MINISTRY OF EDUCATION
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING OF BUCHAREST
DOCTORAL SCHOOL

Reinforced Concrete Columns Strengthening with FRP Composites

Submitted to:
Prof. Dr. Liviu Crainic
Prof. Dr. Radu Pascu
Prof. Dr. Dan Paul Georgescu

Written by:
PhD Student, Ali Almagsoosi

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1. Introduction

Structures in service are being subjected to increased service loads and severe environmental conditions than their original designs. In addition, the plain concrete has low tensile strength and a limited ductility due to its brittle nature which leads to a less energy absorption and a low resistance to crack control. Hence, many structures need to be repaired/rehabilitated or replaced under such conditions. Rehabilitation and retrofitting of existing structures was traditionally done using steel or reinforced concrete jacketing [1].

Natural disasters such as hurricanes, tornadoes, tsunamis, and earthquakes and accidental impacts can damage or destroy deficient structures in a matter of seconds. On the other hand, saltwater, deicing chemicals, and freeze-thaw cycles can cause structural deterioration over a longer period of time. The majority of older buildings and bridges were constructed according to older design codes. These structures are vulnerable during extreme events and need to be retrofitted to meet the current codes and standards. For example; during a severe earthquake, the structure is likely to undergo inelastic deformation and has to depend on ductility and energy absorption capacity to avoid collapse. Such buildings designed for gravity loading need to be strengthened to increase strength, stiffness and ductility [2].

Traditional retrofit techniques include concrete and steel jacketing. These methods are time consuming and labour intensive. They also increase the cross-sectional area of the structural column member. Another more recent method of repair is the use of Fibre Reinforced Polymers (FRP) because of their excellent mechanical properties, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost [2].

Due to the increase in the ultimate compressive strain, the ductility capacity and energy absorption capacity are also considerably improved. The use of FRP in this particular application is similar to that in the rehabilitation due to deteriorating infrastructure. The product is high in strength, light-weight, corrosion resistant, low in cost, and extremely versatile. When dealing particularly with earthquake damaged zones, the importance of avoiding the need for heavy equipment in the repair methods is particularly increased. It has been concluded through various tests of seismically deficient columns both before and after repair, that FRP composite wraps are effective in restoring the flexural strength and ductility capacity of earthquake-damaged concrete columns. [3]

2. Background Information

Steel plate bonding or concrete column jacketing are the traditional methods of external reinforcing. Steel plates bonded to the tension zones of concrete members have shown to be increasing the flexural capacity of the members. This traditional method has been used over the world to strengthening bridges and buildings. However, the corrosion of steel plates, deterioration of the bond between steel and concrete, installation difficulties such as necessity of heavy equipment in installing have been identified as major drawbacks of this technique. As a result researchers investigated FRP strengthening as an alternative to this method. [4]

The United States has shown an interest of fibre based reinforcement in concrete structures since 1930s. However, actual development and research into the use of these materials for retrofitting concrete structures started in the 1980s.

In Europe, FRP systems were developed as alternates to steel plate bonding. Bonding steel plates to the tension zones of concrete members with adhesive resins were shown to be viable techniques for increasing their flexural strengths (Fleming and King 1967). This technique has been used to strengthen many bridges and buildings around the world. Because steel plates can corrode, leading to a deterioration of the bond between the steel and concrete, and because they are difficult to install, requiring the use of heavy equipment, researchers have looked to FRP materials as an alternative to steel. Experimental work using FRP materials for retrofitting concrete structures was reported as early as 1978 in Germany (Wolf and Miessler 1989). Research in Switzerland led to the first applications of externally bonded FRP systems to reinforced concrete bridges for flexural strengthening (Meier 1987; Rostasy 1987). [5]

FRP systems were first applied to reinforced concrete columns for providing additional confinement in Japan in the 1980s (Fardis and Khalili 1981; Katsumata et al. 1987). A sudden increase in the use of FRPs in Japan was observed after the 1995 Hyogoken-Nanbu earthquake (Nanni 1995).

3. Advantages and Disadvantages of Using FRP Composites

The main advantages of FRP are summarized in the following points:

1. High strength.

2. Outstanding fatigue strength.

3. Reduced construction periods.

4. Durability of the strengthening system (Resistance to corrosion, alkalis and other aggressive materials).

5. Availability in any length and ability to be transported in rolls.

6. Light weight.

7. Versatile design of systems.

8. Reduced or eliminate maintenance cost.

The Disadvantages of FRP are as follows:

1. Erratic plastic behavior and less ductility.

2. Susceptible to local unevenness.

3. High cost.

4. FRP Materials

The advanced polymer composite materials consist of strong stiff fibres in a polymer matrix and require scientific understanding from which design procedures may be developed. The mechanical and physical properties of the composite are controlled by the constituent properties and by the microstructural configurations. The matrix must bond well with the fibre surface to enable transfer of stresses efficiently between the fibres. Fibre alignment, fibre content and the strength of the fibre–matrix interface all influence the performance of the composite. Furthermore, highly specialised processing techniques are used which take account of the handling characteristics particularly of carbon fibres, a material now commonly used to upgrade or strengthen structural systems. The successful strengthening of structural members with FRP materials is dependent upon the quality and integrity of the composite adherent, the effectiveness of the adhesive used and the surface preparation of the two adherents to be joined. The basic requirements for the creation of a satisfactory bonded joint are: [6]

• Selection of a suitable adhesive.

• Adequate preparation of the adhesive surface.

• Appropriate design of the joint.

• Controlled fabrication of the joint.

• A post-bonding quality assurance.

