FINAL YEAR PROJECT

Comparison of Retrofitting of Columns with FRPs, Steel Jackets, Concrete Jackets and Ferro cement.

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Dedication

Dedicated to our parents to whom we owe all that Allah has bestowed on us, and to Shuhada's of Tirah Valley.

Undertaking

We certify that project work titled **"Comparison of Retrofitting of Columns with FRPs, Steel Jackets, Concrete Jackets and Ferrocement"** is our own work. No portion of the work presented in this dissertation has been submitted in support of another award or qualification either at this institution or elsewhere. Where material has been used from other sources it has been properly acknowledged / referred.

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Completion of this thesis is the result of co-operation of many dedicated and helpful people. It is difficult to gauge their contributions in helping us to carry out this research work.

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AUTHORS

Abstract

Inadequate design and construction, reinforcing steel corrosion, and deterioration due to variety of aggressive environmental effects all create a need for structural strengthening of concrete. Furthermore, recent earthquakes in Pakistan have promoted an urgency to upgrade seismic deficient structures to reduce casualties and damages.

Some recently developed techniques can play vital role in structural repairs, seismic strengthening and retrofitting of existing structures whether damaged or undamaged. Selection of right materials, techniques and procedures to be employed for a given structure has been major challenge. The selection of techniques to be used depends on many aspects that may be viewed from different perspective i.e. requirement and availability of financial resources, applicability and suitability of material for the repair of damaged structures.

Significant amount of research work has been carried out in recent years to develop various strengthening and rehabilitation techniques to improve the seismic performance of the structures. Seismic retrofit with FRP (Fiber Reinforced Polymers) materials has gain notable acceptance from civil engineering community in recent years as the FRP can help to cure many ills that beset concrete. A thorough literature review will be carried out to determine strength and ductility of column using different retrofitting techniques namely FRP, steel jackets, concrete jackets and Ferrocement. The effective techniques will be highlighted for retrofitting of structures in seismic and non-seismic areas.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

On 8th October 2005, a major earth quake jolted Azad Kashmir and Northern areas of Pakistan resulting into human and material losses. Consequently the seismic hazard maps and seismic zoning have been revised in the Building Code of Pakistan-2007. Almost all major cities are now placed in higher seismic zone. Previously, more than 80% of our cities were located in zone 1 or 2A and now the same areas are declared to be located in much higher zone i.e. 2B up to zone 4. Majority our bridges were constructed prior to October 2005 and these were designed according to a very old building code i.e. West Pakistan Highway Code of 1967. Therefore, most of these structures are prone to major damages. Presently, there are hundreds of bridges structures which need retrofitting to enhance their strength and ductility to meet the requirements of new building code. These bridges can't leave unattended even if these were not damaged in the earth quake of October 2005.

In developing countries particularly in Pakistan, the seismic performance of these buildings may be significantly poor due to insufficient ductility and low concrete strength, as well as other deficiencies. The structural members of this type of buildings may experience severe damages due to low deformability and axial load capacity. One popular solution to the problem of how to strengthen existing reinforced concrete (RC) structures is to place jackets around the structural elements. Jackets have been constructed using concrete, steel elements and fiber-reinforced polymer composites. A variety of techniques have been used to strengthen beams, columns and joints. Several experimental studies have been performed in order to investigate the method. It has been shown that the method improves the bending strength, the shear capacity, the stiffness, the ductility and the axial load carrying capacity of strengthened elements.

Jacketing columns with high strength carbon fiber-reinforced polymer CFRP composite sheets can significantly enhance both deformability and axial capacity of the members, as well as prevents the buckling of the longitudinal reinforcement, improving the shear capacity and enhancing the bond behavior of lap spliced connections of longitudinal reinforcement. The introduction of advanced polymer composites in the civil infra structure has been a very rapid process and the extraordinary properties of these materials have enabled design engineers to have greater confidence in the materials' potential and consequently to use them in various construction, including the strengthening of buildings.

1.2 PROBLEM STATEMENT

A thorough literature review has been carried out to draw a comparison of different retrofitting techniques i.e., steel jackets, concrete jackets, ferrocement and FRPs with a view to ascertain suitability of these techniques for existing structures to evaluate the potential benefits of these techniques for retrofitting.

1.3 SCOPE OF RESEARCH

This report reviews the research work of various researches carried out in different countries. This data is used to analyze the results reported by these people using different techniques to draw a comparison. This comparison is based on conclusions drawn from the research works.

1.4 AIM AND OBJECTIVES

Majority of structural failure of building and bridges in developing countries can be attributed to inadequate seismic design of columns. This may result due to lack of transverse and longitudinal reinforcement. Presently, there are hundreds of concrete structures which need retrofitting to enhance their strength and ductility to meet present code requirements. The present study is being pursued to evaluate effective and economical methods of retrofitting in the existing concrete structures in Pakistan.

1.5 SIGNIFICANCE OF PRESENT REPORT

Earthquakes disclosed the vulnerability of its existing RC structures. In order to resist large seismic action, the structures with comparatively more shear capacity need enhanced ductility as well. Structures designed insufficiently for seismic effects, experienced considerable damages.

The bridges and buildings observed during/after past earthquakes such as Loma Prieta of 1989, Northridge, California of 1994, Hanshin-Awaji (Kobe) of 1995 and Azad Kashmir of 2005 in Pakistan has repeatedly demonstrated their vulnerabilities. For reinforced concrete buildings and bridges, a significant majority of the structural failure could be attributed to inadequate seismic design of the columns. Figure 1.1 shown below, is an example of damaged piers near their base of Adam Wahn Bridge which was affected by October 2005 Earthquake. The picture on the left side clearly indicates lack of transverse reinforcement to be the main cause of their failure. In this case, the bridge did not collapse or damaged extensively. Later on it was rehabilitated using RCC jacketing with sufficient spiral reinforcement. Likewise there are many examples, where bridge columns have been damaged by the earthquake of Azad Kashmir.

Figure 1.1: Damaged Piers of Adam Wan Bridge after October 2005 Earthquake

1.6 OCTOBER 2005 EARTHQUAKE IN PAKISTAN

The earthquake of October 8, 2005 at Balakot and Kashmir located in the north of Pakistan was the most devastating in the history of Pakistan. According to the official website of ERRA (Earthquake Reconstruction & Rehabilitation Authority) the affects of this earthquake were

➢ Magnitude:	7.6 on the Richter scale
➢ Affected area:	30,000 Sq km (in 9 districts)
➢ Human losses:	73,338 dead
➢ Severely injured:	128,304
➢ Houses destroyed:	600,000
➢ Rendered homeless:	3.5 million
➢ Health facilities destroyed:	307
➢ Educational facilities destroyed:	5,344
➢ Roads damaged:	2,393 km
➢ Economic loss:	Over 5.0 billion US $

Fig 1.2 Epicenter of earthquake of October 2005 in Pakistan

Fig 1.3 Bridges destroyed in Azad Kashmir on October 8, 2005

1.7 ORGANIZATION OF CHAPTERS

The project report has been organized into following five chapters

CHAPTER 2:

This chapter highlights following topics

- What is retrofitting
- Need for retrofitting
- Who conduct retrofitting
- Factors should be kept in mind for retrofitting
- General process of retrofitting.
- Advantages and disadvantages of retrofitting
- Parameters for selection of retrofitting techniques.
- Retrofit performance objective
- Methods of retrofitting
- Requirements of strengthening or rehabilitation
- Difference in repair, restoration and retrofitting

CHAPTER 3:

This chapter contains the following topics

- Historical perspective of RC jacketing
- What is RC jacketing
- RC jacketing procedure
- Application of RC jacketing
- Prominent researchers in the field of RC jacketing
- Cost Analysis of RC jacking
- Important conclusions drawn from research works
- Advantages of RC jacketing
- Disadvantages of RC jacketing

CHAPTER 4:

This chapter contains following topics

- Historical perspective of steel jacketing
- Steel jacketing procedure
- Steel jacketing for circular column
- Steel jacketing for rectangular column
- Prominent researchers
- Important conclusions
- Advantages
- Disadvantages
- Application of steel jacketing

CHAPTER 5

This chapter contains following topics

- Historical perspective of ferrocement.
- Definition of ferrocement
- Constituents of ferrocement
- Procedure of ferrocement
- Prominent researchers in field of ferrocement
- Important conclusions of ferrocement
- Cost Analysis
- Advantages of ferrocement
- Disadvantages of ferrocement

CHAPTER 6

This chapter contains following topics

- Historical perspective of FRP
- Definition of FRP
- Constituents of FRP
- Procedure of FRP

CHAPTER 7

CHAPTER 2

RETROFITTING

2.1 DEFINITION OF RETROFITTING

Retrofitting is technical interventions in structural system of a building that improve the resistance to earthquake by optimizing the strength, ductility and earthquake loads. Strength of the building is generated from the structural dimensions, materials, shape, and number of structural elements, etc. [1]

Ductility of the building is generated from good detailing, materials used, degree of seismic resistant, etc. Earthquake load is generated from the site seismicity, mass of the structures, important of buildings, degree of seismic resistant, etc.

In the design of retrofitting approach, the engineer must comply with the building codes. The results generated by the adopted retrofitting techniques must fulfill the minimum requirements on the buildings codes, such as deformation, detailing, strength, etc.

2.2 NEED FOR RETROFITTING

Retrofitting is needed when the assessment of structural capacity results in insufficient capacity to resist the forces of expected intensity and acceptable limit of damages. [2]

It is not merely poor quality of materials and damage of structural elements serves as the reasons to retrofit a building. Change of the building's function, change of environmental conditions, and change of valid building codes could also be the reasons for retrofitting.

2.3 PERSON WHO CONDUCTS RETROFITTING

Retrofitting must be conducted by experts from each field. In most retrofitting process, an engineer plays the main role. An engineer must assess and analyze the structural capacity. An engineer must also design the best retrofitting techniques to strengthen the structural deficiencies. The role of the novice is restricted to identify the possibility of insufficiency of building capacity.

2.4 FACTORS SHOULD BE CONSIDERED FOR RETROFITTING

Some factors should be considered to decide whether to retrofit or not, i.e:

a) Technical aspect

b) Cost intervention

c) Importance of building

d) Availability of adequate technology

e) Skilled workmanship to implement the proposed measures

f) Duration of works.

2.5 GENERAL PROCESS OF RETROFITTING

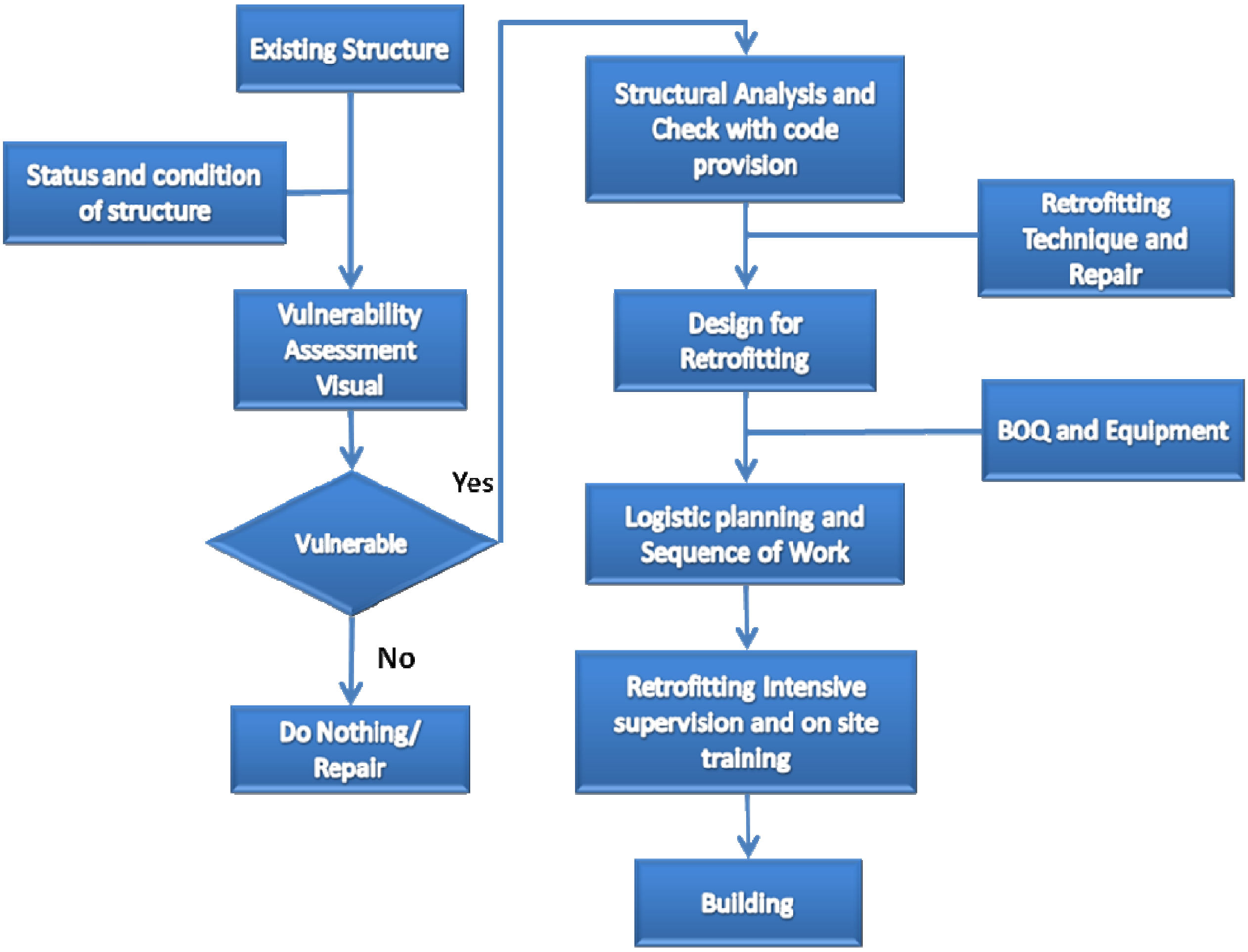

Fig 2.1: General process of retrofitting

2.6 ADVANTAGES OF RETROFITTING

The advantages of adopting retrofitting approach, despite of reconstructing the building, are as follows:

- When retrofitting approach is adopted, retrofitted building can still be operated.
- Retrofitting will take relatively less construction cost with similar structural performance achievement.
- Retrofitting will involve relatively less resources, either human resources or natural resources.
- Retrofitting will not significantly change the building configuration and shape. It is preferable when the retrofitted building has historical values.
- Retrofitting the building will produce less debris than reconstructing the building.

2.7 DISADVANTAGES OF RETROFITTING?

a. The skill of the worker must comply with the adopted retrofitting approaches
b. Limited access of the construction site, since the building could be still in function.

2.8 PARAMETERS FOR SELECTION OF TECHNIQUES FOR RETROFITTING

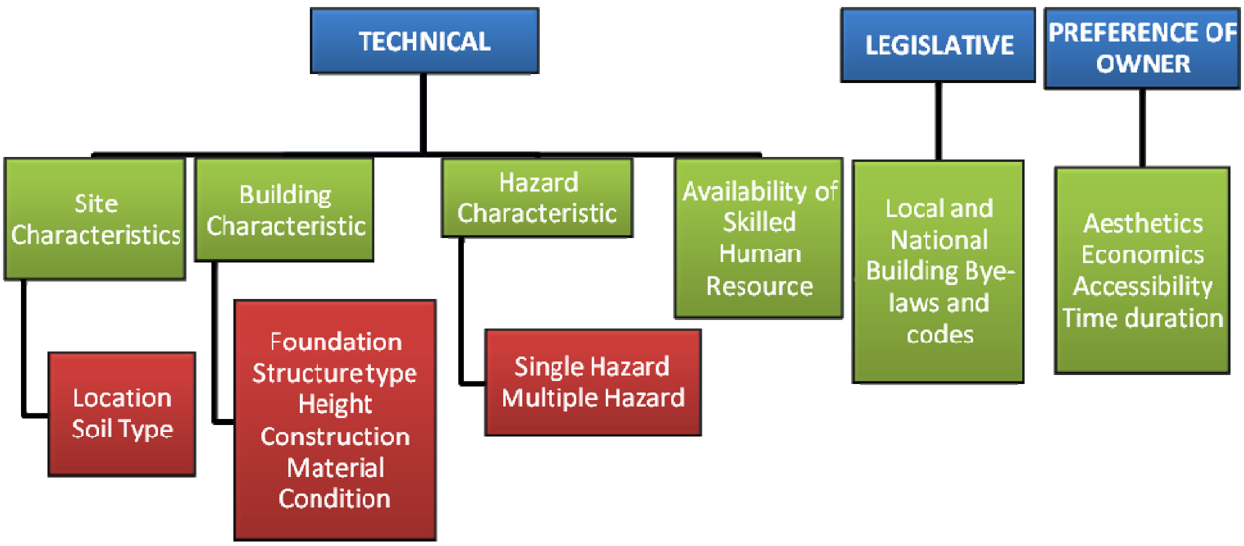

fig 2.2: Parameters for Retrofitting

2.9 RETROFIT PERFORMANCE OBJECTIVES

Pakistan and other countries located in high seismic zones have experienced major earth quakes wherein many structures were damaged being deficient of steel reinforcement, concrete strength and ductility to sustain earthquake energy.

In the past, seismic retrofit is primarily applied to achieve public safety, with engineering solution is limited by economic and political considerations. However, with the development of Performance based earthquake engineering (PBEE), several levels of performance objectives are gradually recognized:

a. Public safety only

The goal is to protect human life, ensuring that the structure will not collapse upon its occupants or passersby, and that the structure can be safely exited. Under severe seismic conditions the structure may be a total economic write-off, requiring tear-down and replacement.

b. Structure survivability

The goal is that the structure, while remaining safe for exit, may require extensive repair (but not replacement) before it is generally useful or considered safe for occupation. This is typically the lowest level of retrofit applied to bridges.

c. Structure functionality

Primary structure undamaged and the structure are undiminished in utility for its primary application. A high level of retrofit, this ensures that any required repairs are only "cosmetic" - for example, minor cracks in plaster, drywall and stucco. This is the minimum acceptable level of retrofit for hospitals.

d. Structure unaffected

This level of retrofit is preferred for historic structures of high cultural significance

2.10 METHODS OF RETROFITTING

Technology is advancing and new techniques are emerging from time to time for the engineering practices including the methods/techniques of retrofitting. Few of these are listed as under:

- Steel plates or tubes welded to the potential plastic hinge region or area where damage has been observed. In practice it is the steel jacketing and reinforcing by using iron strips to act as a kind of spiral reinforcement.
- Steel angels can be used for square and rectangular columns for increasing the strength of corners.
- Fiber reinforced plastics (FRP-wrapping of sheet around columns) can also be used for improving the confinement effects and thereby reducing the chances of local buckling.
- Reinforced concrete shells can also be used for retrofitting of normal RCC columns.
- Using epoxy resins along with other materials for treatment of cracks and concrete spalling etc.
- Precast concrete segments jackets are also effective means of retrofitting.
- Wire wrapping by high strength strands.
- High-strength fiberglass jackets.

2.11 REQUIREMENTS OF STRENGTHENING/REHABILITATION

Strengthening/Rehabilitation of a structure may be required on account of one or combination of the following:

- ✓ Deterioration of structure due to environmental effect.
- ✓ Revision in loading standard.
- ✓ Seismic retrofitting.

2.11.1 DETERIORATION OF STRUCTURE DUE TO ENVIRONMENTAL EFFECT

Ingress of moisture, air or chloride (which is available in air from the sea water in the coastal area) reaches reinforcement of RCC structures. It corrodes the reinforcement. Corroded product is having much more volume than its original volume. To make space for its increased volume, it causes crack in the concrete. Cracked concrete provides easy access to corroding agents, which further corrodes the reinforcement at accelerated rate resulting further deterioration of structure.

2.11.2 REVISION IN LOADING STANDARD

From time to time, loading standard is revised. In the subcontinent, similarly, longitudinal force was not considered initially while designing the railway bridges. First time, it was introduced in the BRIDGE RULE in 1923. It doesn’t mean that initially, the engineers were not aware of the longitudinal forces. Actually, longitudinal forces at that time were of smaller magnitude, which was not having any problem in affecting the section of the substructure since vertical load was predominant. Due to revised loading standard, the old bridges, which are still in sound condition, needs strengthening on account of their capacity enhancement to meet with the increased loading standard.

2.11.3 SEISMIC RETROFITTING

Seismic forces are being revised to ensure safety. Everywhere, this revision is on the upward side. As such, as per the revised code provisions, existing bridges need to be strengthened as far as seismic provisions are concerned. This can be achieved by seismic retrofitting of the structures. [3]

The seismic reinforcement has the following purposes:

- ✓ Improvement of strength and ductility.

- ✓ Improvement of load-bearing capacity.

- ✓ Seismic reinforcement of the reinforced concrete structures increases the ductility which helps to dissipate the energy induced by the lateral load, thus it prevents the brittle failure of the member.

2.12 DIFFERENCE IN REPAIR, RESTORATION, RETROFITTING

A. Repairs

- Actions taken for patching up superficial defects.
- Include cosmetic works only.

B. Restoration

- Actions taken for restoring the lost strength of structural elements.

C. Retrofitting

- Preparing a structure in scientific manner to withstand forces of natural hazards
- Up gradation of existing building for increasing the resistance against natural hazards.[4]

CHAPTER 3

CONCRETE JACKETING

3.1 GENERAL

Concrete jacketing was probably the first of the jacketing methods to be employed in practice. [5] It was widely used in Mexico City after the 1985 earthquake. Several investigations have been carried out on buildings that were damaged by earthquakes. Jacketing should be applied in cases of heavily damaged columns or in cases of insufficient column strength. Low-quality concrete, poor confinement of the end regions, weak column-strong beam behavior, short column behavior, inadequate splice lengths and improper hooks of the stirrups were some of the important structural deficiencies (Yakut et al., 2005).[6]

Jacketing which can be defined as the confinement of the column with new and higher quality reinforced concrete elements may be implemented for various purposes based on the type of deficiencies that the structural member has. [7] Columns subjected to brittle damages can be jacketed in order to enhance resistance against shear and/or axial loads. In that case, although the purpose of jacketing is only to increase axial load or shear strength, some changes will also occur in the bending stiffness and moment capacity of the member after the jacketing application. By considering these changes, during the jacketing design, the jacketed section is ensured to achieve adequate shear and axial load strength.

