REVIEW OF STRENGTHENING TECHNIQUES USING EXTERNALLY BONDED FIBER REINFORCED POLYMER COMPOSITES

Report 2002-005-C-01

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EXECUTIVE SUMMARY

This report reviews the selection, design, and installation of fiber reinforced polymer systems for strengthening of reinforced concrete or pre-stressed concrete bridges and other structures. The report is prepared based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRP systems used to strengthen concrete structures. Information on material properties, design and installation methods of FRP systems used as external reinforcement are presented. This information can be used to select an FRP system for increasing the strength and stiffness of reinforced concrete beams or the ductility of columns, and other applications.

Based on the available research, the design considerations and concepts are covered in this report. In the next stage of the project, these will be further developed as design tools. It is important to note, however, that the design concepts proposed in literature have not in many cases been thoroughly developed and proven. Therefore, a considerable amount of research work will be required prior to development of the design concepts into practical design tools, which is a major goal of the current research project.

The durability and long-term performance of FRP materials has been the subject of much research, which still are on going. Long-term field data are not currently available, and it is still difficult to accurately predict the life of FRP strengthening systems. The report briefly addresses environmental degradation and long-term durability issues as well.

A general overview of using FRP bars as primary reinforcement of concrete structures is presented in Chapter 8.

In Chapter 9, a summary of strengthening techniques identified as part of this initial stage of the research project and the issues which require careful consideration prior to practical implementation of these identified techniques are presented.

1 General

1.1 Introduction

Rehabilitation of deteriorated civil engineering infrastructure such as bridge decks, buildings, beams, girders, parking structures, marine structures, roads etc has been a major issue in the last decades. The deterioration of these structures might be due to ageing, poor maintenance, corrosion due to poor environmental conditions, poor initial design or construction and accidental situations like earthquakes. The need to upgrade the deteriorated civil engineering infrastructure greatly enhances with the ever increasing demands. For example, the increased traffic conditions normally do not match with the initial design load actions. Therefore rehabilitating existing civil engineering infrastructure has been identified as an important issue to be addressed.

Transportation agencies are faced with a continuous challenge to keep bridges in a good operation condition despite limited resources. Bridge structures are deteriorating at a fast rate, and cost for repair and replacement of deficient bridges are continuously rising. Even when resources are available, extended time is often required for performing needed remedies, causing disruption of traffic and inconvenience to the traveling public. The strengthening or retrofitting of existing concrete structures to resist higher design loads, correct deterioration-related damage, or increased ductility has traditionally been accomplished using conventional materials and construction techniques. Externally bonded steel plates, steel or concrete jackets and external post tensioning are just some of the many traditional techniques available. In the context of the strengthening problem, advanced composites have the potential to prove another promising solution.

New technology options in bridge rehabilitation are being developed from polymers, metals, ceramics and composites of these materials, and some of these high performance materials are already being utilized in construction. Composites comprise of several different basic components that together provide physical characteristics superior to what each can provide separately. While the concept of composites has been in existence for several millennia, the incorporation of fiber reinforced polymer (FRP) is less than a century old. These composites combine the strength of the fibers with the stability of the polymer resins. They are defined as polymer matrix, either thermo-set or thermoplastic, that are reinforced with fibers or other reinforcing material with a sufficient aspect ratio (length to thickness) to provide a desirable reinforcing function in one or more directions. These composite materials are different form traditional construction materials such as steel, aluminum, and concrete because they are anisotropic; i.e., the properties differ depending on the direction of the fibers. Due to the resulting benefits, FRP composite applications have revolutionized entire industries including aerospace, marine, electrical, and transportation (Nystrom at el. 2003).

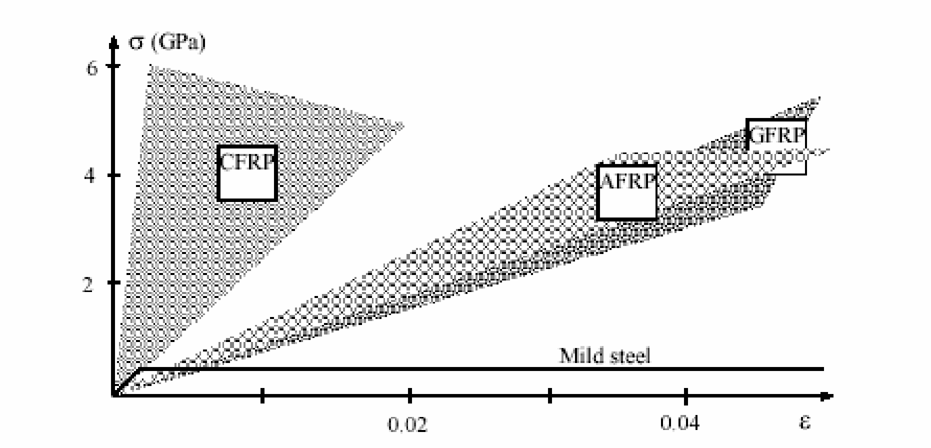
These composite materials gain their superior characteristics from the component materials used. Their strength comes largely from the fibers, which are usually glass, carbon, or aramid fiber.

1.2 Scope and Limitations

This report reviews the selection, design, and installation of FRP systems for externally strengthening of reinforced concrete bridges. FRP systems can be used to rehabilitate or restore the strength of a deteriorated structural member, or retrofit or strengthen a sound structural member to resist increased loads due to changes in use of the structure, or address design or construction errors. It should be determined if a FRP system is a suitable strengthening technique before selecting the type of FRP system. To assess suitability of a FRP system for a particular application, the condition assessment of the existing structure should be performed and the best treatment option would be then determined based on the assessment (ACI, 440, 2002).

Composite materials for strengthening civil engineering structures have several disadvantages too. They in general behave in a linear elastic manner and fails at large strains (no yielding point and reduced ductility). This is contrary to the conventional steel which behaves in an elasto-plastic manner. Typical stress-strain curves for unidirectional composites subjected to monotonic loading are shown in Figure 1-1. A similar curve for steel is also shown in the same figure for comparison.

Figure 1-1: Uniaxial tension stress-strain diagrams for different unidirectional FRPs and steel. CFRP = carbon FRP, AFRP = aramid FRP, GFRP = glass FRP (FIB Bulletin 14, 2001).



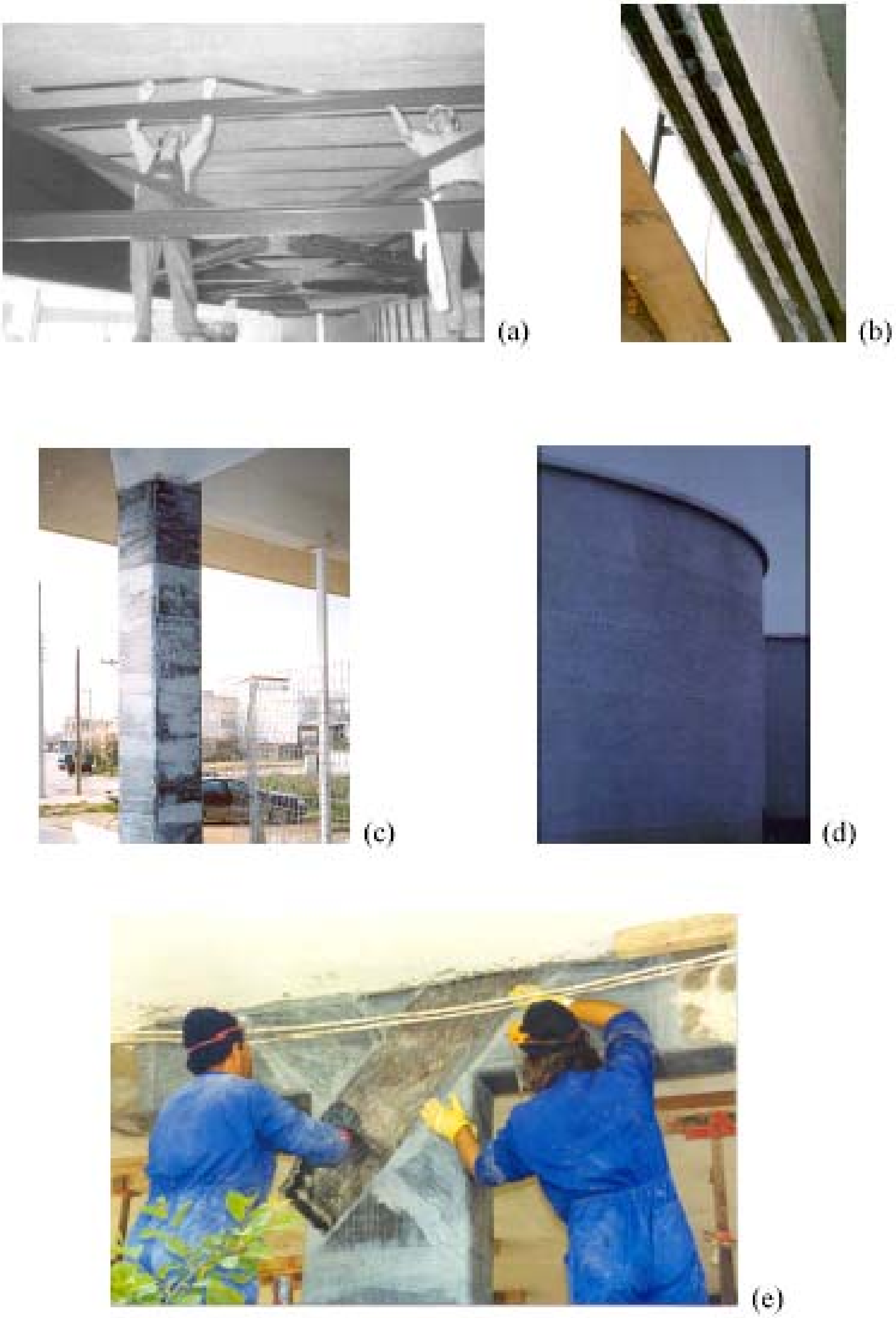
Moreover the cost of composite materials on a weight basis is several times higher than that for steel. However when compared in terms of strength, composites are better. Some FRP materials, e.g. carbon and aramid, have incompatible thermal expansion coefficients with concrete. As a result premature degradation and collapse may occur when subjected to high temperatures. Selection of FRP composites for strengthening purpose has to be based not only on mechanical performance aspects, but also on constructability and long-term durability. Therefore it is necessary to consider all the design issues without treating FRP as a blind replacement of steel.

The durability and long term performance of FRP materials are covered only briefly in this report since reported literature does not fully cover the topic.

1.3 Applications and use

There are a number of applications of FRP composites as the strengthening material 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 (Figure 1-2 a, b).

Figure 1-2: Typical FRP applications as strengthening materials of RC structures: (a) flexural strengthening of slab; (b) flexural strengthening of beam; (c) shear strengthening and confinement of column; (d) wrapping of concrete tank; (e) shear strengthening of beam-column joint. (FIB 14, 2001)


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

FRP fabrics or sheets can be wrapped around reinforced concrete columns thus increasing the confinement and the axial strength. Furthermore it increases the flexural, shear and torsion strengths and improves the ductility (Figure 1-2 c, d).

Shear strengthening in beam-column joints is another application of FRP composites which was developed recently (Figure 1-2 e).

Before using FRP system for strengthening a particular structure, an initial condition assessment of the existing structure needs to be performed. The assessment should be the result of a thorough field inspection and review of existing design. In these inspections, it is possible to study the capacity of the existing structure, identify the deficiencies and causes and determine the condition of concrete substrate. As shown in the ACI Committee 440 (2002), a field inspection should include the following:

- 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; and
- Soundness of concrete, especially the concrete cover, in all areas where the FRP system is to be bonded to the concrete.

1.4 Background Information

Steel plate bonding and steel 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 (Fleming and King, 1967). This traditional method has been used over the world to strengthen 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.

The United Stats has shown an interest of fiber 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 1980’s through the initiatives of the National Science Foundation (NSF) and the Federal Highway Administration (FHWA). Using FRP materials for retrofitting concrete structures was reported as early as 1978 in Germany (Wolf and Miessler, 1989). Same kinds of investigations to retrofit concrete structures were reported in Europe and Japan in the 1980s. Externally bonded FRP systems have been used to strengthen concrete structures around the world from mid 1980s. Research in Switzerland leads to the first applications of externally bonded FRP systems to reinforced concrete bridges for flexural strengthening (Meier 1987; Rostasy 1987). FRP systems were used as an alternative to steel plate bonding in Europe. Using FRP systems to increase the confinement was first applied in Japan in the 1980s (Fardis and Khalili 1981; Katsumata et al. 1987). Utilizing FRP systems around the world has been increasing from a few projects ten years ago to several thousands today (Bakis et al. 2002). In Japan FRP usage has been increased after the 1995 Hyogoken Nanbu earthquake (Nanni 1995).

FRP Externally bonded FRP systems have also been applied to strengthen masonry, timber, steel and cast iron. They have been used in structural elements such as beams, slabs, columns, walls, joints/connections, chimneys and smokestacks, vaults, domes, tunnels, silos, pipes, and trusses.