4.1 Composite Materials

The advanced polymer composite essentially consists of two component materials: (i) the matrix material or polymer, which is generally the low strength and low-modulus component and (ii) the fibre, which is the relatively high-strength and high-modulus component. Under stress, the fibre utilises the plastic flow of the matrix to transfer the load to the fibre; this results in a high-strength and high-modulus composite. The primary phase, the fibres of high aspect ratio, must be well dispersed and bonded into the secondary phase, the matrix. The principal constituents of the composite are, therefore, the fibre, the matrix and the interface. This last component is an anisotropic transition region with a graduation of properties. The interface is required to provide adequate chemical and physical bonding stability between the fibre and the matrix in order to maximise the coupling between the two phases and thus allow stresses to be dispersed through the matrix, and thus transferred to the reinforcement. By wetting the reinforcement with the matrix in the liquid or low-viscosity state, coupling between the two components is provided. In the plate bonding technique, the fibre array is invariably aligned along the longitudinal direction of the beam or aligned transversely around the column. Consequently, the main function of the matrix is to combine and to protect the fibre against the external environment into which the composite will be placed. [6]

4.2 Types of FRP Composites

The primary role of the fibre is to resist the major portion of the load acting on the composite system. Depending on the matrix type and fibre configuration, the fibre volume fraction ranges from 30 to 75%. Strength and stiffness properties of commercially available fibres cover a large spectrum and consequently, the properties of the resulting composite have a considerable variation. Typical fibre reinforcements used in the composite industry are glass (E- and S-glass), carbon, and aramid as the following bellow: [8]

Glass fibres: Glass fibres are the most common of all reinforcing fibres used in composites. Major advantages of glass fibres include low cost, high tensile strength, chemical resistance, and high temperature resistance. The disadvantages are low tensile modulus, sensitivity to abrasion while handling, relatively low fatigue resistance, and brittleness. The two most common types of glass fibres used in the fibre-reinforced plastics industry are electrical glass (also known as E-glass) and structural glass (commonly referred to as S-glass). Figure 1 shows the Glass Fibres rollers.

Fig. 1: The Glass Fibres rollers. (Source: ASD reports, March 2014)

Carbon fibres: Carbon fibres offer the highest modulus of all reinforcing fibres. Among the advantages of carbon fibres are their exceptionally high tensile-strength-to-weight ratios as well as high tensile-modulus-to-weight ratios. In addition, carbon fibres have high fatigue strengths and a very low coefficient of linear thermal expansion and, in some cases, even negative thermal expansion. This feature provides dimensional stability, which allows the composite to achieve near zero expansion to temperatures as high as 570 °F (300 °C). Carbon fibres (figure 2) are commercially available with a variety of tensile moduli ranging from 30,000 ksi (207 GPa) on the low end to 150,000 ksi (1035 GPa) on the high end.

Fig. 2: Carbon Fibre Composites. (Source: A Complete Online Guide for Mechanical Engineering, April 2011)

Aramid fibres: Aramid fibre is a synthetic organic polymer fibre (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. Aramid fibre is bright golden yellow and is commonly known as Kevlar® as show in figure 3, its DuPont trade name. These fibres have the lowest specific gravity and the highest tensile strength-to-weight ratio among the reinforcing fibres used today. They are 43% lighter than glass and approximately 20% lighter than most carbon fibres. In addition to high strength, the fibres also offer good resistance to abrasion and impact, as well as chemical and thermal degradation. Major drawbacks of these fibres include low compressive strength, degradation when exposed to ultraviolet light and considerable difficulty in machining and cutting.

Fig.3: Aramid fibre composites. (Source: CHM Composites LTD)

4.3 Properties of Matrices

The polymer is an organic material composed of molecules made from many repeats of the same simpler unit called the monomer. There are many different polymer matrices used in advanced polymer composites but, within the composite family, there are two major types, the *thermosetting* and the *thermoplastic* binders.

The thermosetting polymers are those which form the matrix material of the composite used in the rehabilitation of structures. They are manufactured from liquid or semi-solid precursors, which harden irreversibly. On completion of the chemical reaction, the liquid resin is converted to a hard solid by chemical cross-linking, which produces a tightly bound three dimensional network of polymer chains. The chemical reaction is known as

Poly condensation, polymerisation or curing. The molecular units forming the network and the length and density of the cross-links of the structure will influence the mechanical properties of the resulting material; *the crosslinking is a function of the degree of cure*. The polymer matrix plays a number of vital roles in the formation of the characteristics of a composite. As has been mentioned the fibre generally has a high stiffness and strength but tends to be brittle. The matrix protects the reinforcement against abrasion or environmental corrosion, both of which can initiate fibre fracture. The load, which is carried by the fibre, is distributed through the matrix to adjacent fibres. The matrix should be both chemically and thermally compatible with the fibres. The most common thermosetting resin systems used in civil engineering generally and specifically in the rehabilitation of structures are the *epoxies* and the *vinylesters*.

To form a structural polymer composite, long fibres are introduced into the resin matrix. This combination of two dissimilar materials leads to a component that has enhanced strength, stiffness and toughness over the properties of the individual parts. The mechanical and in-service properties of the final fibre–matrix composite will be dependent upon the individual properties of the two component parts with the former property (viz. mechanical) being largely dependent upon the fibre and the latter property (viz. in-service) being largely dependent upon the matrix. Therefore, the following will affect the overall mechanical properties and to a lesser extent the in-service properties of the composite: [6]

• The type of the fibre used (viz. carbon, glass or aramid fibres);

• The relative proportions of the polymer and fibre (fibre volume fraction);

• The orientation of the fibre (viz. unidirectional, bidirectional aligned or randomly orientated);

• The method of manufacture;

• The temperature and duration of the cure cycle;

• The age of the polymer composite.