Except for such brittle damages, the jacketing is applied for elements with inadequate bending capacity or ductility. By this way, strength of the columns displaying a splice failure as a result of bending can also be improved. Jacketing of the columns is to produce the best result if it is implemented at 4 sides of the column. Column flexural strength increases with the enlargement of the concrete area and by adding new longitudinal reinforcement. Shear strength, and especially ductility, is improved by better confinement with close transverse reinforcement, ties or steel strips. Equalizing of column stiffness by rearrangement, like separating columns from spandrel walls, improves the compatible behavior of all columns of the structure.

3.2 CONCRETE JACKETING PROCESS

It involves increasing size of the existing reinforced concrete section by adding more reinforcement and concrete. [8] It could be accomplished by either of the following methods:

3.2.1 CONVENTIONAL CONCRETE. Pouring concrete around the member to be strengthened with additional steel reinforcement properly anchored to the existing section. Ordinary concrete jacketing requires formwork and is time consuming due to long curing time. Furthermore, it is difficult to achieve a dense mix in constrained conditions. Adhesion is also an issue, especially for overhead applications.

3.2.2 SPRAYED CONCRETE (SHOTCRETE). Pneumatically projecting concrete on to the reinforced (usually with wire mesh) and prepared surface of the member being strengthened with a spray gun. A variety of additives and admixtures are also introduced to expedite strength gain, reduce rebound, reduce water requirement, curb shrinkage and improve adhesion. The grading of aggregates is critical in sprayed concrete due to the absence of external vibration and the reduction in the quantity of coarse aggregates as a result of rebound. Shotcrete does not require formwork and is useful to retrofit large areas in a relatively short period of time. But, the operation is very messy with enormous loss of sprayed materials, resulting not only wastage of materials but an unsightly-rough surface finish too. It is not economical for small areas of retrofit due to high setup and machinery costs. The sequence of work for sprayed concrete may be listed as follows:

- Hack the damaged concrete to form keys on the surface for bonding purposes.
- Install wire mesh or additional reinforcement where necessary.
- Ensure proper anchorage of the additional reinforcement to the parent concrete.
- Spray the prepared surface with water prior to the projection of sprayed concrete.
- Project sprayed concrete onto the prepared surface.
- Ensure that each layer does not exceed 50 mm in thickness.
- Cut and trowel the sprayed surface.
- Cure it for the stipulated period.

3.2.2.1 ADVANTAGES OF SHOTCRETE

- Spraying in place with force at low water/cement ratio results in a dense, homogeneous concrete
- Reduction or elimination of shuttering/ formwork
- Efficient method of concrete placement on large areas requiring reconstruction as large volumes can be placed in a short duration
- Good bond with the parent concrete and in between the layers
- Sprayed concrete can be useful at difficult access locations as it can be conveyed through longer distances with a hose.

3.2.2.2 DISADVANTAGES:

- Costly for small operations due to fixed costs associated with batching of materials and setting up of the spray equipment.
- Quality of the placed concrete is variable as it is highly dependent on the skill of the operator, spraying distance & grading of the ingredients.
- Large wastage of materials results due to rebound.
- Need to clear area adjoining the repair as spraying is a messy operation.
- Results in a rough and unsightly surface finish- finishing of sprayed concrete is a costly and time consuming affair if aesthetics is the prime consideration.
- Increased cost for the introduction of admixtures and additives.

3.2.3 PRE-PACKED AGGREGATE GROUTING- Pumping of cementitious grout into washed/ graded coarse aggregates placed with properly anchored reinforcement around the member to be strengthened in a tightly sealed formwork. It is one of the better ways of jacketing a concrete member as it results in a dense mix with good surface finish.

The procedure for pre-packed grouting is as follows:

- Remove the cover concrete of the existing section to expose its reinforcement and roughen the surface to form keys for effective bonding of the old concrete with the new
- Drill holes of adequate depth and nos. in the roughened concrete section as per design to anchor the new reinforcement or shear anchors as per design
- Install the new reinforcement and/or shear anchors around/ in the existing section as per requirement

- Install formwork around the new reinforcement cage incorporating sufficient number of grout inlet ports at suitable locations
- Fill up the gap between the existing concrete section and the formwork with graded, washed coarse aggregates
- Use tamping or vibration to reduce voids and tightly pack the aggregates
- Seal up the form work tightly in order to avoid any leakage or undue deformation while pressure grouting
- Pump high strength non-shrink cementitious grout into the pre-packed aggregates beginning from the lowest elevation port to the highest until the whole gap is filled up completely
- Cure the grouted section for sufficient time and strip the form work

3.2.3.1 ADVANTAGES:

- Inexpensive method to strengthen highly deficient members
- Very good surface finish can be achieved

3.2.3.2 DISADVANTAGES:

- Destructive method as it requires hacking and drilling in the weak section
- Requires form work and props to support the new section
- Disruptive to the existing operations of the facility being upgraded
- Results in the increase in section dimensions, which may not be acceptable from aesthetic and space considerations
- Adds in more dead weight to the structural member being strengthened

Following Photograph shows concrete jacketing of a column. Regardless of the method deployed, jacketing results in increase in dimensions as well as dead weight of the retrofitted member.

Fig. 3.1: Concrete Jacketing Is Being Applied

3.3 APPLICATION OF REINFORCED CONCRETE JACKETING

Jacketing can be performed by means of adding reinforced concrete. Reinforced concrete jacketing, according to the available space conditions around the column can be performed by adding jacketing to one, two, three or four sides of concrete column sections (Figure).[9]

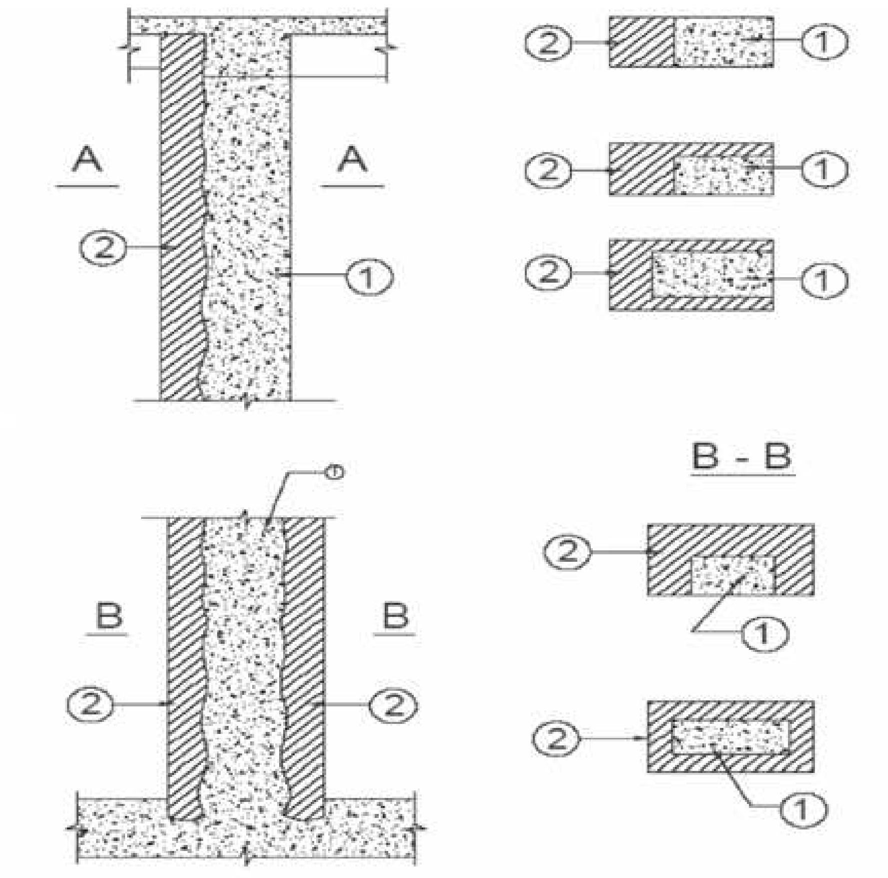

Fig 3.2: Repair of concrete column by Jacketing **(1.** Existing column & **2.** Jacketing Concrete**)**

It is strongly recommended that columns be jacketed on all four sides for best performance in future earthquakes. In order to achieve the best bond between the new and the existing concrete, four-sided jacketing is also most desirable. In case one, two or three sided jacketing is all that is possible, the concrete cover in the jacketed parts of the existing column must be chipped away so new ties can be welded to existing ties. In case of a four-sided jacketing, only roughening of the surface of the existing column may be required unless greater load transfer is desired.

Jacketing only in the story space without reinforcement penetrating through the floor structure can improve the local axial and shear strength of the column (Figures 3.4 and 3.5.a). However, the flexural column strength is not improved and the column-to-beam joint is not strengthened. Thus, the total frame structure may show poor behavior in future earthquakes. Jacketing only within the story is a local strengthening which does not improve seismic response unless significant shear walls are also added. Adequate column flexural strength can be achieved by passing the new longitudinal reinforcement through holes drilled in the slab and placing new concrete in the beam-column joint region (Figure 3.5.b)

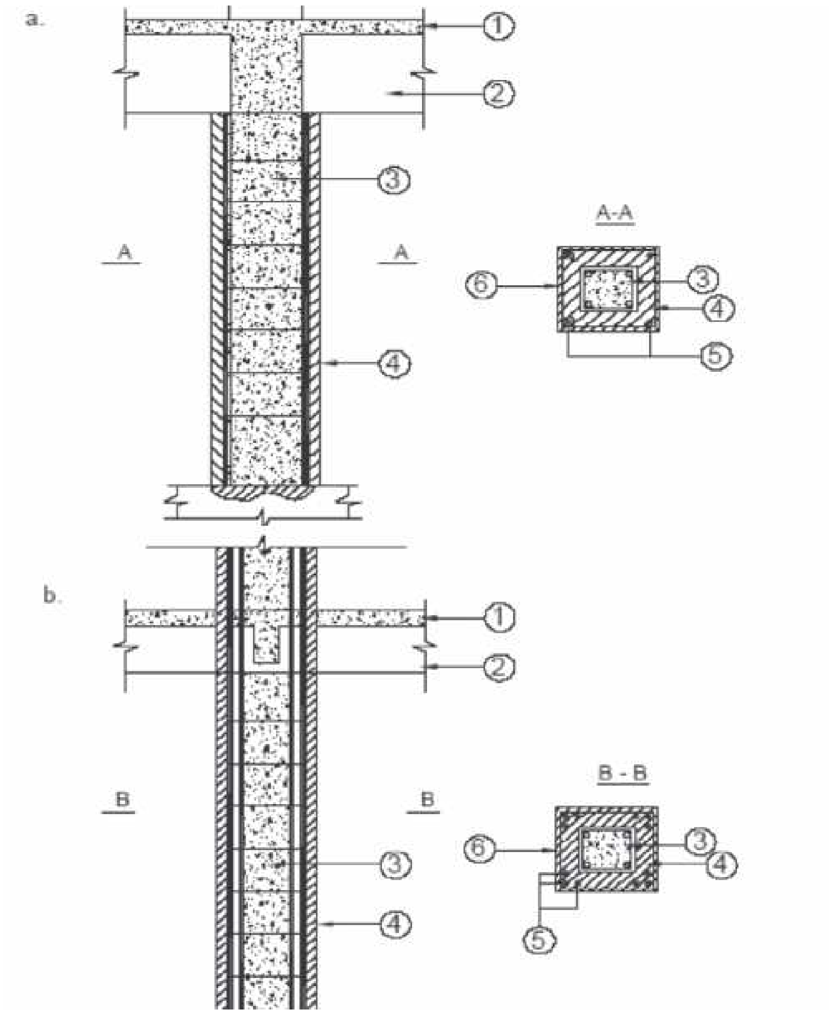

Figure 3.3: Repair of concrete column by **(a)** local and **(b)** Global jacketing **(1.** Slab: **2** Beam; **3.** Existing column; **4.** Jacket; **5.** Added longitudinal reinforcement; **6.** Added ties**)**

Fig 3.4: An RC jacketing application (Photo by Ahmet Sarism)

In the case of a one-sided jacket, adequate connection between existing and new concrete must be achieved by good detailing and closely spaced, well anchored, additional transversal reinforcement (Figure 3.5). This can be achieved by providing anchorage with ties to the existing longitudinal reinforcement (Figure 3.5). Welding is not necessary, but chipping free space for passing the hooks of the additional ties is necessary.

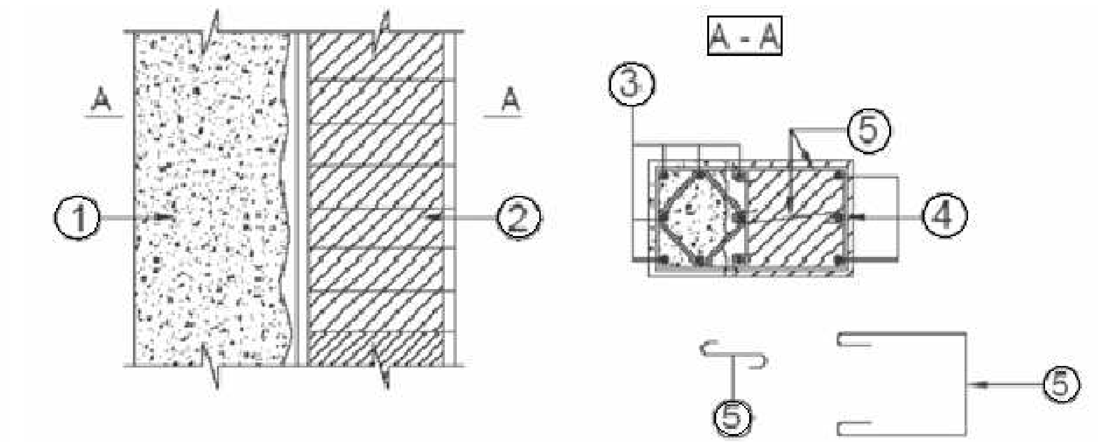

Fig 3.5: Repair of concrete columns by one-sided jacketing (1. Existing column; 2. Jacker; 3. Existing Reinforcement; 4. Added Longitudinal Reinforcement; 5. Added ties)

Similar detailing is applied in case of two or three-sided lateral jacketing. In the usual case of four-sided jacketing, jacketing with ties is recommended (Figure 3.6). Concentration of the newly-added longitudinal reinforcement at the corners of the cross section allows an adequate confinement of all longitudinal bars. The jacket should be of sufficient thickness with closely spaced ties to provide confinement. With the new longitudinal reinforcement passing through holes, drilled in the slab, this procedure provides a continuous connection of the jackets to the upper story and lower story columns.

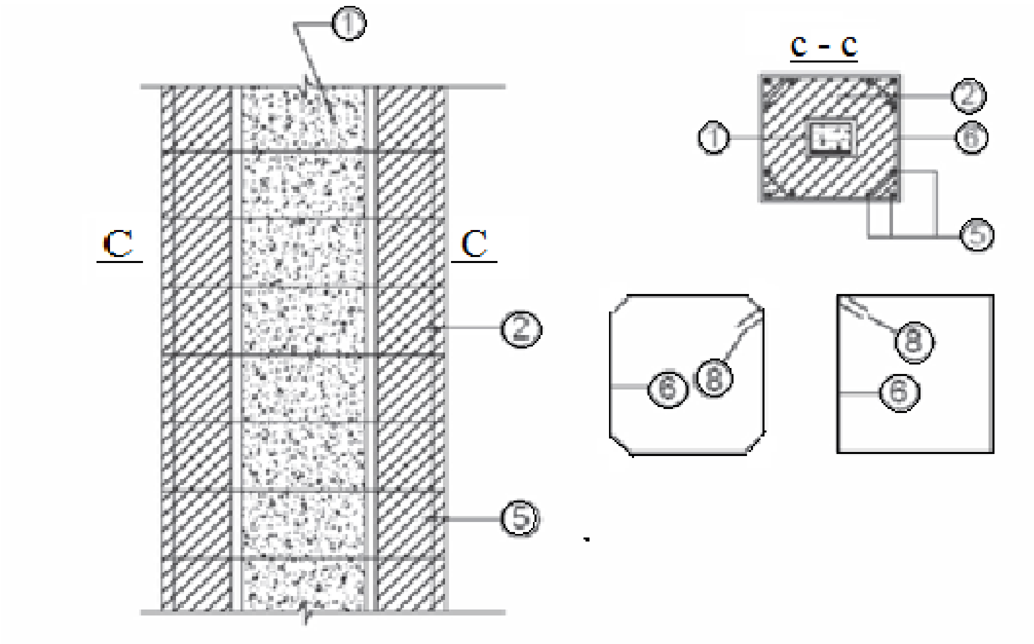

Fig 3.6: Repair of concrete column by four-sided jacketing (1. Existing column; 2. Jacket; 3. key; 4. Bent bars; 5. Added reinforcement; 6. Ties; 7. Welding; 8. Alternatve corner)

3.3.1 <u>PROVISIONS FOR CONCRETE JACKETING</u>

Reinforced concrete jacketing should also conform to the following provisions:

- The strength of the new materials must be equal or greater than those of the existing columns.

Fig 3.7: Reinforcement for Concrete Jacketing

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- Concrete strength should be at least 500 psi (3.45 MPa) greater than the strength of the existing concrete.
- The thickness of the jacket should be at least 1½ in. (38.1 mm) for shotcrete application or 4 in. (102 mm) for cast-in-situ concrete.
- The area of longitudinal reinforcement should not be less than 0.01 and no more than 0.06 times the gross area of the jacket section. The reinforcement should not be less than four bars for four-sided jacketing and bar diameter should be at least 5/8 in. (16 mm).
- Ties should be arranged so that every corner and alternate longitudinal bar should have lateral support provided by corners of the ties with an included angle of no more than 135 degrees. No intermediate bar should be farther than 4 in. (102 mm) from corners of the

ties. In some cases, it will be necessary to drill into the core of the existing column and epoxy hooked ties into the hole or drill completely through the existing column core to install new ties.

- The diameter of ties (except welded wire fabric) should be minimum 3/8 in. (9.5 mm), but not less than 1/3 of the longitudinal bar diameter.
- Vertical spacing of ties shall not exceed 4 in. (102 mm). In addition, it is advisable that the spacing of ties should not exceed the thickness of the jacket.
- Jackets can be installed either as conventional or special cast-in-situ concrete or by shotcrete (gunite). For both methods, the existing concrete surface must be thoroughly roughened by chipping and cleaned of all loose material, dust and grease. The surface should be thoroughly moistened before placing the concrete or shotcrete.

3.3.2 DETAILS FOR REINFORCED CONCRETE JACKETING

Properties of jackets	• Match with the concrete of the existing structure. • Compressive strength greater than that of the existing structures by 5 N/mm^2 or at least equal to that of the existing structure
Minimum width of jacket	• 10 cm for concrete cast-in-place and 4 cm for Shotcrete. • If possible, four-sided jacket should be used. • A monolithic behaviour of the composite column should be assured. • Narrow gap should be provided to prevent any possible increase in flexural capacity.
Minimum area of longitudinal reinforcement	• 3Afy, where, A is the area of contact in cm^2 and fy is in kg/cm^2

	• Spacing should not exceed six times of the width of the new elements (the jacket in the case) up to the limit of 60 cm. • Percentage of steel in the jacket with respect to the jacket area should be limited between 0.015and 0.04. • At least, 12 mm bar should be used at every corner for a four sided jacket.
Minimum area of transverse reinforcement	• Designed and spaced as per earthquake design practice. • Minimum bar diameter used for ties is not less than 10 mm or 1/3 of the diameter of the biggest longitudinal bar. • The ties should have 135-degree hooks with 10bar diameter anchorage. • Due to the difficulty of manufacturing 135-degree hooks on the field, ties made up of multiple pieces, can be used.
Shear stress in the interface	• Provide adequate shear transfer mechanism to assured monolithic behaviour. • A relative movement between both concrete interfaces (between the jacket and the existing element) should be prevented. • Chipping the concrete cover of the original member and roughening its surface may improve the bond between the old and the new concrete. • For four-sided jacket, the ties should be used to confine and for shear reinforcement to the composite element.

Connectors	• Connectors should be anchored in both the concrete such that it may develop at least 80% of their yielding stress. • Distributed uniformly around the interface, avoiding concentration in specific locations. • It is better to use reinforced bars (rebar) anchored with epoxy resins of grouts.

Table 3.1: Standards for concrete jacketing

3.4 PROMINENT RESEARCHERS;

Teran and Ruiz (1992)

Teran and Ruiz (1992) reviewed the seismic retrofit practices used in Mexico City. In their paper, they give quantitative detailing recommendations as well as general guidelines and emphasis the need for good connections between the original and new structural material. They note that jacketing only mildly affects strength and stiffness but substantially increases ductility.

Gomes and Appleton (1998, 1996)

In Portugal Gomes and Appleton (1998, 1996) tested 9 RC columns with reversing cyclic loading in order to assess the efficiency of column jacketing. Concrete jacketing was used in this project which effectively increased the column dimensions from 200x200*mm* to 260x260*mm*. Additional longitudinal steel was added to keep the reinforcement ratio at approximately 1%. Jacketing increased the strength by 250% and greatly improved the hysteretic behaviour. [10]

Bracci et al (1997)

Bracci et al (1997) presented a static pushover analysis procedure for evaluating the seismic performance and retrofit options for low-to-medium rise RC buildings. The technique is based on the capacity spectrum method and was illustrated by application to the 1/3-scale 3-storey RC frame model that had been previously tested on the shaking table at Buffalo. Three retrofit examples were considered. These were (1) prestressed concrete jacketing of internal columns, (2) RC fillets around beam-column joints, and (3) post-tensioning of additional column longitudinal reinforcement. Retrofit increased the frame's base shear strength by 66%.

