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Review on Strengthening of Damaged Reinforced Concrete Columns

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ABSTRACT

In recent years, rehabilitation has been the subject of extensive research due to increased spending on repairing of built works. The reinforced concrete columns are essential elements in the reinforced concrete structures, which support the vertical loads and provide bracing against the horizontal loads. The reinforced concrete columns might encounter the issue of strength capacity reduction due to columns overloading or earthquake. This research highlighted different techniques for the strengthening of damaged reinforced concrete columns such as steel jacketing, reinforced concrete jacketing, and wrapping by glass fiber reinforced plastic.

It found that the steel jacketing increased the column stiffness between 10% and 20% due to addition confinement from the jacket. Besides, the strength and ductility of concrete columns increased significantly by wrapping the damaged reinforced concrete columns by glass fiber straps. In contrast, strengthening of damaged reinforced concrete columns by concrete jacketing was much stronger and stiffer than the original undamaged columns based on the using sandblasting to increase the bond strength between old damaged concrete and concrete jacketing.

KEYWORDS:*Concrete columns, Damage, Repairing, and Strengthening*

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LIST OF ABBREVIATIONS

SYMBOL	DESCRIPTION
FRC	Fiber Reinforced Concrete
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
MPC	Magnesium Phosphate Concrete
PC	Polymer Concrete
PCC	Polymer Cement Concrete
RCC	Reinforced Concrete Column
UHPFRC	Ultra High Performance Fiber Reinforced Concrete

I. INTRODUCTION

1.1 Background

Repairing is a process doing to restore the structure or the damaged part to its designed state to be able to do the function that it's intended for or increasing its performance to the designed performance. While strengthening is a process performed to improve the performance of the structure or the damaged part to a level more than it is initial or intended production.

Repair and strengthening of harmed reinforced concrete structures are significant to ensure the safety of residents. Before the restoration of structural members, it should determine whether a structural analysis should be carried out to decide if the members are overloaded or under designed for the service loads. The analysis should consider both serviceability and strength and should include consideration of the causes of structural failure or degradation. Based on previous evaluations and analytical results, the engineer should decide whether repair only or repair plus strengthening is required.("ACI 546R-04 Concrete Repair Guide," 2004). Columns are significant structural components for withstanding loads, so trying to find efficient repair and strengthening methods and techniques are necessary for terms of maintaining the safety of the structures.

The selection of the repair and strengthening method to reuse the structure relies on the structural behavior objectives, and the decision to repair has to be made only after the inspection of the structure, structural evaluation and a cost study of the possible solutions.

The necessity of repairing a structure may be needed at any time from the beginning of the construction until the end of the structure's life (Ju´lio, Branco, & Silva, 2003).

1.2 Repairing a reinforced concrete element

Repairing a reinforced concrete portion may be called an attempt to restore the strength and stiffness of a damaged or deteriorated reinforced concrete part to its original state. (Ju´lio et al., 2003), as shown in Figure 1.1.

Figure 1.1: Concrete crack repairing with epoxy injection

1.3 Strengthening a reinforced concrete element

Strengthening a reinforced concrete part may be described as an attempt to increase the initial stiffness and strength of the reinforced concrete element, as shown in Figure 1.2.

In the case of an undamaged concrete element, there can't be, by definition, a need to repair the concrete item. In this situation, only the strengthening of this element without repairing can do, But in the case of a deteriorated or damaged reinforced concrete element, repairing must do with strengthening.

The repairing operation should precede the strengthening of an element. The importance and also cost of the latter rely entirely on the structural hypotheses, assumed by the designer, relative to the contribution of the initial element to the strength of the resulting composite component (Ju´lio et al., 2003).

Figure 1.2: Strengthening of concrete elements

1.4 Repair & strengthening cases in the reinforced concrete columns

1- Desire to increase the column load in case of an existing error in the base design or the situation of increasing building floors.
2- The appearance of rust on the surface of reinforcement bars. Then, falling of concrete cover as shown within the Figure 1.3.

Figure 1.3: Rusty reinforcement and falling of concrete cover

3- The compressive strength of the concrete column or the type and ratio of the reinforcement bars isnot identical to the standard specifications.
4- The occurrence of cracks in the column, as shown in Figure 1.4.

1.5 Causes of damaging in concrete columns (PCA, 2002)

Damage in reinforced concrete columns is anything that causes Physical harm that impairs the value of a normal function of reinforced concrete columns. There are many causes of damaging in concrete columns such as the following:

1- Column design or construction errors.
2- Corrosion of embedded metals.
3- Freeze-thaw deterioration.
4- Chemical attacks.
5- Alkali-aggregate reactivity.
6- Abrasion.
7- Fire.
8- Overload impact.
9- Collisions.
10- Earthquakes.

Figure 1.4: Cracked columns

5- Sway[1] In column or settling[2]In foundations, as shown in Figure 1.5.

[1]is lateral and sideways movement of a framed structure, which makes the structure unstable geometrically.

Figure 1.5: Sway column

6- The occurrence of adequate nesting[3]Within the column's concrete as shown in Figure 1.6.

Figure 1.6: Nested column's concrete

1.6 Strengthening methods of damaged (Deteriorated) reinforced concrete columns (Takiguchi & Abdullah, 2000)

There are various methods of strengthening available, different materials used each with distinct advantages and disadvantages, such as the following:

1- Steel plate jacket.
2- Reinforced concrete jacketing.
3- Ferro-cement jacket.
4- Circularization.
5- Carbon fiber sheet[4].

[2]Settling is a term used to define a structure's gradual sink into the ground over time. The settlement will take place at the soil layer under the foundation when it begins to shift.
[3] Nesting: lack of access in the concrete mix to a part of the column.
[4] A strong, stiff, thin fiber of nearly pure carbon, made by subjecting various organic raw materials to high temperatures, combined with synthetic resins to produce a robust and lightweight material used in the construction of aircraft and spacecraft, and as a strengthening material.