The development of the design rules and guidelines for the field application of externally bonded FRP systems is ongoing in Europe, Japan, Canada and United States. Within last 10 year Japan Society of Civil Engineers (JSCE, 2001) and the Japan Concrete Institute (JCI, 1997 and 1998) and the Railway Technical Research Institute (RTRI, 1996) made several publications related to FRP systems in concrete structures (Japan Concrete Institute 1997; Neale (2000), Dolan et al. (1999); Sheheta et al. 1999; Saadatmanesh and Ehsani (1998), Benmokrane and Rahman 1998).

Previous research and field applications for FRP rehabilitation and strengthening are described in ACI Committee 440 (2002). In Europe Task Groip 9.3 of the International Federation for Structural Concrete (FIB) published a bulletin on design guidelines for externally bonded FRP reinforcement for reinforced concrete structures (FIB Bulletin 14, 2001). Section 16, “Fiber Reinforced Concrete”, of the Canadian Highway Bridge Design Code was completed in 2000 (CSA 2000) and the Canadian Standards Association (CSA) recently approved the code “Design and Construction of Building Components with Fiber Reinforced Polymers (CSA 2002).

1.5 Commercially Available Externally Bonded FRP Systems

Composite materials for strengthening structures are available in the form of unidirectional thin strips made by pultrusion or sheets or fabrics made of fibres one or at least two different directions.

Suppliers of FRP systems in Australia are Master Builders Technologies (MBT) and Sika Services Corporate Construction. MBT supplies two MBrace Composite Strengthening Systems. The first one is the MBrace FRP fabric (sheet) materials including carbon, aramid and glass fibres while the other system is MBrace S&P CFK laminate strip (plate) (carbon fibre laminate materials). Sika CarboDur composite strengthening systems supply flexural strengthening products (plates), shear strengthening products (L-shaped strips) and shear strengthening and confinement products (flexible sheets). The Sika products include carbon, aramid and glass fibres. These commercially available composite strengthening systems are described in brief in the following sections of the report.

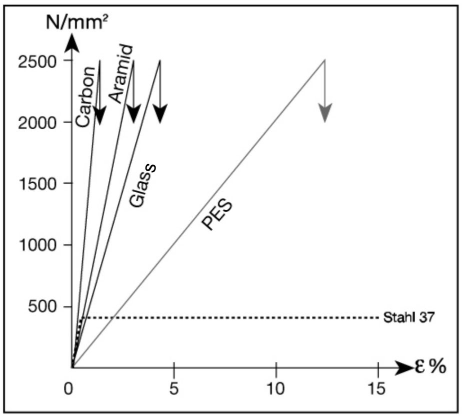
1.5.1 MBrace composite strengthening systems (MBT Australia)

The MBrace Composite Strengthening System comprises of a family of lightweight FRP materials. They are externally bonded to the surface of structures to enhance the strength. These systems provide very high tensile strength and are used for flexural and shear reinforcement and axial compression confinement of concrete, masonry and timber elements.

The MBT-MBrace sheets (either uni-directional or bi-directional) can be applied as dry and wet lay ups and also as preimpregnated Prepegs. Types of fibres used in MBrace FRP systems are carbon, aramid and glass (uncoated E-glass which corrodes in alkaline environment and Alkali resistant glass-AR glass). Stress-strain diagram for these fibres is shown in

Figure 1-3.

Figure 1-3: Stress-strain diagrams (MBT Australia)



The basic fibers in MBrace FRP systems are embedded in a polymer matrix where the arrangement of fibers can be either unidirectional or bidirectional.

1.5.1.1 ***MBrace FRP fabric (sheet) materials***

MBrace FRP fabric sheets can be stretched or woven and uni-directional or bi-directional.

1.5.1.1.1 Stretched sheets

Uni-directional arrangement:

In the stretched sheets fibres are bonded to a tight mesh and parallel fibres are stretched. Therefore these sheets have high elastic modulus. These are more suitable for increasing the structural capacity of an element.

1.5.1.1.2 Woven sheets

Bi-directional arrangement:

Woven sheets are produced by weaving and the arrangement of fibres is bi directional. These sheets are less suitable for increasing the structural capacity of an element as the fibres are slightly wavy. These bi directional sheets are more suitable for increasing the ductility of a structure component.

1.5.1.1.3 Uni-directional and bi-directional MBT-MBrace FRP sheets

Either cold curing epoxy resin matrix or the thermally curing epoxy resin matrix is used to ensure the load transfer from the sheets to the substrate.

1.5.1.1.4 Cold curing epoxy resin matrix:

Uni directional and bi directional sheets are applied as a dry lay up if the weight is less than 400 gm/m^2. In this case the cold curing epoxy resin is rolled onto the structural element and dry sheet is applied into the matrix.

Stretched and woven sheets are applied as a wet lay up if the weight is less than 400-800 gm/m^2. Contrary to the dry lay up situation, in this case the sheets are impregnated with the cold curing epoxy matrix and then applied wet to the structural element.

1.5.1.1.5 Thermally curing epoxy resin matrix:

The uni-directional and bi-directional sheets are impregnated with the thermally curing epoxy adhesive at the manufacturer's facility. Thermal curing is done by applying additional heat to the epoxy resin on the element. This method is called the Prepeg systems.

1.5.1.2 MBrace S&P CFK laminate strip (plate)

Prefabricated FRP is supplied to the job site as a composite (laminate). The supplier does the impregnation with the epoxy resin matrix and thermal curing under controlled factory conditions. A commonly used laminate used for structural strengthening is the MBT-MBrace Laminate CFK.

1.5.2 Sika CarboDur composite strengthening systems (CD ROM)

Sika CarboDur composite strengthening systems include flexural strengthening products (plates), shear strengthening products (L-shaped strips) and shear strengthening or confinement products (flexible sheets).

2 Materials

In this chapter, the physical and mechanical properties of FRP composites are presented. The characteristics of FRP composites depend on many factors such as type of fiber, its orientation and volume, type of resin used and quality control used during the manufacturing process. It is possible to obtain the characteristics of commercially available FRP composites from the manufacturer. However, some generic material characteristics are described in this chapter.

2.1 Constituent Materials

There are several constituent materials in commercially available FRP repair systems such as resins, primers, putties, saturants, adhesives, and fibers.

2.1.1 Resins

A large variety of resins are used with FRP systems. The most commonly used resins can normally be used in different environmental conditions. However as shown by the ACI Committee 440 (2002), FRP system manufacturers use resins that have the following characteristics:

- Compatibility with and adhesion to the concrete substrate;
- Compatibility with and adhesion to the FRP composite system;
- Resistance to environmental effects, including but not limited to, moisture, salt water, temperature extremes, and chemicals normally associated with exposed concrete;
- Filling ability;
- Workability;
- Pot life consistent with the application;
- Compatibility with and adhesion to the reinforcing fiber; and
- Development of appropriate mechanical properties for the FRP composite.

2.1.1.1 ***Primer***

The primer is used to penetrate the surface of the concrete, providing an improved adhesive bond for the saturating resin or adhesive.

In MBrace FRP systems, MBrace primer is the recommended primer to ensure maximum bond for MBrace Laminate Adhesive and MBrace Saturant. It is a two-part epoxy product with low viscosity and 100% solids content.

2.1.1.2 ***Putty fillers***

The putty is used to fill small surface voids in the substrate, such as bug holes, and to provide a smooth surface to which the FRP system can bond. Filled surface voids also prevent bubbles from forming during curing of the saturating resin.

2.1.1.3 ***Saturating resin***

The saturating resin is used to impregnate the reinforcing fibers, fix them in place, and provide a shear load path to effectively transfer load between fibers. The saturating resin also serves as the adhesive for wet lay-up systems, providing a shear load path between the previously primed concrete substrate and the FRP system.

MBrace Saturant is the recommended resin adhesive for use with MBrace Fiber sheet (wet or dry) lay-up systems. It is a two-part epoxy product with 100% solids content.

2.1.1.4 ***Adhesives***

Adhesives are used to bond precured FRP laminate systems to the concrete substrate. The adhesive provides a shear load path between the concrete substrate and the FRP reinforcing laminate. Adhesives are also used to bond together multiple layers of precured FRP laminates.

MBrace Laminate Adhesive is the adhesive for the MBrace S&P CFK Laminate System and a filling compound for irregular surfaces.

2.1.1.5 ***Protective coatings***

The protective coating is used to protect the bonded FRP reinforcement from potentially damaging environmental effects. Coatings are typically applied to the exterior surface of the cured FRP system after the adhesive or saturating resin has cured.

2.1.2 Fibers

Continuous glass, aramid, and carbon fibers are common reinforcements used with FRP systems. The fibers give the FRP system its strength and stiffness.

2.1.3 MBrace FRP systems

These systems consist of the following components.

- Primer – improves the bonding of the composite to the substrate
- Concresive 1444/1446 to even out any imperfections in the base (pitting, macro roughness etc)
- MBrace Saturant for wetting out the fiber sheet materials in a “Dry or Wet Lay-Up”, to form the composite in-situ
- MBrace Resicem Saturant for wetting out the fiber sheet materials in a “Dry or Wet Lay-Up”, to form the composite in-situ, which is vapor permeable
- MBrace Laminate Adhesive for adhesion of carbon laminates (and a leveling compound)
- MBrace Fibre (Carbon, Aramid or Glass) fiber sheet reinforcement for “Dry or Wet Lay-Up”
- MBrace S&P CFK Laminate prefabricated composite carbon fiber laminate
- Barracryl D acrylic topcoat, resistant to UV rays

2.2 Physical Properties

2.2.1 Density

The densities of FRP composites with Glass, Carbon and Aramid are shown in Table 2-1 (ACI Committee 440, 2002). The density of steel is also presented there as comparison. It is clearly seen from the table that density of FRP composites are four to six times lower than that of steel. The reduced density is a desirable property as it reduces transportation and handling cost and additional dead load on structure.

Table 2-1: Typical densities of FRP materials, kg/m^3 (ACI Committee 440, 2002)

Steel	GFRP	CFRP	AFRP
7900	1200 - 2100	1500 - 1600	1200 - 1500

2.2.1.1 MBrace fiber

The commercially available MBrace FRP strengthening system in Australia also uses carbon, aramid and glass fibers. The density of each FRP composite is shown in Table 2-2.

Table 2-2: Typical densities of MBrace FRP composites, kg/m^3

MBrace fiber	Density (kg/m^3)
Carbon – high modulus	2100
Carbon – high tensile	1700
Aramid	1450
E-glass or AR-glass	2600 (2680)

2.2.2 Coefficient of thermal expansion

Table 2-3 (ACI Committee 440, 2002) shows the coefficients of thermal expansion for typical unidirectional FRP materials. It is clearly seen that it changes in the longitudinal and transverse directions and also depending on the type of fiber, volume of fiber and resin. The coefficient of thermal expansion of concrete ranges from 7×10^{-6} to 11×10^{-6}/C and is usually assumed to be isotropic. Steel has an isotropic coefficient of thermal expansion of 11.7×10^{6}/C.

Table 2-3: Typical coefficients of thermal expansion for FRP materials. (ACI Committee 440, 2002)*

Direction	Coefficient of thermal expansion, $\times10^{-6}$/C		
	GFRP	CFRP	AFRP
Longitudinal	6 to 10	-1 to 0	-6 to –2
Transverse	19 to 23	22 to 50	60 to 80

2.3 Mechanical Properties

FRP materials compose of a number of continuous, directionalized, nonmetallic fibers, bundled in a resin matrix. Normally, the volume fraction of fibers in FRP strips is about 50-70% and that in FRO sheets is about 25-35%. Fibers are the principal stress bearing constituents, while the resin transfers stresses among fibers and protects them. If these volume fractions and properties of constituent materials (fibers and matrix) are known for a particular FRP composite then mechanical properties can be obtained as shown in FIB Bulletin 14 (2001).

$$E_f = E_{fib} V_{fib} + E_m V_m \tag{2- 1}$$

$$f_f \approx f_{fib} V_{fib} + f_m V_m \tag{2- 2}$$

where, E_f = Young's modulus of FRP in fiber direction, E_{fib} = Young's modulus of fibers, E_m= Young's modulus of matrix, V_{fib} = volume fraction of fibers, V_m = volume fraction of matrix, f_f = tensile strength of FRP in fiber direction, f_{fib} = tensile strength of fibers and, f_m = tensile strength of matrix. Note that in the above equations $V_{fib} + V_m = 1$. Also, typical values for the volume fraction of fibers in prefabricated strips are in the order of 0.50 – 0.65.

FIB Bulletin 14 (2001) shows the properties of commercially available FRP prefabricated strips (Table 2-4). For these strips normally manufacturer provides the material properties.