Ciampoli (1995)

While Ciampoli (1995) in Italy was conducting an extensive series of comparative analyses of a RC bridge girder to study the effectiveness of seismic upgrading using either concrete jacketing or isolation/energy dissipaters. In Taiwan, meanwhile, Sheu and Chang (1995) had proposed hysteresis rules for short RC columns based on the analysis and testing of 16 different columns. Three groups of columns were tested. Group 1 was a collection of conventional reinforced concrete columns. Group 2 columns were strengthened with wire mesh and additional concrete. Group 3 columns were strengthened with steel hoop plates and concrete. The strength of group 2 and 3 columns was equal to or slightly (20%) greater than the group 1 columns.

Aguilar et al. (1989)

Aguilar et al. (1989) performed a statistical study on the repair and strengthening methods of 114 RC buildings damaged after 1985 earthquake in Mexico City. According to his work, the most commonly used techniques were addition of shear walls and the RC jacketing of columns. [11]

Julio et al. (2001)

Julio et al. (2001) performed test on RC columns strengthened by jacketing. The steel bars of added longitudinal reinforcement were anchored to the footing of the original column by two component epoxy resin. The models were subjected to monotonic tests, consisting of a constant axial force combined with an increasing bending and shear force. Initially, failure of all steel bars of longitudinal reinforcement of the original column and slipping of all the corresponding steel bars of the added jacking were observed. Pull-out tests were performed to analyze the problem and were concluded, without any doubt, that the bars slipped because the holes drilled to footings had not been adequately cleaned. So, the use of a vacuum cleaner was enough to guarantee the change from slipping failure to tension rupture of the added steel bars.

Julio (2001) performed shear test and pull off test on specimens, considering different interface surface situations and also considering the application of a commercial two component epoxy resin. The values of the shear and tension strength of interface reduced when the epoxy resin was applied on the sand-blasted surfaces, contrarily to what happened when other roughening methods were used. [12]

Bass et al.,1989; Mohebbimoghaddam, 2008)

Studies on shear transfer between old and new concrete were done by Bass and his colleagues. They found that shear strength was increased by increasing connector steel, the depth embedment and strength of concrete. Moreover the preparation of common surface did not give any distinctive effect as a connecting factor with result. The performance of jackets becomes more important when the columns are boundary component of frame. The improvement techniques of present splice, is including removal of concrete coat, using welded overlap bar and surrounding coating splice with reinforced concrete jacket and new reinforcement in jacket. [13]

Bett et al., 1988; Tonkabonipour, 2005; Beer et al., 2006

According to test result the lateral capacity of reinforced column can be predicted carefully that it's supposed concrete jacket and main column are completely agreeable. They tested three concrete columns to study the effect of column strengthening and jacketing.

The basic un-strengthened column was 12"x12" (300x300*mm*) with 8 No.6 bars and 6*mm* ties at 8" (200*mm*) spacing. This specimen was tested and then repaired by removing all loose cover, adding 4 No.3 corner bars and 4 No.6 mid-face bars, 6*mm* ties at 2.5" (63.5*mm*), epoxy bonded No.3 cross-ties at 9" (229*mm*) and a 2.5" (63.5*mm*) shotcrete shell.

The second specimen had the same basic concrete core but was jacketed with 4 No.3 corner bars, 6*mm* ties at 2.5" (63.5*mm*) and a 2.5" (63.5*mm*) shotcrete shell.

The third specimen was strengthened and jacketed in the same way as the first specimen. Specimens 2 and 3 were in "as-new" condition when strengthened and jacketed. All three specimens were tested in their jacketed condition. Results indicate that columns strengthened by jacketing, both with and without supplementary cross-ties, were much stiffer and stronger (about 90 kips (400*kN*)) laterally than the original, un-strengthened column (about 45 kips (200*kN*)). The column repaired by jacketing was also much stiffer and stronger (about 80 kips (355*kN*)) laterally than the original column and performed almost as well as the strengthened columns.[14]

Valluan et al., (1993)

Valluan et al., (1993) presented the result of retrofitting of column splice by meld and cross-steels. The results indicated the bond in the zone of splice by melding longitudinal reinforcement decreased the risk of buckling for the bars in order that additional layer can show integrated behaviour until failure.[15]

Ersoy et al. (1993)

Ersoy et al. (1993) ran two series of test to study the behaviour of strengthened and repaired concrete jacketed columns. The first series compares the behaviour jacketed columns with a monolithic reference specimen under monotonic axial loading. All the concrete for the monolithic specimen was cast with the base column and retrofit reinforcement in place, to provide a specimen with perfect interaction and the bond between base column and retrofit material, hoop reinforcement is used in the base column and retrofit reinforcement. The jackets are applied under two conditions: after the compression loading was applied and removed, as well as while the axial load still applied. It determined that columns jacketed after loading performed well, reaching 80% to 90% of the strength of monolithic reference specimen. Repair jackets applied while the column is still under load did not perform as well and only reached 50% of the axial load carried by monolithic specimen. The second series of tests study the effectiveness of concrete jackets with columns tested under combined axial loading and bending. Both repair and strengthened jackets behave adequately under monotonic and reversed cyclic loading.[16]

Rodriquez and Park (1994)

Rodriguez and Park (1994) conducted testing on rectangular columns repaired and strengthened by concrete jacket under compressive axial loading as well as lateral loading. Rebar hoops are provided as the retrofit reinforcement for the concrete jackets. Concrete jackets increase the strength and stiffness of the as built (un-retrofitted or base) columns by up to three times. It is also shown that Damage before the retrofit has no significant influence on the performance of the jacketed columns. Overall, concrete jackets with reinforcement significantly improve stiffness, strength and ductility of typical reinforced concrete columns, but the construction is very labor intensive.[17]

Lehman et al. (2001)

Lehman et al. (2001) used concrete jackets to repair severely damaged columns. Three repair methods are considered and implement for the damaged columns, which were built to modern seismic specifications. Initial damage to the concrete includes crushing of concrete, buckling and fracture of longitudinal reinforcement and fracture of spiral reinforcement, which was the result of axial and lateral loading. Concrete jacketed columns are reinforced with spiral transverse reinforcement. Loose concrete is removed from the cover as well as the base column. The concrete retrofitted column displays increase stiffness and strength, comparable to the original column before damage.[18]

Hellesland & Green

Hellesland & Green performed an experimental study on repaired RC columns. All models were first submitted to a complex loading history, consisting of a sustained load period, followed by a cyclic load period and finishing with a brief, deformation controlled, loading to maximum capacity and beyond. The models were repaired by straightening the columns, chipping out concrete from the failure zone, replacing old stirrups and adding new stirrups in this zone and placing new concrete. The authors state that the load capacities of the repaired columns were found to be 15–20% less than the original load capacities, and the stiffness values were 50–90% of the original values.[19]

Stathis Bousias, Alexis-Loukas Spathis, Michael N. Fardis

The effectiveness of RC jackets for seismic retrofitting of rectangular columns with poor detailing, and in particular with lap splicing of bars at floor level, was investigated. Four cantilever columns with smooth bars and hooked ends and another 3 with ribbed bars and straight ends were cyclically tested to failure, after jacketing. The tests of companion un-retrofitted columns show that, for smooth bars with hooked ends, the low deformation capacity and energy dissipation does not depend on lapping length - at least for lapping as short as 15 bar-diameters. Un-retrofitted columns with straight ribbed bars exhibit a remarkable loss of deformation capacity and energy dissipation with decreasing lap length, below 45 bar-diameters.

RC jacketing of columns with smooth bars and hooked ends is very effective in increasing their resistance, cyclic deformation capacity and energy dissipation to levels sufficient for earthquake resistant construction and to those of a monolithic column without lap splicing. In columns with straight ribbed bars RC jacketing cannot fully re-instate cyclic deformation capacity and energy dissipation to that of a monolithic column, if the original column has very short lapping, e.g. in the order of 15 bar-diameters.

Experimental program

The results of an experimental program on RC jacket retrofitting of rectangular RC columns with deficient lap-splicing of their longitudinal - smooth or ribbed – reinforcement, at the base of the column are discussed.

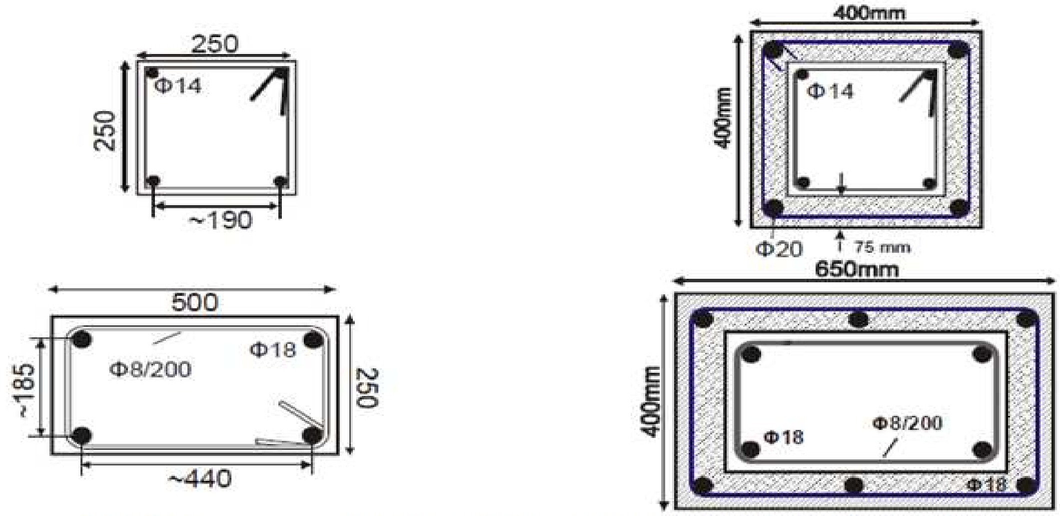


Fig 3.8: Cross - section of original test columns and of RC-jacketed ones

The experimental program comprises 14 column specimens with dimensions, reinforcement detailing and materials typical of old RC buildings without detailing for earthquake resistance. The testing program includes two column geometries (Figure 1):

Type-Q: a 250mm-square cross-section, reinforced longitudinally with four-14mm smooth (plain) bars with nominal yield strength of 220MPa (Figure 1(a)).

Fig 3.9: Laps at column base in type-Q specimen (left) and in type-R specimen (center); jacket reinforcement (right)

Type-R: a 250×500mm cross-section, reinforced longitudinally with four-18mm ribbed (high bond) bars with nominal yield strength of 500MPa (Figure 1(b)).

The specimens were cast into a heavily reinforced 0.6m-deep base, within which ribbed vertical bars were anchored with 90-degree hooks at the bottom and smooth bars with 180°-hooks. The behavior of the columns is studied under cycling of transverse displacements at amplitudes increasing in 5mm steps, under constant axial force. The load history with closely spaced single cycles was chosen over the usual protocols of 3 cycles at few ductility levels, to capture better the cyclic behavior of the specimen up to failure.

Both types of specimens (Q and R) were tested after being retrofitted with a 75-mm thick concrete jacket. The jacket is reinforced longitudinally with four 20-mm ribbed bars in Q-type specimens, or six 18-mm bars in R-type specimens. These vertical bars were embedded in the column base at the time of casting of the original un-retrofitted column. Jacket transverse reinforcement consists of 10-mm stirrups at 100mm centers, in both specimen types. Shotcrete with a mean compressive strength of 36MPa was used for the jacket. The conclusions of this study are as follows.

- ✓ Concrete jackets are effective in removing the adverse effect of lap-splicing of straight ribbed bars on strength and deformation capacity, even for very short lap lengths.
- ✓ The RC jacket is equally effective in repair and retrofit of a column with lap splices of smooth bars cyclically damaged.

3.4.1 CONCLUSIONS FROM ABOVE RESEARCH WORKS

1) Concrete jacket is an effective method in increasing strength and stiffness in component of a frame and structural frame as well. Although sometimes supplying the anchorage bond of extra reinforcement concrete jacket, passing these bars from connection joint of beam-column, drilling of zones in executing stirrups and also using bent down connection bars with melded bars, cause difficulties in performing of this method. Proper techniques for executing design model are as under.

- ❖ In line with earlier studies by Bass et al. (1989), Bett et al. (1988), Valluan et al. (1993), Erosy et al. (1993) and Vandoros and Dritsos (2008), use of reinforced concrete as a method of strengthening has suggested. It can be cheaper than other methods has been used in concrete frame. This is because of availability of material and familiar implementation of this style.
- ❖ For establishing complete bond of beam-column in a way that moment could be transferred to frame components corresponding to increased resistance, the new

longitudinal reinforcements in columns should be passed through floor and they should be surrounded in a concrete jacket too.

- ❖ For improving inappropriate function arising from inadequate development length and slip of reinforcement in the connection of extra reinforcement to the column base, this length can be designed by using of epoxy.
- ❖ The study of epoxy resin bond tests on concrete samples with a fixed nominal resistance showed that by providing minimum length required, epoxy can be used for connecting old and new concrete instead of passing cross-stirrup through section of old concrete.
- ❖ Studies by Bett et al. (1988) showed that in designing computational models of structures that don't have adequate seismic strength, the reduction of stiffness and resistance for reinforced section should be considered.

3.5 COST ANALYSIS

Owing to their cost-effectiveness, concrete jackets have been, in the last quarter of 20^{th} century, by far the most widely-used technique for seismic upgrading of existing concrete members. This cost effectiveness is due to a number of reasons, namely:

(a) The familiarity of engineers and of the construction industry alike with the field application of structural concrete,

(b) The suitability of concrete jacketing for simultaneous repair of serious seismic damage, involving local or more extensive concrete crushing, or even buckling of bars and fracture of stirrups,

(c) The versatility and shape-adaptability of reinforced concrete to fully encapsulate existing concrete members and joints and provide structural continuity between different components.

(d) The ability of a concrete jacket to have, through the appropriate reinforcement, multiple effects, i.e. to enhance member stiffness, flexural resistance, shear strength, deformation capacity and anchorage and continuity of reinforcement in anchorage or splicing zones.

3.6 ADVANTAGES OF REINFORCED JACKETING

- ➢ Additional concrete and reinforcement contribute to strength increase.
- ➢ The stiffness of the system is highly increased.

- Durability of original column is increased.
- It does not require specialized workmanship.
- RC Jacketing is widely used & cost-effective for RC buildings:
- Familiar to engineers and construction industry ;
- suitable for repair o f damage ;
- Jacket can encapsulate members and joints providing structural continuity ;
- Multiple effects on stiffness, flexural /shear resistance deformation capacity, anchorage and continuity of reinforcement.

3.7 DISADVANTAGES OF REINFORCED JACKETING

- Minimum allowable thickness of jacket = 100 mm
- The sizes of the sections are increased and the free available usable space becomes less.
- Huge dead mass is added
- Requires adequate dowelling to the existing column
- Longitudinal bars need to be anchored to the foundation and should be continuous through the slab
- Requires drilling of holes in existing column, slab, beams and footings.
- Increase in size, weight of the column
- The speed of implementation is slow.
- Placement of ties in beam column joints is not practically feasible.

CHAPTER 4

STEEL JACKETING

4.1 GENERAL

Steel jacketing seems to have first appeared widely in the literature in the early 1990s, possibly as a consequence of the 1989 Loma Prieta earthquake that caused a number of highly publicized collapses of concrete bridge and elevated freeway structures.
Steel jacketing is an effective retrofitting method for deficient reinforced concrete columns. It improves column strength and ductility. Steel jacketing is a term used to describe the external encasement of columns prefabricated steel shells welded in situ. Depending on type of column i.e. circular or rectangular, the jacket is either circular or elliptical. If the column is circular, the jacket is fabricated slightly oversized and the gap between the jacket and column is filled with cement based grout to ensure composite action between the column and the jacket. Extensive experimental research has shown that the steel jacketing is effective in enhancing the flexural capacity and ductility as well as the shear capacity of the column, (Chai et al …1991). [20]

The steel jacket may be idealized conservatively as a series of independent closely spaced peripheral hoops with thickness and spacing equal to the jacket thickness. The steel jacket will normally be required over the full height of the column if the shear strength enhancement for the columns is needed. For example, full-height steel jacketing is mostly used for retrofitting the squat column. However, for the typical bridge column type (i.e., tall prismatic circular and relatively slender columns, which account for a considerable portion of the bridge columns), full height steel jacketing may attract excessive seismic force because of its greatly increased stiffness. In this case, using partial-height steel jackets is appropriate
Jacketing with steel elements is a practical method used frequently for various applications. A typical steel jacketing application is shown in Figure 4.1. Steel jacketing can readily be used to especially enhance the shear strength of reinforced concrete elements. With the maintenance of continuity between storeys, steel jacketing can also be used to increase the bending strength. The

maintenance of adequate strength between the steel element and reinforced concrete element is inevitable for the improvement of bending capacity.

Fig 4.1: steel jacketing applied to RC columns

4.2 STEEL JACKETING –PROCEDURE

The procedure for steel jacketing is as follows

- Repair surface defects such as honeycombs, spalls, loose pockets, cracks etc. with suitable repair methods for the RC member required to be strengthened with steel plates
- Prepare the concrete surface for receiving steel plates by drilling holes at suitable locations to insert chemical anchors as per design
- Install chemical anchors at the drilled locations
- Cut steel plates of appropriate thickness & sizes as per design with matching holes at the anchor locations
- Make provision for epoxy injection ports at suitable locations in the steel plates
- Secure the steel plates with the member using chemical anchors, leaving 2-3mm gap between the plate and the concrete surface
- Weld together the steel plates meeting at the joints or at angles
- Inject epoxy in the gap between the steel plate and the concrete surface after properly sealing the edges
- Let the epoxy cure as per supplier's recommendations
- Upon curing, clean the surface and apply corrosion protection or fire proofing treatment as per specifications

.

4.3 STEEL JACKET FOR CIRCULAR COLUMNS:

Providing a jacket around an existing column which has insufficient ductility and strength capacity is effective to prevent premature failure. The jacket is fabricated so that its radius is 12.5 to 25 mm larger than the column radius. After positioned over the areas to be retrofitted and are site-welded up the vertical seams to provide a continuous tube with a small annular gap around the column, the gap is grouted with epoxy resign or a pure cement grout.

The jacket resists not only tension and compression but also shear of the column. Lateral confinement to the core concrete can also be provided by the jacket. Because a jacket can not sufficiently provide the lateral confinement to a rectangular column if special detailing is not included, the steel jacketing is more appropriate to circular columns than rectangular columns. However restriction exists for hollow circular columns in which confinement from inside cannot be well provided. Furthermore, because columns with much larger radius than buildings are used in bridges, effectiveness of the steel jacket to columns with large radius (over 4 m) is still required to be clarified.

Smooth setting of a steel jacket and availability of structural steel plates restrict a minimum thickness of the jacket. Because a steel plate with a thickness in the rage of 6-12 mm is generally used for the jacket, an amount of steel of a jacket is very large compared to the existing longitudinal and tie bars.

A steel jacket enhances the shear and flexural strength and the ductility capacity of the column. Generally the enhancement of shear and flexural strength of the column increases the moment and shear demand of the foundation. Because redundancy of the moment and shear capacity of a foundation which was designed in the early days is limited, and because retrofit of a foundation is much costly than the retrofit of a column, the increase of the moment and shear demand of the foundation is not most likely preferable.

Consequently, there are essentially two practices in the steel jacketing. First practice is to restrict an amount of the increase of moment and shear demand of the foundation as small as possible. For this purpose, it is recommended to provide a space between the jacket and the footing or cap beam to avoid excessive flexural and shear strength enhancement of the plastic hinge. The gap depends on the radius of the column, but a 50-100 mm gap is generally recommended so that stable plastic hinge can be formed at the plastic hinge.

The other is to allow a certain amount of the increase of moment and shear demand of the foundation. If the foundation has some redundancy on the moment and shear capacity, this is effective to restrict excessive plastic displacement of the column. In particularly, it is appropriate to avoid excessive residual displacement of the column.

The jacket is effective in passive_confinement. The level of lateral confinement induced in the concrete by flexible restraint as the concrete attempts to expand laterally in the compression zone depend on the hoop strength and stiffness of the steel jacket. A similar action occurs in resisting the lateral column dilation associated with development of diagonal shear cracks. In both the confinement of flexural hinges or potential shear failures, the steel jacket can be considered equivalent to continuous hoop reinforcement.

4.4 STEEL JACKET FOR RECTANGULAR COLUMNS

A rectangular steel jacket is effective for enhancing the shear and moment capacity of a rectangular column, but it cannot provide sufficient lateral confinement in critical region as the size of the column increases.

Based on the studies, rectangular steel jackets on rectangular columns are not generally recommended although they can be expected to be fully effective for shear strength enhancement. An elliptical jacket is recommended to a rectangular column.

4.5 PROMINENT RESEARCH WORKS:

4.5.1 Aboutaha, 1996

For rectangular columns, it is a good practice to be retrofitted by oval or circular steel jackets. The large gap between steel jacket and column is filled with normal weight concrete after flushing with water. Because of the continuous curvature and membrane tension, better ductility and energy dissipation capacity of columns are expected. However, retrofitting rectangular columns with rectangular jackets to improve flexural ductility has been proved to be unsuccessful.[21]

4.5.2 Xinbao Yang, Wancheng Yuan, Genda Chen And Lichu Fan

The technique of steel jacketing was originally developed to retrofit circular bridge columns. The experimental results of four bridge piers retrofitted with externally encased steel jackets indicate that retrofitting rectangular bridge piers with steel jackets can significantly improve the displacement ductility and energy dissipation capacity due to the firm confinement provided by the jacket and can also increase the strength and stiffness of the piers to some degrees. Important conclusions drawn from this study are:-

- Confining effect by transverse reinforcement plays an important role on the seismic performance of RC bridge piers.