6- FRP (Fiber Reinforced Polymers)[5].

1.7 Repairing methods for reinforced concrete columns before strengthening techniques

Some preparations have to do before strengthening of reinforced concrete columns. One of the most important qualifications is surface preparation of repair area; proper surface preparation is an indicator of good repair. Another development is concrete removal which is removing the damaged or defective concrete, which can be done by (cutting, plastering, Impacting, splitting, milling, ...etc.) methods. Also, Reinforcement repairing must be done, which is removing the rust and detrimental chlorides, and paint could use as a precaution after cleaning to protect the reinforcement bars, but the paint is not an alternative of the cleaning so it should be cleaned well before.

Figure 1.7(a): steel plate jacketing

Figure 1.7(b): Ferro-cement jacketing

Figure 1.7(c): Circularization method

Figure 1.7(d): strengthening with carbon sheets

[5] A general term for a composite material comprising a polymer matrix reinforced with fibers in the form of fabric, mat, strands, or any other fiber form.

Figure 1.7(e): Strengthening with FRP

Besides, anchors are often used in conjunction with supplemental reinforcement to prevent new repairs from dislodging from parent concrete in the event of bond failure.("ACI 546R-04 Concrete Repair Guide," 2004)

1.7.1 Materials used in repairing
1- Special concrete admixtures.
2- Special concrete mixes.
3- Special cement mortar.
4- Epoxy paint.

1.7.2 Types of paint that used in reinforcement bars during repairing process
1- Cement slurry
2- Improved cement slurry.
3- It can be using epoxy- with or without alkaline admixtures.
4- Inhibitive Primer.
5- Sacrificial primer.
6- Cement mortar with special mix design.

2.1 Strengthening materials
This section contains various types of materials that available for strengthening of reinforced concrete columns.

2.2 Cementitious materials
To match the properties of the concrete repaired and strengthened as firmly as possible, Portland cement concrete and mortar or other cementitious compositions using similar proportions of ingredients are the best choices for repair materials.

2.2.1 Ferro-cement
Ferro-cement is a thin wall reinforced concrete and made of cement mortar, and layers of fine wire mesh tightly bond together to create a stable and robust structural form, as shown within Figure 2.1.

Ferro-cement Confinement generally applied to compression member, to increase their load carrying capacity, enhancement of flexibility and for seismic up gradation. The unique properties of ferro-cement such as fire resistance, durability, low self-weight, waterproof and crack resistance makes it an ideal material for broader applications, and it has a great potential to be used as a jacketing material for strengthening of reinforced concrete columns (Masud & Kumar, 2016).

Figure 2.1: Ferrocement

2.2.2 Fiber Reinforced Concrete

Fiber reinforced concrete is a sort of concrete that has fibrous substances that increase its structural strength and cohesion, as shown in Figure 2.2. Fiber reinforced concrete has small distinct fibers that homogeneously spread and orientated haphazardly. The fibers used are glass fibers, steel fibers, artificial and natural fibers. The characteristics of fiber reinforced concrete changed by the alteration of certain factors: type and quantity of fibers, geometric configuration, direction, dispersal, and concentration.

Portland cement concrete is believed to be a relatively brittle substance. Once un-reinforced concrete exposed to tensile stresses, it may cause a fracture or probably fails Since the start of the nineteenth century, studies were conducted to reinforce concrete using steel. After reinforcing concrete with the steel, it becomes a combined group in which steel resists the tensile stress. When concrete reinforced with fiber in the mixture, it increases the tensile strength of the composite system even more. Studies have indicated that the strength of concrete may be improved enormously by the addition of fiber. Since the stretching ability under a load of reinforcing fiber is more significant than concrete, without loading the composite system is functioning as un-reinforced concrete. However, the fiber reinforcing will be activated when the composite system is additionally loaded, which then holds the concrete mix together (Aggeliki).

Figure 2.2: Fiber Reinforced Concrete

2.2.3 Grouts

The grouts that discussed herein categorized as hydraulic cement or chemical.

a) Cement grouts: Cement grouts are mixtures of hydraulic cement, aggregate, and admixtures that when blended with the water, a trowel capable of flowing, or pump capable consistency is produced without separation (segregation) of the components as shown within Figure 2.3. Admixtures are frequently added to the grout to accelerate, or retard setting time, minimize shrinkage, improve the ability of pumping or workability, or to improve the durability of the grout. When significant amounts of grout are needed, mineral fillers can use for commercial purposes. Cement grouts can only be used for injection repairs if the opening width is adequate to accept the energetic particles suspended in the grout.

Typical applications of cement grout may vary from grout slurries for bonding old concrete with the new one to the filling of large dormant cracks or the voids around the concrete structure or under it (Zaky, 2013).

Figure 2.3: Cement Grout

b) Chemical grouts: Chemical grout consists of chemical solutions that react to form either a solid or a gel precipitate as compared to cement grouts comprising solid particle suspensions in a fluid, as shown within Figure 2.4. The reaction in the solution may involve only the constituents of the solution, or it may include the response of the solution with other substances, such as water, encountered in the use of the grout. The reaction causes a decrease in fluidity and a tendency to solidify and fill voids in the material into which the grout has been injected (Zaky, 2013).

Figure 2.4: Chemical Grout

2.2.4 Magnesium Phosphate Concrete

Magnesium phosphate concrete (MPC) is different from ordinary Portland cement, which based on a hydraulic cement system. MPC can achieve Rapid patch repairs economically. It has low shrinkage rates, high strength of bonds, and setting times of 10 to 20 min, which can offer 14 MPa early strength development within 2 hours, which may enhance to (45 to 60) min at room temperature for mixtures that include retarders. The abrasion resistance of MPC is comparable to ordinary concrete of similar strength when aggregates add. These can set at temperatures as low as 0 °C. The material has low permeability and excellent bond strength to Portland cement.