4.4 Filaments and fibres

The three fibres, which are used for the rehabilitation of structural components, are (i) the carbon fibre, (ii) the aramid fibre and (iii) the glass fibre. Probably, the most used of these for flexural, shear and wrapping of beams and columns is the carbon fibre, but the fibre finally chosen would depend upon the material of the structural unit to be upgraded and the required strength, stiffness, in-service properties and cost. Fibres generally consist of a number of long filaments, which have exceptionally high specific stiffness and strength. Their diameters are of the order of 10 μm with an aspect ratio, of length to diameter, between 1000 and infinity for continuous fibres. The filaments are extremely fragile and should be handled with extreme care.

The properties of long fibre–polymer composites will generally be anisotropic unless an orientated angle ply system of fibre arrays of 0°, 30°, 60° or 90° is used, or randomly orientated short fibre arrays are used in which case the composite will exhibit quasi-isotropic properties. The direction and volume fraction of the fibres in composites will determine the strength and stiffness of the composite. In flexural plate bonding solutions, the fibres are unidirectional aligned along the longitudinal length of the member. In order to maintain the alignment, particularly during the manufacturing procedure, it may be necessary to add a small percentage of fibres in the transverse direction. For shear strengthening, again the unidirectional aligned fibres are used. For the rehabilitation or the retrofitting of RC columns, continuously-wound fibres in the hoop direction are applied to the column at a slight positive angle. These fibres confine the concrete in the columns and, as the tensile fibres can resist a much greater tensile strength compared with that of the concrete, the column will contain a much higher compressive load. [6]

4.5 The Mechanical Properties of Advanced polymer composites

***Tensile properties*:** It has been stated above that the fibre strength and stiffness, volume fraction and orientation will determine the mechanical properties of the final composite; this is illustrated in Table 1 which gives typical properties of composites manufactured by the *pultrusion* technique using epoxy resin and long directionally aligned fibre reinforcement of glass, aramid and carbon with a fibre–matrix ratio by weight of 60%.

Table 1: Typical mechanical properties of long directionally aligned fibre–matrix composites (fibre weight fraction 58%) manufactured by the pultrusion technique, (the matrix material is epoxy). (Source: L.C. Hollaway and J.G. Teng, Book, 2008).

Composite material	Specific weight	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (Gpa)
E-glass	1.90	750–1050	40.00	1450	40.00
S-2 glass	1.80	1650	55.00	–	–
Aramid 49	1.45	1150–1400	70–110	–	–
Carbon (PAN)	1.60	2670–1950	150–220	1600	–
Carbon (pitch)	1.80	1400–1500	280–350	*Failure strain* ≃ *0.40* > 330	

Compressive properties: The integrity of both the fibre and matrix in a composite under a compressive load is far more critical than in tensile loading. The fibres are the principal load-bearing elements in a composite and are supported by the matrix to provide local stability and prevent a micro-buckling failure of the composite. Consequently, local resin and interface damage would lead to fibre instability that is more severe than the fibre isolation mode, which occurs in tensile loading. The possible failure modes for FRP under longitudinal compression are

(i) Transverse tensile failure,

(ii) Fibre micro-buckling and

(iii) Shear failure;

The compressive strengths of FRP composites normally increase as the tensile strengths increase; however, of the three fibre composites used in construction, aramid fibre reinforced polymer (AFRP) exhibits non-linear behaviour in compression at a relatively low level of stress. Typical values of the compressive moduli of elasticity and compressive strengths of glass fibre reinforced polymer (GFRP), AFRP and carbon fibre reinforced polymer (CFRP) composite materials compared with their tensile strengths are generally lower by approximately 80%, 100% and 85% and 55%, 20% and 78%, respectively. [6]

Creep characteristics of FRP composites under a tensile load: The two components of the composite, namely, the polymer and the fibre, have vastly different creep characteristics; the polymer is a visco-elastic material and, therefore, will creep under load but the carbon, glass and aramid fibres have virtually no creep component. Consequently, the fibres have a stabilising effect on the creep characteristics of the polymer; therefore, the overall creep rate characteristics of the FRP composite materials and the final creep value will be much lower than that of the polymer. The actual creep value of the FRP composite will depend upon the fibre volume fraction, the fibre orientation and the type of fibre used. [6]

Fatigue resistance of advanced polymer composites: The fatigue behaviour of fibrous composite materials is more complex than that of metals due to the anisotropic nature of the material. Complex failure mechanisms and excessive, damage modes can be caused by fatigue cycles and their possible interaction. Generally, polymeric composites experience progressive fatigue degradation due to failure of the fibres, fibre stacking sequence and type of fatigue loading. However, the magnitude of peak stress in a load cycle is usually a small proportion of the ultimate stress in practical applications and the in-plane fatigue endurance of composites is generally good. The most fatigue-sensitive modes of failure are matrix-dominated modes but, if the failure strain of the matrix exceeds that of the fibre, fibre fracture will dominate fatigue failure. Under fatigue loading there are four basic failure mechanisms of polymeric composites:

• *Fibre breakage interface debonding;*

• *Fibre-matrix interface failure;*

• *Delamination.* The mainly directional fibre composites used in the rehabilitation of structural systems contain a small percentage of transverse fibres for stability of the laminates. In the longitudinal direction, the composites will have strength and stiffness, but they tend to be weak in the through-thickness direction. This weakness can increase the likelihood of delamination between the layers of the laminates particularly in areas of high interlaminar shear.