Table 2-4: Typical properties of prefabricated FRP strips and comparison with steel (FIB Bulletin 14, 2001)

Material	Elastic modulus (GPa) - E_f	Tensile strength (MPa) - f_f	Ultimate tensile strain (%) - ε_{fu}
Prefabricated strips			
Low modulus CFRP	170	2800	1.6
High modulus CFRP	300	1300	0.5
Mild steel	200	400	25*

** Yield strain = 0.2 %*

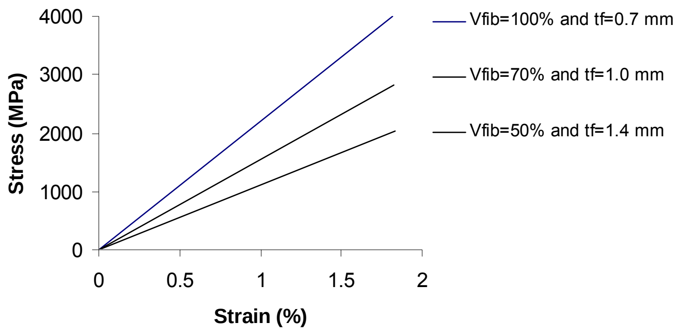
In in-situ resin impregnated systems, the final FRP thickness and thus the fiber volume is uncertain. Therefore the composite material properties based on the properties on fibers and matrix may not be appropriate. Sometimes manufacturers provide the material properties for the bare fibers. There is a strong relationship between the fiber volume fraction and the FRP properties to be used in the property calculation of FRP composite. This is shown in Table 2-5 and Figure 2-1.

Table 2-5: Example showing the effect of volume fraction of fibers on the FRP properties (FIB Bulletin 14, 2001)

<table>
<tr><td colspan="9">Properties for constituent materials of FRP composite:
Fiber:
Young's modulus: 220 GPa Tensile strength: 4000 MPa
Matrix:
Young's modulus: 3 GPa Tensile strength: 80 MPa</td></tr>
<tr><td colspan="3">Cross sectional area</td><td></td><td colspan="3">FRP properties</td><td colspan="2">Failure load</td></tr>
<tr><td>A_{fib} (mm^2)</td><td>A_m (mm^2)</td><td>A^*_f (mm^2)</td><td>V_{fib} (%)</td><td>E_f (MPa) Eq. (2-1)</td><td>f_f (MPa) Eq. (2-1)</td><td>Ultimate strain (%)</td><td>(kN)</td><td>(%)</td></tr>
<tr><td>70</td><td>0</td><td>70</td><td>100</td><td>220000</td><td>4000</td><td>1.818</td><td>280.0</td><td>100.0</td></tr>
<tr><td>70</td><td>30</td><td>100</td><td>70</td><td>154900</td><td>2824</td><td>1.823</td><td>283.4</td><td>100.9</td></tr>
<tr><td>70</td><td>70</td><td>140</td><td>50</td><td>111500</td><td>2040</td><td>1.830</td><td>285.6</td><td>102.0</td></tr>
<tr><td colspan="9">* In case of a strip with a width of 100 mm dividing this value by 100 mm gives the thickness of the strip.</td></tr>
</table>

It is clearly seen that for a constant amount of fiber volume, an increase in the amount of resin has minor effect on the failure load. However, the FRP composite properties are strongly influenced by the matrix proportion.

Figure 2-1: Stress strain relations corresponding to various fiber volume fractions V_{fib} in Table 2-5



In case of an uncertainty of the FRP thickness (in-situ resin impregnated systems), it is convenient to perform the calculations based on the fiber properties and fiber cross sectional area provided that the material properties and the thickness supplied by the manufacturer are used instead of the actual thickness realized. In This situation the second part of Equations (2-1) and (2-2) may be ignored and the resulting property (elastic modulus, tensile strength) should be multiplied by a reduction factor r. This factor r should be supplied by the supplier based on test results. Alternatively the FRP supplier can provide the properties of in-situ impregnated system (thickness, elastic modulus, and tensile strength) based on test results.

2.3.1 MBrace FRP strengthening systems

Table 2-6: Properties of MBrace FRP fabric strengthening systems

Type of fibre	Elastic modulus (kN/mm^2)	Tensile strength (MPa)	Ultimate tensile strain
S&P A sheets 120 (dry or wet lay up)			
Aramid	120	2900	0.025
S&P C sheet 240/640 (for dry lay up)			
Carbon	240/640	3800/2650	0.017/0.004
S&P G-sheet (dry lay up)			
E-glass	73	3400	0.045
AR-glass	65	3000	0.043
S&P G-sheet (wet lay up)			
E-glass	73	3400	0.045
AR-glass	65	3000	0.043

Table 2-7: Properties of MBrace FRP plate strengthening systems

Type of fibre	Elastic modulus (kN/mm^2)	Tensile strength (MPa)
S&P Laminate 150/2000	164’000	205’000
S&P Laminate 200/2000	2’700 – 3’000	2’400 – 2’600

2.3.2 Sika CarboDur composite strengthening systems

The mechanical properties of the Sika CarboDur strengthening systems are as shown in Table 2-8.

Table 2-8: Properties of Sika CarboDur strengthening systems (CD ROM)

Type of fibre	Elastic modulus (kN/mm^2)	Ultimate tensile strain
Plates		
CarboDur S-series	165	0.0170
CarboDur M-series	210	0.0135
CarboDur H-series	300	0.0045
L-shaped strips		
Carboshear	120	0.019
Flexible sheets		
SikaWrap Hex 103-C	231	0.015
SikaWrap Hex 230-C	231	0.017
SikaWrap Hex 430-G	70	0.031

2.4 Time-dependent behavior and durability

2.4.1 Creep-rupture

When FRP composites are subjected to a constant load over a time they fail suddenly. This failure is known as the creep rupture and this time period is known as the endurance time. The endurance time decreases when the ratio of sustained tensile stress to the short-term strength of the FRP laminates increases. Furthermore it decreases with adverse environmental conditions such as high temperature, high alkalinity, freezing-thawing cycles and wet-dry cycles

As stated in ACI Committee 440 (2002) the relationship between creep rupture strength and the logarithm of time for FRP bars is linear. The ratios of stress level at creep-rupture after 500,000 hours to the initial ultimate strength of the GFRP, AFRP, and CFRP bars were extrapolated to be 0.3, 0.47, and 0.91, respectively (Yamaguchi et al. 1997). Similar values have been determined elsewhere (Malvar 1998). The vulnerability of carbon, aramid and glass fibers to creep rupture is increasing respectively.

2.4.2 Fatigue

Fatigue behavior and life prediction of stand alone FRP materials have been studied in the last 30 years (American National Research Council 1991). In these studies aerospace materials were the primary subject of investigation. Based on the test results some general observations on the fatigue behavior have been made. Test conditions that raise the temperature and moisture content of FRP materials generally degrade the ambient environment fatigue behavior.

Of all FRP composite type, CFRP is least susceptible to fatigue failure having a survival limit of 60 to 70% (one million cycles) of the initial static ultimate strength of CFRP. In a stress versus logarithm of the number of cycles at failure graph, the downward slope of CFRP is about 5% of the initial static ultimate strength per decade of logarithmic life. Fatigue strength of CFRP is not normally affected by moisture and temperature exposures of concrete structures unless the resin or fiber/resin interface is substantially deteriorated by the environment.

Individual glass fibers showed a delayed rupture caused by stress corrosion under ambient environment laboratory conditions (Mandell 1982). A cyclic tensile fatigue effect of approximately 10% loss in the initial static strength per decade of logarithmic lifetime is observed for GFRP composites (Mandell 1982). Generally, no clear fatigue limit can be defined. Environmental factors such as moisture, alkaline, and acidic solutions can play an important role in the fatigue behavior of glass fibers.

Aramid fibers exhibit a good fatigue behavior and the tension-tension fatigue behavior of an impregnated aramid fiber strand is excellent. Strength degradation per decade of logarithmic lifetime is approximately 5 to 6% (Roylance and Roylance 1981). Commercial AFRP tendons for concrete have a survival limit of 54 to 73% of the ultimate tensile strength in two million years (Odagiri et al. 1997).

2.4.3 Durability

The tensile strengths provided by the manufacturers of FRP systems are based on tests conducted in a laboratory environment which does not simulate the real environment conditions. However, the mechanical properties of FRP systems reduce with many factors such as the adverse environmental exposure (high temperature, humidity and chemicals), the duration of exposure, resin and fiber type and resin curing method.

3 INSTALLATION

FRP system installation procedure is normally developed by the system manufacturer. It differs between systems and even within a system depending on the condition of the structure. This chapter gives general guidelines for FRP system installation based on international guidelines (FIB Bulletin 14, 2001 and ACI Committee 440, 2002) as well as procedures developed by Australian manufacturers.

3.1 Techniques for FRP Strengthening

The strengthening techniques concern the application of FRP as structural reinforcement bonded to an existing concrete substrate structure. The technique can be used under different conditions and at different locations of the structural member taking into account all specifications and requirements.

3.1.1 Basic technique

The most widely used FRP strengthening technique is the manual application of wet lay-up (hand lay-up) or prefabricated systems using cold cured adhesive bonding. The main and the important feature of this technique is that the fibers of externally bonded FRP composites are in parallel as practicable with the direction of principal tensile stresses. Typical applications of the hand lay-up and prefabricated systems are illustrated in Figure 3-1. The basic technique of FRP strengthening described here refers to the manual application of FRP reinforcement to an existing member. A two-part cold cured bonding agent (normally epoxy-based) is used to achieve bonding.

Figure 3-1: (a) Hand lay-up CFRP sheets. (b) Application of prefabricated strips (FIB Bulletin 14, 2001).

(a) (b)

The basic technique involves three acting elements, defined as follows.

3.1.1.1 *Substrate*

FRP composite is bonded to an existing structure to enhance its strength. The material type of that structure is the substrate. The behavior of the thus strengthened structure heavily depends on a good concrete substrate and the preparation of the concrete surface. As shown by FIB Bulletin 14 (2001) the initial conditions of the concrete surface in terms of strength, carbonation, unevenness, imperfections, cracks, type and possible corrosion of internal steel reinforcement, humidity, level of chloride and sulphate ions, etc. should be known.

3.1.1.2 ***Adhesive/Resin***

A suitable adhesive/resin should be selected for a particular FRP strengthening system. This is normally specified by the manufacturer to meet all the requirements regarding the installation system. The bonding agent normally assures the bond between the substrate and the FRP reinforcement. It may have to impregnate "wet lay-up" types of FRP system depending on the type of FRP reinforcement.

For example in MBrace FRP strengthening systems, they use cold curing epoxy resin systems. MBT-MBrace Resicem is a newly developed cementitious epoxy matrix

3.1.1.3 ***FRP reinforcement***

Depending on the application of the FRP composites, they can be categorized as follows.

- *"Prefab" or "pre-cured" strips or laminates*

These FRP strips are provided as fully cured composites, which have their final shape, strength and stiffness. They are mostly available as thin strips or laminates (thickness about 1.0 to 1.5 mm), similar to steel plates. For this type of strip the adhesive provides the bond between the strip and the concrete only.

- "*Wet lay-up (hand lay-up)" or "cured in situ" sheets or fabrics*

These FRP materials are available as "dry fiber", which means that no resin is inside the FRP before applying, or "prepreg", having a very small amount of resin already inside the sheet before applying. In the latter case, the amount of resin is not sufficient for polymerization. For these types of sheets the application of the adhesive is required to both bond the sheet to the concrete and to impregnate the sheet.

Table 3-1: Main characteristics and typical aspects of FRP composites, basic technique (FIB Bulletin 14, 2001)

	Pre-cured (Prefab)	Cured in situ (Wet lay-up)
Shape	Strips or laminates	Sheets or fabrics
Thickness	About 1.0 to 1.5 mm	About 0.1 to 0.5 mm
Use	Simple bonding of the factory made elements with adhesive	Bonding and impregnation of the sheets or fabrics with resin (shaped and cured in-situ)
Typical application aspects	If not pre-shaped only for flat surfaces	Regardless of the shape, sharp corners should be rounded
	Thixotropic adhesive for bonding	Low viscosity resign for bonding and impregnation
	Normally 1 layer, multiple layers possible	Often multiple layers
	Stiffness of strip and use of thixotropic adhesive allow for certain surface unevenness	Often a putty is needed to prevent debonding due to unevenness
	Simple in use, higher quality	Very flexible in use, needs

	guarantee (prefab system)	rigorous quality control
	Quality control (wrong application and bad workmanship loss of composite action between FRP EBR and substrate structure, lack of long term integrity of the system etc)	

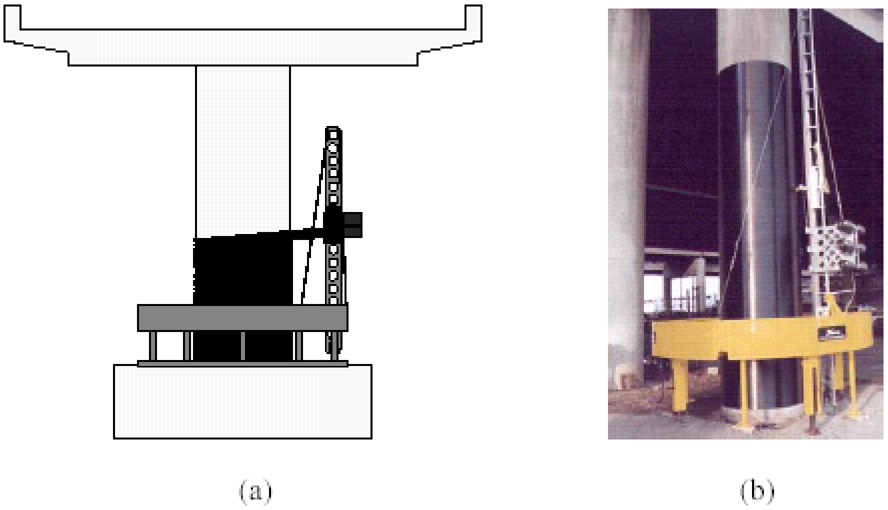
3.1.2 Special techniques

Considering the basic requirements of FRP strengthening, several special techniques have been developed to speed up the construction or protect FRP reinforcement. The following sections provide a brief overview of a number of these special techniques. Some of them are patented by the companies that developed them.