- Steel jacket retrofitting is a viable technique for repairing and retrofitting RC bridge piers for enhanced seismic performance.
- If circular steel jackets are used to retrofit rectangular columns, it is recommended that the columns be retrofitted in full length.

4.5.3 Research at CALTRAN:

Retrofit of columns using steel jackets has been extensively studied in 1990's, mainly in the context of bridge column. This research was primarily founded by CALTRAN (California Transportation Department).[22] They have shown that this technique provide good overall behaviour with increase ductility, shear strength, and energy dissipation. This method is now widely used in United States and in Japan.

The principal behind this technique is that steel jacket act as passive confinement reinforcement. The jacket will prevent the concrete from dilating, forcing it in lateral compression and increasing its ductility.

For circular columns, the method uses two semicircular half sections that are field welded along the entire height of the jacket. A gap of about 1 inch (2.5 cm) is left between the column and jacket. It is filled with a cement based grout that will ensure a good bonding and composite behaviour. Use of expensive grout instead of the cement base does not improve the performance. A gap of 2 inches (5 cm) is also left between the columns and the top the footing to avoid possible bearing of the jacket on the footing.

For rectangular columns the retrofit options are to either use a rectangular jacket or a circular (or elliptical) jacket. In the case where a rectangular jacket is used the procedure is the same, and two L shaped panels are field welded together. For circular (or elliptical) jackets, the gap created is larger and should be filled with concrete instead of a grout. It should also be noted that depending on the application condition and failure mechanisms partial jacket or steel collar may be used.

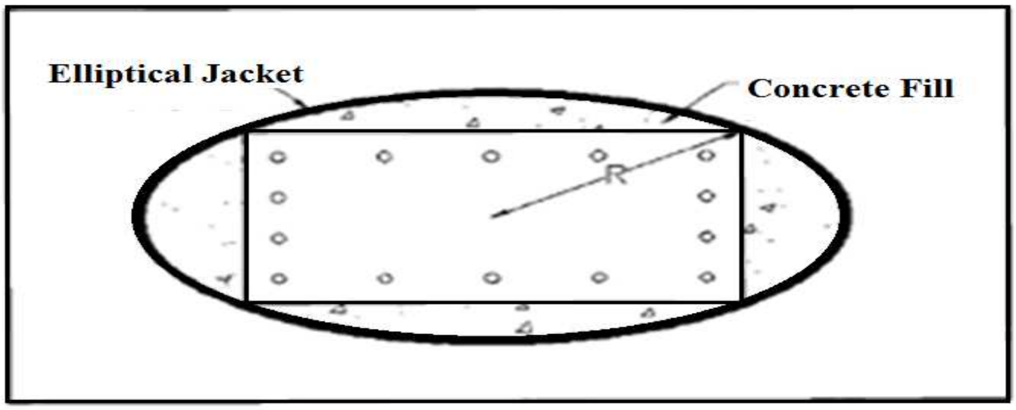


Fig 4.2: Seismic Retrofit of a Rectangular Section

The design and requirements for steel jacket depends on the mode of failure, flexural or shear. Each mode is discussed below.

4.5.3.1 Flexural strength failure and/ or flexural capacity

The first failure type is inadequate strength and/or flexural capacity. This type of failure comes from a lack of confinement of the concrete core followed by a failure in the plastic hinge region. This may result from a deficient detail that insufficient splicing length of the longitudinal bars was provided at the bottom of the columns.

Fig 4.3: Column failures in 94' Northridge quake, (a) Spalling at column end; (b) Crushed column due to insufficient concrete-core confinement. (Cooper,et al, 1994)

Current practices have column designed with closely spaced lateral reinforcement. In comparison, they behave with an increase in compressive strength and in ultimate strain of the core (the strain goes from 0.003 to 0.005), as well as with the development of stable hysteresis loops. To provide the same type of confinement to the deficient columns, lateral reinforcement would need to be placed outside column, weld lap, and cover with shotcrete. A comparable (if not better) reinforcement can be provided by steel jackets and are simpler, less expensive, and more esthetic than the FRP method.

The flexural capacity at the base of a column is related to the confinement level in the plastic hinge region. When cracks occur at the concrete steel interface, a steel jacket will provide a radial pressure through passive confinement. See the following figure

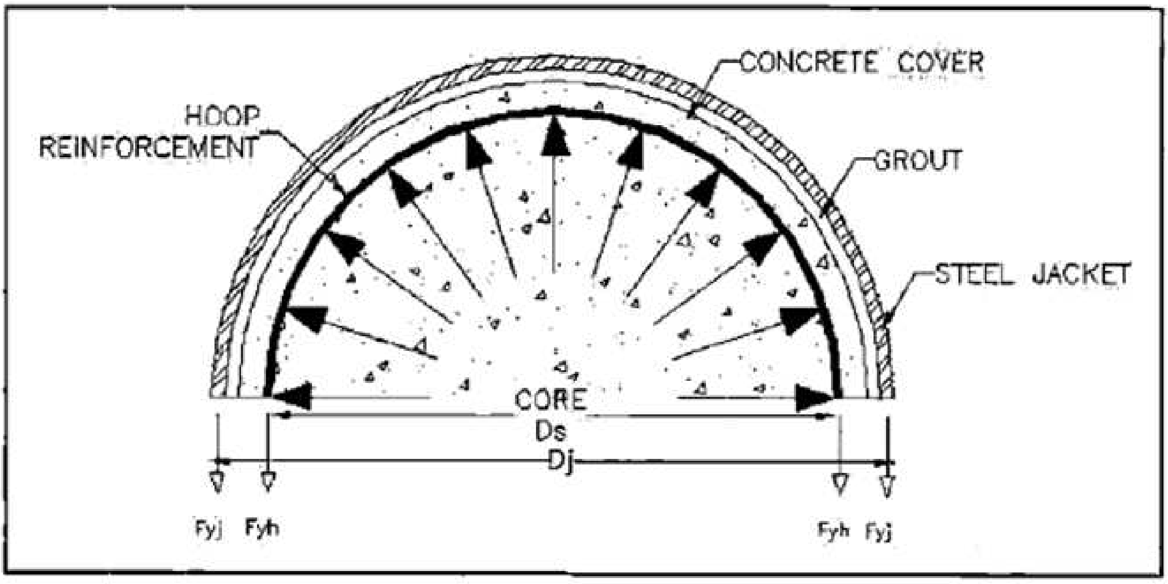


Fig 4.4: Confining action of Steel Casing

When the flexural failures are considered, failure will occur at the plastic hinge and so the location of the failure can be predicted. Research has shown just confining the critical area with a partial jacket would be sufficient for the retrofitting the column (confining an area 1.5 times the splice length).

Research also focused on rectangular column. A rectangular jacket will not provide enough confinement pressure to be as effective as a circular jacket and so it is recommended that for flexural failures a circular or elliptical jacket be used (the difference between elliptical or circular jackets are minor). In cases where this is not practical (especially in building where spaced is limited), it was found that rectangular jackets will enhance the response, especially if they are stiffened with at least four adhesive anchor bolts: two at the top and two at the bottom.

4.5.3.2 Shear failure

This type of failure is brittle and non-dissipative. It is characterized by diagonal cracks in the concrete (as soon as the tensile stress of the concrete is reached), then transverse reinforcement yields followed by the buckling of the longitudinal rebar, at which stage the concrete is completely crushed. Care must be taken to avoid this failure mode. Shear failure appears when the transverse reinforcement is insufficient.

The second major type of failure in column is shear failure. For columns subjected to shear failure the jacket should be applied to the entire length of the column. Different researchers have studied rectangular column subjected to shear failure both rectangular or circular (or elliptical) jackets are possible and effective. It should be noted that rectangular jackets are often associated with de-bonding failure between the jacket and the concrete and that anchor bolts should be provided.

4.5.4 Prestley, et al (1994)

Prestley et al. (1994) conducted a program of 14 large-scale column tests involving “as-built” and steel-jacketed columns. In the experiments, circular columns were retrofitted with steel jacket, filled in cement grout; and rectangular columns employed elliptical steel jackets. In the “as-built” columns, shear deformation was predominated, but in jacketed columns it was changed to flexural predominated. As a result, all the “as-built” columns failed brittle in shear, or because of low flexural ductility. Jacketed columns exhibited extremely stable lateral force-displacement hysteretic response. The flexural over-strength of strengthened columns was averagely 29 percent more than the calculated strength based on an extreme compression strain of 0.005, including effects of confinement and strain hardening. Elastic stiffness of the columns was on average increased 30 percent for circular columns, 64 percent for rectangular columns. The displacement ductility capacity was tested to be greater than or equal to $\mu_\Delta = 8$.[23]

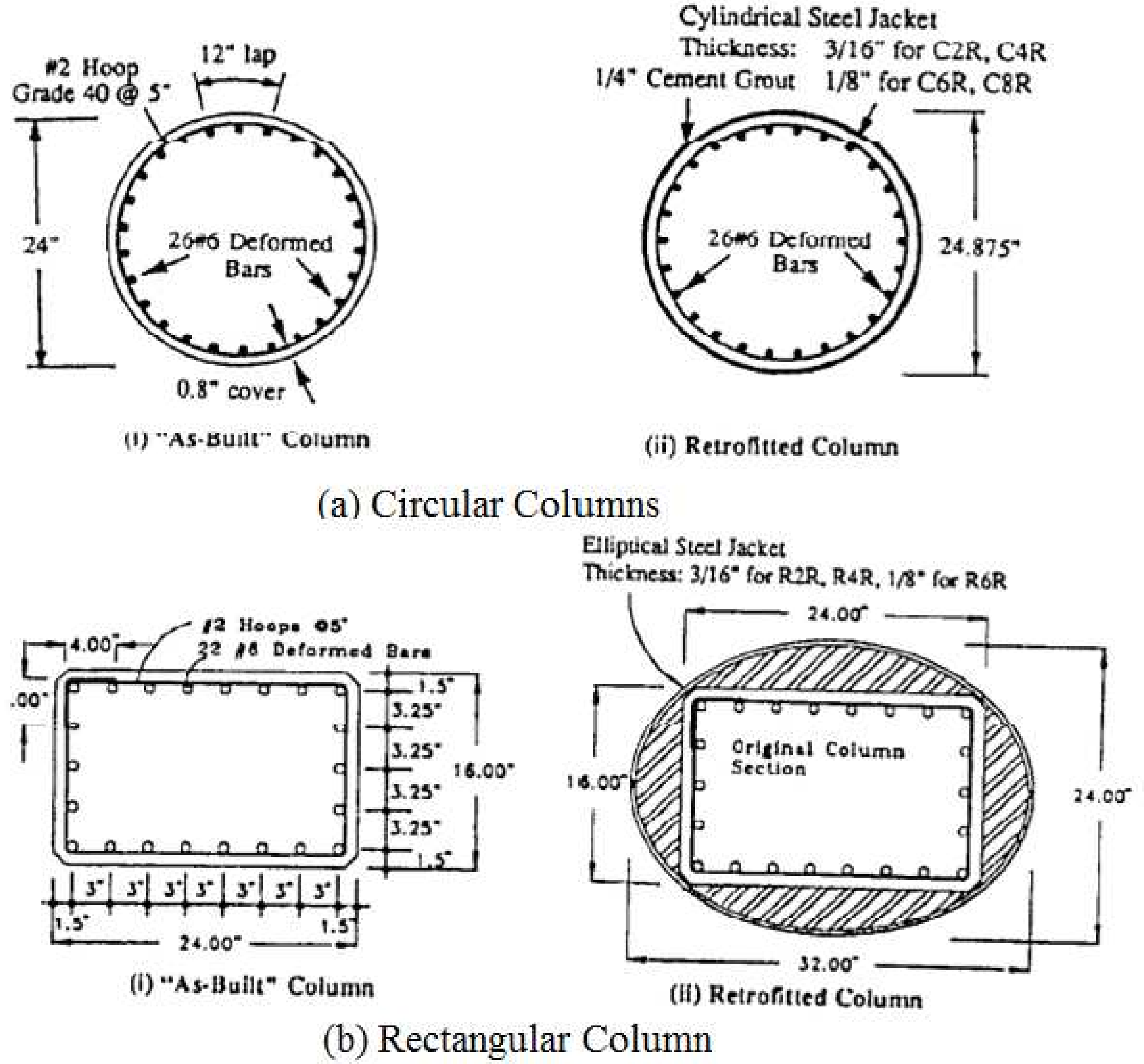


Fig 4.5: Retrofit of circular and Rectangular Column with Steel Jackets (Priestley et al, 1994, 1994a)

4.5.5 <u>Daudey and Filiatrault (2000)</u>

Daudey and Filiatrault (2000) conducted both experimental and numerical analysis for steel jacketed reinforced concrete bridge piers with complex cross-sectional geometries and lap-splices in plastic hinge region. The overall behavior proved to be very good. The tests indicated that the gap size of 50mm (2 inches) between the bottom of jacket and the top of the footing is adequate. This distance is effective to prevent stress concentration in the longitudinal reinforcement and avoid premature bar failure in tension at large inelastic displacement. The experiment also indicated that the geometry of the steel jacket does not influence on the efficiency of the reinforcement. Stable hinging occurred in the gap, where inelastic deformations sustained without significant strength loss. The displacement ductility reached 6.0, before sliding of longitudinal bars took place. The research also verified the prediction of the plastic hinge length, *Lp*, of a reinforced concrete pier retrofitted with steel jackets by Priestley (1996).[24]

4.5.6 <u>Guran, M. Zakariaey</u>

Guran, m. Zakariaey carried out nonlinear finite element analysis of circular reinforced concrete columns retrofitted by steel Jackets. The geometry of the column and material properties of concrete, steel jacket and reinforcements are taken from Priestly et al (1994).[25] The conclusions drawn from this study are as follows.

- The Steel Jackets are beneficial in Earthquake Design of structures.
- Thickness and tensile strength of steel jackets have significant influence on increasing the strength against Earthquake
- Compressive strength of R.C has significant effects on Earthquake resistance of columns retrofitted by steel jackets
- Effects of axial loads and reinforcement on strength of column are not drastic.
- A procedure for determination of optimal thickness of steel jacket for maximum shear strength was proposed. The results are tabulated according to height and diameter of the columns.

4.5.7 <u>Research work at NCREE</u>

A 4 years coordinated research effort on seismic retrofit of existing bridge columns has been established at the National Center for Research on Earth Engineering (NCREE) since 1998. Major objectives of this program are to develop effective seismic retrofit methods of existing bridges in Taiwan due to

- Inadequate design strength.
- Inadequate confinement at potential plastic hinge region
- Inadequate shear strength due to large lateral steel spacing.
- Lap- splicing in the plastic hinge region etc identified as some the most severe weaknesses of the existing RC bridge columns for seismic hazard.

Observations of the bridge damage during the 1999 Chi-Chi earth quake indicate that many existing bridges in Taiwan are indeed vulnerable to major earthquakes and coordinated research program is necessary and urgent. Many retrofit techniques that have been extensively studied and widely implemented in the United States, Japan and New Zealand are studied in this joint research.

4.5.7.1 <u>Experimental program</u>

More than 60 large scale specimens were tested. Cross sectional dimensions of the rectangular columns and circular columns are 600mm by 750mm and 760mm diameter, respectively. The worst details that may be expected in the existing bridges are assumed in the specimens, such as the double U-shaped transverse reinforcements with large spacing, and the lap-spliced of main reinforcements at the plastic hinge region. Retrofit techniques used in the specimens include steel jacketing, FRP wrapping.

4.5.7.2 <u>Summary of results</u>

The summary of above research work is as follows:

<u>4.5.7.3 Seismic retrofit of rectangular RC Bridge columns Using FRP Jacket</u>

(**<u>1) flexural failure mode</u>**

1. Test results show that failure of the flexural type specimen under larger axial load will result in speeding up the degradation of strength and energy dissipation capacity.

(2) **<u>Shear failure mode</u>**

1. Brittle shear failure occurs due to insufficient transverse reinforcement spacing.
2. Retrofitted by wrapping FRP shows great performance in improving shear strengths, and transfer the failure mode to flexural-shear type.

(**<u>3) lap spliced failure mode</u>**

1. Without enough confinement stress, bond slip occurred between the lap-spliced longitudinal reinforcements and resulted in brittle failure.
2. Applying CFRP directly can’t provide enough confinement stress to increase frictional force between the lap spliced longitudinal reinforcements.
3. A new method by attaching steel plates before wrapping FRP shows great potential in increasing the confinement stress and energy dissipate capacity for rectangular RC members. The strength, ductility, and energy dissipation capacity are also greatly improved. Further study is necessary to better understand the mechanism and to the critical parameter for retrofit design applications.

4.5.7.4 **<u>Steel jacketing retrofit design</u>**

The following conclusions were drawn after retrofitting the specimens with steel jacketing.

- The rectangular steel jacketing is effective in providing lateral confinement.
- Test results confirmed that the seismic performance of the rectangular RC bridge columns can be significantly and equally enhanced by properly constructed elliptical or octagonal steel jacket.
- It is found that the cost of the octagonal jacketing is 15% lower than that for elliptical jacketing
- Using a thicker jacket can reduce the cross-sectional area of octagonal steel jacketing rectangular RC bridge column.
- Rectangular steel jacketing can effectively prevent a shear-deficient column from shear failure; however, it is not effective in improving the flexural ductility.
- Octagonal steel jacketing scheme is cost-effective and can provide lateral confinement and shear strength to mitigate seismic failures of rectangular RC bridge columns due to lack of lateral confinement, improper lap-splice or inadequate shear capacity.
- A smaller cross-sectional area and better seismic performance than the elliptical steel jacketing scheme have been achieved from the octagonal steel jacketing.

4.5.7.5 **<u>Conclusions from this study:</u>**

- Using CFRP to retrofit bridge columns, the performance of bridge with circumference cracks is almost the same as the bridge columns without cracks.
- With steel jacketing and CFRP jacketing, the failure mode changes from flexural failure to the breaking of longitudinal bar in the bottom of the columns, and the ductility and maximum lateral force have increased.
- For lap splice failure mode, using steel and CFRP jacketing can tremendously increase the confinement strength and ductility of bridge columns. The more layers of CFRP can obtain higher ductility.
- For shear failure mode, using steel and CFRP jacketing can also tremendously increase the confinement strength and ductility of bridge columns. But, more

layers of CFRP may not higher ductility, yet more layers result in different failure modes, which cannot be compared with each other.[26]

4.5.7.6 Uomoto et al. [1987]

Uomoto et al. (1987) studied the effects of corrosion damage on the load bearing capacity of reinforced concrete columns. Corrosion was accelerated by adding sodium chloride to the mixing water, and applying a constant current (from 45 to 180 mA) to the reinforcement for 2 to 10 days. Columns were tested in uniaxial compression and failure loads of the corroded columns ranged between 70 to 80% of the non-corroded column strength. Strength tests were also performed on corroded longitudinal bars recovered from the loaded specimens and these indicated that losses in the bearing capacity were in the range of only 5 to 10%. Uomoto concluded that reductions in the bearing capacities of corroded columns is not caused simply by reductions in the strength or effective areas of the reinforcing bars, but also by cracks formed during the corrosion process.[26]

4.5.7.7 CONCLUSIONS FROM THE RESEARCH WORK IN STEEL JACKETING:

- Steel jacket retrofitting is a viable technique for repairing and retrofitting RC bridge piers for enhanced seismic performance.
- For rectangular columns, it is a good practice to be retrofitted by oval or circular steel jackets.
- Retrofitting rectangular columns with rectangular jackets to improve flexural ductility has been proved to be unsuccessful.
- If circular steel jackets are used to retrofit rectangular columns, it is recommended that the columns be retrofitted in full length.
- This technique provide good overall behaviour with increase ductility, shear strength, and energy dissipation.
- It should also be noted that depending on the application condition and failure mechanisms partial jacket or steel collar may be used.

- A rectangular jacket will not provide enough confinement pressure to be as effective as a circular jacket and so it is recommended that for flexural failures a circular or elliptical jacket be used (the difference between elliptical or circular jackets are minor).
- For columns subjected to shear failure the jacket should be applied to the entire length of the column.

4.6 ADVANTAGES

- It does not add significant weight to the structure (or to its footings) in comparison with concrete
- It saves on construction time (no curing time)
- The members are pre-fabricated offsite and more rapidly installed which is less disruptive to the building occupants than other techniques.
- Useful to enhance the stiffness of the member experiencing excessive deflections without appreciable increase in its depth.
- Can enhance shear, flexural and compression capacities.

4.7 DISADVANTAGES

The disadvantages are linked to construction issues :-

- Steel can be labor intensive.
- It is a time consuming technique.
- It requires heavy equipments to handle thousands of tons.
- It requires constant maintenance especially in corrosion protection.
- A destructive method as it requires hacking and drilling in the weak section
- It is hard to lift and align heavy steel plates in position
- Disruptive to the existing operations of the facility being upgraded
- Steel plates need to be tailored to the size of the member and it is hard to profile them for curvilinear shapes
- Surface finish with anchor studs is aesthetically not pleasing
- Adds in more dead weight to the structural member being strengthened
- Prone to environmental corrosion

4.8 APPLICATION OF STEEL JACKETING

4.8.1 STEEL JACKETING IN CALIFORNIA

Steel jacketing has been widely used in California for lap splice retrofit as shown in Fig. 4.5 as the major retrofit technique for bridge columns, with several hundred bridges thus retrofitted by 1994. Extensive experimental studies were conducted to develop steel jacketing technique (Chai et al 1990)[27]. During the 1994 Northridge earthquake, some 50 bridges with steel jacketed columns were subjected to peak ground acceleration of 0.3g or higher. None of these bridges suffered damage to columns requiring subsequent remedial work.