MPC can’t be placed in a dry pack condition (water content can’t adjust for this technique of placing), and hard troweling isn't possible. Any variation in the water content from that indicated by the manufacturer decreases both the durability and strength of the MPC mortar. For using it in warm conditions, hot weather formulas are present. Special care must be taken when putting the material in isolated cavities due to rapid exothermic reaction or in thickness greater than 100 mm. ("Magnesium Phosphate Concrete,") MPC has shown in Figure 2.5.

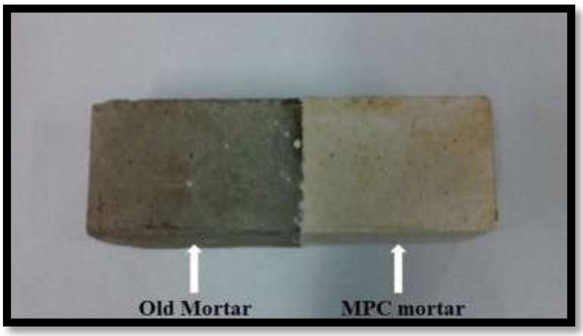

Figure 2.5: Ordinary and MPC mortar

2.2.5 Rapid Setting Concrete

Rapid Setting Concrete is an excellent concrete combination appropriate for use in all general concrete works, both externally and internally, where ever fast setting and rapid development of strength are needed.

Rapid Setting Concrete has to mix with 2.5 – 3.3 liters of clean drinking water to produce a workable concrete mixture. Slight water modifications may be required to achieve the desired consistency. Excessive addition of water will significantly weaken the blend. Rapid Setting Concrete is the only sufficient material which can install in 10 minutes.

There are many advantages of rapid setting concrete over ready mixed mortar such as Rapid Setting, Rapid strength development, Weatherproof, Eliminates wastage, and easy to use. ("Rapid Setting Concrete,") as shown in Figure 2.6.

Figure 2.6: Rapid setting cement

2.2.6 Shotcrete

Shotcrete is a standard concrete, which is sprayed through a nozzle under pressure, as shown in Figure 2.7, on a prepared concrete surface with low water content. This pressure force compacts the shotcrete, producing a dense homogenous mass, used for replacement of damaged or deteriorated concrete as well as for jackets.

The provided shotcrete reinforcement usually weld wire fabric and deformed bars that tack into the current concrete surface, which improves the bond between existing and new concrete. The application by shotcrete requires no formwork and apply to any concrete surfaces, including inclined and vertical surface and also roof slabs. The results are excellent with proper compaction due to an application under pressure and excellent adhesion between new and old concrete.

Thus, using a low water-cement ratio in shotcrete results in low shrinkage and high strength of repairing concrete. The shotcrete's permeability is less than that of regular concrete and results in better steel protection against erosion ("Materials for Concrete Repair, Replacement and Jacketing,").

Figure 2.7: Shotcrete

2.2.7 Shrinkage-compensating concrete

Shrinkage-compensating concrete produce from expansive cement, which expands during the first week of curing, through the formation of ettringite crystals, as shown within Figure 2.8. The concrete returns to its initial size, when the moist cure completed, standard concrete is not doing this. The concrete starts to shrink after pouring due to the volume loss due to water evaporation and contracts to a smaller size. If the floor didn't adequately design and constructed, this causes the joints to crack, curl ultimately and spall. Shrinkage-compensating concrete will resist and minimize cracking and curling. Its size increases throughout the expansion restrained by internal reinforcement. Compressive stress is put on the concrete internally, which is then relieved by subsequent minimal shrinkage. The expansive property regulates the contraction in such a way as to eliminate or reduce that seen in normal cement ("Exactly What is Shrinkage-Compensating Concrete,").

Figure 2.8: Expansive cement admixture

2.2.8 Silica fume concrete

Silica Fume (as shown in figure 2.9) is now used widely for high strength structures, the silica fume density ranges between 150 and 700 kg/m³, and it is ideal as a concrete additive when its density is around 550 kg/m³. It contains more than 90% silicon dioxide, and other constituents are sulfur, carbon, and oxides of iron, aluminum, magnesium, sodium, calcium, and potassium.

It has several advantages of various types of concrete, and it improves the characteristics of hardened and fresh concrete, Fresh concrete produced from silica fume is more cohesive, reduces bleeding and segregation, improves the concrete durability, Lack of bleeding makes a more efficient finishing process. Loose and fresh silica fume showed in Figure 2.10.

Some problems exist while using silica fumes such as availability of the product, Handling, and cost problems ("Silica Fume Concrete,").

Figure 2.9: Silica Fume **Figure 2.10**: Fresh Silica Fume Concrete

2.2.9 Ultra high-performance fiber reinforced concrete

Ultra-High Performance Concrete is a cementitious material that has a much higher compressive strength than ordinary concrete and to some degree also has a valuable tensional strength. Studies and tests have been conducted to apply this material in strengthening or retrofitting of structural components such as beams, slabs, or columns.

Ultra-high performance fiber reinforced concrete is concrete of which its compressive strength can reach over 180 MPa and its tensile strength over 10 MPa by the included fiber. This high strength can enable the use of the ordinary concrete jacketing to display a more significant strengthening effect. The thickness of the jacket can also be reduced by less than 30-50 mm due to high UHPFRC fluidity, thus minimizing the major disadvantage of standard concrete jacketing. There are other benefits of UHPFRC retrofitting like good adjustability with different situations, high durability, and the ability to combine it with other products like wire mesh or textile mesh for better performances. (Koo & Hong, 2016) It shows in Figure 2.11.