3.1.2.1 *Automated wrapping (FIB Bulletin 14, 2001)*

This technique was first developed in Japan in the early 90s and a little later in the USA. The schematic diagram and a photo of the technique are shown in Figure 3-2. In this technique, wet fibers have been continuously winding with slight angle around columns or other structures (e.g. chimneys, in Japan). The main advantage of this technique is its fastness.

Figure 3-2: Automated RC column wrapping. (a) Schematic (b) Photograph of robot-wrapper (FIB Bulletin 14, 2001)



3.1.2.2 *Prestressed FRP*

It may be more favorable to bond an externally prestressed FRP composite onto the concrete surface. It has been proven experimentally and analytically (e.g. Triantafillou et al. 1992, Deuring 1993) that this method provides advancement to the FRP strengthening technique. Furthermore, Luke et al. (1998) have developed a method of prestressing FRP composites under real life conditions. This method has several advantages as well as some disadvantages. The main advantages a shown by FIB Bulletin 14 (2001) are as follows.

- Control the deflection at the early stage and provides stiffer behavior

- Delays crack formation in the shear span

- Closes pre-existing cracks
- Improves serviceability and durability due to reduced cracking.
- Improves the shear resistance of member
- The same strengthening is achieved with smaller areas of FRP reinforcement
- Greater structural efficiency as the neutral axis remains at a lower level in the prestressed case
- The internal steel begins to yield at a higher applied force compared to a non-stressed member.

The technique has also some disadvantages (FIB Bulletin 14, 2001):

- It is more expensive than normal strip bonding
- The operation also takes longer.
- The equipment to push the strip up to the soffit of the beam must remain in place until the adhesive has hardened sufficiently.

Figure 3-3 shows the basic steps of applying a prestressed FRP strip and a schematic illustration of the stressing device is shown in

Figure 3-4.

Figure 3-3: Strengthening with pre-stressed FRP strips (a) pre-stressing (b) bonding (c) end anchorage and FRP release upon hardening of the adhesive

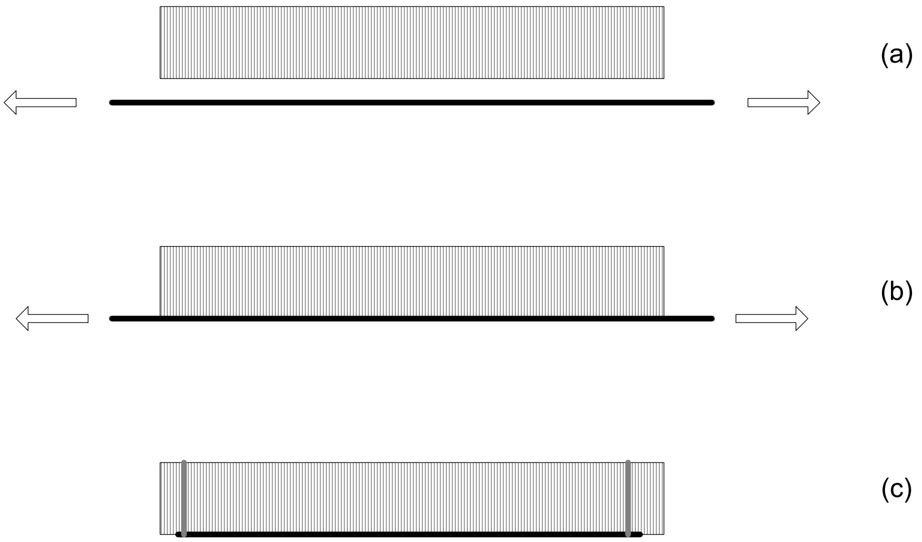
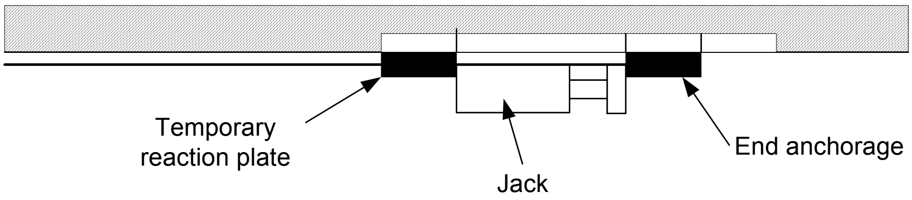


Figure 3-4: Schematic illustration of active anchorage



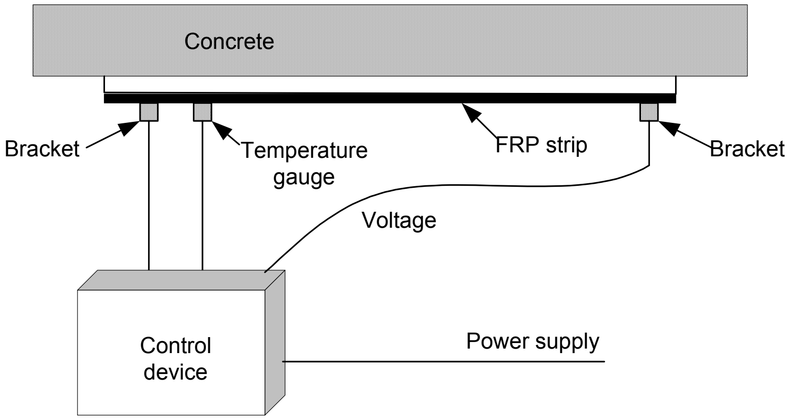
The major problem of using prestressed FRP is failure of the beam due to release of the prestressing force at the two ends of the beam. Therefore the design and the construction of end zones require special attention.

Active confinement in strengthened columns can be achieved by pretensioning the fibers bundles during wrapping or by making use of expansive mortar or injection of mortar or epoxy under pressure between the FRP jacket and substrate concrete.

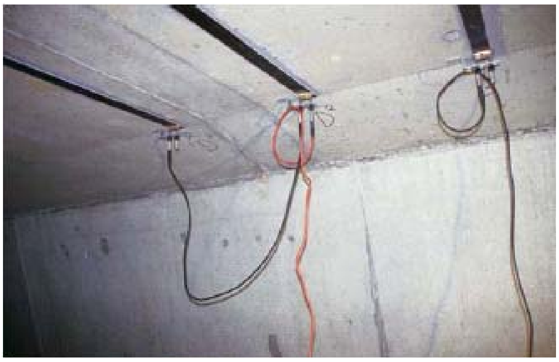
3.1.2.3 ***In-situ fast curing using heating device***

In this technique heating devices are used to cure the bond interface thus reducing the curing time. This technique can be applied in cold weather regions. Different heating systems such as electrical heaters, IR (infrared) heating systems and heating blankets can be used. This technique is shown in Figure 3-5.

Figure 3-5: Fast curing using heating device: (a) Schematic, (b) Photograph of end brackets



(a)



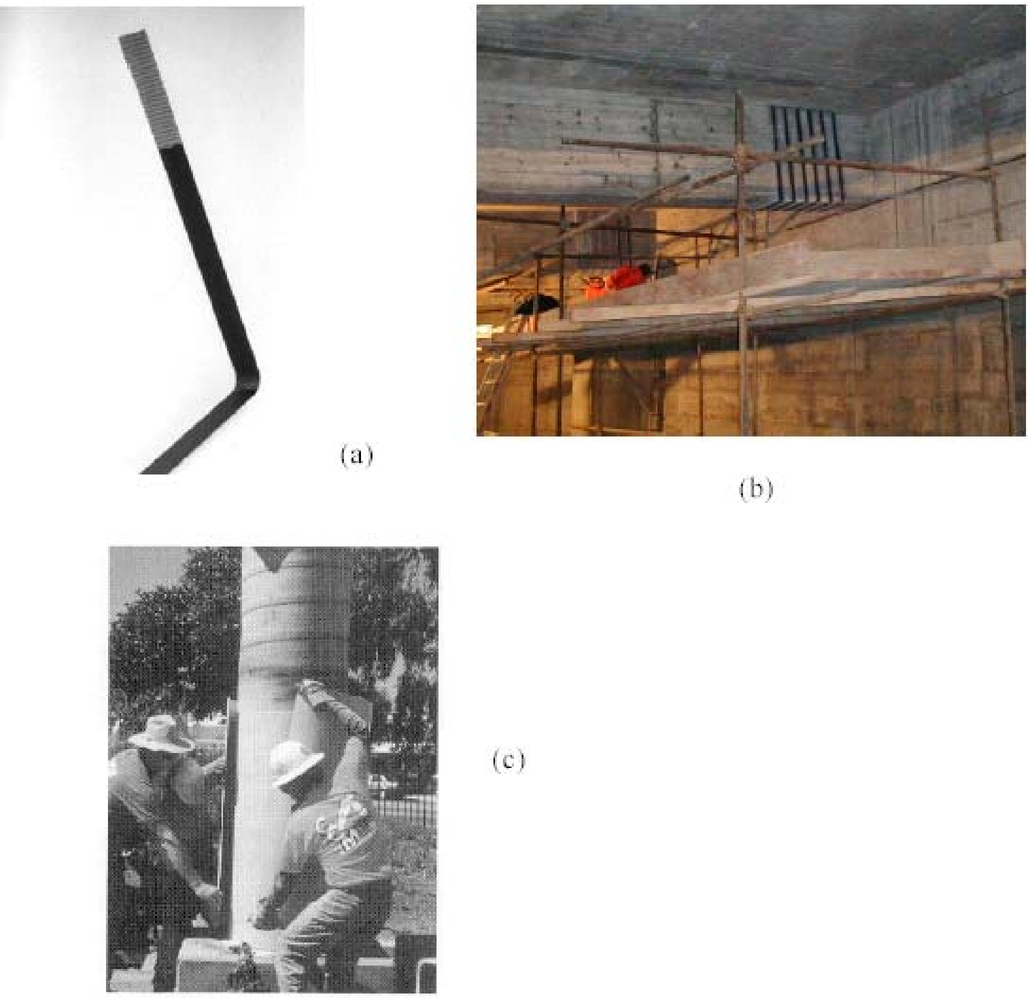
(b)

This system can be used when rapid strengthening is required.

3.1.2.4 ***Prefabricated shapes***

In some projects, use of prefabricated shape of FRP not only reduces the installation time but also allows better quality control. Prefabricated FRP are normally developed in the form of straight strips but other forms like angles, shells are also possible. These systems can be used in applications where normally wet lay-up systems are used. Prefabricated angles can be used for shear strengthening of beams as shown in Figure 3-6 *a* and *b*. Prefab FRP shells or jackets also can be used for the confinement of circular and rectangular columns (Figure 3-6 *c*).

Figure 3-6: Example of prefab shapes for strengthening (a) angle (b) application of angles, (c) shell (FIB Bulletin 14, 2001)

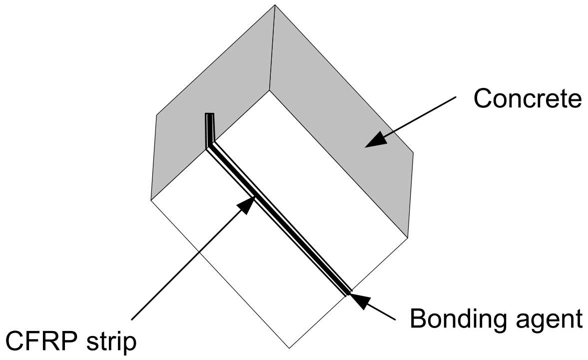


3.1.2.5 **CFRP inside slits**

In this system, the slits are cut into substrate concrete with the depth smaller than the concrete cover of existing reinforcement and then CFRP strips would be glued into the concrete slits (Figure 3-8).

Blaschko and Zilch (1999) conducted bond tests and beam tests to observe the mechanical behavior of the system. Compared to a system with CFRP strips bonded to the surface of concrete structure, the new system provided higher anchoring capacity. It showed a stiffer mechanical behavior under serviceability loads, but more ductile behavior in the ultimate limit state. The concrete substrate protects the CFRP from demolition and fire. The bond behavior allows reaching a maximum strengthening capacity without peeling-off. Therefore CFRP when glued into the slits in concrete acts more effectively than that glued on to the surface of concrete.