(a) (b)

Fig 4.5: Steel jacket retrofit of columns; **(a)** Los Angeles, and **(b)** San Francisco

4.8.2 STEEL JACKETING IN JAPAN

Steel jacketing has been also used in Japan for retrofit of premature shear failure resulted from termination of longitudinal reinforcement with inadequate development length.[28] After this problem was first recognized due to damage in 1982 Urakawa-oki earthquake, extensive experimental studies were conducted. As shown in Figs. 4.6, steel jacket with 9 or 12 mm thick structural plates were used depending on column diameters. Columns which were retrofitted in 1989 as shown in Fig. 4.6 were subjected to 0.8g or higher peak ground acceleration during the 1995 Kobe earthquake. None of the columns retrofitted suffered damage but the columns which were not retrofitted suffered extensive damage. After 1995 Kobe earthquake, over 27,000 columns of road bridges were retrofitted in Japan.

Fig. 4.6: Steel Jacket Retrofit at Hanshin Expressway in 1989, which was effective during the 1995 Kobe earthquake

CHAPTER 5

FERROCEMENT

5.1 GENERAL

In 1850, away from Paris in country estate in Provence, a horticulturist took a revolutionary step and built a boat out of concrete using meshes mortared with sand and cement. Lambot began the history of reinforced concrete and ferrocement. This phase lasted for 100 no substantial acquirements. In 1940, Nervi rediscovered ferrocement and he gave it a dimension ever seen. Ferrocement applications continued up to 1960s decade, when it use went to a decay, mainly because man-labor cost had been increasing and other competitors to thin components were developed. In 1960 decade, Nervi accomplishment stimulated another phase, the worldwide application of ferrocement, but mainly in developing countries. High structural performance of ferrocement has allowed the application of the material in quite different thin walled construction from ship hulls to housing panel.[29]

Rehabilitation and strengthening appears as a large potential field of ferrocement application. Ferrocement has been applied for water proofing and proposed for masonry wall and even structural concrete strengthening.

Ferrocement is probably one of the many traditional construction material which in spite of excellent technical and economic advantages that it offers, has not found widespread application in developed countries. This material has always been looked up on as a material fit for third world countries.

Ferrocement can offer a method of construction that is stiff, durable, and economic.[30] It is obviously unrealistic to talk of ferrocement replacing reinforced concrete for all purposes but it is undeniable that there are many situations where the use ferrocement concept can be cost effective in terms of construction cost, performance and service life.

5.2 DEFINITION OF FERROCEMENT:

Defined as a thin wall reinforced concrete and made of cement mortar and layers of fine wire mesh closely bound together to create a stiff structural form, ferrocement has a great potential to be used as a strengthening jacket material for substandard reinforced concrete columns.[31]

5.3 CONSTITUENT MATERIALS

a) Cement:

The cement should comply with ASTM C 150-85a, ASTM C 595-85, or an equivalent standard. The cement should be fresh, of uniform consistency and free of lumps and foreign matter. It should be stored under dry conditions and for as short duration as possible. Cement factors are normally higher in ferrocement than in reinforced concrete. Mineral admixtures, such as fly ash, silica fumes or blast furnace slag, may be used to maintain a high volume fraction of fine filler material. Rice Husk Ash (RHA) cement can be economically used as partial replacement of cement in mortar mixes. When RHA does not exceed 35% by weight of the blended cement, the compressive strength at 28 days is similar to that of Type I Portland Cement Mortar.

b) Fine Aggregates:

Normal weight fine aggregate (sand) is the most common aggregate used in ferrocement. It should be clean, hard, strong, free of organic impurities and deleterious substances and relatively free of silt and clay. It should be inert with respect to other materials used and of suitable type with respect to strength, density, shrinkage and durability of the mortar made with it. Grading of the sand is to be such that a mortar of specified proportions is produced with a uniform distribution of the aggregate, which will have a high density and good workability and which will work into position without segregation and without use of high water content. The fineness of the sand should be such that 100% of it passes standard sieve no. 8.

c) **Water:**

Water used in the mixing is to be fresh and free from any organic and harmful solution which will lead to deterioration in the properties of the mortar. Salt water is not acceptable but chlorinated drinking water can be used. Potable water is fit for use as mixing water as well as for curing ferrocement structures.

d) **Admixture:**

Chemical admixtures used in Ferrocement serve one of the following four purposes: water reduction, which increases strength and reduces permeability; air entrainment, which increases resistance to freezing and thawing; and suppression of reaction between galvanized reinforcement and cement.

e) **Mortar Mix:**

The reaction of Portland cement and water results in formation of hardened cement paste. The ranges of mix proportions recommended for common Ferrocement applications are sand-cement ratio by weight, 1.5 to 2.5, and water-cement ratio by weight, 0.35 to 0.5. Fineness modulus of sand, water-cement ratio and sand-cement ratio should be determined from trial batches to insure a mix that can infiltrate (encapsulate) the mesh and develop a strong and dense matrix. Water reducing admixtures may be used to enhance mix plasticity and retard initial set, as with conventional concretes. The behavior of mortar is similar to that of plain concrete.

f) **Reinforcing mesh:**

One of the essential components of ferrocement is wire mesh. Different types of wire meshes are available almost everywhere. These generally consist of thin wires, either woven or welded into a mesh, but the main requirement is that it must be easily handled and, if necessary, flexible enough to be bent around sharp corners. The function of the wire mesh and reinforcing rod in the first instance is to act as a lath providing the form and to support the mortar in its green state. In the hardened state its function is to absorb the tensile stresses on the structure which the mortar, on its own, would not able to withstand. A structure is subjected to great deal of pounding, twisting and bending during its life time resulting in cracks and fractures unless sufficient steel reinforcement is introduced to absorb these stresses. The degree to which this fracturing of the structure is reduced depends on the concentration and dimensions of the embedded reinforcement. The mechanical behavior of ferrocement is highly dependent upon the type, quantity, orientation and strength properties of the mesh and reinforcing rod.

g) <u>Skeletal Steel:</u>

Skeletal steel as the name implied is generally used for making the framework of the structure upon which layers of mesh are laid. Both the longitudinal and transverse rods are evenly distributed and shaped to form. The rods are spaced as widely as possible up to 305 mm (12 in.) apart where they are not treated as a structural reinforcement and are often considered to serve as spacer rods to the mesh reinforcements. In some cases skeletal steel is spaced as near as 75 mm (3 in.) center-to- center thus acting as a main reinforcing component wire mesh in highly stressed structures, e.g. boat, barges, tubular sections, etc.

h) <u>Coating:</u>

In general, ferrocement structures need no protection unless they are subjected to strong chemical attack that might damage the structural integrity of their components. A plastered surface can take a good paint coating. In terrestrial structures, ordinary paint is applied on the surface to enhance the appearance. Marine structures need protection against corrosion and vinyl and epoxy coatings were found to be the most successful organic coatings.

5.4 PROCEDURE – FERROCEMENT

Step 1:

Breaking, open the damaged spalled cover or the affected zone or the cover of RCC elements (such as beams or columns) with the help of a chisel and hammer.

Step 2:

Exposing the original reinforcing bars and scraping of corrosive layers of reinforcement and applying anti-corrosive paints (if any) or cutting and replacing the corroded reinforcement

Step 3:

Roughening the concrete surface, and placing chicken and/or galvanised wire/ weld mesh in position and the mesh should get fixed/ embedded to original slab/beam/column reinforcement. Use skeletal reinforcement, if required.

Step 4:

Applying cement mortar on the reinforcing wire-mesh by hand or through spraying (similar to guniting/ shotcreting methods)

Step 5:

Provide necessary curing for 28 days.

5.5 PROMINENT RESEARCHERS

Large number of buildings getting deteriorated with time due to various factors and they need strengthening. Now days use of ferrocement laminates are extensively used for retrofitting due to its properties such as ease of being casted to any shape without needing significant formwork are preferred over other sheets. Many researchers put their theory for use of ferrocement laminates for retrofitting

Investigation by many researchers have indicated that by providing external confinement at plastic region or over the entire reinforced columns, the strength and ductility can be enhanced.

5.5.1 NED University, 1998

Taking the lead from its potential use in enhancing earthquake resisting abilities, 5 houses were built in Northern area of Pakistan, using indigenous materials and local skills utilizing Ferrocement bands to improve the earthquake resisting of such houses in 1990 (NED university, 1998). The houses since then have performed remarkably well and have sustained low to moderate shocks effectively. The details were simple to follow and execute by the local skilled workers, and materials were readily available from nearby cities.[32]

5.5.2 Mohammad Taghi Kazemi et al (2005)

Mohammad Taghi Kazemi et al (2005) had performed a study to evaluate a retrofit technique for strengthening shear deficient short concrete columns. Ferrocement jacket reinforced with expanded steel mesh is used for retrofitting in this study. They had concluded that expanded meshes were more effective ties in shear strengthening of concrete columns and also specimens strengthened with expanded meshes showed distributed fine shear cracking even at large amounts of displacement ductility capacity.[33]

5.5.3 Katsuki Takiguchi and Abdullah

A technique by using ferrocement jacket for seismic strengthening of reinforced concrete column was investigated and compared with different strengthening methods by Katsuki Takiguchi and Abdullah. They studied three methods of strengthening, i.e. steel jacket, carbon fiber sheet, and ferrocement jacket, aimed at developing methods for strengthening existing reinforced concrete columns by ferrocement jacket to enhance their seismic resistance.[34]

A strengthening method using circular ferrocement jacket to improve the confinement of a substandard column was investigated and compared with control specimens and different strengthening methods. Five 1:6 scale model square columns were constructed and tested under constant axial load while simultaneously being subjected to cyclic lateral load. Two columns were tested as control specimens; one column was strengthened with circular ferrocement jacket and was compared with those of other two identical square RC columns strengthened circularly with steel plate and carbon fiber. The control specimens suffered shear failure and significant degradation of strength during testing whereas the strengthened columns showed a ductile flexural response and higher strength. The test results indicate that circular ferrocement jacket can be an effective alternative material to strengthen reinforced concrete column with in adequate shear resistance.

5.5.3.1 Details of experiment

a. **Ferrocement jacket**

Woven wire mesh was used. One person held the first end of the wire mesh in position while the second person wrapped the rest of it around the column. At several places, the first and the second layer of the wire mesh were tie together with the same diameter of steel wire. Similarly, this process was repeated when the third layer, and the fourth layer has been wrapped around the column. One hundred mm overlapping of wire mesh was provided in lateral direction. A clear cover of 3-mm on outer face of jacket was provided by bonding 5 x 5 mm square of 3-mm thick steel plates at several places. It needs about 3 hr starting from cutting the wire mesh from its roll until the steel mold was ready to be set.

Infill mortar was made with water-cement ratio = 0.55 and cement sand ratio of 1:2.5. Natural sand passing through sieve No. 1.2 (1.19 mm) was used. In order to improve workability, 0.05 % of cement weight of super plasticizer were added.

The infill mortar and mortar for ferrocement jacket were cast at the same time. Even though special care was applied when fresh infill mortar with slump of 180 mm was cast, and properly vibrated by two units of hand vibrators, some defects were observed on the surface of concrete. It was observed that only about 150 mm of jacket height was penetrated properly by mortar. Meanwhile within almost 90 % of the rest part of jacket, mortar penetrated up to the outer layer of wire mesh, and a number of layers of wire mesh were not fully covered by mortar on the rest part of jacket. This 10 % part was concentrated mostly at the corner of the square section of original column. Therefore, repair work by epoxy resin was executed to fill-up the 3-mm cover and part of the jacket that did not filled-out by mortar

b. Steel plate jacket

Another column specimen was strengthened with steel jacket fabricated from 0.8 mm thick steel plate. Two half shells of steel plate are positioned over the area to be strengthened and are connected using 5 mm high tensile strength bolt up the vertical seem to provide a continuous tube around the column. Bolt were arranged in double shear at spacing of 15 mm. Gap between the steel jacket and the concrete column was filled with mortar.

c. Carbon fiber sheet

Prior to the application of the epoxy coat to the bare column of specimen SCCF, the concrete surface was cleaned from dust. The carbon fiber sheet which is available in 300 mm wide roll was then wrapped directly on the fresh epoxy coat. One hundred mm overlapping was provided in lateral direction and no overlapping for vertical direction. Any air-trapped under neat the carbon fiber sheet was forced out by hand operated pressure roller. About 30 minutes later, the second epoxy coating was applied on the surface of carbon fiber sheet. These works also carried out by two people.

5.5.3.2 Conclusions

Five columns have been prepared and tested in this experiment. Based on the work performed, starting from preparation of the strengthening material until the completion of the test of specimens the following conclusions can be drawn.

- Test results show that the two origin column specimens suffered shear failure and significant degradation of strength at a relatively low lateral displacement. Both columns were unable to develop their flexural strength.
- By providing external circular confinement using carbon fiber sheet and ferrocement jacket to the origin columns, the stiffness, strength, energy dissipation, and ductility are improved significantly and the mode of failure changed from brittle shear failure to ductile flexural failure.
- Although it seemed that the effect of the jacket is to concentrate plasticity at the gaps, as indicated from this research if they were designed properly the earlier fracture of the longitudinal bar can be prevented.

- The results of this investigation indicated that strengthening of a square reinforced concrete column with circular ferrocement jacket was considered to successful.
- They had concluded that by providing external confinement over entire length RC columns the ductility is enhanced tremendously.
- They had also concluded that ferrocement jacket can be used to strengthen RC column with inadequate shear strength to enhance its ductility.[35]

5.5.4 V.M. Shinde, J. P. Bhusari

Use of ferrocement as an external confinement to concrete specimen was investigated by V.M. Shinde, J. P. Bhusari with reference to layers of confinement and orientation of meshes. The effectiveness of confinement is achieved by comparing the behavior of confined specimen with that of unconfined specimen. Results showed that the confinement of cylindrical specimen can improve the ultimate strength with single and double layer of mesh compared to unconfined specimen. Ultimate compressive strength increases with the change in orientation of square mesh from 90º to 45.[36]

5.5.4.1 Experiment

Experimental investigation was to investigate the influence of number of layers and orientation of meshes on compressive strength of ferrocement confined column. Major parameters affecting behaviour of concrete column confined externally with ferrocement are considered as number of layers, orientation of mesh and concrete grade. For this experimental program effect of orientation of meshes varying from 90°, 80°, 70°,60°, 45°, and number of meshes is studied with reference to compressive strength of ferrocement confined column.

5.5.4.2 Materials

- **Cement**

  .Portland cement

- **Sand.**

  Locally available natural river sand owing to its rounded shape was used in this work, as it ensures better packing characteristics than the crushed sand.
- **Coarse aggregate**

  Crushed graded aggregate of quartzite origin having a maximum size of 20 mm was used as coarse aggregate. Coarse aggregate had negligible water absorption.

5.5.4.3 Mix proportion.

Water cement ratio 0.43.

5.5.4.4 Casting

For this investigation, plain cement cylindrical specimens of size 120mm dia. and 600 mm in length were casted. The concrete was mixed by using concrete mixer. First, cement and fine aggregate were mixed in a dry form until uniformity was achieved and lastly coarse aggregate was added. Then, water was sprinkled and mixed thoroughly until a uniform mix was obtained. The specimens were de-moulded after 24 hour, and the specimens were kept for curing in a water tank till the age of the testing (28 days).

5.5.4.5 Confinement of plain cement concrete

For the preparation of confined specimens, the plain cement concrete specimens were wrapped with ferrocement laminates. The specimens were taken out after curing (28 d), and then the surface of the specimen was roughened. A rich mortar of 1:1 was applied on the roughened surface of the specimens, and then welded wire mesh (WWM) of a single layer mesh or double layer mesh as per the requirement was wrapped around the specimen. Finally, the specimens were plastered with 1:2 mix mortars with water: cement ratio of 0.43 with a confinement thickness of 20 mm. Thus, the diameters of the confined specimens were 160 mm, i.e. the diameter of plain concrete, 120 mm, plus ferrocement confinement thickness equal to 20 mm around the specimen. The dimensional detail of the confined concrete specimen is shown in Fig.1.

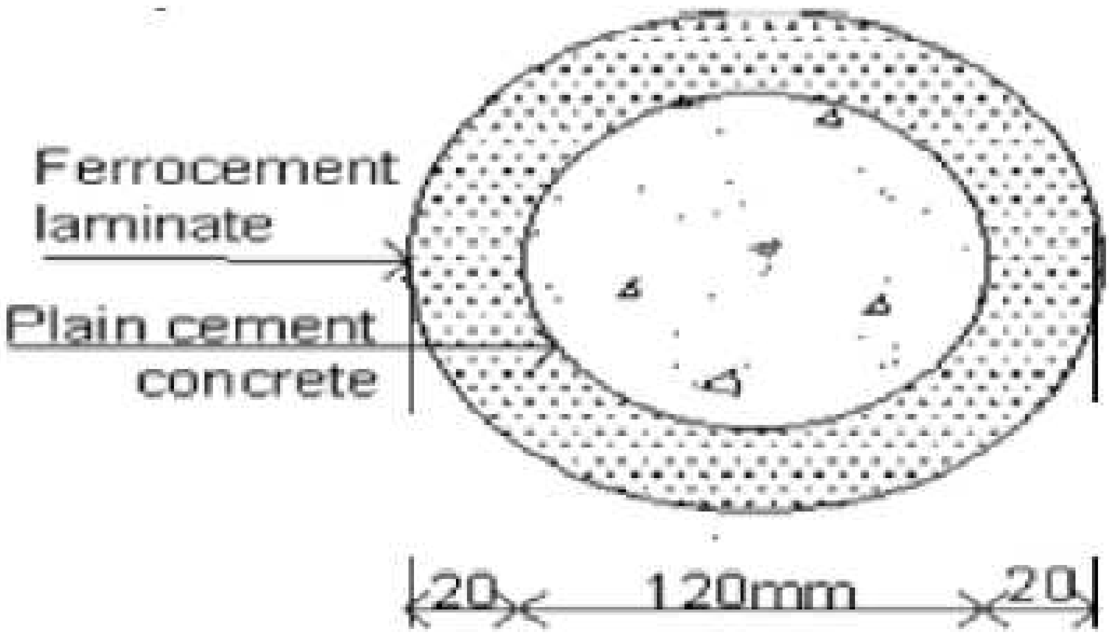


Fig 5.1: Dimensional detail of the confined concrete specimen

5.5.4.6 Testing

Specimens were loaded under UTM up to failure. The load was applied gradually up to failure.

5.5.4.7 Important Conclusions

- The crack pattern is similar in the entire concrete specimen but initiation of cracks is somewhat late in concrete specimens with double layer specimen as compared to single layer concrete specimens.
- Ferrocement laminates can be used as good strengthen material, or it can be used for retrofitting technique as confined specimen gives more strength than the unconfined specimen.
- Double layer of welded wire mesh (WWM) gives nearly double strength than the single layer of WWM.
- There is increase in strength with change in orientation of mesh from 90º to 45º
- Effect of orientation of mesh is more in single layer; this is found to be about 36% as compared with double layer.

5.5.5 T. Ahmad Sk.S Ali and J.R. Choudhury

T. Ahmad Sk.S Ali and J.R. Choudhury conducted experimental study of ferrocement as a retrofit material for masonry column. The study demonstrates that the use of ferrocement coating strengthens brick columns significantly. They investigated the possibility of using ferrocement as a retrofit material for masonry column.[37] Uniaxial compression test were performed on three uncoated brick columns, six brick columns coated with unreinforced plaster and six brick columns coated with a 25mm thick layer of ferrocement. Three hollow ferrocement columns with 25mm thick shells were also tested to investigate the confinement effect imposed on masonry column due to ferrocement coating. All the specimen were tested for axial loads using universal testing machine. The observations were made for cracking loads, failure loads and failure pattern..

5.5.5.1 High lights and conclusion of study:

a. **Experimental study**

Among the available coating procedures, a thin ferrocement overlay has been suggested as one having considerable promise for use with unreinforced masonry columns that requires enhanced in-plane strength and ductility. The study, whose results are reported here, deals with compressive behaviour of masonry columns coated with ferrocement.

A total of 18 brick masonry columns of 24.5 cm * 24.5 cm * 122 cm size were constructed in the laboratory with 1:5 cement-sand mortar and tested to failure under uniaxial compressive loading. The ratio of mortar for plaster and ferrocement coating was 1:2. For all the coated specimens, the ferrocement coating or plaster coating was applied two days after the construction of the column. In case of ferrocement coating, a 8 mm thick layer of mortar was applied around the column on which one layer of wire mesh was wrapped around the column and tied around it. Then another 8 mm thick layer of mortar was applied. On this mortar layer another layer of wire mesh was wrapped on which additional 8 mm mortar was applied to make 25 mm to make thick ferrocement coating. All the specimens were moist cured for fourteen days.

b. Test results and discussions

All the specimens were tested using universal testing machine. The following conclusions were drawn from this study

- The application of ferrocement coating on bare masonry column enhances the compressive strength quite significantly.
- The cracking resistance and stable crack growth mechanism of bare masonry column is improved quite significantly due to provision of ferrocement coating.
- As expected, there is no appreciable increase of load carrying capacity of brick masonry column due to application of rich mortar coating.
- The failure of bare masonry column and column coated with plaster is very sudden and the cracks widen very rapidly after their formations, leading to brittle failure for the system.

5.5.6 Singh, K.K. ; Kaushik, S.K. And Prekash, A.(1988).

A simple method for strengthening of brick masonry column using ferrocement was suggested by Singh, K.K.; Kaushik, S.K. And Prekash, A.(1988). The method consists of wrapping of a few layers steel wire mesh around the column, and nailed to it by u nails, or tied around it; rich sand-cement mortar, 1:1.5 to 1:2.5, is then applied to the mesh and made to penetrate into it and adhere to the column surface. On setting, it forms a casing around the column. Thus application of ferrocement casing is not very much different from plastering. Using the procedure outlined above, Singh reports the failure load to be double than that of uncoated columns. In this case failure was due to the failure in casing under combined bending and tension under lateral loads.[38]

5.5.7 Reinhorn, A.M. ; Prawal ,S.P. And Jia, Zi-He. (1985)

Reinhorn, A.M. Prawal, S.P. And Jia, Zi-He. (1985) successfully used a thin ferrocement coating on the sides of unreinforced walls. Ferrocement coating was mounted on the two sides of the wall with tension ties provided through masonry.[39] The result of the tests showed the suitability of ferrocement as a retrofit material. The strength, ductility and stiffness enhancement of coated walls have values nearly double of those for an uncoated wall and composite strength does not appear to depend on mesh size.