Figure 2.11: Ultra-High Performance Fiber Reinforced Concrete

2.3 Bonding materials

Bonding materials can use to bond new repair materials to an existing prepared concrete substrate. Bonding materials are of three types: epoxy based, latex based, and cement based.

a) Epoxy: Care should be taken in hot weather when using these materials. High temperatures may cause premature curing and the creation of a bond break. Most epoxy resin bonding materials create a moisture barrier between the existing substrate and the repair material.

b) Latex: Latex bonding agents classify as

Type I – Redispersible

Type II – Non – dispersible

Type I bonding agents may be applied to the bonding surface several days before the repair materials place; however, the strength of the bond is lower than that provided by Type II bonding agents. Bonding agents of type I must not be used in areas that subject to water or high humidity and structural applications.
Type II systems act as bond breakers after skinning or curing.
c) Cement: The methods based on cement have used for many years. Cement bonding systems use neat Portland cement or a mix of Portland cement, and excellent aggregate filler generally proportioned one to one by weight. Water is added to provide a uniformly creamy consistency (Zaky, 2013).

2.4 Polymeric materials

Three types of polymer materials discussed below.

2.4.1 Polymer Concrete (PC)

Polymer concrete is a composite material in which the aggregate in a matrix with a polymer binder is bound together, as shown within Figure 2.12. There is no hydrated cement phase in the composites, although Portland cement may use as an aggregate or filler. The formulation of polymer concrete composites relies on a unique mixture of characteristics. These include rapid curing at ambient temperatures ranges between –18 to +40°C (0 to 104°F), high flexural, tensile, and compressive strengths, excellent long-term durability with respect to freezing and thawing cycles, excellent adhesion to the most surfaces, low permeability to water and aggressive solutions, lightweight and excellent chemical resistance ("Polymer Concrete,").

Figure 2.12: Polymer Concrete

2.4.2 Polymer Cement Concrete

Polymer cement concrete (PCC) is a concrete composite of polymer in which both cement paste and polymer served as binders. PCCs most commonly made by adding a polymer emulsion (i. e. latex) to the fresh concrete mixture. The performance of (PCC) is investigated with a particular focus on concrete block paving characteristics, both mechanical properties such as abrasion resistance, impact resistance, and tensile/flexural strength and durability related characteristics such as freezing/thawing resistance, capillary suction, and chemical resistance. Specific examples given for each of the properties and the relevance of concrete block paving discuss. The importance of choosing the right principle to compare PCC with normal concrete and the correct type of polymer are stressed.

Depending on the type of polymer, the polymer dosage and the principle of comparison, a PCC material may provide characteristics of interest for concrete block construction, enhanced abrasion resistance, increased impact and tensile strength, enhanced freeze-thaw resistance, reduced capillary suction, and enhanced chemical resistance. The most cost-effective dosage of dry polymer used in PCC is generally 10 % of the cement weight. (Justnes) PCC shows in Figure 2.13.

Figure 2.13: Polymer Cement Concrete

2.4.3 Fiber Reinforced Polymer (FRP)

Fiber-reinforced plastic or polymer (FRP) is a composite material made of the fiber-reinforced polymer matrix. Fiber Reinforced Polymers (FRP) as a type of composite materials have become common in the strengthening of the reinforced concrete structures.

The use of fiber-reinforced polymer materials in concrete strengthening has increased rapidly on site in various shapes as a referenced material in many applications.

The use of such polymers as a significant application of composites for strengthening has risen rapidly in the latest years (Gunaslan & Karasin, 2017).

FRP is suitable for strengthening RC columns due to their excellent resistance to corrosion, high strength and stiffness-to-weight ratio, lightweight, excellent mechanical properties, quickly and easily applied, and minimal effect on columns geometry. Over the last two decades, many studies have been conducted to investigate the behavior of RC columns strengthened by CFRP sheets. It concludes that the level of strengthening of RC columns using CFRP depends on many factors: concrete strength, the columns' cross-section and slenderness ratio, the number of CFRP layers, fiber orientation, type of matrix, and the bond at the interface between concrete and the composite sheet. FRP shows in Figure 2.14.

Figure 2.14: Fiber Reinforced Polymer

3.1 Strengthening techniques

We have several methods of strengthening using different techniques and materials. This chapter contains several previous pieces of research on different strengthening methods of damaged reinforced concrete columns, each with tests and experimental programs done by the authors used to prefer using one method over the others.

3.2 Reinforced concrete columns strengthened by steel reinforcement

Chai et al., (1991)studiedthe performance of columns strengthened with steel jacketing in the plastic hinge regions, six large-scale models of circular columns test at the University of California at San Diego. The columns diameter were 610 mm in, and their height was 3657 mm. They were considered to be (0.4-scale) models of a prototype 1524 mm diameter columns. They were constructed with a footing to allow the monitoring of the foundation's interaction. The ratio of longitudinal steel reinforcement was 2.53%, while the proportion of the lateral reinforcement was 0.174%. Transverse reinforcement consisted of #2 circular hoops with the center to center spacing of 127 mm. The lap splices closed the hoops in the concrete cover. A (6.3 mm) gap was provided between the jacket and the column and was pressurized with water/cement grout. Design variables between specimens give in Table 3.1. For column 5, a thin sheet of Styrofoam was added between the column and injected grout to allow a controlled dilution of cover concrete at massive displacement. All the columns were tested under an axial load of 1779 kN (400 kips) and reversed cyclic loading (Yau, 1998).