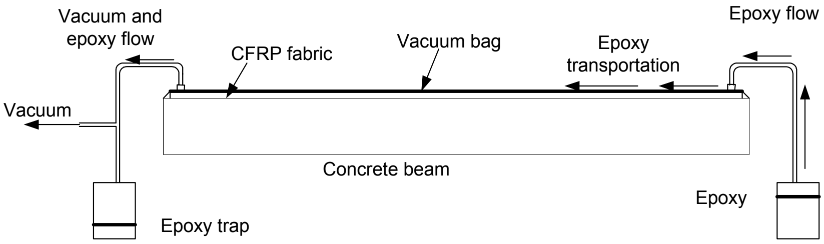
Figure 3-7: CFRP strips glued into slits



3.1.2.6 ***FRP impregnation by vacuum***

This system is common in plastics industry but it is comparable with the wet lay-up system. The preparation of the concrete substrate before strengthening should be thorough using sandblasting, grinding or water jet blasting. The surface should be cleaned and dried before applying primer. After curing primer, fibers are placed in predetermined directions. The sheets or fabrics should have channels so that the resin can flow. A vacuum bag is placed on top of the fibers, the edges of the bag are sealed and a vacuum pressure is applied (Täljsten and Elfgren 2000). There are two holes in the vacuum bag, one for the application of vacuum pressure and the other for injecting resin (Figure 3-8). A special sealant of epoxy putty can be used in the sides of the beam to achieve good vacuum pressure.

Figure 3-8: Strengthening with vacuum injection system (Täljsten and Elfgren 2000)



This system has some advantages over traditional wet lay-up systems (FIB Bulletin 14, 2001).

- Hand contact with the epoxy adhesive can be avoided and waste at the work site can be kept to a minimum.
- The quality of the composite can also be improved.

However, achieving a high degree of vacuum is difficult with surfaces of rough texture or in complicated geometries and locations. This method also needs higher costs to implement..

3.2 Temperature, Humidity, and Moisture Considerations

Surface temperature of the concrete, temperature, relative humidity of air before and during installation can affect the FRP strengthening procedure. Primers, saturating resins, and adhesives generally should not be applied to cold or frozen surfaces. If the temperature of concrete surface is below a minimum level as proposed by the manufacturer, an auxiliary heat source must be used to increase the surface and air temperature. If this is not used, improper saturation of the fibers and curing of the resin constituent materials may occur. The heating device should not contaminate uncured FRP system.

It is a general practice to apply resins and adhesives to dry and clean concrete surface. If FRP systems are applied to concrete surfaces that are subject to moisture vapor transmission, it will result in surface bubbles and lead to failure of the bond between the FRP system and the substrate.

3.2.1 MBrace FRP strengthening system

MBT Australia recommends that CFRP should not be applied when the ambient temperature is below 5^0C. Auxiliary heating is allowed in this type of systems to increase the surface and air temperature. However the method of heating should be approved. Similarly, when temperature exceeds 20^0C, care shall be taken with batch life of epoxies and special precautions may be necessary.

Presence of moisture may slow down adhesion of primer and/or resin. MBT Australia recommends that FRP should not be applied when rain or condensation is expected. No application shall take place unless the concrete temperature and air temperature are at least 3 degrees higher than the dew-point temperature.

3.3 Equipment

Each FRP strengthening system needs unique equipments, which designed specifically for the application of the materials for that system. This equipment can include resin impregnators, sprayers, lifting/positioning devices, and winding machines.

3.4 Substrate Repair and Surface Preparation

Concrete substrate and proper preparation and profiling of the concrete surface can affect the behavior of concrete members strengthened or retrofitted with FRP systems. Debonding or delamination of the FRP system can be resulted from an improperly prepared substrate concrete, before achieving the design load transfer. The bond behavior of strengthened member can also be affected by an improper surface preparation. The FRP system manufacturers usually provide a specific guideline for a particular FRP system. Noise, dust, and disruption to building occupants can be generated during the substrate preparation.

Concrete substrate should be checked for corrosion of existing reinforcing steel. The cause of corrosion needs to be addressed and corrosion related deterioration should be repaired before strengthening commences. The compatibility of the materials used to repair the substrate and the FRP system should be discussed with the FRP system manufacturer.

Some FRP manufacturers have a concern that the cracks of 0.3 mm or wider can affect the performance of externally bonded FRP through delamination or fiber crushing of FRP. Therefore cracks wider than 0.3 mm should be pressure injected with epoxy. Resin injection or sealing is recommended for minor cracks to prevent corrosion of the existing steel reinforcement. However relevant standards and guidelines should be used for detailed methods of repair and surface preparation of concrete (ACI Committee 440, 2002).

As shown by ACI Committee 440 (2002), applications of FRP systems can be categorized as bond-critical or contact-critical. The surface preparation requirements should be based on the category of FRP application. Bond-critical application requires an adhesive bond between the FRP system and the concrete. The application of bond-critical method is in flexural or shear strengthening of beams, slabs, columns, or walls. In this method, surface preparation must be done using sand blasting, grinding or water blasting. All laitance, dust, dirt, oil, curing compound, existing coatings, and any other matter that could interfere with the bond of the FRP system to the concrete should be removed. Bug holes and other small surface voids should be completely exposed during surface profiling. After the profiling purpose is over, the surface should be cleaned and protected before FRP installation.

Contact-critical application requires intimate contact between the FRP system and the concrete, such as confinement of columns. In this method, surface preparation should promote continuous intimate contact between the concrete surface and the FRP system.

3.4.1 MBrace FRP strengthening systems (MBT Australia)

MBT Australia (CD ROM) provides a number of guidelines in the surface preparation for application of FRP composites.

1. The substrates should be clean and free of surface moisture and frost. Dust, laitance, grease, curing compounds, waxes, impregnations, foreign particles and other bond inhibiting materials should be removed from the surface by a method of blasting or equivalent mechanical means.

2. Deteriorated concrete or corroded reinforcing steel must be repaired as required by the MBT, Australia. Any corroded steel reinforcement should be cleaned and prepared thoroughly by abrasive cleaning, and the area patched prior to installation of FRP system. Do not cover corroded reinforcing steel embedded in concrete with FRP Systems. Existing uneven surfaces must be filled with an appropriate repair mortar or must be ground smooth.

3. before starting the surface preparation procedure, the contractor should prepare a sample area. The sample area shall be prepared in accordance with the requirements of the guidelines provided here, and shall be used as a reference standard depicting a satisfactory prepared surface. Normal requirement is the surface must present similar to 60-grit sandpaper. The strength of the concrete or repaired area shall be verified after preparation by random pull-off testing. Minimum tensile strength of substrate required is 1.0 MPa.

4. When required by the contract documents, the contractor shall install a trial or sample area (1m^2 min) of the FRP System for purposes of in-situ bond testing to verify preparation, system application and bond.

5. Maintain control of concrete chips, dust and debris in each area of work. Clean up and remove such material at the completion of each day of blasting.

4 GENERAL DESIGN CONSIDERATIONS

The successful structural repair and upgrading involves four basic elements: concepts used in system design; compatibility and composite behavior of existing members with upgraded system; field application methods; and most importantly, design details.

The status of the structure to be strengthened should be investigated and repairs should be performed as appropriate. It is of great importance to select the best FRP system for a particular rehabilitation need. Proper designing, detailing and applying it in a particular structure should guarantee the overall structural behavior and safety of the strengthened member. Therefore, the design and execution of the externally bonded reinforcement specifically need to comply with related documents concerning the design of reinforced concrete and pre-stressed concrete members, and concerning repair techniques will apply as well. FRP strengthening systems should be designed to resist tensile forces while maintaining strain compatibility between the FRP and the concrete substrate. It should be ensured that only approved FRP systems are used. However, there are many FRP systems available which vary from one another depending on type of FRP, type of adhesive, method of curing, material preparations, etc.

4.1 Design Philosophy

In common with most codes of practice for structural design, the design methods contained in this report are based on limit-state philosophy. This ensures that a strengthened member will not reach a limit state during its design life. All necessary design situations and load combinations should be considered. In assessing the effect of a particular limit state on the structure, the designer will need to assume certain values for the design loading and the design strength of the materials. This method ensures safety levels in serviceability limit state (deflection, cracking) and ultimate limit state (failure, rupture, fatigue). The possible failure modes, stresses and strains resulting from that in each material should be assessed in order to find the nominal strength of a member. The design of a FRP strengthening system should include the effects of FRP composites, force transfer through bond interface, detailing rules and special provisions. Design calculations are based on analytical or (semi-) empirical models.

A thorough field inspection, review of existing design and a structural analysis should be performed for the structure to be strengthened by FRP. Depending on that investigation, proper repair should be undertaken as the application of FRP is not meant to confine defects such as steel corrosion. Redistribution of moments is not normally allowed in FRP as it lacks plasticity. In strengthening columns and walls using FRP composites, it is necessary to consider the out-of plane deformations (second order effects).

Verification of both the serviceability limit state (SLS) and the ultimate limit state (ULS) should be performed in the design procedure. As shown in FIB Bulletin 14 (2001), the following situations may be considered:

- Persistent situation, corresponding to the normal use of the structure
- Accidental situation, corresponding to debonding or delamination of the FRP system (due to e.g. impact, vandalism, fire)

- Special design considerations (e.g. bond stresses due to differences in coefficient of thermal expansion, fire resistance, impact resistance).

4.1.1 Verification of the serviceability limit state

The serviceability of a strengthened member (deflections, crack widths) under service loads should satisfy acceptable provisions of relevant standards. To meet this requirement, the Serviceability Limit State verification normally should consider:

- Stress limits (prevent steel yielding, damage or excessive creep of concrete and excessive creep or creep rupture of the FRP)
- Acceptable deformations or deflections
- Cracking (including interface bond cracking)

If the aim of applying a strengthening procedure is to improve the serviceability, then Serviceability Limit State will govern the design, rather than the Ultimate Limit State.

4.1.2 Verification of the ultimate limit state

The strength of strengthened member depends on the controlling failure mode. All possible failure modes should be investigated for an FRP strengthened section (GangaRao and Vijay 1998). In general, the failure modes can be subdivided to those assuming full composite action between the reinforced concrete / prestressed concrete member and the FRP and those verifying the different debonding mechanisms that may occur.

Load combinations and partial safety factors should apply as specified in relevant code and standards.

4.1.3 Accidental situation

The level of strengthening that can be achieved through use of externally bonded FRP reinforcement is often limited by considerations of the accidental design situation as required by design codes. The structure should be checked for loss of the FRP strengthening due to e.g. impact, vandalism or fire.

The un-strengthened member is then subjected to all relevant accidental load combinations. This need verification in the ultimate limit state, considering the partial safety factors for the materials and considering reduced partial safety coefficients and combination factors for the loads, as provided in relevant codes and standards.

4.1.4 Special design considerations

Environmental conditions uniquely affect resins and fibers of various FRP systems. Special design considerations such as cyclic loading, extra bond stresses due to the difference in thermal expansion between FRP and concrete, impact and fire resistance may also be relevant.

The material properties used in design should account for the degradation and effect of impact and fire. However, it is important that sufficient attention is paid to the special design aspects, as they can have a considerable influence on the structural safety.

4.1.5 Durability

Many FRP systems exhibit reduced mechanical properties after exposure to certain environmental factors, including temperature, humidity, and chemical exposure. Hence the environmental conditions must be taken into account from the start of the design process. The exposed environment, duration of exposure, resin type and formulation, fiber type, and resin-curing methods are some of the factors that influence the extent of the reduction in mechanical properties. These factors and their influences with respect to the durability should be considered and if needed protective measures can be taken.

4.2 Safety concept and strengthening limits

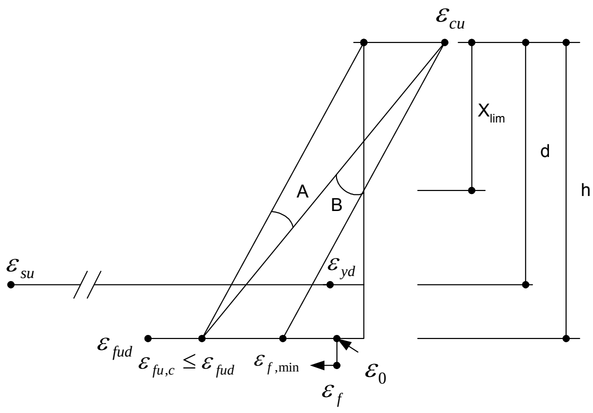
FRP strengthening system should be designed to provide the sufficient structural safety, including sufficient ductility. A major task involved in design is the choice of appropriate margin of safety for the different limit states together with corresponding value for the associated safety coefficient.

4.2.1 Safety concept with respect to the ultimate limit state

In limit state design, the variability of material properties is taken into account by assuming a characteristic strength. Characteristic strength usually is taken as the value below which not more than 5% of test results lie. A similar approach is used to define characteristic strength of FRP, but the acceptable failure rate may be reduced to 1%.

The modeling of the strengthened member should consider the different failure modes that may occur. Using FRP materials with no yielding capacity and, considering concrete substrate with unfavorable post-failure in tension leads to a brittle failure. Therefore, the brittle failure modes, such as shear and torsion, should be prevented in design of FRP system. For the same reason, it should be guaranteed that the internal steel is sufficiently yielding in Ultimate Limit State, so that the strengthened member will fail in a ductile manner.