5.5.8 Singh and Kaushik et al, 1998

Ferrocement over the years have gained respect in terms of its superior performance and versatility, and now is being used not only in housing industry but its potentials are being continuously explored for its use in retro-fitting and strengthening of damaged structural members.[40]

5.5.9 Desia, 1999, Wasti and Erberik et al, 1998

Ductility requirements are the main feature of an efficient earthquake restraint design process, and Ferrocement being highly ductile material have led to its application in rehabilitation of houses damaged by earthquake and the effectiveness of its use has been reported by Desia, 1999, Wasti and Erberik et al, 1998.

5.5.10 Ahmed et, al.

Ahmed et, al. presented results of three dimensional linear elastic finite element analysis of composite action between brick column and ferrocement overlay. From this linear elastic analysis the authors established some critical parameters which affect the composite behaviour of masonry column coated with ferrocement.

5.5.11 P.J. Nedwell, M.H. Ramesht And S. Rafei-Taghanaki

They investigated the repair of short square columns using ferrocement. The important conclusions of their study are as follows:

- ✓ Ferrocement, when applied as a sheet of material over an entire element, has the capacity to provide not only a durable repair but also additional strength.
- ✓ The use of ferrocement retrofit coating to damaged columns increases the apparent stiffness of the column and significantly improves the ultimate load carrying capacity.

5.5.12 Andrew and Sharma, Basanbul et al, and Lub and Wainroi

Andrew and Sharma, Basanbul et al, and Lub and Wainroi have investigated on ferrocement as a strengthening material for RC beams.

5.5.13 Andrew and Sharma (1998)

Many experimental studies have been conducted in recent years to strengthen flexure members by using various materials. Andrew and Sharma (1998) in an experimental study compared the flexural performance of reinforced concrete beams repaired with conventional method and Ferrocement. They concluded that beams repaired with Ferrocement showed superior performance both at service and ultimate load. The flexural strength and ductility of beams repaired by Ferrocement was reported to be greater than the corresponding original beams and the beams repaired by conventional method.

5.5.14 Arya and Singh

Arya and Singh have studied on ferrocement as a repair and strengthening materials for low rises housing.

5.5.15 Sakthivel, P.B:

A study by Sakthivel, P.B. recommends ferrocement as the best alternative material to RCC and also a construction material of the future due to its following properties/ advantages.

- Ferrocement elements undergo high deformations before collapse. It has high level of impact and cracking resistance, toughness and ductility.
- The ferrocement structures are thin and light-weight compared to conventional reinforced concrete. Hence there is considerable reduction in self-weight of the structure and saving in foundation cost. Transportation cost is also less
- Ferrocement can be fabricated into any desired shape or configuration. Pre-casting is suitable for thin ferrocement elements, and mechanized methods can be adopted in case of mass production of ferrocement components.
- Ferrocement structures can be easily maintained, and also repaired in the event of structural damage without any major problems.

- Ferrocement is also suitable for repair or rehabilitation/restoration of ancient or heritage building structures. The repaired elements can withstand long years without cracking.
- Less or no formwork construction processes is involved in ferrocement repair methodology.

5.5.16 Wail Nourildean Al-Rifaie

Wail Nourildean Al-Rifaie studied the following characteristics of ferrocement

a. Impact Resistance of Ferrocement:

Ferrocement is very adequate to resist the impact, due to its higher ability of absorbing impact energy as compared with the conventional reinforced concrete, and the damage is localized at the impact zone. Tests were carried out at the laboratory of Civil Engineering Department at the University of Nottingham, U.K.

b. Rehabilitation/or Strengthening Technique by Ferrocement:

It is concluded that strengthening of reinforced concrete element by using ferrocement technique is very effective in increasing the cracking, ultimate loads and increasing the impact resistance. Tests were carried out at the National Center of Construction Laboratory, Baghdad, Iraq

c. Fire Resistance:

The ferrocement building components can withstand direct fire with a temperature values up to 756^{o} C for a period of 2½hours with no segregation in the surface of the elements facing the fire. Tests were carried out at ferrocement factory, Baghdad, Iraq.[41]

Fig 5.2: Fire Resistance tests on ferrocement buildings at Ferrocement Factory, Baghdad, Iraq.

d. **Blast protection:**

Blast protection for structures under direct or indirect threat from explosive hazards often requires retrofit solutions with minimal or temporary environmental impact whilst providing structural shielding from shock waves and shrapnel and spall fragments. These situations include structures under direct assault or in post-conflict areas where unexploded ordinance pose a continuing hazard.

Ferrocement paneling provides a effective solution. The incorporation of continuous steel wire reinforcement increase ductility under impact loading which boost structural integrity compared with conventional reinforced concrete and concentrates damage at the impact zone. Splinter penetration is minimal through the thickness of such slabs and short range proving tests with 7.62mm rounds have demonstrated excellent damage tolerance for relatively low density installations.[42]

5.6 IMPORTANT CONCLUSIONS DRAWN FROM RESEARCH WORK IN THE FIELD FERROCEMENT:

- By providing external circular confinement using carbon fiber sheet and ferrocement jacket to the origin columns, the stiffness, strength, energy dissipation, and ductility are improved significantly and the mode of failure changed from brittle shear failure to ductile flexural failure.

- The results of this investigation indicated that strengthening of a square reinforced concrete column with circular ferrocement jacket was considered to successful.
- They had concluded that by providing external confinement over entire length RC columns the ductility is enhanced tremendously
- There is increase in strength with change in orientation of mesh from 90º to 45º
- The application of ferrocement coating on bare masonry column enhances the compressive strength quite significantly.
- The strength, ductility and stiffness enhancement of coated walls have values nearly double of those for an uncoated wall and composite strength does not appear to depend on mesh size.
- Ferrocement being highly ductile material have led to its application in rehabilitation of houses damaged by earthquake
- The use of ferrocement retrofit coating to damaged columns increases the apparent stiffness of the column and significantly improves the ultimate load carrying capacity
- The ferrocement structures are thin and light-weight compared to conventional reinforced concrete. Hence there is considerable reduction in self-weight of the structure and saving in foundation cost. Transportation cost is also less

5.7 ADVANTAGES

- High degree of durability
- High degree of ductility
- It is economical
- Ferrocement is a low self wt. construction, reduction being about 50% vis-à-vis RCC
- environment friendly
- Resist fire for almost 2½hours up to 756 ^{o} C and can be made to resist higher temperatures.
- Do not require major repairs in its life time
- Remain almost intact during earthquake and cyclone
- Prevention of buckling of columns.

- Crack formation along reinforcement even after repairs by other systems shall not take place.
- Research on repairs with Ferrocement Technology has proved that RCC members improve in strength by 125% to 300% as compared to original undamaged condition.
- The treatment around the columns contribute less increase in dimension

5.8 DISADVANTAGES

- It is labor intensive, which makes it expensive for industrial application in the western world
- Threats to degradation (rust) of the steel components is a possibility if air voids are left in the original construction, due to too dry a mixture of the concrete being applied, or not forcing the air out of the structure while it is in its wet stage of construction, through vibration, pressurized spraying techniques, or other means.
- If the voids occur where there is untreated steel, the steel will rust and expand, causing the system to fail.

5.9 COST ANALYSIS

Ferrocement uses steel wire meshes that are about 2 to 5 times more expensive by weight than ordinary steel bars. The assemblage of those meshes requires medium level or non- skilled labor, which is advantage in developing countries where cost of labor is relatively low. However, this work often takes much time and the productivity goes down. In prefabrication plants this lack of productivity can raise the cost and so ferrocement or reinforced mortar may become non competitive against other industrialized products.

The tendencies are in general to reduce the mesh content or to substitute them for other suitable meshes and fibers that may reduce the production cost. There are examples of production rationalization, by using long beds stretching the meshes, or by using prestressing. Application of short fibers in conjunction with continuous wires also has been proved to be economical in many situations.

The application of prestressing techniques to ferrocement (or generally to thin walled reinforced mortar or “fine grain concrete”) has a great potential in the light prefabrication and some of the precast concrete production techniques can be adapted to ferrocement. This also should reduce the cost, because mesh content and wiring labor could be minimized.

Quality control is very important aspect in prefabrication, not only because a good quality of elements must be reached, but also because quality control can reduce the cost.

CHAPTER 6

FIBER REINFORCED POLYMER

6.1GENERAL

One of the most important issues currently for civil structural engineers world-wide, is the repair of deteriorated, damaged and substandard concrete structures. Fiber Reinforced Polymer (FRP) composite was first used in the building industries during late 1960, to construct all composite buildings. In the late 1980, composite material started to have their first major successes in the field of flexural, shear strengthening and seismic retrofitting of degraded concrete structures.[43] This initial thrust has now been extended to areas such as confining concrete columns and strengthening beam/ column joints.[44] In the strengthening and seismic retrofitting, the cost of FRP materials is only a relatively small percentage of overall cost for the work. Its speedy fabrication on the site and low weight has economic benefit. The rehabilitation and retrofitting of reinforced concrete (RC) and pre-stressed concrete (PC) structures utilizing advanced polymer composites are now well establish techniques. During last three decades, externally bonded FRP composite strengthening has been attractive and it has advantages including light weight and strength of FRP laminates. Ease of handling and installation techniques without use of heavy equipments are the added advantages.

Before we proceed further, it is essential to differentiate between the following terms as these are erroneously interchanged.

a) **Repair**. It implies the filling of a crack in a concrete member by injection of a resin polymer into the crack.
b) **Rehabilitation.** Means the improvement of the functional deficiency of a structure such as severely degraded structural member to return to its original structural form.
c) **Strengthening.** Means addition or application of structural component would enhance the existing designed performance level.

d) **Retrofit.** This term is specifically used to relate to upgrading of the part of structure damaged during a seismic event. This could involve use of composite jackets for the confinement of a damaged column.

6.2 DEFINITION

Composite is defined as a mechanically separable combination of two or more component materials, different at the molecular level, mixed purposefully in the order to obtain a new material with optimal properties, different than the properties of the components.[45]

FRP composites are the combination of polymeric resins, acting as matrices or binders with strong and stiff fiber assemblies which act as reinforcing phase. The combination of the matrix phase with a reinforcing phase produces a new material system analogous to steel reinforced concrete, although the reinforcing fraction vary considerably (i.e. RC in general rarely contains more than 5% reinforcement) whereas in FRP composites according to various sources, reinforcing volume fraction ranges from 30% to 70%.[46]

6.3 FIBER

A fiber is a material made into a long filament. A single fiber usually has a diameter up to 15 um. Bigger diameter generally increases the probability of the surface defect. They usually occupy 30% to 70% of the volume of the composite and 50% of its weight.[47]

6.3.1 FUNCTION:

The main functions of fibers are to carry the load and provide stiffness, strength, thermal stability and other structural properties to the FRP. To perform these functions, the fibers in FRP composite must have high modulus of elasticity, high strength, and low variation of strength among fibers, high stability of their strength during handling.

6.3.2 FORMS OF FIBERS: There are various forms of fibers used as reinforcement of polymers composite. Basically there are two forms of reinforcement; roving and fabrics.

a. Roving:

Roving as one-dimensional reinforcement of polymer composite is formed as under:-

I. **Smooth roving.** The bundle of filaments arranged longitudinally in a free manner.

II. **Interlaced roving.** The bundle of filaments arranged longitudinally with elementary fibers interlaced in a loop to mechanically connected neighbouring roving's.

III. **Tangled roving.** The bundle of filaments arranged longitudinally, interlaced manually in order to provide better cooperation of the neighbouring filaments in a single roving.

IV. **Stapled fiber.** Short filaments made by cutting the smooth roving.

V. **Minced fiber.** Very short filaments obtained by milling and sifting stapled fibers.

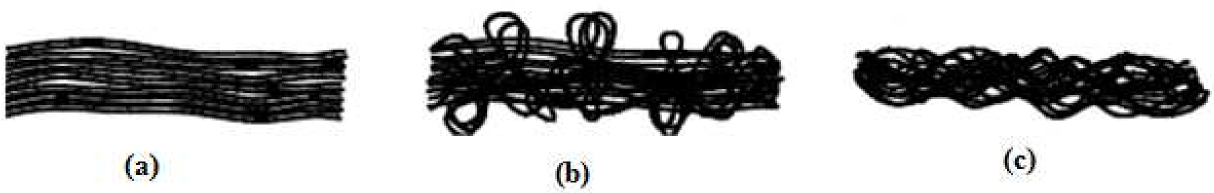


Fig 6.1: Various forms of roving: a) smooth roving, b) interlaced roving, c) tangel roving.

b. **Fabric:**

In order to strengthen the surface elements in more than one direction of reinforcement, the following forms are applied

I. **Smooth roving fabrics -** fabrics made of interlaced roving.

II. **Interlaced roving fabrics -** connect neighbouring roving.

III. **Mates -** made of continuous, random fibers.[48]

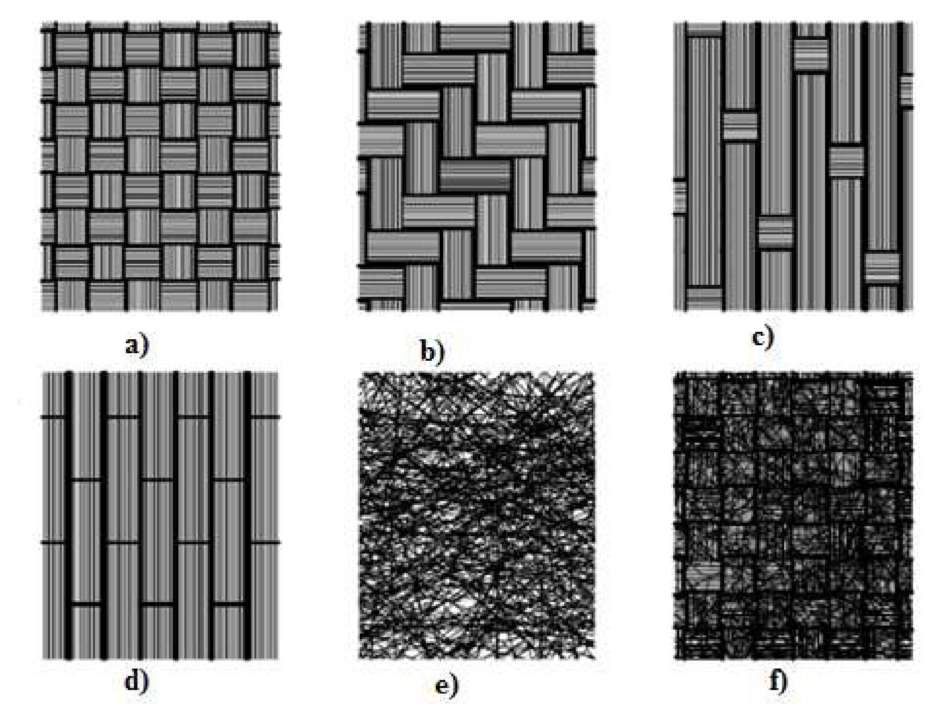


Fig 6.2: Examples of surface reinforcement; plain roving fabrics; **a)** oblique, **c)** satin, **d)** Smooth unidirectional roving fabric, **e)** mat, **f)** roving plain interlaced weave fabric

6.3.3 TYPES OF FIBERS:

There are three types of fibers dominating civil engineering industry; glass, carbon and aramid fibers.

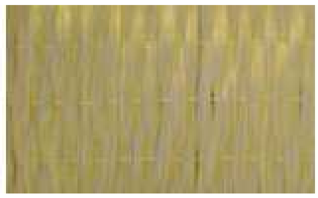
a. **Glass Fiber**

Glass fibers are processed from glass which is composed of numbers of oxides (mostly silica oxide) together with other raw materials such as limestone, fluorspar, boric acid and clay. There are five forms of glass fiber used for the reinforcement of matrix material. The glass fiber strand and woven fabrics are most commonly used in civil engineering. E-glass fibers are a relatively low Young's modulus, the low humidity and alkaline resistance as well as low long term strength due to stress rupture. To overcome it a more alkaline resistant AR fiber has been developed with increased Zircon oxide contents.[49]

b. Carbon fiber

Carbon fibers are manufactured by controlled pyrolysis and crystallization of organic precursors at temperature above 2000°C. During the process carbon crystallites are produced and oriented along Carbon fibers have high elastic modulus and fatigue strength than those of glass fibers. Studies suggest that carbon fiber reinforced polymers have more potential than aramid and glass fibers. Their disadvantages include inherent anisotropy (reduced radial strength), comparative high energy requirements in their production as well as relative high costs.[50]

c. Aramid fibers



Aramid or aromatic polyamide fiber is one of the two high performance fiber used in civil engineering application. It is manufactured by extruding a solution of aromatic polyamide at a ter and -80°C into a hot cylinder at 200°C. Fibers left from evaporation are then stretched and drawn to increase their strength and stiffness. During the process, aramid molecules become highly oriented in the longitudinal direction. Aramid fibers have high static, dynamic fatigue and impact strength. The disadvantages are; low compressive strength (500 - 1000MPa) reduced long term strength (stress rupture) as well as sensitivity to UV radiation. Aramid are difficult for cutting and machining.[51]

<u>The table below represents properties of types of fibers</u>.

Typical	GLASS		ARAMID		CARBON	
Properties	E-GLASS	S-GLASS	KEVLAR 29	KEVLAR 49	HS (high strength)	HM (high modulus)
Density ρ [g/cm^3]	2,60	2,50	1,44	1,44	1,80	1,90
Young modulus E [GPa]	72	87	100	124	230	370
Tensile strength [MPa]	2,000	4,750	2,860	3,750	2,860	2,900
Typical	2.40	2.90	2.80	1.80	11.00	0.50

Table 6.1: Properties of Types of Fibers.

6.3.4 ORIENTATION OF THE FIBERS

While strengthening the member, orientation of the fiber is of utmost importance. This is so, because strength of FRP product is not equal in all directions. In the axial direction of fiber, its strength is the maximum.[52] In flexural members, tension is along the span direction and mainly for that, steel reinforcement is provided. In similar way, while providing the FRP sheet, the same should be in such a manner that direction of the fiber should be mainly along the span.

6.4 FRP CONSTITUENTS

FRP consists of fibers, fabrics, resins, sizing, additives, and coatings.

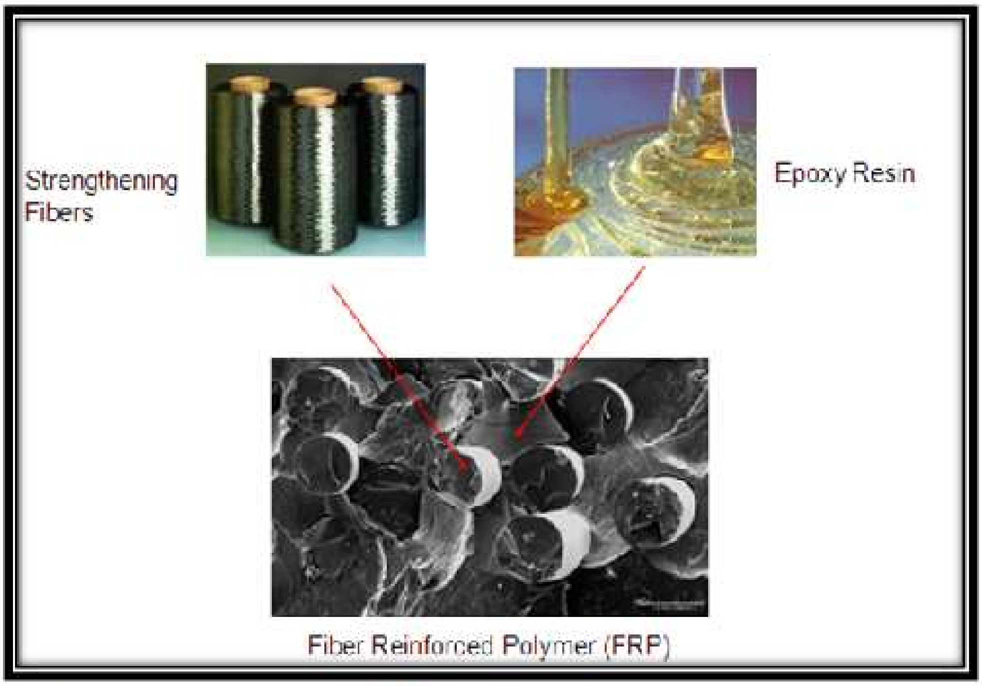


Fig 6.4: Strengthening Fibers & Epoxy Resin two main components of FRPs

6.4.1 FIBERS

Glass and Carbon are the most common types of fibers used as reinforcements in composites. Other types of reinforcements are organic fibers such as Kevlar, boron, silicon carbide, ceramic and others. Fibers can be long (continuous), short, chopped, milled, or in the form of elongated single crystals. Continuous fibers come in the form of untwisted bundles as strands, or twisted bundles as yarns, and also as a collection of parallel continuous strands, which is referred to as roving.

6.4.2 RESINS:

Resins are the polymer binders that hold the fibers together and transfer the loads between the fibers in addition to protecting them from environmental factors and carrying shear loads. Thermo-set resins (e.g. polyester, epoxy) transform in to matrix binders after curing the resin through an irreversible chemical reaction. By heating, thermoplastic resins are softened from solid state before processing (making a composite) without chemical reactions. Thermoplastics return to solid state (matrix) once processing is done.