Table 3.1 Details of Test Specimens

Column No.	Column and Footing Details		Remarks
1	20 d_b lap for longitudinal bars without steel jacket	Weak footing	Reference
2	20 d_b lap for longitudinal bars with steel jacket	Weak foundation	Full retrofit
3	Continuous column bars with steel jacket	Strong footing	Reference
4	Continuous column bars without steel jacket	Strong footing	Complete retrofit
5	20d_b lap for longitudinal bars, $1/4$ in. Styrofoam wrap and steel jacket	Strong footing	Partial retrofit
6	20 d_b lap for longitudinal bars with steel jacket	Strong footing	Full retrofit
1-R	20 d_b lap for longitudinal bars, repaired by steel jacket	Weak footing, 300 kips pre-stress	Repair

The experimental program indicated that strengthening of circular bridge columns by steel jacketing resulted in an enhancement of flexibility and flexural strength of the columns. The following conclusions give from the results of the study (Yau, 1998):

- A lap length of 20 times the longitudinal bar diameter was insufficient to develop yield stress of longitudinal bars. The strength of unstrengthened columns due to bond failure degraded rapidly.
- Footings designed before 1970 might be susceptible to joint shear failure in the region right under the column.
- The steel jacket enabled a displacement ductility factor of 7 to achieve.

The columns failed by low-cycle fatigue of longitudinal reinforcement. No bond failures occurred.

- Steel jacketing increased the stiffness of the column by 10 to 20% due to additional confinement from the jacket.

Coffman et al. (1993)Studied the seismic performances of four half-scale, circular, reinforced concrete columns. The columns were 3048 mm in height with a diameter of 456 mm. The longitudinal reinforcement splice to the dowels of foundation with a lap length of 660mm (35 times the diameter of the longitudinal rebar). The dowels were welded and screwed to a thick column base plate. Transverse reinforcement with #3 hoops at 305 mm centers, with 356 mm lap splices in the concrete cover provided. Three of the columns were strengthened with pre-stressed, outer circular hoops at intervals along with the lower 1219 mm, and the fourth was unaltered.

The retrofit hoops were grade 60 bars formed into semicircular pieces connected by swaging opposing threaded coupling. The specimens details present in Table 3.2

All the columns test under a reversed cyclic lateral loading until failure and an axial load of 700 kN. The following results were reported (Yau, 1998):

- For cycling at u = 4, the control column sustained only one cycle before losing structural integrity. The strengthened columns suffered a minimum of twelve cycles.
- The total energy dissipated depended on the spacing and size of the hoops.

Column C-4, which had the most significant hoop spacing combined with the smallest hoop size, produced the highest dissipation of energy.

- The strengthening did not change the column stiffness or remarkable increase in the strength.

Table 3.2 Details of Specimens

Spec.	F'c (MPa)	Longitudinal Steel			Lateral Steel			Retrofit External Hoops			
		No. of bars	Size*	f_{yt} (MPa)	Size*	Spacing (mm)	f_{yb} (MPa)	Spacing (mm)	Size *	ρ_s	f_{yb}
C-1	22	9	#6	379	#3	305	559	------	------	----	----
C-2	22	9	#6	379	#3	305	559	76	#4	0.0152	492
C-3	22	9	#6	379	#3	305	559	76	#3	0.0083	559
C-4	22	9	#6	379	#3	305	559	102	#3	0.0062	559

*US bar size #3: 77 mm^2 (0.11 $in.^2$), #4: 129 mm^2(0.20 $in.^2$), #6: 283 mm^2 (0.44 $in.^2$)

3.3 Reinforced columns strengthened with FRP composites

Priestley et al. (1992)Investigated the behavior of columns strengthened using a combination of active and passive confinement provided by the jackets of fiberglass/epoxy composites. Seven tests conduct three on circular columns with lap-spliced longitudinal reinforcement dominated by flexural action, and two tests, each of circular and rectangular columns subjected to double bending controlled by shear failure.

For the flexural tests, the diameter of the column was 610 mm and 3660 mm long to the point of application of the load. The specimens design to approximately model typical (1950-70) details, at a scale of (0.4:1).

They were strengthened usingactive confinement — the details of the specimens given in Table 3.3.

Table 3.3 Details of Specimens for Flexural Tests

Spec.	F'_c (MPa)	Grout			GFRP	
		Type	Thickness (mm)	Pressure (MPa)	Thickness (mm)	Height (mm)
C – 1	34.5	Epoxy grouted	2.44	1.72	3.25	305
C – 2	34.5	Epoxy grouted	1.22	0.69	3.25	305
C – 3	34.5	Cement grouted	1.83	1.38	3.25	305

For the shear test, two circular columns had the same dimension as the flexural test, and the two rectangular columns had 620x406 mm cross sections. The two rectangular columns were strengthened with passive confinement only while the two circular columns were strengthened using active confinement — all four columns subjected to double bending.

It concludes that the use of fiber glass/epoxy composite jackets enhanced the flexural ductility and inhibited lap splice failure. Besides, it increased the shear strength of the rectangular columns to the amount that brittle shear failure modes converted to ductile inelastic flexural deformation modes (Yau, 1998).

Saadatmanesh, Ehsani**,** and Li (1994)proposed an analytical model to investigate the effectiveness of strengthening concrete columns with high-strength fiber composite straps.

The variables that examined include concrete compressive strength, type of strap, thickness, and spacing of the straps.

A parametric analytical study conducted on the behavior of rectangular and circular columns strengthened with composite straps under monotonic loading. The columns cross sections shown in Figure 3.1. The stress-strain curves for both carbon fiber straps and E-glass shown in Figure 3.2. The analytical study was the same for both rectangular and circular columns, and it divides into three parts. For each element, the columns analyze as unstrengthened, carbon fiber-wrapped, and E-glass fiber-wrapped.

The details of the specimens shown in Table 3.4, where t = thickness of swap and s' = clear spacing between the straps. The width of the strap was 152 mm (Yau, 1998).