Figure 4-1: Strain distribution at Ultimate Limit State in the critical section of strengthened flexural members



In order to discuss about the failure of the strengthened member, strain distribution at Ultimate Limit State in the critical section can be considered as shown in Figure 4-1 (FIB Bulletin 14, 2001). ε_o is the initial strain at the extreme tensile fiber before strengthening, $\varepsilon_{f,min}$ is the minimum allowable FRP strain at ultimate and $\varepsilon_{fu,c}$ is the FRP strain in the critical section at ultimate.

In case FRP fracture is governing, $\varepsilon_{fu,c}$ equals the design value of the ultimate FRP strain $\varepsilon_{fu,d}$. In case of bond failure, $\varepsilon_{fu,c}$ equals the FRP strain in the critical section when debonding occurs. This debonding may initiate at another location than the critical section that is considered for the verification of the flexural capacity. Bond failure will be allowed in the design if $\varepsilon_{fu,c} \geq \varepsilon_{f,min}$. Optimum design will correspond with simultaneous concrete crushing ($\varepsilon_{cu} = 0.0035$) and FRP tensile failure ($\varepsilon_{fu,d}$) (Figure 4-1). Therefore, the governing failure mode of a flexural member will be either steel yielding or concrete crushing (before FRP rupture or debonding) (This relates to zone B in Figure 4-1), or steel yielding or FRP failure (either FRP rupture or bond failure) (This relates to zone A in Figure 4-1).

Strengthening is not always a primary goal of the application of externally bonded reinforcement. For example, in columns, FRP wrapping is used to improve ductility as well as load carrying capacity by activating multiaxial stresses or by counteracting lateral tensile stresses and shear forces. This technique favorably influences the structural safety as confinement results in increased ductility.

4.2.2 Strengthening limits

There should be strengthening limits to protect the strengthened structure against collapse due to bond failure or other failure of FRP system caused by fire, vandalism or other causes. ACI Committee 440 (2002) suggested a careful consideration to determine reasonable strengthening limits. It has been recommended by some designers and system manufacturers that even the unstrengthened structural member should have sufficient strength to resist a certain level of load so that in case FRP system is damaged the structure is still capable of resisting excessive load without collapse. ACI Committee 440 (2002) recommended that the existing strength of the structure should be sufficient to resist a level of load as described by Eq. (4-1).

$$(\phi R_n)_{existing} \geq (1.2\,S_{DL} + 0.85\,S_{LL})_{new} \tag{4-1}$$

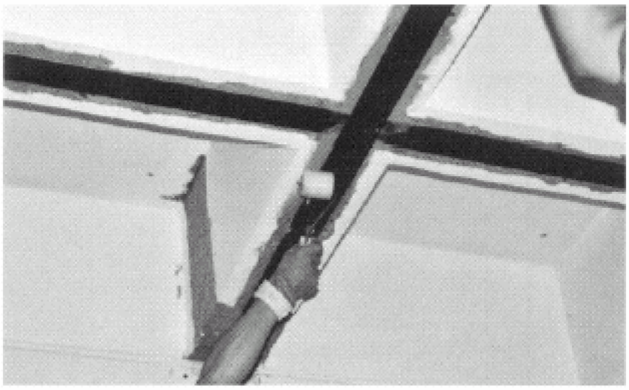
4.3 Ductility

The use of externally bonded FRP reinforcement for flexural strengthening will reduce the ductility of the original member. In some cases, the loss of ductility is negligible. Sections that experience a significant loss in ductility, however, should be addressed. To maintain a sufficient degree of ductility, the strain level in the steel at the ultimate-limit state should be checked.

5 FLEXURAL STRENGTHENING

Traditional methods which are commonly used for flexural strengthening of RC beams include external post tensioning and bonding of steel plates. These methods suffer from inherent disadvantages ranging from difficult application procedures to lack of durability. In recent years, the bonding of FRP plates or sheets has become a very popular method for the flexural strengthening of reinforced concrete elements, such as beams and columns. Flexural strengthening using FRP strips is illustrated in Figure 5-1.

Figure 5-1: Flexural strengthening of RC beams with CFRP strips (FIB Bulletin 14, 2001)



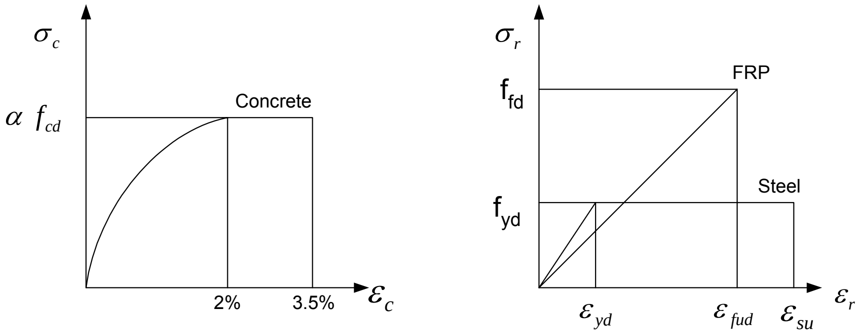
Most of existing research on FRP plate bonding for flexural strengthening has been carried out in the last decade (e.g. Ritchie et al. 1991, Saadatmanesh and Ehsani 1991, Triantafillou and Plevris 1992, Chajes et al. 1994, Sharif et al. 1994, Meier 1995, Quantrill et al. 1996, shahawy et al. 1996, Takeda at el. 1996, Arduni and Nanni 1997, Garden et al. 1997, 1998, Varastehpour and Hamelin 1997, Buyukozturk and Hearing 1998, GangaRao and Vijay 1998, Grace et al. 1998, 1999, Spadea et al. 1998, 2000, Ross et al. 1999, Swamy and Mukhopadhyaya 1999, Vecchio and Bucci 1999, Bonacci and Maalej 2000, Ramana et al. 2000, Nguyen et al. 2001, and Rahimi and Huchinson 2001). FRP strengthening systems has drawn a great attention as the need for structural strengthening is increasing and the cost is reduced if FRP is used.

The analysis for the ultimate limit state in flexure for such elements may follow well-established procedures for reinforced concrete structures, provided that: (a) the contribution of external FRP reinforcement is taken into account properly; and (b) special consideration is given to the issue of bond between the concrete and the FRP.

Figure 5-2 illustrate the Idealized stress-strain curves for concrete, FRP and steel. The ultimate strain at the extreme concrete compression fiber is taken to be 0.0035. These curves, along with the assumption that the slip at the concrete-FRP interface may be ignored, form the basis for the ultimate strength limit state analysis of concrete elements strengthened in flexure. As the behavior of the FRP composite is brittle, the ultimate strain of the concrete may not have been reached when the FRP ruptures.

Central to the analysis of these elements is the identification of all the possible failure modes. A number of failure modes for RC beams bonded with FRP plates have been observed in numerous experimental studies to date (e.g. Ritchie et al. 1991, Saadatmanesh and Ehsani 1991, Triantafillou and Plevris 1992, Chajes et al. 1995, Sharif et al. 1994, Shahawy et al. 1996, Takeda at el. 1996, Arduni and Nanni 1997, Garden et al. 1997, 1998, Grace et al. 1998, Ross et al. 1999, Bonacci and Maalej 2000, Nguyen et al. 2001, and Rahimi and Huchinson 2001). These are described below, following a brief presentation of the effect of initial load acting on the members at the time of strengthening.

Figure 5-2: Design stress-strain curves of constitutive materials at Ultimate Limit State (FIB Bulletin 14, 2001).



5.1 Initial Situation

The pre-loading including the self weight of structure is likely to exist in the practical applications prior to and during strengthening. Therefore, the effect of the pre-loading has to be considered in the structural analysis of the strengthened member.

The effect of pre-loading due to self-weight and service loads is generally beneficial if the beam fails by FRP rupture, but this effect is generally insignificant. The effect of pre-loading is more significant and detrimental if the beam fails by concrete crushing and should be investigated in design calculations. As the service moment, M_o is typically larger than the cracking moment, M_{cr}, the calculation will be based on a cracked section.

5.2 Design Assumptions

For a section strengthened with an externally bonded FRP system, the following assumptions are made in calculating the flexural strength (ACI Committee 440, 2002).

- Design calculations are based on the actual dimensions of the existing member to be strengthened, its configuration of reinforcing steel, and its material properties;
- The strains in the reinforcement and concrete are directly proportional to the distance from the neutral axis, that is, plane sections remain plane after loading;
- There is no relative slip between external FRP reinforcement and the concrete;
- The shear deformation within the adhesive layer is neglected since the adhesive layer is very thin with slight variations in its thickness;

- The maximum usable compressive strain in the concrete is 0.0035;
- Concrete resists no tension; and
- The FRP reinforcement has a linear elastic stress-strain relationship until failure;

5.3 Failure Modes

The failure modes observed in experimental studies reported in the literature, can be classified into seven main categories as follows.

- flexural failure by FRP rupture,
- flexural failure by crushing of compressive concrete,
- shear failure,
- concrete cover separation,
- plate-end interfacial de-bonding,
- intermediate flexural crack-induced interfacial de-bonding, and
- intermediate shear cracked-induced interfacial de-bonding.

All these failure modes can be divided into two categories.

- Full composite action of concrete and FRP is maintained until the concrete reaches crushing in compression or the FRP fails in tension (such failure modes may also be characterized as “classical”) and
- Composite action of concrete and FRP is lost prior to failure (e.g. due to de-bonding or peeling-off of the FRP).

A brief description of each failure mode is given below:

5.3.1 Full composite action

If the ends of the plates are properly anchored, the ultimate flexural capacity of the strengthened member is reached when either the FRP plate fails by tensile rupture or the compressive concrete is crushed. This is very similar to the classical flexural failure of RC beams, except for small differences due to brittleness of bonded FRP plate. FRP rupture generally occurs following the yielding of the longitudinal steel bars, although steel yielding may not have been reached if the steel bars are located quite far away from the tension face. In case of relatively low ratios of both steel and FRP, flexural failure may occur with yielding of the tensile steel reinforcement followed by tensile fracture of the FRP.

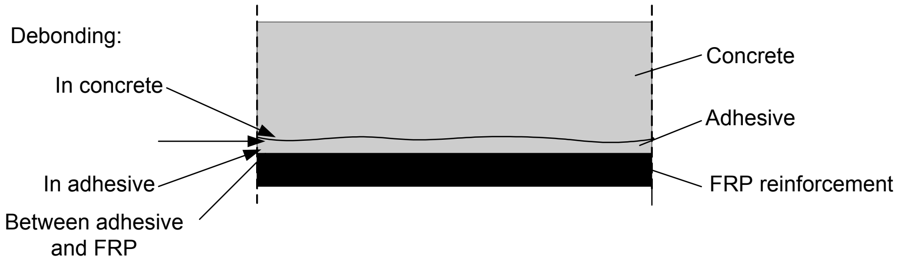
The strength gain and the ductility reduction are the two main consequences of flexural strengthening of RC beams using FRP plates. Beams, which fail by concrete crushing when a large amount of FRP is used, shows much reduced ductility. This mode is brittle and certainly undesirable.

While normal RC beams are designed to fail in flexure rather than in shear which is a brittle failure, the shear failure mode can be made critical by flexural strengthening. In such situations, shear strengthening should be considered simultaneously to ensure that the required flexural strength is not compromised by shear failure and that flexural failure still precedes shear failure.

5.3.2 Loss of composite action

Premature failure may occur before the ultimate flexural capacity of the beam is reached owing to debonding. Therefore, bond failure modes need a careful consideration. In bond failure, composite action between the concrete and the FRP reinforcement is completely lost. It may occur at different interfaces between the concrete and the FRP reinforcement, as shown in Figure 5-3.

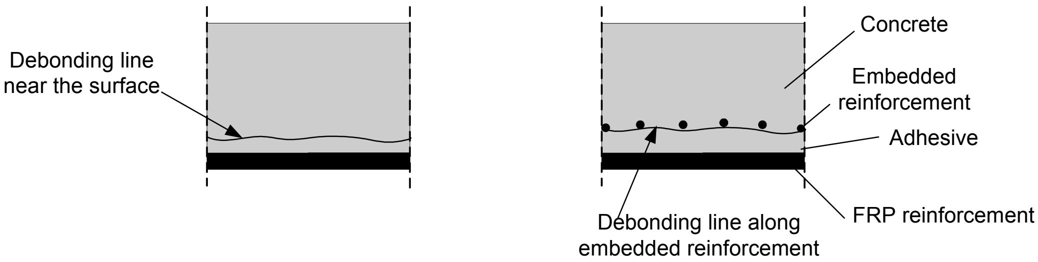
Figure 5-3: Different interfaces for bond failure



5.3.2.1 *Separation of concrete cover*

The most commonly reported mode of debonding in experimental studies has been the separation of the concrete cover (Figure 5-4) that initiates at or near one of the two ends of the soffit plate. As the failure occurs away from the bond line, this is not a debonding failure mode in strict term, although it does stem from stress concentration near the ends of the bonded plate. It is generally believed that failure of concrete cover is initiated by the formation of a crack at or near the plate end, due to high interfacial shear and normal stresses caused by the abrupt termination of the plate.