Although all thermo-sets are amorphous, thermoplastics can be amorphous or semi-crystalline. The primary advantage of thermoplastic resins over thermo-set resins is their high impact strength and fracture resistance, which is exhibited by their excellent damage tolerance property. Thermoplastic resins also provide higher strains-to-failure, which is manifested by better resistance to micro-cracking in the matrix of a composite. Some of the other advantages of thermoplastic resins are:

- Unlimited storage (shelf) life at room temperature.
- Shorter fabrication time.
- Post-formability (e.g., by thermoforming)
- Ease of repair by (plastic) welding, solvent bonding, etc.
- Ease of handling (no tackiness).
- Recyclability.
- Higher fracture toughness and better de-lamination resistance under fatigue than thermo-sets such as epoxies

The disadvantages of thermoplastics are low creep resistance and poor thermal stability

Reinforcing thermoplastics with fibers is more difficult than reinforcing with thermo-sets because of their high viscosities.

The advantages of thermo-set resins over thermoplastic resins are:

- Better creep and chemical resistance.
- Lower stress relaxation.
- Better thermal stability.

Thermo-sets achieve good wet-out between fibers and resins, which results in better mechanical properties in relation to thermoplastics

However, they also have some limitations:

- Low strain-to-failure.
- Long fabrication time in the mold.
- Limited storage life at room temperature (before the final shape is molded).

6.4.3 FIBER SURFACE TREATMENT (SIZING) :

Sizing is the treatment of fiber surface with coupling agents (that couple resin to fibers), to protect the fiber against moisture and reactive fluid attacks.

Sizing improves wet ability of the fiber surface against the matrix, therefore creates stronger bond between the fiber and matrix.

It is necessary for effective transfer of stresses between the fibers and the matrix.

Functions of sizing for different fibers are:

- Improving interfacial bond of glass fibers with the matrix and to protecting the glass fibers from environmental attacks that are of main concern in the strength degradation of glass fibers
- Promoting good chemical bonding with a binder for carbon fiber surfaces that are chemically inactive. The sizing treatment creates porous carbon fiber surface; hence increases the surface area by creating pitting to provide large number of fiber-matrix interfacial contact point.
- Enhancing weak surface adhesion of polymeric fibers (e.g. Kevlar 49)

6.4.4 ADDITIVES AND CURING:

Additives are constituent components that may be added to the composite matrix to modify its properties and in general, enhance its performance.

- Catalysts, promoters, and inhibitors are used to accelerate or slow the rate of polymerization.
- Release agents are used to facilitate the removal of composite from the mold.
- Other agents are used to improve process ability like plasticizers or product durability.
- Fire retardants are used to extinguish fire upon contact.
- Viscosity control agents help control the flow of the resin, while air release agents reduce air voids.
- Toughness agents increase the toughness of fibers.
- Electrical conductivity agents shield conductivity from certain fibers and antistatic agents reduce static or electrical charge.
- For thermoplastic resins, heat stabilizers are used to protect polymers from degradation due to heat, and UV stabilizers protect polymers from UV degradation.
- fillers are added to both thermo-set and thermoplastic resins in order to reduce cost, control shrinkage, improve mechanical and physical properties, and to provide ultra violet (UV) protection, weathering protection, surface smoothness, temperature resistance, impact strength, and fire resistance.

6.4.5 <u>COATING</u>:

Coatings are applied to improve FRP performance against abrasion, fire, and environmental attacks and to improve the adhesion to other construction materials.

6.5 FACTORS THAT HAVE IMPACT ON FRP DURABILITY:

Fig 6.5-a: Fectors effecting Durability of FRPs

a) Moisture

First, important moisture is likely to cause a decrease in the strength of the matrix because of soft molecular bondings (Van der Walls). The moisture is more important for important stresses as moisture will develop in the micro-cracks. An appropriate choice in the matrix resin, for example vinyl-ester matrix, can decrease the effect of moisture. It has also been shown that polyester resin has to be avoided in environment where moisture is important. For CFRP, the degradation has been linked to the rate of saline water in the environment.

b) Alkalinity

Alkalinity consideration is particularly relevant when the FRP is used as a reinforcement bar in a concrete structural member. Another problem that has been shown is the loss of 20% of the tensile strength in alkaline environment such as concrete for E-Glass fibers. Indeed, concrete is very porous and its **pH** is usually more than **11.** Therefore the sensibility to alkalinity of the material used as reinforcement must be carefully looked at. This sensibility is particularly important for fiberglass such as E-Glass where a deterioration of both matrix and fibers will substantially decrease the tensile strength of the reinforcement bars made of FRP. For moisture and alkalinity issues research studies show that the most efficient resin is vinyl-ester. Again, polyester must be avoided. One of the simple solution to limit the effect of this problem is to apply a protective coating on the FRP material that will be moisture and alkali resistant. AR-Glass (Alkali Resistant fibers) are very un-sensitive to alkalinity but are more expensive than other glass fibers.

c) Temperature

It has been shown that FRP lose their mechanical properties when exposed to high temperatures. The typical temperature of this deterioration is the glass transition temperature which range is between 60º and 1200º Celsius or between 1400º and 2480º Fahrenheit. This is one of the reasons, but not the only one to be taken into consideration. And it is one of the reasons why FRP have not been as widely used for buildings as compared for bridges. Indeed, for buildings the security as regards fire is clearly more demanding. One of the main concerns as regards fire in buildings using FRP is that the smoke resulting from the burning FRP is extremely toxic and dangerous for humans.

Besides for temperature above 5000º Celsius or 932º Fahrenheit, the fiber reinforced polymers lose about 80% of their tensile strength.

However one of the solutions to solve that issue is to use CFRP, indeed carbon fibers are almost un-sensitive to high temperature, until 10000º Celsius or 1832º Fahrenheit, which is, among other, one of the reasons it has been used in the aviation industry.

The American Concrete Institute (ACI) has finally published an interesting paper in 2006 that does not recommend the use of FRP for buildings where structural integrity has to be maintained in case of a fire.

d) Loss of material properties due to UV exposition

It is well understood that UV damage polymers by "breaking chemical bonds" between chains (photo-degradation) for particular wavelengths. However this phenomenon only appears on a thin surface layer of the polymer and glass or carbon fibers are not subject to this phenomenon. Again FRP can be protected by appropriate coating.

6.6 PROCEDURE - FRP:

Mainly following two methods, which are predominantly being used in strengthening/rehabilitation of structures with the help of FRP. The same are given below:

- 1. Wet lay- up method.
- 2. Pre-fabrication of FRP followed by its application.

6.6.1 SURFACE PREPARATION:

Before start of the work, it is very much essential to ensure that surface should be dry, clean, free from oil and grease and any type of loose materials. To ensure little roughness, light sand blasting or grinding can be done followed by proper cleaning of the surface to remove dust particles. Any protrusion should be made good otherwise, it may create void in the nearby area. Crack more than 0.3mm width, if any, needs to be properly epoxy grouted to ensure good quality.

6.6.2 WET LAY-UP METHOD :

This method is in-situ preparation of FRP product and its application required in connection with strengthening/rehabilitation work of structures. Firstly, one coat application of good quality epoxy is required. Then saturated fiber in the appropriate resin should be applied on the surface.
Misalignment of the fiber may lead to unsound work. As such, fiber should be properly aligned and slightly stretched to avoid any bend/twist, if any. Number of layers will depend upon the requirement of thickness. After placement of saturated fiber, the same should be properly rolled to ensure its proper compression as well as adhesion to the surface on which the same is applied. Presence of any void will affect the strength.

Normally, polyester resins are used in wet lay-up process. However, venyl-ester or epoxy resin can also be used. Fibers may be either Glass Fiber or Carbon Fiber. In most of the field application, where wet lay-up method is being used, normally glass fiber, which is cheaper than the carbon fiber will suffice the requirement.

Main advantage of wet lay-up process is that pre-fabrication of FRP product is not required. Exact surface profile and corner of the structures are covered up properly in this process.

6.6.3 PRE-FABRICATION OF FRP FOLLOWED BY ITS APPLICATION:

Here, pre-fabricated FRP component is being used. The same may be prepared either by pultrusion process or by any other suitable process. Appropriate size is properly made for fixing the same to the structure in the field. Surface preparation is the same, as is done in case of wet lay-up process (explained earlier). After application of good layer of epoxy, pre-fabricated FRP product of the appropriate thickness and size is pasted and surface is properly rolled so as to ensure good adherence to the parent surface. After curing of the surface applied epoxy, it becomes part of the structure. Quality of this work is better than the wet lay-up process, since FRP product has been prepared in factory environment under good quality control. Only problem is that the surface profile, which is not regular and corner cannot be properly covered in this method.

6.6.4 SURFACE FINISH:

Surface finish is possible on the FRP products irrespective of either of the above mentioned two strengthening methods adopted. For further better surface finish, even paint can be applied to the repaired surface. Regarding this, acrylic paint or urethane coating can be applied.
Due to aging of infrastructures worldwide, repair rehabilitation and retrofitting of damaged steel reinforced concrete structures using FRP are increasingly becoming a topic of interest in civil engineers. Researchers are sharing their valuable investigation and findings on FRP composite through electronic media. A literature review of some of the topics of interest has been carried out. Highlights of these studies are covered in the ensuring paragraph.

6.7 HIGHLIGHTS OF FRP – PROCEDURE:

Fiber strengthening technique by wrapping the element with fiber composite sheets is a relatively simple process. While installation of the composite strengthening system may vary among various manufacturers and installers, the process generally involves the following steps:

1. Inspect the surface condition of the member that needs to be strengthened.

2. Repair the cracks and spalled regions with epoxy injection and mortar.

3. Prepare the surface of the member (with hand grinders and wet blasting if necessary) to remove projections and to ensure a proper profile.

4. Apply primer and putty to ensure good adherence of the fiber sheets.

5. Apply the first coat of saturant.

6. Apply fiber sheets on to the surface in a manner that is similar to hanging wallpaper.

7. Apply second coat of saturant after the sheets have been properly cured, usually within an hour.

8. Repeat steps 6 and 7 until the required number of layers of fiber sheets has been installed.

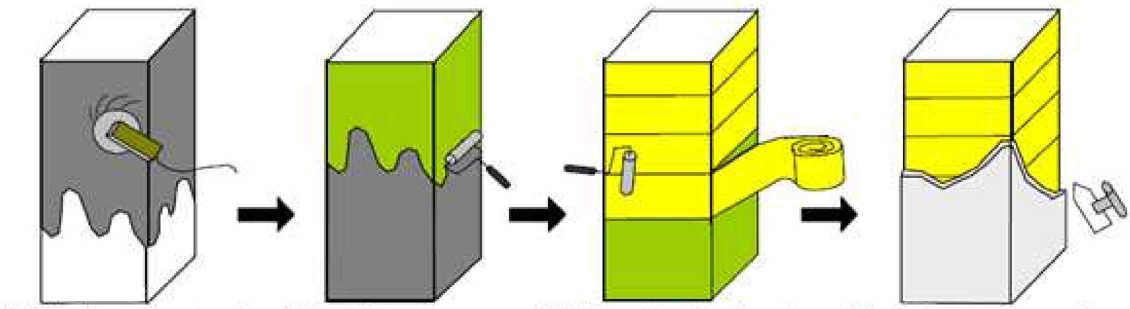


Fig 6.5-b: Application of FRP sheets

<u>6.8 PROMINENT RESEARCHES:</u>

<u>6.8.1 Guoqiang Li , Samuel Kidane , Su-Seng Pang , J.E. Helms , Michael A. Stubblefield</u>

A finite element analysis using ANSYS_ was utilized to conduct a parametric analysis by a group consisting of Guoqiang Li , Samuel Kidane , Su-Seng Pang , J.E. Helms , Michael A. Stubblefield. Experiments were also conducted to justify the finite element analysis results. A reasonable agreement was found between the finite element analysis and the test results. The effect of the thickness, stiffness, and fiber orientation of the FRP layers as well as the interfacial bonding between the FRP wraps and the concrete on the strength and stiffness of the repaired columns was evaluated using the finite element modeling. The following preliminary conclusions are obtained:

- The effect of the interfacial bonding on the strength and stiffness is considerable. Increasing the interfacial bonding can increase the strength and the stiffness of the repaired columns.
- The thickness of the FRP wraps has a significant effect on the strength and stiffness of the repaired columns. Increasing the thickness of the FRP layers can increase the strength and stiffness considerably.
- The effect of the fiber orientation on the strength and stiffness is coupled with the effect of the interfacial bonding. With perfect interfacial bonding, fibers in axial direction are more effective than those in hoop direction; with weak interfacial bonding, however, the effect of fiber orientation can be neglected.
- The effect of the modulus of elasticity of the FRP wraps on the strength and stiffness is substantial. Using stiffer fibers can achieve a much higher strengthening efficiency

6.8.2 Manfredi et al (2001).

He provides an overview of the up-gradation of structures in seismic regions using FRP along with its advantages and limitations. The shear strengthening of columns and piers is carried out using CFRP and AFRP jackets whose fibers when externally bonded in the hoop direction increases their shear capacity.

6.8.3 Parvin et al (2001)

He tested a series of square concrete columns jacketed with varying plies of FRP under axial compressive loading applied monotonically. The effects of various eccentricities and thickness of FRP jacket thicknesses was examined. The numerical analysis results from the software MARC (1994) were correlated with the experimental results.

6.8.4 Shehata et al (2002)

Shehata et al (2002) carried out tests on 54 short columns externally wrapped with CFRP to investigate the gain in strength and ductility. The variables used in the research were cross sectional shape and number of CFRP sheets applied to the models. The experimental results were used to propose confined concrete strength and ultimate confined concrete strain as function of confining lateral strain. The 54 concrete columns were divided into three equal groups having square, circular and rectangular cross section and sub-divided into unconfined, single wrapped and double wrapped CFRP subgroups. The failure of any geometrical cross section for single wrapped columns occurred by tension at mid-height of column. For double wrapped columns the failure initiated from one-fourth to midway height and occurred abruptly. The results show an strength increase of 81% and 138% for single and double wrapped circular column respectively, while for rectangular columns they were 10% and 37% while square columns at 27% and 51%. Equations for strength and deformation are given for each cross section column and their values are compared with different existing equations.

6.8.5 M.Yaqub, C.G. Baily

Concrete structure usually offer good fire resistance due to concretes low thermal conductivity which results in the temperature within structural member , away from exposed face, remaining low during a fire. It is rare for a concrete building to collapse as a result of fire; most fire damaged concrete structures can be success-fully repaired. Experimental results highlight the effectiveness of using unidirectional glass and carbon FRP for repairing heat damaged circular reinforced concrete columns. Salient's are as under:-

a. The strength of reinforced circular concrete columns was reduced up to 42% after heating to 500 ^{o}C.
b. The reduction in residual stiffness of heat damaged column was greater than the reduction is compressive strength. Therefore, more consideration should be given to deformation and stress redistribution of post-fire concrete structure.
c. The strength of a seriously spalled post-heated column repaired with CFRP jacket was increased by 29 % more than the original strength of un-heated columns and 122% higher than post-heated columns.
d. The strength of seriously spalled post-heated column repaired with epoxy resin mortar was increased by 15 % compared to the post-heated column which did not experience any spalling.
e. The strength of a seriously spalled post –heated column was increased by 10% higher than unheated original columns and 65% higher that the post –heated seriously spalled columns when repaired with a GFRP jacket.

f. The strength of a seriously spalled post heated column was increased to 20% higher than the unheated original column and 80 % higher than the post-heated seriously spallled columns when repaired with epoxy resin mortar and CRFP jacket.
g. The post-heated column wrapped with single layer of CRFP jacket regained approximately the same strength as un-heated columns
    - The GFRP or CFRP is very effective in improving the compressive strength of fire –damaged circular columns. It is due to the post-heated columns becoming 'soft' after heating and displaying more lateral dilation compared to un-heated columns. Therefore, confinement effect of GFRP or CFRP was more pronounced in post-heated columns.

h. The effects of GFRP or CFRP or epoxy resin mortar on the stiffness of columns were negligible.
i. The ductility of post-heated columns was increased compared to the in-heated columns.
j. It should be noted that properties of FRP at higher temperature degrade considerably.
k. Therefore FRP will require some passive fire protection to remain effective.

6.8.6 <u>Daiyu Wang, Xiaolan Pan</u>

A study was conducted to evaluate effectiveness of different CFRP rehabilitation schemes in promoting the seismic performance of existing non ductile RC frames. Three non-ductile RC frames with different heights representing low, medium and high-rise buildings were investigated.

It was found that for low-rise frames (5 x storeys), the seismic performance is enhanced effectively by only retrofitting the columns of ground floor. However, for the medium- rise frames (10 x storeys) and the high-rise frames (15 x storeys), rehabilitation of column was not as effective as the rehabilitation of both column and beams. The CFRP rehabilitation should result in the weak floor transfer of frames.

In the past decade FRP composite material have been widely used to retrofit or strengthen RC structures due to their light weight, high strength and ease of application.

The FRP composite materials are usually used by the wrapping or partially wrapping the structural elements i.e. columns and beams to increase their ductility and shear strength capacity.

a. **Retrofit strategy.** Six different retrofit strategies were investigated for each of the studied structures. The studied patterns included retrofitted columns only:

- In the first floor for low and medium rise frame, and in the lower 5 floor for high-rise frame.

- In the lower 3, 5 and 10 floor for the lower-medium and high-rise frame respectively.
- Along the full height and retrofit all the beams along the full height, and selected columns with the same positions as pattern 1 to 3
- A high tensile strength uni-directional carbon fibre reinforced polymer (CFRP) material with nominal thickness of 0.167mm was designed to retrofit the frame columns and beams.

- The columns were retrofitted by wrapping 5 layers of CFRP composites in the lateral direction. The beams were retrofitted with using two patterns. For low and medium-rise frames, the beams were retrofitted by external bonding 3 x layers of CFRP composite at their upper and bottom surfaces along longitudinal axis to increase flexural capacity while for high-rise frames beside the strengthened in the flexural capacity, the shear capacity was also strengthened by using one layer of CFRP u-wraps with the spacing centre of 110mm.

b. **Conclusions:**

Based on the conducted analysis, the following conclusions can be drawn:

- For existing RC frames, external bonding CFRP wrap can obliviously improve the ductility and shear capacity of frames without changing the initial stiffness of structure.
- The maximum peak ground acceleration (PGA) resisted by frames is obviously improved and weak floor should be changed after retrofitting by CFRP composite.

- Basing on analytical results the conceptual retrofit strategy for RC frames is suggested i.e. for low–rise frames, the first floor columns should be retrofitted. While for medium-rise and high-rise frames, all the beams and columns in the lower half of structural height should be retrofitted.

6.8.7 Houssam A. Toutanji

FRP have revolutionized engineering technology. They are particularly suitable for repair being lightweight presumably durable corrosion resistant and have high modulus and stiffness. The lower density of FRP is important and only because it adds less weight to the existing structure but also because it is very important during construction as heavy equipment is required for repair. The fact that these composites are electrically non-conductive and impact resistant also helps in certain applications. The long term durability of FRP composited is crucial factor in their successful application as repair materials or as reinforcement for concrete.

Tests were performed to evaluate the durability performance of concrete columns confined with fiber reinforced polymer sheets. Main conclusions drawn were as under:-

a) Confinement of concrete cylinders with FRP sheets improves the compressive strength and ductility. Improvement in strength and ductility is dependent on the types of FRP composite sheet.
b) The specimens confined with CFRP sheets, regardless of the type of epoxy used, showed good durability and insignificant strength reduction.
c) Wet/dry exposure produced no loss in ductility in specimens wrapped the CFRP sheets, where as those wrapped with GFRP sheets exhibited a reduction is ductility.

6.8.8 F. Colomb, H. Tobbi, E. Ferrier, P. Hamelin:

A study to evaluate the increase in strength and ductility resulting from the use of FRP concluded following:-

a. FRP reinforcement completely changed the failure mode of columns. For the two entirely wrapped columns brittle shear failure changed to ductile bending failure while in the stripped- reinforced columns failure was due to shear bending.

b. Reinforcement by strips provides a more advantageous dissipative behavior than the fully wrapped columns. This is due to ductility gained through the following two mechanisms:-
   a. Damage to the concrete by cracking between the FRP strips.
   b. Yielding of the reinforcement in all column sections.
c. For the columns which were fully wrapped in FRP, ductility was increased mainly due to transfer to the embeddings, creating a hinge by advanced yielding of the longitudinal reinforcement.
d. The FRP reinforcement allowed rotation in the embedding sections, without buckling of the compressed reinforcements, although they greatly exceeded their elastic limits.
e. Even for the short columns, the central section was less solicited that the embedding sections. So it seemed that using a different thickness of reinforcement would be advantageous.
f. Composite material reinforcement endowed the short columns with ductile behavior, although transversal reinforcement ratio.
g. Care must be taken not to oversize the FRP reinforcements as these results in the transfer of effort to the nodes
h.

6.8.9 <u>Saadatmanesh:</u>

A highly effective energy dissipating Carbon Wrap system is invented by Dr. Saadatmanesh. It can provide remarkable strength to structures against explosions. The system dissipates the blast energy and reduces it significantly before it reaches the framing of the structure.

- **<u>Test Site: Before Blast</u>**

Two identical concrete block walls were built. One was retrofitted with Carbon Wrap™; the other was used as the control wall.

Fig 6.6: Test Walls during the construction

Test Site: During Blast

Blast impact resulting from over 200 lbs of TNT hits the wall. Measured surface pressure was 185 psi.

A. Un-retrofitted Masonry

B. Retrofitted Masonry

Fig 6.7: Test site before & during the test

Test Site: After Blast

Un-retrofitted wall: Destroyed

However, the retrofitted wall survived the blast completely protecting the inside.