• *Matrix cracking.* This mechanism does not usually apply to FRP composites used for rehabilitating structural systems due to the mainly unidirectional aligned fibre composites. Cracking will normally occur in the off-axis plies and is usually the first damage mechanism due to lack of fibres orientated in the direction of the applied load, thus causing more load to be distributed to the matrix. [6]

Durability: The long-term durability of a FRP composite depends intrinsically upon the choice of constituent materials, processing methods and the environmental conditions to which they are exposed throughout their service life. Exposure to a variety of adverse and sometimes harsh environmental conditions in construction could degrade the FRP composite material and thus this degradation will alter their mechanical performance. Exposure to high and low temperature variations, moisture and salt solution ingress, ultra-violet rays from the sun and fire will all lead to reduced mechanical performance. Composite materials do offer some significant durability advantages over the more conventional construction materials. Durability from a civil engineering point of view may be divided into six groups: [6]

• Moisture and aqueous solutions;

• Alkaline environment;

• Age of the polymer composite;

• Fire;

• Thermal effects;

• Ultra-violet radiation.

Fire Resistance of FRP: The matrix component of the composite used for rehabilitation is composed of carbon, hydrogen, oxygen and nitrogen atoms and will burn, but not all polymers are equally prone to ignition and fi re growth on their surfaces; the degree of ignition will depend strongly upon the thermal stability of the polymer. In addition, when the material is relatively thin, it burns away quite quickly; conversely, when the material is relatively thick, it quickly forms a protective char and can then survive for relatively long periods before it loses a significant proportion of its strength. There are some fi re-resistant polymers, but they are generally impracticable for infrastructure use by virtue of their high cost. An exception is phenolic resin, which is both relatively inexpensive and fi re-resistant but is difficult to pultrude to a sufficient quality to use in plate bonding and the in-service properties required of it in this capacity are not sufficient. [6]

4.6 Adhesion and surface preparation

One of the most important aspects in adhesive bonding and laminating is surface preparation, which is a critical topic that is often not given the attention that it requires. When surface preparation is undertaken as part of the fabrication of bonded joints, whether in a factory or on a construction site, it is vital that designers, operatives and their supervisors understand the principles behind obtaining satisfactory short- and long-term adhesion. Adhesives and resins are frequently blamed for ‘not sticking’, but the source of the trouble lies generally with the surface preparation. A major barrier to the more confident use of adhesives and resins is a lack of understanding about adhesion, appropriate surface preparation techniques and their effects on initial bond strength and, to a greater degree, long-term durability.

The purpose of surface preparation is to remove contamination and weak surface layers, to change the substrate surface roughness at a micro level and/or introduce new chemical groups onto the surface to link with the adhesive (or primer). The key stages involved in achieving this purpose are: [6]

• cleaning;

• Material removal and surface modification;

• Further cleaning (to remove contamination introduced by treatments, such as oil-mist, dust or chemical residues).

4.6.1 Surface Preparation of Concrete

The chemical and physical nature of the surface of concrete is complex and variable. The surface of this multiphase material may contain exposed aggregate, sand, unhydrated cement particles and cement gel, together with cracks and voids; the surface moisture content may also be variable. Surface treatments should remove significant contamination, cement-rich layers and traces of mould release agents. In essence, the purpose of surface preparation is to remove the outer, weak and potentially contaminated skin together with poorly bound material, in order to expose small- to medium-sized pieces of aggregate (Fig. 4). This must be achieved without causing micro-cracks or other damage in the layer behind; this would lead to a plane of weakness and hence a reduction in strength of the adhesive connection. [6]

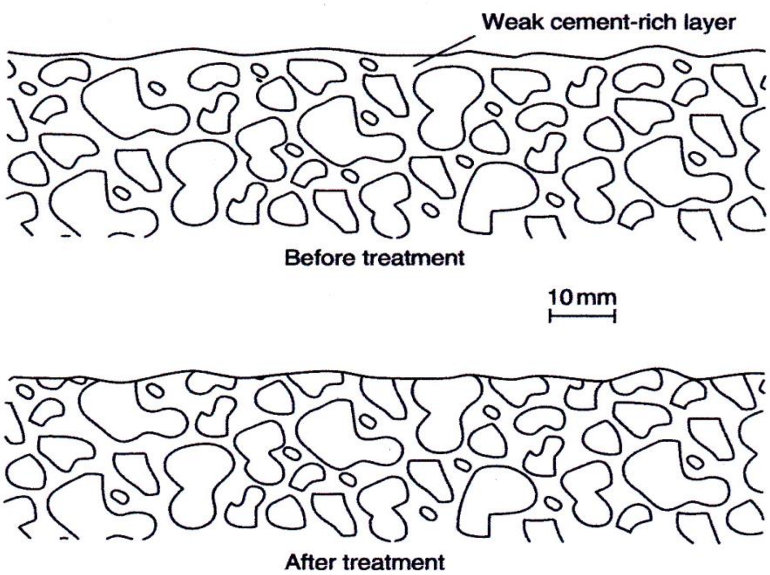

Fig. 4: Schematic idealisation of concrete following surface preparation. (Source: L.C. Hollaway and J.G. Teng, Book, 2008).

4.7 The Bonding Operation

The initial investigation of the condition of the structure should include a thorough inspection of the surface areas on which the bonding will be undertaken. Assessments of soundness should be undertaken and any requirements for defect repairs should be identified. Trials of the adhesion of candidate adhesive/primer systems should also be undertaken at this stage. The aspects that impinge directly on adhesion and joint quality are:

• Evaluation of surface condition;

• Surface preparation;

• Protection of the working environment;

• Mixing, application and curing of the adhesive;

• Quality control samples.

The working environment should be dry and as clean as possible. Many adhesives will not cure below about 5 °C, so attention must be paid to controlling both the ambient temperature and the temperature of the component surfaces. For example, a warm adhesive applied to a very cold surface, even if properly prepared, may not adhere to it adequately because of the tendency to ‘skin’ due to thermal shock.