Table 3.4 Details of Columns

Part 1 t = 5 mm, s' = 0 mm	Part 2 f'_c = 34.45 MPa, t = 5 mm	Part 3 f'_c = 34.45 MPa, s' = 0 mm
f'_c = 20.67 MPa	s' = 0 mm	t = 5 mm
f'_c = 27.56 MPa	s' = 152.4 mm	t = 10 mm
f'_c = 34.45 MPa	s' = 305.0 mm	t = 15 mm

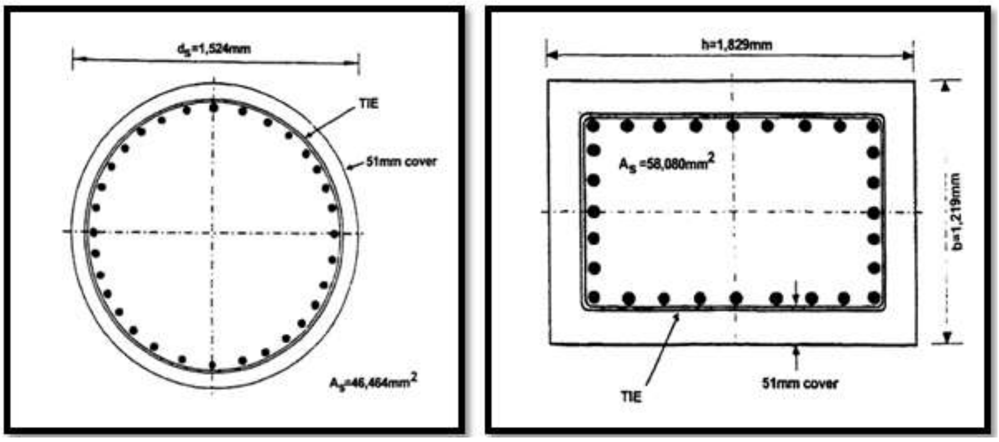

Figure 3.1 Cross section of columns

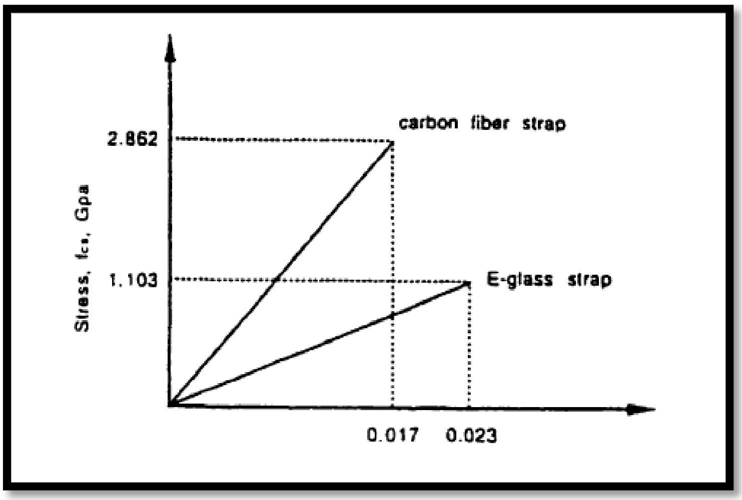

Figure 3.2 Stress-strain curves of fibers

The stress-strain models for confined concrete, developed by Mander. Priestley and Park (1988), and based on an equation proposed by Popovics (1973), were adopted in the analysis of rectangular and circular columns confined with composite straps.

According to the analytical studies, flexibility and the strength of concrete columns increased significantly by wrapping fiber straps around them.

The following conclusions conclude by the researchers (Yau, 1998):

- The stress-strain models for concrete confined with composite straps showed significant increases in strain and compressive strength at failure when compared with that of unconfined concrete.
- Carbon fiber had a larger energy-absorbing capacity. Based on an energy balance approach, the increase in ductility and ultimate axial load as a result of strengthening with carbon fiber is more significant than that with E-glass, for the same volume of the straps.
- The increase in the maximum moment capacity was less than that in the ductility factor and ultimate axial load.
- The gain due to confinement by FRP, in the ductility, ultimate axial load and maximum moment capacity decreased with increasing concrete strength.
- Linearly the ductility factor increased as the strap thickness increased. Also, the rate of increase in the ductility factor decreased as strap spacing increased.

Saadatmanesh et al., (1996)conducted an experimental program to study the seismic behavior of circular columns strengthened with glass fiber reinforced plastic (GFRP) composite straps. Five reinforced concrete bridge column footing assemblages constructed with a 0.2-dimensional scale factor. Only a single column bent consider in this study. The layout of the specimens shown in Figure 3.3 and the details of the column specimens presented in Table 3.5. For specimens C- 1, C-2 and C-3, the longitudinal reinforcement was extended into the footing using starter bars overlapped with the main longitudinal bars over a length of 20 times bar diameters, Le., 254 mm.

For specimens C-4 and C-5, the reinforcement extended into the footing and anchored with a 90°standard hook.

The composite straps used for this project were 0.8 mm thick and had a modulus of elasticity and tensile strength of 18.6 GPa and 532 MPa, respectively. The GFRP apply to the potential plastic hinge region; i.e., 635 mm long portions of the column above the top face of the footing before testing. Both passive and active strengthening methods test in this experiment. For the passive strengthening scheme, the composite with fiber orientation in the circumferential direction directly wrap onto the column. For the active strengthening scheme, the composite straps were oversized slightly for the column, and the resulting gap injected with pressurized epoxy resin. For both strengthening systems, the columns wrap with six layers of composite straps. While covering for the interlaminar bond, an epoxy applied to the straps.

The specimens tested in a steel reaction frame, as shown in Figure 3.4. First, by pre-stressing the high-strength steel rods, the axial load of 445 kN was applied.

Then, the reversed cyclic lateral load apply by an MTS ±489 kN hydraulic actuator. Ten electrical Inclinometers distributed over both opposite faces of the column within the plastic hinge region to measure the rotations of the plastic hinge. Four displacement transducers were used to measure the column deflection. Strain in the column bars and hoops were measured using twelve strain gauges. Besides, for each strengthened column, twelve strain gages were used to measure strains in the composite straps (Yau, 1998).