Figure 5-4: Different debonding lines in the concrete



5.3.2.2 *Separation of FRP plate*

A less commonly observed debonding mode that also initiates at or near the plate end is the separation of the FRP plate from RC beam soffit. The general agreement among researchers is that debonding failure of this form is initiated when high interfacial shear and normal stresses near the end of the plate exceeds the strength of weakest element, generally the concrete. Debonding may occur through the adhesive in situations where the strength of adhesive is lower than that of concrete.

Therefore this type of debonding may occur at high temperatures or when the strength of concrete is high.

5.3.2.3 *Bond failure in interface*

When the surface preparation for FRP application is not good enough, the weakest point in the bond between the FRP and the concrete is in the concrete layer near the surface. This will result in a bond failure in the interface between concrete and adhesive.

Debonding may initiate at a flexural or a mixed flexural shear crack away from the plate ends and then propagates towards one of the plate ends. Debonding generally occurs in the concrete, adjacent to the adhesive-to-concrete interface. Depending on the starting point of the debonding process, the following failure modes can be identified as shown in Figure 5-5 (FIB Bulletin 14, 2001).

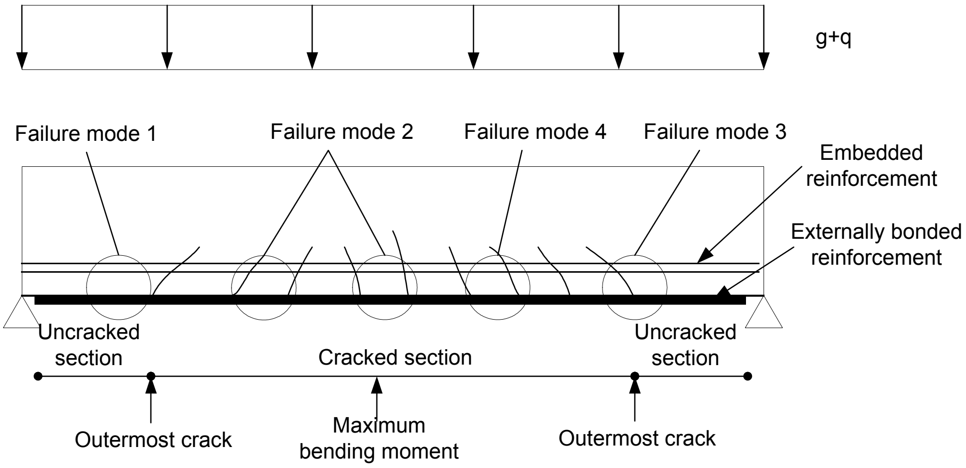
Mode 1: peeling-off in an un-cracked anchorage zone

Mode 2: peeling-off caused at flexural cracks

Mode 3: peeling-off caused at shear cracks

Mode 4: peeling-off caused by the unevenness of the concrete surface

Figure 5-5: Bond failure modes of a concrete member with EBR (Blaschko et al. 1998).



5.4 Summary of Design Procedure

Existing research suggests that the ultimate flexural strength of FRP-strengthened RC beams can be predicted using existing RC beam design approaches with appropriate modifications to account for the brittle nature of FRP. However, the procedure for dimensioning FRP-strengthened RC elements in flexure may be summarized as follows:

- The resisting design moment (ultimate limit state) can be determined for the member before strengthening. It would then be checked for the serviceability limit state where valuable information of the strengthened member with respect to Serviceability Limit State could be obtained.

- The initial strain at the extreme tension fiber can be determined from the service moment M_0 prior to strengthening. Effect of creep and shrinkage can also be considered in the calculation.
- The required FRP cross section is calculated from the design moment after strengthening to fulfill the Ultimate Limit State (assume full composite action)
- The obtained ductility is verified
- The deflections in the Serviceability Limit State are calculated. If the maximum allowable deflection is exceeded, FRP cross section dimensions are changed to satisfy the deflection requirements.
- The stresses in the concrete, steel and FRP in the Serviceability Limit State are calculated and compared with allowable stresses. If they exceed the allowable, FRP cross-section dimensions are changed to satisfy the stress limitation requirements.
- The FRP bond width is checked to be sufficient to control crack widths in the Serviceability Limit State. The FRP width or thickness can be increased if necessary.
- The resisting shear force at which bond failure due to shear cracks (vertical crack displacement) needs to be verified in the Ultimate Limit State. If this failure mode dominates, FRP cross section dimensions should be recalculated.
- The possibility of bond failure at the end anchorage and along the FRP (e.g. in regions where flexural cracking dominates) should be checked. In such a failure, mechanical anchorage should be provided.
- If required shear strengthening at the ends should be provided so that end shear failure is avoided.
- The accidental situations need to be considered.

5.5 Special Cases

5.5.1 Pre-tensioned or post-tensioned concrete elements

FRP strengthening of pre-stressed elements has been addressed only in few studies both experimentally and theoretically. From the FRP strengthened bridges so far, only 10% are pre-stressed (FIB Bulletin 14, 2001). Therefore, FRP-strengthening of pre-stressed elements needs careful attention.

The following sections cover the FRP strengthening of bridge superstructures (girders, beams and decks) and slabs for prefabricated floors. Strengthening of elements with either un-bonded tendons, external tendons, or made from lightweight aggregate concrete is not covered here.

5.5.1.1 FRP strengthening of pre-stressed concrete members

Strengthening of a pre-stressed member usually takes place after all long term phenomena (creep, shrinkage, relaxation) have fully developed. As a result, the assessment of the existing pre-stressed structure before FRP strengthening has become more complicated. Therefore conceptual implications of the long term phenomena should be clearly understood and careful attention should be paid in designing a FRP strengthening of a pre-stressed member. As shown in the FIB Bulletin 14 (2001), construction sequence, pre-stressing phases, correct description of long-term phenomena along with their superposition and mutual interaction, and evaluation of damage effects (due to impact, etc.) on the section stress pattern should be carefully analyzed in the assessment of the existing pre-stressed structure. Assessment itself should be in accordance with the national standards.

All time dependent effects can be considered as a one single reduction coefficient and pre-strengthening stress/strain behavior can be computed. The effects of such simplifications in economical and safety aspects should be studied. However, this kind of simplifications should be avoided where more detailed preliminary assessment is needed (e.g. many construction phases follow this strengthening and impact damage has induced stress redistribution).

5.5.1.2 Safety considerations

The conventional procedures for pre-stressed concrete (accordance with relevant national codes) can be applied for the design of FRP strengthening system once the existing stress state of the pre-stressed member is assessed. FRP contribution can then be included in the same form as adopted for reinforced concrete.

The FRP-strengthened member should be checked for cracking criteria according to the serviceability limit state. Moreover, verifications should be made for the stress limits for steel and concrete given by the national codes. A controversial issue exists in the strengthening design philosophy about the presence of tensile stresses in the pre-stressed concrete section after it is strengthened by FRP. This requires careful consideration.

Determining the initial strain in the pre-stressed element where FRP application is to be made, is another important part in the design procedure. The actual FRP strain will be computed by subtracting the initial strain from the strain obtained from the plane section assumption. This is needed to be considered in the ultimate limit state, as FRP rupture is the governing event leading to collapse. Therefore it should be calculated to the maximum accuracy.

5.5.1.3 Modeling issues

Fiber section models can be used to verify the effectiveness of the design procedures because all long term phenomena can be included in the material level and finally integrated over the section analysis. The finite element analysis can be used to obtain the global analysis of the strengthened member. The numerical method needs to have all the issues discussed above.

5.5.2 Strengthening with pre-stressed FRP

5.5.2.1 *Design*

The cracking and yield loads of a beam can be determined using conventional reinforced concrete theory provided that the initial stress in the strips for strengthening is included in the calculations. However, premature failure through other modes must be examined. As the flexural ultimate load is approached, cracking of the concrete will inevitably occur and the section will revert to normal reinforced concrete behavior. In this case the ultimate shear strength of a beam strengthened with a stressed strip will be the same as that of the original beam. The contribution of the strip to dowel action must be ignored in calculating the shear resistance, unlike the main tensile steel reinforcement that can be included. The reason for this is that any vertical movement may lead to peeling-off failure resulting in de-bonding of the strip from the concrete. The strip would need to be enclosed by the shear links to increase the effectiveness.

The ultimate flexural strength of a beam with a stressed strip will be similar to that of a beam with an unstressed strip. However, the initial strain in the strip will be added to that induced by bending so that strip failure is more likely and the failure mode of “steel yielding followed by FRP fracture” may be activated.

5.5.2.2 *Pre-stress losses*

Losses in prestress as shown below should be considered in design procedures.

- Relaxation of the steel tendons
- Immediate elastic deformation of the concrete
- Creep and shrinkage of the concrete under compressive pre-stress over the service life of the structure
- Slippage of the tendons at their ends that occurs when the pre-stress is transferred into the anchorages.
- Friction between the strip and the concrete if the strip does touch the concrete

5.5.2.3 *FRP end anchorage*

Experimental studies have shown that only about 6% of the ultimate strength of the FRP strip can be transferred into the concrete by the adhesive alone (e.g. Triantafillou et al. 1992, Deuring, 1993). Therefore a suitable anchorage system is necessary to transfer a great pre-stressing force (50% of the ultimate strength of the strip) and to avoid peeling off the end. The value of 50% of the ultimate strength of the strip should not be exceeded. Where the tests are based on the ultimate strength of coupon specimens this value should not exceed 33%. Developed FRP end anchorage systems must be investigated with appropriate tests.

6 STRENGTHENING IN SHEAR AND TORSION

Flexural and shear failure are the two main failure modes for normal RC beams. Flexural failure is generally preferred to shear failure as the strength-governing failure mode because the former is ductile, whilst the latter is brittle. A ductile failure allows stress re-distribution and provides warning to users, whilst the brittle failure is sudden and thus catastrophic.

When a RC beam is deficient in shear or when its shear capacity is less than the flexural capacity after flexural strengthening, shear strengthening must be considered. The shear strength of existing concrete beams and columns can be increased by fully or partially wrapping the members using FRP systems (Malvar et al. 1995; Chajes et al. 1995; Norris et al. 1997; Kachlakev and McCurry 2000). Providing additional shear strength is effective if the fiber orientation is transverse to the axis of the member or perpendicular to potential shear (Sato et al. 1996). Increased shear strength of the FRP strengthened member can result in flexural failure which is desirable to shear failure.

Apart from the common advantages of corrosion resistance and high strength-to-weight ratio of FRPs, the versatility of FRPs in coping with different sectional shapes and corners is also a benefit for shear strengthening applications. Furthermore, shear strengthening can be provided at locations of possible plastic hinges, stress reversals and where post yield flexural behavior of members in moment frames needs to be enhanced.

6.1 General Design Considerations

A number of failure modes have been observed in experiments of RC beams in shear strengthened with bonded FRPS. These included shear failure with FRP rupture, shear failure without FRP rupture, shear failure due to de-bonding and local failure. However, detailed analysis of shear strengthening of RC members have been relatively little. Most researchers have idealized the shear strengthening of RC members using FRP composites with those using internal steel stirrups.

RC beams strengthened in shear using externally bonded FRPs show complex behavior. Both the shear strength and the failure mode are influenced by many factors such as the size and geometry of the beam, the strength of the concrete internal shear and flexural reinforcement, loading conditions, the method of strengthening, and the properties of the bonded FRP. However all existing models use the following expression to calculate the shear strength of a strengthened member, V_c:

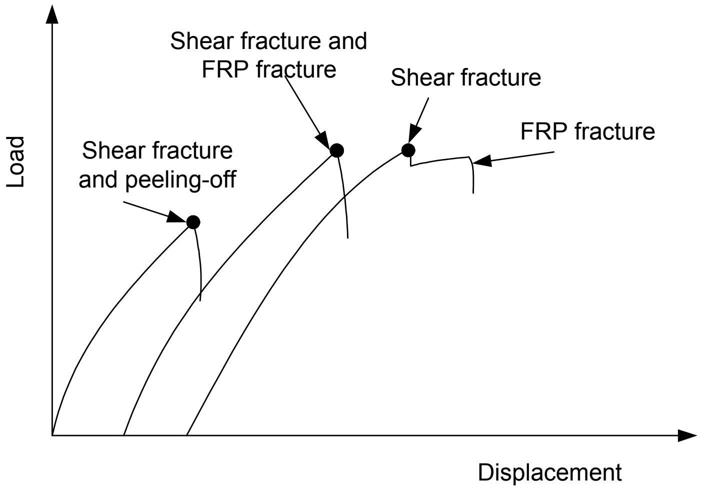
$$V_n = V_c + V_s + V_{frp} \tag{6-1}$$

where V_c is the shear capacity of the concrete, which consist of shear contribution of concrete in compression, aggregate interlock and dowel action of steel flexural reinforcement, V_s is the contribution of the steel stirrups and bent up bars and V_{frp} is the contribution of FRP. V_c and V_s may be calculated according to provisions in existing codes, so the main differences between available models lie in the evaluation of the FRP contribution.