Where two component adhesives are mixed together in a can or container, there is a finite usable life or pot-life. The viscosity, and therefore ease of application, of adhesive material can vary significantly with temperature. Adhesives with the correct characteristics at 20 °C may be impossibly viscous at 5–10 °C, or too fluid at 30 °C. It is important to spread the adhesive soon after mixing to dissipate the heat generated and extend its usable life.

5. Installation Techniques

As although a variety of techniques can be used to apply external CFRP reinforcement to reinforced concrete structures, two similar techniques are most widely used [7]. The first is referred to as wet lay-up. In this technique, flexible sheets or fabrics of raw or pre-impregnated fibres are saturated with an epoxy adhesive resin and placed on the surface of the concrete. As a result, the resin acts both as the adhesive and as the CFRP matrix. The second technique involves the adhesion of pre-cured rigid FRP strips or Plates to the surface of the concrete using an epoxy adhesive. In this technique the adhesive does not become the matrix for the FRP, so a well-defined bond-line is created. The second technique is more akin to conventional rehabilitation techniques, but does not offer the flexibility enjoyed by the wet lay-up procedure.

6. Application and Use

There are a number of applications of FRP composites as the strengthening materials of reinforced concrete elements. FRP composite strips can be bonded to the external tension zones of beams and slabs thus increasing the flexural strength of the element [4]. (Figure 5 a, b). FRP fabrics or sheets can be wrapped around reinforced concrete columns thus increasing confinement and axial strength. Furthermore it increases the flexure, shear and torsion strengths and improves ductility [4]. (Figure 5 c).

Shear strengthening in beam-column joints is another application of FRP composites which was developed recently [4]. (Figure 5 d).

To assess the suitability of an FRP system for a particular application, the licensed design professional should perform a condition assessment of the existing structure that includes establishing its existing load-carrying capacity, identifying deficiencies and their causes, and determining the condition of the concrete substrate. The overall evaluation should include a thorough field inspection, a review of existing design or as-built documents, and a structural analysis in accordance with ACI 364.1R. Existing construction documents for the structure should be reviewed, including the design drawings, project specifications, as-built information, field test reports, past repair documentation, and maintenance history documentation. The licensed design professional should conduct a thorough field investigation of the existing structure in accordance with ACI 437R and other applicable ACI documents. As a minimum, the field investigation should determine the following [5]:

• Existing dimensions of the structural members.

• Location, size, and cause of cracks and spalls.

• Location and extent of corrosion of reinforcing steel.

• Quantity and location of existing reinforcing steel.

• In-place compressive strength of concrete.

• Soundness of concrete, especially the concrete cover in all areas Where the FRP system is to be bonded to the concrete.

Fig. 5: Typical applications as strengthening materials of RC structures. (Source: Teach Engineering Lessons).

7. FRP Confinement of Concrete Columns

High-strength composites have been very effective in retrofitting columns to improve earthquake resistance. A large number of investigations conducted in the laboratory and field applications in buildings and bridges established the viability of composites for improving the performance of axially loaded members (ACI Committee 440, 2002). The composites are essentially used to confine the concrete, resulting in improvement of: [8]

(i) Compressive strength or axial force capacity,

(ii) Flexural and shear strength,

(iii) Flexural ductility, and

(iv) Performance of lap splices. Composites can also be used to repair and rehabilitate cap beams and beam–column joints.

FRP sheets or encasement can be used to increase the axial load carrying capacity of the column with minimal increase in the cross-sectional area. Confinement consists of wrapping the column with FRP sheets, prefabricated jacketing, or in situ cured sheets with fibre running in circumferential direction. The use of confinement increases the lateral pressure on the member which results in more ductility and higher load capacity.

Confinement is less effective for rectangular and square than circular shape RC columns due to the confining stresses that are transmitted to the concrete at the four corners of the cross-section. This phenomenon is presented in Figure 6, where confinement effectiveness is shown as gray shaded area for various column shapes. Confinement effectiveness improves with the increase in the corner radius. Recent studies show that application of FRP materials in the hoop or lateral direction can effectively increase the load carrying capacity and concrete strain capacity of columns under axial loading. [2]

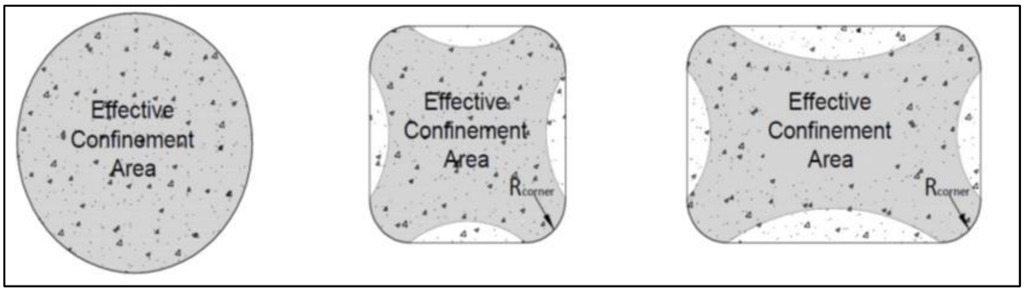

Fig. 6: Effective confinement areas in circular, square and rectangular columns.
(source: Azadeh Parvin and David Brighton, 2014)