Table 3.5 Details of Column Specimens

Spec.	f'_c (MPa)	Longitudinal Steel				Lateral Steel			Retrofit
		No. of bars	Size*	$\rho_{t\,(\%)}$	f_{yt}(MPa)	Size (mm)	Spacing (mm)	f_{yb}(MPa)	
C – 1	36.5	14	#4	2.48	358	3.5	89	301	None
C – 2	38.3	14	#4	2.48	358	3.5	89	301	Passive
C – 3	38.5	14	#4	2.48	358	3.5	89	301	Active
C – 4	36.6	14	#4	2.48	358	3.5	89	301	None
C – 5	36.5	14	#4	2.48	358	3.5	89	301	Passive

*US #4: 129 mm^2 (0.2 $in.^2$)

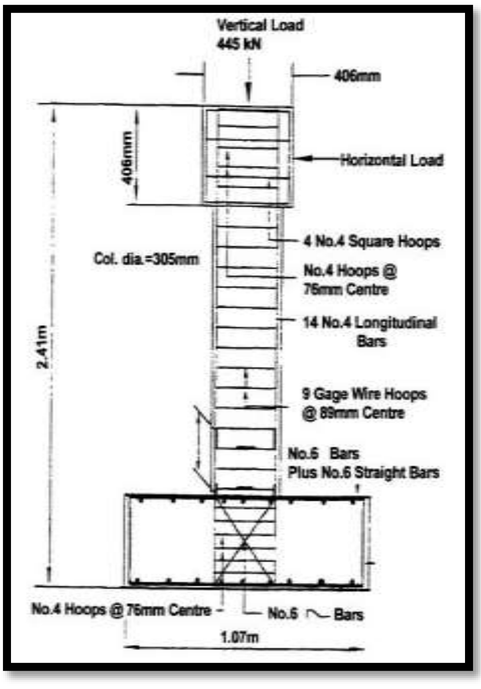

Figure 3.3 Layout of specimens

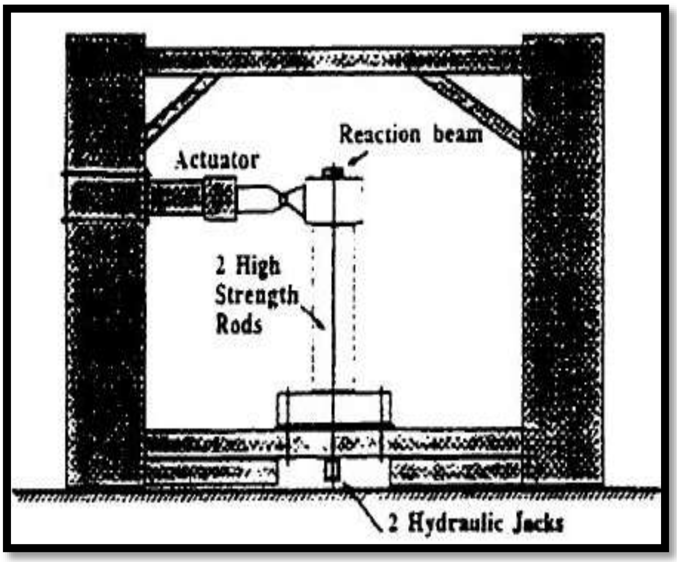

Figure 3.4 Test setup

It concludes that the displacement ductility and strength of a circular column externally wrapped with GFRP composite straps, significantly improved as a result of the confining action of the straps. The straps are highly effective in preventing the longitudinal reinforcement from buckling under cyclic loading and confining the core concrete. It also concluded that both active and passive strengthening schemes provided additional confinement; however, other researches are necessary to investigate the benefits of active over passive confinement further.

Saadatmanesh et al. (1997) investigated the flexural behavior of earthquake-damaged reinforced concrete columns repaired with glass fiber reinforced plastic (GFRP) wraps. Four columns tested in this experiment. Columns R-l and R-2 were rectangular while C-l and C-2 were circular. A11 columns were 0.2 scales of prototype bridge columns. The design details of the test specimens showed in Figure 3.3. Columns R-1 and C-I had starter bars with a lap length of 30 times the bar diameter, while Columns R-2 and C- 2 had continuous reinforcement. The material properties of the specimens presented in Table 3.6. The mechanical properties of GFRP wraps were determined according to ASTM D3039-76 and given in Table 3.7. All the columns tested to an absolute damage level under reversed inelastic cyclic loading. They were then repaired with composite wraps and proved again.

Before repair work began, the damaged columns pushed back to the original position, i.e., zero lateral displacements. The repair procedures included chipping out loose concrete, filling the cavity with quick-setting concrete and applying an active strengthening scheme. The active strengthening scheme consisted of wrapping columns with slightly oversized straps and filling the gap with pressurized epoxy. The repaired columns were subjected to the same loading sequence, approximately one week after the repair operation was completed (Yau, 1998).

Table 3.6 Material Properties of Columns

Column	f'cMPa	Longitudinal Steel		Transverse Steel			GFRP Wraps		
		fyMPa	ρμ %	fyMPa	ρst %	Spacing mm	fuMPa	t/layer mm	Layers
C – 1	36.5	358	2.48	301	0.1704	88.9	-----	-----	-----
C – 1/R	36.5	358	2.48	301	0.1704	88.9	532	0.8	6
C – 2	36.6	358	2.48	301	0.1704	88.9	-----	-----	-----
C – 2/R	36.6	358	2.48	301	0.1704	88.9	532	0.8	6
R – 1	34.9	359	2.70	301	0.133	114.3	-----	-----	-----
R – 1/R	34.9	359	2.70	301	0.133	114.3	532	0.8	8
R – 2	33.4	359	5.45	301	0.133	114.3	-----	-----	-----
R – 2/R	33.4	359	5.45	301	0.133	114.3	532	0.8	8

Table 3.7 Mechanical Properties of GFRP

Fiber Volume Ratio	Vf = 50.2 %
Tensile Strength MPa	532
Tensile Modulus MPa	17.755
Ultimate Strain mm/mm	0.030

The following concludes from the test results (Yau, 1998):

- GFRP composite wraps were effective in restoring the flexibility and flexural strength of earthquake-damaged reinforced concrete columns.
- Initially, columns R-1 and C-1 failed as a result of debonding of longitudinal reinforcement in the lapped region. R-2 failed in shear and C-2 failed by buckling of longitudinal bars.

