post tension are quite effective and pose good potentiality. The flexure strength can be increased up to 26 times by FRP bars and 12 times by laminates. For shear, increases of 4 times by laminates and 1.5 times by FRP bars have been observed. CFRP sheet can increase ductility up to 200% for walls and 1250% for columns. An increase of 1808% and 1362% of ultimate loads can be possible by strengthening with CFRP sheet (5 cm wide) on extrados and intrados of arch respectively. For both new and rehabilitated masonry, the ranges of conditions under which the currently observed modes of failure occur, need to be elucidated: simple analytic methods need to be developed for codification.

5.2 Recommendations for further studies

Researches in strengthening masonry structures are relatively new. Very few researchers are working hard to develop this field. Still now a lot of questions are available in strengthening masonry structures. Some fields which especially demand further research are listed below.

- There is a need to determine the effective strain of the laminate as a function of the amount of strengthening. Though the available literature (Velazquez et al., 2000) has suggested fixing the effective strain to a value of 0.004 for design purposes, it needs further experiments to evaluate and verify this value.

- Additional research is needed in order to accurately determine the optimum percentage of orthogonal polymer composites reinforcements for applying cross-ply.

- The bond characteristics of the various pastes used to apply NSM rods needs to be further investigated to properly evaluate the true strength of the anchorage details.

-Further research is needed to evaluate the aggressive environmental factors such as temperature, freeze-thaw cycles, UV exposure, alkalinity etc. Very few researches are available on these areas. These serviceability issues which have received little attention to date should be investigated.

- While experimental test an isolated and ideal structural member is generally tested. As for example, when a wall is tested generally as isolated wall with no opening and no special architecture is tested. But in reality that type of wall may not be present. So some real samples or perfect representative of real members should be tested.

-Further research is needed to evaluate the optimal amount of reinforcement to strengthened square and rectangular columns, as it is found that there is almost proportional relation in increase in strength and number of layers applied.

-Small-scale testing of the connection examining several parameters including angle radius, plate thickness, cantilever length, and GFRP composites configuration should be conducted. It is especially important that the load transfer efficiency relative to the angle radius be examined.

- Especially designed FRP connectors with higher toughness in maintaining integrity in the structure need to be developed for masonry.

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