The effect of “hoop-angle-hoop” and “angle-hoop-angle” ply configurations (shown in Figure 7) for FRP-wrapped concrete cylinders under uniaxial compressive loading have also been considered. The terms ‘‘hoop’’ and ‘‘angle’’ indicate that wraps were oriented at an angle of 0° and 45° with respect to circumferential direction for this case. The results showed substantial increase in the axial compressive strength and ductility of the FRP-confined concrete cylinders as compared to the unconfined ones. The cylinders with “hoop-angle-hoop” ply configuration in general exhibited higher axial stress and strain capacities as compared to the cylinders with the “angle-hoop-angle” ply configuration. Likewise, the performance of axially loaded FRP-confined concrete columns with three different wrap thicknesses, wrap ply angle configurations of 0°, ±15°, and 0°/±15°/0° with respect to the circumferential direction, and concrete strength values of 20.7 to 41.4 MPa was investigated. The gain in axial compressive strength in FRP-wrapped columns was observed to be higher for lower strength concrete and the highest in the columns wrapped with the 0° ply angle configuration. Not only the combination of angle and hoop wrap plies configuration, but also their stacking sequence, provide different level of strength and ductility enhancement for the same total wrap thickness. Therefore, based on strength and/or ductility demand, the proper wrap configuration can be selected for design purposes. [2]

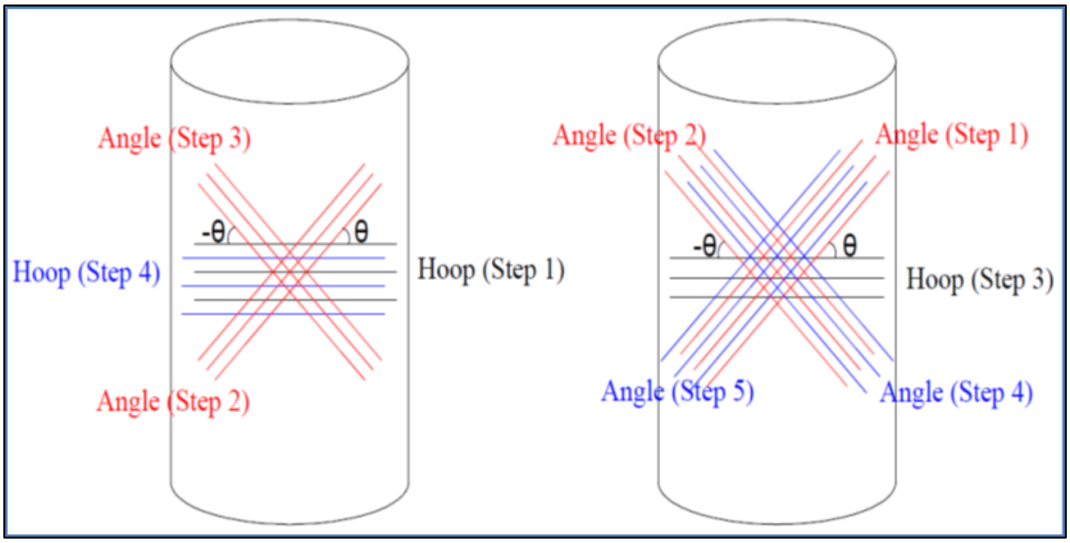

Fig. 7: Ply configurations in fibre reinforced polymers (FRP)-wrapped cylinders. (a)Hoop-angle-hoop; and (b) Angle-hoop-angle. (source: Azadeh Parvin and David Brighton, 2014)

7.1 Behavior of confined concrete

It is well established that confined concrete can sustain much higher compressive strength and strain than unconfined concrete. The confinement prevents the expansion of uniaxial loaded specimens, contributing to higher load capacity. In the case of concrete confined by high-strength composites, Figure 8, the confinement is passive. At low load levels, the expansion of concrete is proportional to Poisson's ratio, and the magnitude is small. Therefore, the stresses induced in the composite are small until the longitudinal cracks develop in concrete. Depending on the type of concrete, the longitudinal cracks can occur at load levels ranging from 0.5 f'_c for low-strength concrete to 0.9 f'_c for very high strength concrete. Typical behavior is shown in Figure 9.

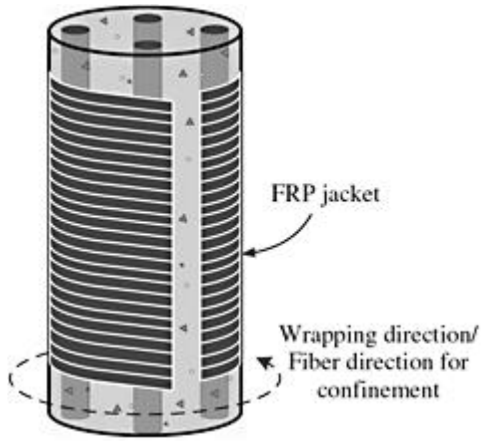

Fig 8: Schematic of an FRP wrapped column showing fibre orientation (Source: Master Builders, Inc. and Structural Preservation Systems, 1998).

The right side of Figure 9 represents the stress-uniaxial strain and the left side presents the lateral strain or expansion. After longitudinal cracks develop, the specimen expands rapidly. This phenomenon induces stresses in the confining reinforcement. The amount of confinement pressure will depend on the stiffness and thickness of the confining reinforcement. Increase in confinement pressure will result in increased compressive strength and strain, as shown in Figure 10.