After repair, columns with lapped starter bars developed stable hysteresis loops up to the displacement ductility of u = ±4. u = 6 achieved without any sign of structural degradation for columns with continuous reinforcement.

- The rate of stiffness degradation in repairing columns under extensive reversed cyclic loading was lower than the corresponding original columns. However, due to pre-existing damage, the initial stiffness of repairing columns was lower than that of original columns.

3.4 Reinforced columns strengthened by concrete jacketing

Aguilar et al. (1989) investigated 114 buildings, which strengthened after the earthquake in Mexico in 1985. It reported that the most frequently used strengthening method in the buildings less than 12 floors were the concrete jacketing of columns.

Bett et al. (1988) have concluded that columns strengthened by jackets, both with and without additional crossties, were much stronger and stiffer than the original, unstrengthened columns.

Saatcioglu and Ozcebe (1989) pointed out that a cross-tie with 90º hook at one corner and with an extension of 10 times the diameter of bar performs as satisfying as that with 135º hook with similar extension and at both ends.

Bousias and Fardis (2003) proved that concrete jackets are very efficient, in reducing the adverse effect of lap splicing on flexural capacity, even for tiny lap lengths.

Alcocer (1993) (also Alcocer and Jirsa, 1993) tested beam-column-slab specimens under bidirectional cyclic loading to investigate the impact of jacketing on the shear strength of joints. Various layouts of the columns new longitudinal bars researched. It found that the distributed bars are preferred for better bonding behavior, bundling of bars near the column’s corners increased the strength, energy dissipation, and stiffness property of the samples.

Ersoy et al. (1993) concluded that when the jacket constructed after unloading the column, a strengthened column behaved better.

Valluvan et al. (1993) tested samples of columns with longitudinal bar lap splicing. It found from the experiments that removing the concrete cover to add the new ties is not an efficient technique for strengthening the location of splice because it results in micro-cracking inside the concrete core. External reinforcement (i.e., steel component or ties) around the splice region improves the concrete’s confinement and splice strength. Steel dowels place in the interface of the old concrete and the jacket in front of the original columns for the better shear transfer.

Rodriguez and Park (1994) used stub beams to test jacketed columns. The additional longitudinal bars in a specimen were put in bundles near the column corners and passed through the slab through drilled holes. By drilling the stub beams, additional ties placed at the joint. Significant improvements have noted in the lateral stiffness, strength, and ductility of the samples.

Vandoros and Dritsos (2006) tested and designed a typical ground floor column of a framed building under displacement-controlled cyclic loading. Self-compacting concrete used in the jacket. The original column's longitudinal bars connected to the additional longitudinal bars with steel inserts in the jacket. It concluded that when the jacket constructed with dowels, but without any treatment of the old surface, an almost similar behavior could achieve. There have been significant increases in strength and stiffness.

Concerning the bonding of old and new concrete, Stoppenhagen et al. (1995) roughened the surface of the column with an electric concrete hammer to obtain monolithic behavior of the whole concrete.

Abu-Tair et al. (1996) introduced the slant shear test and modified modulus of rupture test to investigate the effect of the surface treatment on the bond strength at the interface, under monotonic and cyclic loadings. It found that both experiments work to study the strength of the bond.

Austin et al. (1999) used tensile pullout tests to compare the bond strength. The surface preparation effect and the mismatch of the moduli of the repair material and substrate researched. A failure envelope was presented based on the theory of Mohr-Coulomb and Griffith fracture criterion.

Climaco and Regan (2001) performed bond tests and the effects of bond coats, surface preparation, and base concrete aging. The Coulomb criterion was used to analyze test results.

Excellent bond strength can achieve, when the surface of the base is dry, by casting the repair material against the old concrete without any bonding agent. Julio et al. (2003) investigated the effects of surface preparation, bonding agents, and steel connectors. It found that the monolithic behavior of a jacketed member could achieve by using bonding agents or steel connectors, without increasing the surface roughness.

Beushausen and Alexander (2008) tested the following types of surface preparation:sandblasted, plain, without any intentional roughening, and notched surface.

From the tests, it found that the rough surface showed higher bond strength than the sandblasted and the plain interfaces, even at 26 months after casting of the new concrete (Kaliyaperumal & Sengupta, 2009).

4.1 Conclusions

The following conclusions can be drawn from this studyon the concrete column strengthening using different techniques and materials:

1. The experimental program indicated that strengthening of circular bridge columns by steel jacketing resulted in enhancement of flexural strength and ductility. A lap length of 20 times
2. The steel jacket enabled a displacement ductility factor of 7 to achieve.
3. Steel jacketing increased the column stiffness by 10 to 20% due to additional confinement from the jacket.
4. According to the analytical studies, the strength and ductility of concrete columns increased significantly by wrapping fiber straps around them.
5. The ductility factor increased linearly as the strap thickness increased. However, as strap spacing increased, the rate of rising in ductility factor decreased.
6. It found that the strength and ductility of the circular column wrapped externally with GFRP composite straps, increased significantly as a result of the straps confining action. GFRP composite wraps were efficient in restoring the earthquake-damaged concrete columns ductility and flexural strength.
7. columns strengthened by jackets, both with and without additional crossties, were much stronger and stiffer than the original, unstrengthened columns.
8. Substantial improvements have noted in the lateral stiffness, strength, and ductility of the samples.
9. It concluded that when the jacket constructed with dowels, but without any treatment of the old surface, an almost similar behavior could achieve. There have been significant increases in strength and stiffness.

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