Fig 6.8: Test site after blasting

6.9 IMPORTANT CONCLUIONS

- The thickness of the FRP wraps has a significant effect on the strength and stiffness of the repaired columns. Increasing the thickness of the FRP layers can increase the strength and stiffness considerably
- The effect of the modulus of elasticity of the FRP wraps on the strength and stiffness is substantial. Using stiffer fibers can achieve a much higher strengthening efficiency.
- The strength of a seriously spalled post-heated column repaired with CFRP jacket was increased by 29 % more than the original strength of un-heated columns and 122% higher than post-heated columns
- The strength of a seriously spalled post –heated column was increased by 10% higher than unheated original columns and 65% higher that the post –heated seriously spalled columns when repaired with a GFRP jacket.
- For existing RC frames, external bonding CFRP wrap can obliviously improve the ductility and shear capacity of frames without changing the initial stiffness of structure.
- The maximum peak ground acceleration (PGA) resisted by frames is obviously improved and weak floor should be changed after retrofitting by CFRP composite.
- Confinement of concrete cylinders with FRP sheets improves the compressive strength and ductility. Improvement in strength and ductility is dependent on the types of FRP composite sheet.
- Wet/dry exposure produced no loss in ductility in specimens wrapped the CFRP sheets, where as those wrapped with GFRP sheets exhibited a reduction is ductility.

➢ FRP reinforcement completely changed the failure mode of columns. For the two entirely wrapped columns brittle shear failure changed to ductile bending failure while in the stripped- reinforced columns failure was due to shear bending.

Fig 6.9: Retrofitting of column by Carbon fibers in shear ,confinement & Flexure

6.10 ADVANTAGES -FRP

FRP composites are being referred to as the material of current century because of following inherent advantages over traditional materials.

- ➢ Superior thermo-mechanical properties such as high strength and stiffness, and light weight.
- ➢ Excellent corrosion resistance.
- ➢ Design flexibility.
- ➢ Long-term durability under harsh service environments.
- ➢ Composites can be three to five times stronger, two to three times stiffer and three to four times lighter than metals such as steel and aluminum.
- ➢ Composites are dimensionally stable, aesthetically pleasing and cost effective with better durability and lower maintenance than the conventional materials.
- ➢ Structural rehabilitation using FRP costs a fraction (1/15th to 1/10th) of the replacement cost and extends the service life by additional 25-30 years. Rehabilitation also results in less environmental impact and green house gas emissions. Similarly,

new FRP construction provides superior FRP thermo-mechanical properties and lower life-cycle costs

- The fiber can be introduced in a variety of positions, volume fractions and directions in the matrix to obtain maximum efficiency.
- The resulting materials have high strength and stiffness in the fiber direction.
- Transportation and handling the composite material are easy.
- Continuous length of FRP can be readily produced.
- CFRP (carbon fiber reinforced polymer) and AFRP (aramid fiber reinforced polymer) composites exhibit excellent fatigue and creep properties and require less energy per kg to manufacture and to transport to the site than for steel.
- Less false work is required than with steel plates and FRP composite can be used in areas of limited access.
- Fiber Reinforced Plastics are best suited for any design program that demands weight savings, precision engineering, finite tolerances, and the simplification of parts in both production and operation.
- Increases the durability of the structure by protecting it against the aggressive action of chlorides and freezing and thawing cycles.
- FRP is used in designs that require a measure of strength or modulus of elasticity that non-reinforced plastic and other material choices are either ill suited for mechanically or economically.
- It has also proved itself cost-effective in a number of field applications strengthening concrete, masonry, steel, cast iron and timber structures.
- Retrofitting is popular in many instances as the cost of replacing the deficient structure can greatly exceed its strengthening using CFRP

6.11 DISADVANTAGES - FRP

The drawbacks of usage of FRP are as follows:

- The intolerance to uneven bonding surfaces which may cause peeling of the plate away from the concrete surface.
- The possibility of the brittle failure modes.
- Risk of fire.

- Risk of accidental damages unless the strengthening is protected. Bridges over road have the risk of soffit reinforcement being hit over-height vehicles.
- High material cost, FRP composite will generally be more expensive than conventional materials. However cheaper transportation from factories to the sites and installations savings can offset the higher material cost.
- Slightly higher initial costs, limited experience with these materials by design professionals and contractors, lack of data on long-term field performance, and absence of full spectrum of codes and specifications similar to conventional materials.

6.12 APPLICATION OF FRP IN OTHER FIELDS

- Carbon fiber reinforced polymer has found a lot of use in high-end sports equipment such as racing bicycles and other sporting goods applications include rackets, fishing rods and rowing shells.
- Much of the fuselage of the new Boeing 787 Dream liner and Airbus A350 XWB will be composed of CFRP, making the aircraft lighter than a comparable aluminum fuselage, with the added benefit of less maintenance thanks to CFRP's superior fatigue resistance.

- Due to its high ratio of strength to weight, CFRP is widely used in micro air vehicles.
- CFRP has also found application in the construction of high-end audio components such as turntables and loudspeakers and in a variety of musical instruments.
- A molded polymer artifact is cheaper, faster, and easier to manufacture than cast aluminum or steel artifact, and maintains similar and sometimes better tolerances and material strengths.

Fig 6.10: Other uses of FRPs

- Carbon fiber reinforced polymers (CFRPs) have an almost infinite service lifetime when protected from the sun.
- Some FRP materials, e.g. carbon and aramid, have incompatible thermal expansion coefficients with concrete. As a result degradation and collapse may occur when subjected to high temperatures.

6.13 USE OF FRP COMPOSITES IN PAKISTAN

FRP composites are quite popular in Pakistan and they are being utilized by the construction firms in retrofitting, repairing and rehabilitating the projects including some projects of national importance. Some of the projects are.

1. Fauji Cement Factory , Sangjani

Pre-heating tower of the factory was repaired and strengthened. Its deep R.C. beams (up to 2 m deep) showed extensive cracking. Cracks widths were large and were visible from distance. The structure was about ten years old when the repair work was done in 2003. All cracked beams were first repaired by injection of epoxy resin.

The repaired beams were then strengthened by fixing of 4240 Rft of CFRP strips in the flexure zone and by fixing CFRP Wrap on 3280 Sqft of shear zone.

2. G.H.Q Gymnasium, Rawalpindi

The R.C structure was completed in 2005 but before its inauguration, it suffered severe damage due to heavy rains. There were cracks in beams & columns and roof concrete was washed away exposing steel reinforcement.

Three types of repairs were done:

a. Patch repair with high strength epoxy repair mortar.
b. 815 Rft of CFRP strips.
c. 1022 Sqft of CFRP Wrap.

3. Pak Tower, F-10, Islamabad

This residential multi-storey structure (opposite the collapsed Margalla Tower) was damaged in Oct. 2005 earthquake. Its beams cracked and the column-slab joints were twisted. All occupants were first evacuated. The following repair was done:

I. Injection of epoxy in cracked beams.
II. Repair of column-slab joints with high strength epoxy repair mortar.
III. 1250 Rft of CFRP Strips.
IV. 435 Sqft of CFRP Wrap.

In the above-described repaired structures, the residual strength of damaged R.C elements were considered negligible and the basis of load-carrying capacity was strengthening done by CFRP composite system.

4. Kulsum Plaza, Blue Area, Islamabad:

It is a case of CFRP application for a structure whose utilization was modified. The commercial plaza was converted into multistory hospital. The R.C. Structure needed strengthening due to installation of heavy hospital equipment. Additionally some load-bearing walls were removed to create larger circulation space on different floors. Even the wall openings were increased for bigger lifts to allow patients beds and hospital equipment to be transported.

Products used were:

I. Epoxy repair mortar
II. 815 Rft of CFRP Strips
III. 1240 Sqft of CFRP Wrap

5. **Doctors Hospital , Lahore**

The hospital administration decided to add two upper floors to the existing 2-storey building. The consultant reviewed the original designs and recommended that the compression load capacity of existing columns needed to be increased by at least 50%. The hospital administration opted for CFRP composite system because it had the following advantages:

I. Light weight with additional dead load.
II. Minimum increase in original column diameters (2mm average increase) which did not reduce the floor circulation space.
III. Dust free and quick work without any shutdown of hospital.

Therefore all columns from basement to second floor were CFRP Wrapped for a total area of 460 Sqft.

6. **Kabul River Bridge, Chamkani(Nowshera):**

An 80 m long, pre-stressed girder required strengthening because the pre-stressing tendons (two out of five) were broken inside the duct. In order to make up for the 40 % deficiency in flexure and shear, caused by broken pre-stressing tendons, a total 470 Rft of CFRP strips and 380 Sqft of CFRP Wrap was applied.

As a dry-run case, fully loaded trucks were then allowed to ply over the CFRP strengthened bridge and no deflection/damage occurred.

7. **National Telecommunication Corporation H.Q., Islamabad**

The NTC HQ Building needed strengthening because heavy transmission towers were to be installed on its roof in 2008 the beam and columns were strengthen by using following quantities of CFRP system:

I. 522 Rft of CFRP Strips
II. 995 Sqft of CFRP Wrap

8. **Dolman Tower, Karachi:**

The R.C. beams in the tower suffered corrosion due to the structure being close to the seashore. The spalled, cracked concrete was removed and the beam cross-sections were restored by using epoxy repair mortar. After that 1820 Rft CFRP Strips were used in the flexure zone of the beams to compensate for the loss of reinforcement steel.

Major Projects Supervised for Repair & Restoration with CFRP System.

Some of other projects that were supervised by Imporient Chemicals (Pvt) Ltd during the last ten years are as under.

- Park Tower, F-10 Islamabad.
- Mustafa Tower, G8, Markaz.
- Bharia College, Naval Headquarters, Islamabad.
- Jamia Mosque, Naval Headquarters, Islamabad.
- Swimming Complex, Naval Headquarters, Islamabad.
- Sailor Barracks, Naval Headquarters, Islamabad.
- College of Safari Villas Rawalpindi,
- PAF Jinnah Camp College, Rawalpindi
- AWT Plaza Mall Road, Rawalpindi
- Frobels Intl School, H-8 Islamabad.
- Head Start School, F-7 Islamabad.
- Kohinor Textile Mills, Gujjar Khan.
- BTS Cell Tower at Chakwal and Tallagang.
- Telenor Switch Building Fazale Haq Road, Islamabad.
- Pakistan Military Academy Kakul, Abbottabad

- Army Burn Hall College, Abbottabbad.
- Nandipur Hyral Power Project.
- Mangla Dam Raising Project.
- Mari Gas Head Office, Mauve Area Islamabad.
- Chrat Cement Company, Ditrict Nowshera.
- Permanent Art Gallery Lahore.
- Planning & Development Building, Govt. of Punjab.
- Issa Cement Factory, Hyderabad.
- Karachi port Trust Wharf.
- Telenor Building Faisalabad.
- Telenor Building Sahiwal.
- Allama Iqbal Airport, Lahore.
- Tariq Heights, Islamabad.
- Fauji Fertilizers Factory, Sadiqabad.
- Kulsum Plaza, Blue Area, Islamabad.
- GHQ Gymnasium, Islamabad.
- Taunsa Barrage, Multan.
- Kabul River Bridge, Chamkani, Peshawar.
- Fauji Cement Factory , Sangjano
- Telenor Building, Gujranwala.
- Doctors Hospital, Lahore.
- Pakistan Railway Bridge Tando Adam
- Telenor MSC Building, Davis Road, Lahore
- Pakistan Railways Bridge, Muridke.
- Cherat Cement Factory, Nowshera, Phase II
- CWO Jarra Camp, Rawalpindi
- Railway Bridge Sukkur
- Bharia Town Housing, Lahore & Rawalpindi.
- Railway Bridge , Lala Musa
- Pak-American Fertilizer Factory , Mianwali
- Tariq Heights, F-11 Islamabad
- Telenor Embassy, I-9 Islamabad.

- Paktel Embassy, I-9 Islamabad.
- Mobilink Office, Blue Area, Islamabad.
- FWO Chappegram Bridges, Batgram
- Pakistan Railways, Lalamusa Bridge
- POF Sajwal
- Railway Bridge, Tando Adam
- Dolman Tower, Karachi
- HBL Bank, Main MAket, Gulberg, Lahore
- Pakistan Navy Flats, Karachi
- Beari Sindh Feede Piers, Kashmore.

Before further discussions, it is necessary to have certain idea about the strength parameters of various types of FRP products. The same is given as below

Cost analysis

CFRP retrofitting is relatively new in Pakistan as compared to the other developed countries, there are many, who may like to know its cost effectiveness of complete retrofitting process.the normal cost of materials and labour required for CFRP retrofitting is given in the table . it may be noted the material cost pertains to the period of 2012 and 2013. Due escalation in cost may be required for periods later than 2012.

Details	Cost in Pakistani Rupees per sq ft	Cost in US $ per sq ft
Filling of voids using repair mortar Chemdur-31, pourable epoxy grout Injection Chemdur-52 for filling of internal cavities of concrete cracks.	400	4.43
Epoxy primer Sikadur-300	125	1.36

CFRP 230-C	650	7.06
Labour charges	100	1.09
Total	1275	13.86

Table 6.2: Cost of retrofitting.

.

CHAPTER 7

COMPARISON AND CONCLUSION

7.1 PARAMETERS FOR COMPARISON

A brief comparison of different retrofitting techniques is as under:-

CONSTRUCTION PERIOD:

The construction period differs greatly according to the construction target. In general, however, the construction period of the continuous fiber sheet method is shorter than that of the concrete jacketing, the steel plate jacketing and ferrocement methods.

TOTAL COST:

The total cost of the retrofitting method using fiber sheets varies according to the types of construction. However, the total cost is normally equivalent to or slightly higher than that of the concrete jacketing method and is often lower than that of the steel plate jacketing and ferrocement methods.

CONSTRUCTIONAL WORKABILITY:

The concrete jacketing method requires chipping of surfaces to maintain continuity between the new and the old concrete, arrangement of reinforcing bars, form installation and concrete casting. The steel plate jacketing method requires various works that demand specialization and skilled workers including anchor casting, field welding of steel plates and mortar grouting. The rehabilitation method using continuous fibers requires rounding off the corners, removing of the existing finishes and smoothing the surface of concrete. However, because continuous fibers can be wrapped directly around the structural surface, works required in other methods namely chipping, bar arrangement, welding, form installation and concrete/mortar injecting, are no longer necessary. Furthermore, work can be done in small areas, showing good constructional workability compared to the concrete jacketing, steel plate jacketing and ferrocement methods.

WEIGHT:

Since the retrofitting method that uses continuous fibers takes advantage of utilizing lightweight materials such as fibers and resins, the increase in weight can be ignored in the design. In addition, the light-weight of continuous fibers can be transported in rolls, making lifting machines unnecessary.

STIFFNESS OF MEMBERS:

When reinforcing against shear, both the concrete jacketing and the steel plate jacketing methods augment stiffness of the members. Therefore, an increase of stress on structural members during earthquakes must be taken into consideration. In contrast, the rehabilitation method using continuous fibers does not change stiffness of the members. Consequently, rehabilitation work is carried out without influencing the balance of the structural members of the buildings.

MAINTENANCE:

Since continuous fibers are superior materials against corrosion, maintenance, such as regular painting, is barely required.

IMPACTS ON CONSTRUCTION WORKERS AND SURROUNDING PEOPLE:

The continuous fiber sheet method may produce noise, dirt and vibrations slightly during the process of base treatment. However, during other processes, the method scarcely causes any effect that could harm the residents or surrounding people.

INCREASE IN FLEXURAL STRENGTH:

The main benefit of the FRP confinement is the minimal increase in flexural strength, despite its high capacity in improving ductility. As a result, the FRP retrofitted structural element is not subjected to additional forces and premature failure of the frame work is thus prevented.

APPLICATION :

The application of FRP confinement is fast and easy. Downtimes are therefore substantially reduced. Furthermore, FRP jacket are thin and require less adaptation of adjacent building components.

Description	Concrete Jacketing	Steel Jacketing	FRP Wrapping	Ferrocement	Remarks
Mode of strengthening	Increase in concrete and steel area	Confinement	confinement	confinement	
Preparation of column for strengthening	Significant dismantling of cover concrete. At least 40mm cover concrete to	No major dismantling work involved. Mainly plaster to be removed and	Only plaster to removed and epoxy primer to be applied on exposed surface. For	Remove any deteriorated /contaminated mortar. The rougher the surface, greater the	FRP involves minimum surface preparation.

	be removed. Epoxy primer to be applied on exposed surface.	epoxy primer to be applied on exposed surface.	rectangular columns, corners to be rounded off.	area available for bonding.	
Drilling of holes	Large amount of drilling is required.	Large amount of drilling is required.	No drilling is required.	No drilling of holes is required.	FRP involves minimum work since no drilling is required.
Additional weight	Extremely high. (Weight becomes 225% for just 50% increase in strength.	Very high (weight becomes 169% for 50% increase in strength)	Negligible. No increase in weight at all.	Self weight of ferrocement element per unit area is quite small.	FRP does not increase the dead weight of the structure.
Size increase	Very high (diameter of column increases from 400mm to 600mm for 50% increase in strength.	High. The diameter of column increases from 400mm to 450mm for 50% increases in strength.	Negligible. The total increase in diameter is less than 5mm.	Size increases	The size remains unaltered thus retaining the free area.

Stiffness of members against shear	Augment structural stiffness of member. Therefore increase in shear stress during earthquakes	Augment structural stiffness of member. Therefore increase in shear stress during earthquakes	Does not change the stiffness of member.	Stiffness improved significantly.	
Total cost	Lower	Higher	Higher than cement but lower than steel	20% to 30% less as compare to RC jacketing	
Increase in weight	Weight of structure increases	Weight of structure increases	No increase in weight.	Increase in weight	
Corrosion	Steel rebar can easily corrode in not properly treated.	Steel sheets corrode easily in moist environment.	FRP sheets don't corrode in harsh environment.	Wire mesh liable to corrosion attack.	FRP sheets are durable in harsh environment.
Application	Labor intensive.	Heavy machinery is required for installation purposes.	Only skilled workers are required	Labor intensive	In installing FRP sheets only skilled workers are required.

Working period	Long	Moderate	Fast and easy	Short	FRP is a quick construction material.

Table 7.1: Comparison among different Techniques of Retrofitting

7.2 Discussion:

- The suitable retrofitting solution should be selected taking into account many criteria, like construction cost, activity disruption, space consumption, fire resistance.
- The reinforced concrete jacketing involves the lowest material cost. The disadvantages come from time consuming construction procedures and changes in the building's architecture (the column's sizes increase more than 20 cm). From the fire resistance point of view this is the most suitable solution.
- The carbon fiber jacketing is appropriate for ductility upgrade if a proper shear reinforcement ratio of fiber sheet is selected. The main disadvantages are the materials' cost and low fire resistance. The following advantages can be mentioned: minimum changes in the building architecture and a reduced construction period in comparison with the other two solutions.
- The steel jacketed column presented a good ductility. The material cost is moderate. The jacket width can be reduced if a non shrinkage high fluidity mortar is used.

7.3 CONCLUSION

Past earthquakes have demonstrated the power of nature and the catastrophic impact of such power upon urban cities. Casualties and damages associated with older buildings, which were designed and constructed using codes that are now known to provide inadequate safety, are far worse than that for newer buildings which have been designed and built in accordance with more stringent code requirements. Protecting the existing and potentially vulnerable older buildings through retrofitting is a challenge to the seismic hazard mitigation community. Seismic retrofitting of buildings is a relatively new activity for most structural engineers. Changes in construction technologies and innovation in retrofit technologies present added challenges to engineers in selecting a technically, economically and socially acceptable solution.

However, Fiber strengthening technology is among the most efficient and effective new technologies for seismic retrofit of columns. Its application is rather simple, very non-intrusive to building occupants, and not labor intensive – making it one of the more desirable alternatives for the seismic retrofit of existing buildings. The carbon fiber's non-corrosive characteristics and resistance to most chemicals give the carbon fiber strengthening system a considerably longer life compared with conventional materials such as steel, i.e. longer economical value over the long run.

We have discussed different retrofitting techniques, highlighting their merits and their demerits. While assessing the state of the structures for deciding retrofit technique and strategy the engineers have to keep certain aspects in mind for adopting the best retrofit technique. Apart from technical reasons, cost effectiveness, availability of resources and desired life span of the retrofitted structure will figure out in making the choice of the retrofit technique.

7.4 RECOMMENDATIONS

Pakistan has faced worst type of terrorist attack on the buildings belonging to intelligence and law enforcing agencies resulting in to loss of human life and material. World over, steel jacketing and composite wrap technology has been used extensively for upgrading the blast resistance and seismic resistance of reinforced concrete columns. Sensitive structures are retrofitted with either of the technique which is appropriate for enhancing the blast resistance.

Some researchers have concluded that FRP when exposed to high temperature (between 60ºC to 120ºC), lose their mechanical properties. Another main concern is that smoke resulting from burning of FRP is extremely toxic and dangerous for human being. From the study we conducted in this dissertation we have come to following points, which must be kept in mind while choosing any retrofitting technique.

1) For temperature above 500ºC, the FRP lose their 80% of the strength. One of the solutions is the use CFRP as carbon fibers are almost insensitive to high temperature.

2) We can also use ferrocement as a retrofitting technique in housing sector where fire security is clearly more demanding.

3) Strengthening corroded RC column with combined CFRP sheets and steel jacket is more effective than strengthening only with steel jacket or only with CFRP sheets in improving the strength and ductility.

4) The structural behaviour of a building rehabilitated by RC jacketing of the columns, like any other strengthening technique, is highly influenced by details. In this method special attention should be paid.

5) The carbon fiber's non-corrosive characteristics and resistance to most chemicals give the carbon fiber strengthening system a considerably longer life compared with conventional materials such as steel, i.e. longer economical value over the long run. So it can be used in areas where water contains salts, like conditions in Risalpur. As this system was used in Dolman Tower, Karachi where tower suffered damage due to the structure being close to the seashore.

6) For space restrictions and aesthetic purposes FRPs can be used as retrofitting method.

7) In general selection of retrofitting technique depends upon ingenuity of Engineer, economy and site condition, but one must comply to design specifications and specified standards.

8) As we have discussed earlier, compression load capacity of retrofitted columns of Doctors Hospital, Lahore increased by 50%, by using CFRP composite system, without any shutdown and without effecting environment. So for speedy and environmentally friendly work CFRP system is recommended to be used.

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Appendix