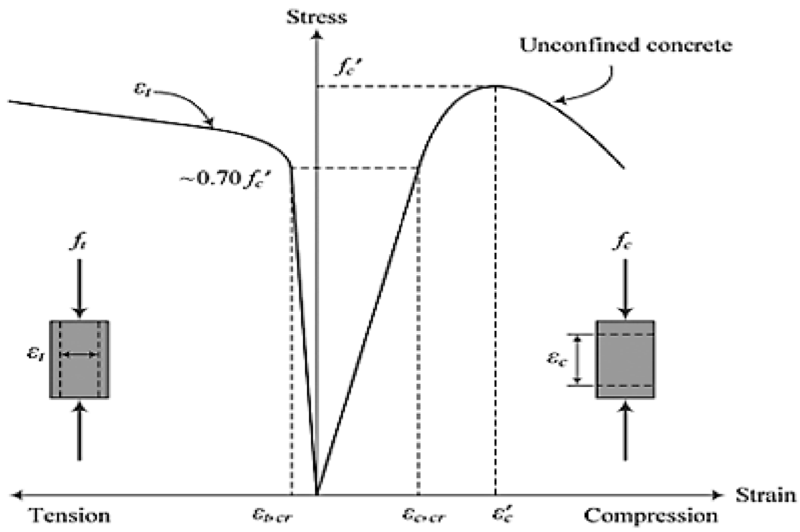

Fig.9: Typical relationship for uniaxial loaded unconfined concrete showing stress versus longitudinal, transverse, and volumetric strain. (Source: Master Builders, Inc. and Structural Preservation Systems, 1998).

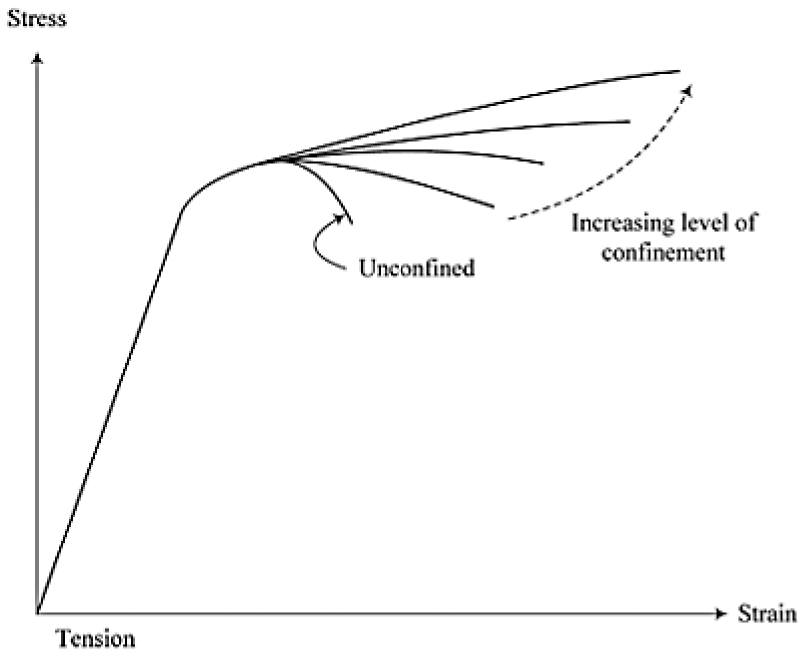

Fig. 10: Stress–strain curves for concrete under various levels of confinement. (Source: Master Builders, Inc. and Structural Preservation Systems, 1998).

7.2 Behavior of columns confined with composites

7.2.1 FRP-confined concrete in circular cross-sections column

The cracking of concrete induces tension in the composite hoop. The first step is to establish equations for computing confining pressure. The free-body diagram of a circular cross-section confined by a composite whose thickness is t_j is shown in Figure 11. Using the principles of strength of materials, confining pressure to induce on the column, f_{cp} can be expressed as a function of composite thickness and stiffness.

$$f_{cp} = \frac{2 t_j f_f}{D} \qquad \text{......................} \ (1)$$

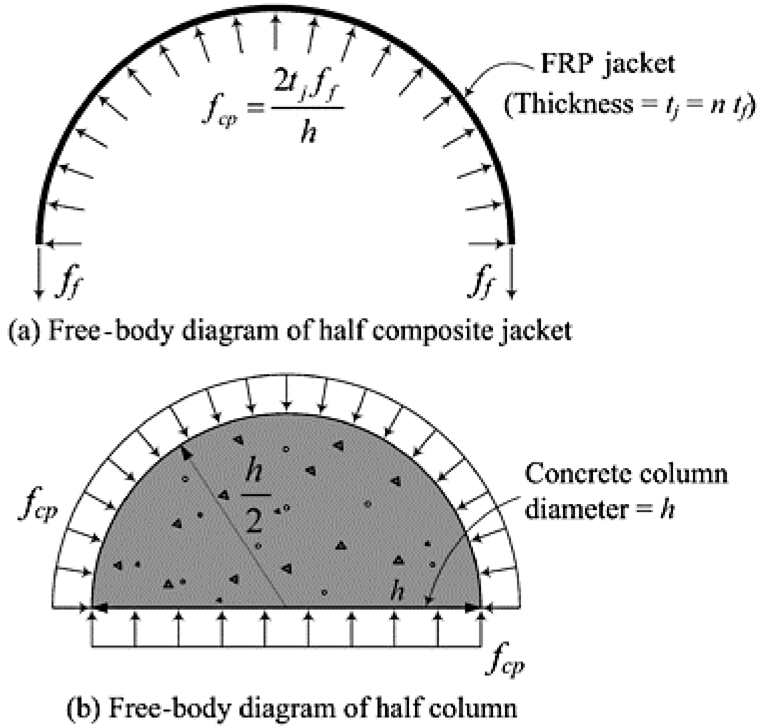

Fig. 11: Free-body diagram showing the internal and external forces on the FRP jacket and concrete column. (Source: Master Builders, Inc. and Structural Preservation Systems, 1998).

Where

D= is the diameter of the column

f_f = is the force generated by the composite

E_f= is the modulus of the fibre (composite)

t_j= is the equivalent thickness of fibres

ε_f= is the hoop strain

n_f= is the number of layers

Then:

$f_f = n_f\, t_f\, E_f\, \varepsilon_f$ ……………………………….(2)

Therefore:

$f_{cp} = \frac{2\, n_f\, t_f\; E_f\, \varepsilon_f}{D}$ ……………………………….(3)

Based on experimental results *(ACI Committee 440, 2002),* the compressive strength at this confining pressure, f_{cc} , can be expressed as:

$$f_{cc} = f_c \left[2.25 \sqrt{1 + 7.9 \frac{f_{cp}}{f_c'}} - 2 \frac{f_{cp}}{f_c'} - 1.25\right] \quad \text{.................................(4)}$$

The strain corresponding to this peak stress:

$$\varepsilon_{cc}' = \varepsilon_c' \left[\frac{6 f_{cc}'}{f_c'} - 5\right] \quad \text{.................................(5)}$$

Where

f_c'= the peak compressive stress

ε_c' = the corresponding strain for the unconfined concrete

If ε_c' is not given, it can be estimated using the equation:

$$\varepsilon_c' = 1.71 \frac{f_c'}{E_c} \quad \text{.................................(6)}$$

The enhanced compressive strength,f_{cc}' , can be used for the computation of column axial force capacity. A reduction factor of φ_f is recommended for the concrete contribution.

The recommended value for φ_f is = 0.95.

For nonprestressed members, the nominal capacity of a column can be computed using the equations recommended in ACI code *(ACI Committee 440, 2002).*

For a column with spiral reinforcement:

$$P_n = 0.85 \left[0.85 f_{cc}' \varphi_f \left(A_g - A_{st}\right) + A_{st} f_y\right] \quad \text{................................(7)}$$

For a column with lateral ties:

$$P_n = 0.80 \left[0.85 f_{cc}' \varphi_f \left(A_g - A_{st}\right) + A_{st} f_y\right] \quad \text{................................(8)}$$

Where:

$A_g =$ is the cross-sectional area of concrete.

$A_{st} =$ is the area of longitudinal reinforcement.

7.2.2 FRP-confined concrete in rectangular columns

It has been well established that FRP confinement is much less effective for rectangular columns (including square columns as a special case) than for circular columns, even with the rounding of corners. This is because in the former, the confining pressure is non-uniformly distributed and only part of the concrete core is effectively confined. Failure generally occurs at the corners by FRP tensile rupture (Fig. 12). The stress–strain curves are more likely to feature a descending branch, but in such cases FRP confinement normally provides little strength enhancement. The effectiveness of confinement increases as the amount of FRP or the corner radius increases and as the aspect ratio of the section (ratio between the longer and shorter sides of a rectangular section) reduces. Figure 13 shows two experimental stress–strain curves of FRP-confined concrete in square columns corresponding to two different amounts of FRP confinement. For ease of comparison, the axial stress and the strains are normalised by the compressive strength of unconfined concrete and its corresponding axial strain, respectively. Of the two curves, the one for a smaller corner radius and a single-ply jacket features a descending branch. [6]

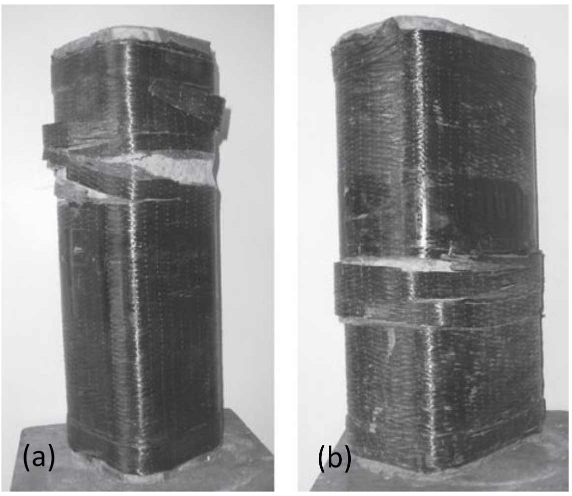

Fig. 12: Failures of FRP-confined square and rectangular concrete columns with rounded corners by FRP rupture: (a) square column; (b) rectangular column. (Source: L.C. Hollaway and J.G. Teng, Book, 2008).

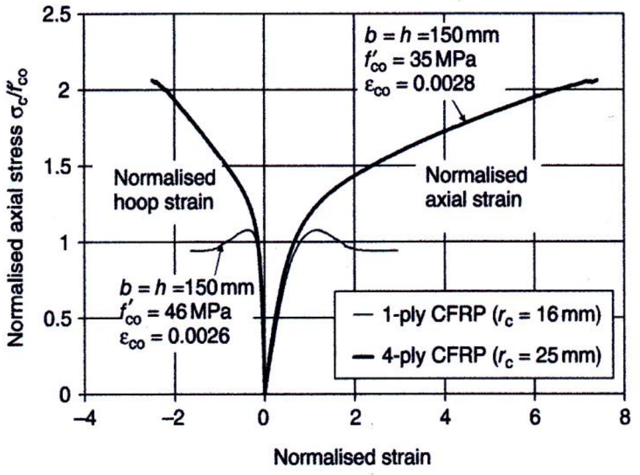

Fig 13: Typical stress–strain curves of FRP-confined concrete in square columns. (Source: L.C. Hollaway and J.G. Teng, Book, 2008).

8. Failure Modes

Structural failure can occur in FRP materials when [9]:

1. Tensile forces stretch the matrix more than the fibres, causing the material to shear at the interface between matrix and fibres.

2. Tensile forces near the end of the fibres exceed the tolerances of the matrix, separating the fibres from the matrix.

3. Tensile forces can also exceed the tolerances of the fibres causing the fibres themselves to fracture leading to material failure.

4. The failure in the adhesive material, causing separating the FRP composites from the concrete surface.

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