Triantafillou (1998) and Triantafillou and Antonopoulos (2000) argued that to predict accurately the contribution of FRP to shear resistance is impossible, because it depends on the failure mechanism which in turn depends on various factors. They used a semi-quantitative approach. It has been shown that just before concrete fails in shear, the externally bonded FRP strips stretched in the principal fiber direction upto a strain level known as effective strain $\varepsilon_{f,e}$. This effective strain is normally less than the tensile fracture strain of FRP composites, ε_u. Effective strain multiplied by the elastic modulus of FRP in the principal fiber direction, E_f and the FRP cross sectional area will ultimately give the total force carried by FRP at the shear failure of the member.

The effective FRP strain is extremely difficult to be estimated. However, a detailed analysis of experimental data will help in estimating this. It should be noted that failure is assumed to be always defined by concrete diagonal tension splitting. The failure may occur either prematurely, as a result of FRP debonding, or after the FRP has been stretched considerably as illustrates in Figure 6-1. In the latter case the FRP may fracture either exactly at the peak load or a little after, due to overstressing in the vicinity of the diagonal cracks.

Figure 6-1: Schematic illustration of shear failure response



The chief disadvantage of this model is that no distinction is made between the different strengthening schemes or failure modes. It may be also argued that at the ultimate limit state a certain degree of FRP debonding at the concrete-FRP interface is always expected, even if the ultimate failure does not occur simultaneously with peeling-off.

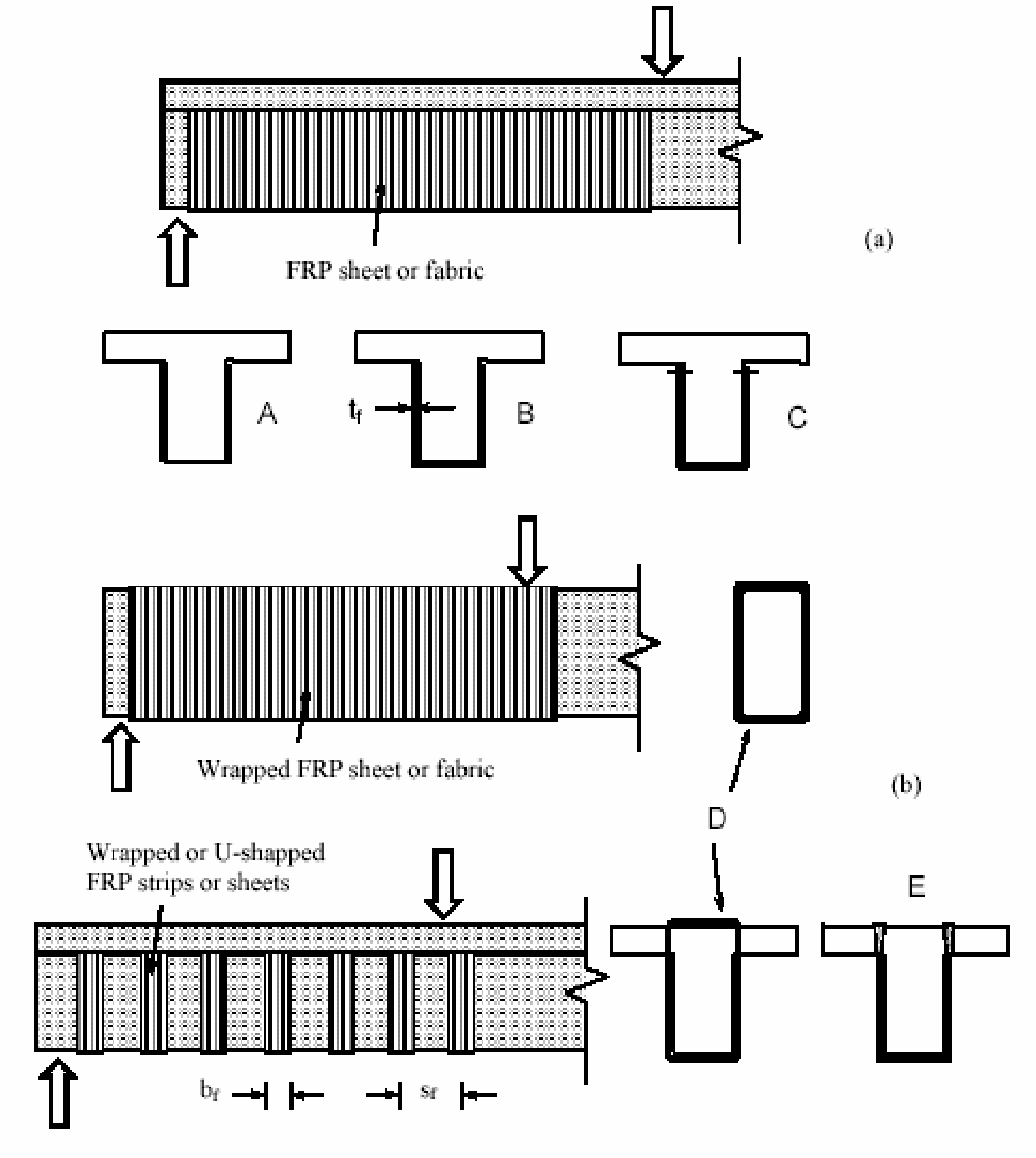
6.2 Wrapping Schemes

Various FRP bonding schemes have been used to increase the shear resistance of an RC member. These include bonding FRP to the side of a beam only, bonding FRP jackets to both the sides and the tension face, and wrapping FRP around the whole cross section. Both FRP strips and continuous sheets have been used.

Figure 6-2 and Figure 6-3 shows different types of FRP wrapping schemes used to increase the shear strength of rectangular beams, or columns. In situations where access to all four sides of a column is possible, completely wrapping the FRP system around the section on all four sides is the most efficient wrapping scheme. This is the most commonly used wrapping scheme in such situations. Most commonly used wrapping schemes to increase the shear strength in beam applications are wrapping the FRP system around three sides of the member (U-wrap) or bonding FRP to both the sides of the member.

Figure 6-2: Shear strengthening of: (a) beam end; (b) short column (FIB Bulletin 14, 2001)

Figure 6-3: Schematic illustration of reinforced concrete element strengthened in shear with FRP: (a) FRP sheets or fabrics bonded to the web; (b) wrapped or U-shaped FRP (the concept shown in D is applicable to both beams and columns) (FIB Bulletin 14, 2001).

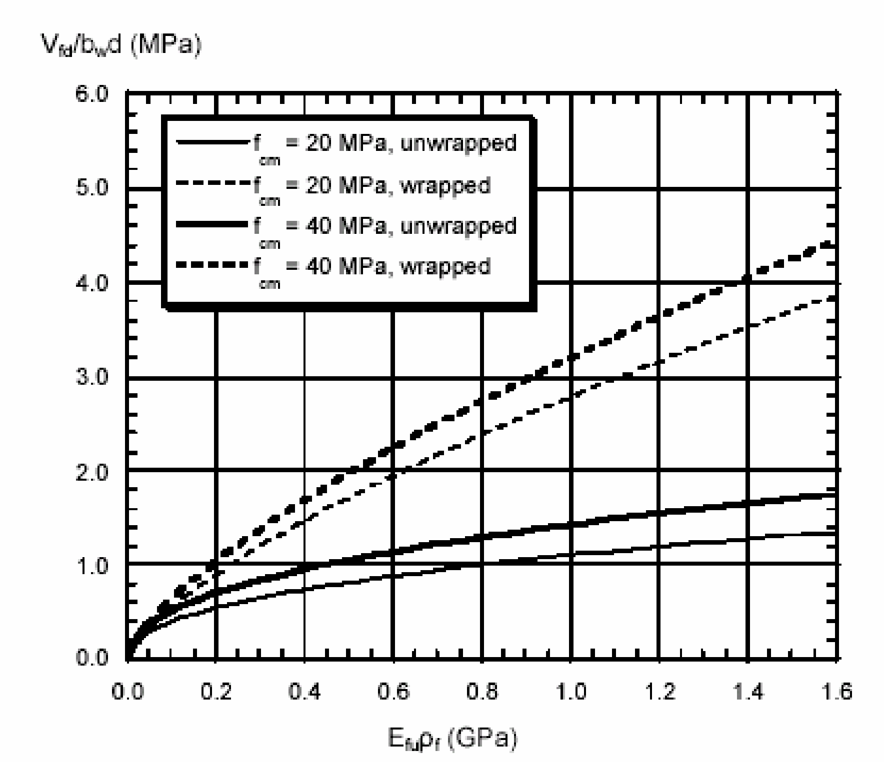


The three methods explained above increase the shear strength. However, completely wrapping is the most efficient, followed by the three-sided wrapping (U wrap) and the two sided wrapping. In all wrapping schemes, either the FRP system can be applied continuously along the span length of a member where exposure to moisture is minimized or as discrete strips. In situations where complete wrapping is infeasible, it is recommended that FRP system should be anchored to the compressive zone of RC member.

6.3 Shear Strength

From the studies carried out by Triantafillou (1998) and Triantafillou and Antonopoulos (2000), the behavior of FRP composites resemble that of internal steel. FRP carries only normal stresses in the direction of the principal material direction. In the ultimate limit state in shear (concrete diagonal tension), FRP system is stretched to an effective strain in the principal FRP material direction.

Figure 6-4: CFRP contribution to shear capacity for two different concrete strengths and fully wrapped (properly anchored) versus unwrapped configurations (FIB Bulletin 14, 2001)



From the CFRP shear strengthening results shown in Figure 6-4, the following conclusions can be made.

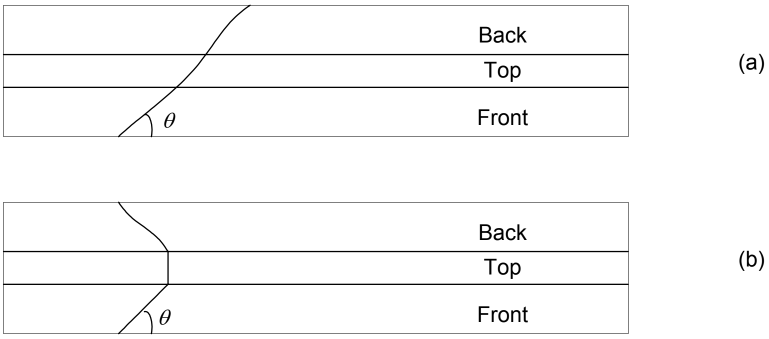
- If peeling-off combined with shear fracture (e.g. side or U jackets) governs the failure, concrete strength plays an important role while the shear capacity becomes of secondary importance; and
- If shear fracture combined with or followed by CFRP fracture (e.g. fully wrapped jackets) governs failure, the increase in shear capacity becomes important while the effect of concrete becomes a secondary issue.
- In the serviceability limit state, normally externally bonded FRO strips do not de-bond which is favorable in moisture penetration and crack propagation.

6.4 Strengthening in Torsion

Strengthening concrete structures in bending with external composite reinforcement is relatively common around the world. The shear strengthening applications using FRP are fewer and only a few examples of torsional strengthening has been so far published. This indicates that most likely the needs for strengthening a structure for torsion is not in great demand compared to strengthening in bending or shear. However, it may be required to increase torsional capacity of a box girder or a conventional beam or a column. A concrete structure loaded in torsion may be compared to a concrete structure affected by shear. Hence, the principles applied to strengthening in shear are also valid in the case of torsion. There are a few minor differences, which will be highlighted below.

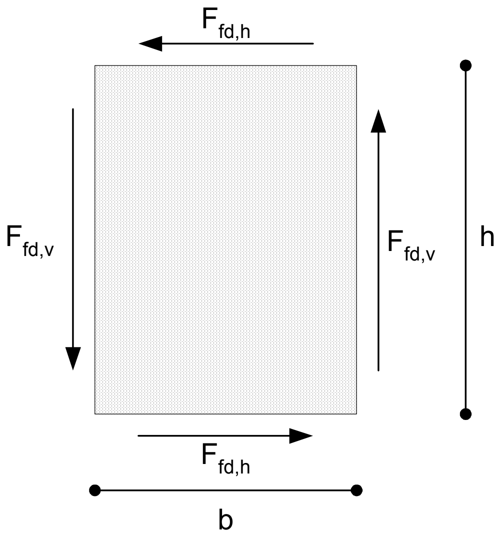
Cracks in concrete due to torsional loading usually follow the same mechanisms as concrete cracking under shear loading. However it is important to understand how a torsional fracture develops. The main difference between shear and torsional cracking, is that torsional crack forms a spiral patterns (Figure 6-5). The crack opens when the principal strains exceed the tensile strength of the concrete. Therefore when the FRP system is placed in such a way that forms an angle with member axis, one side is more susceptible to diagonal cracking than the other. In designing torsional strengthening using FRP, this point needs to be taken into account.

Figure 6-5: (a) Torsional and (b) shear cracking.



In the case of torsional strengthening of a concrete structure with fiber composites, it is assumed that the truss-model applies. However, the fiber composite is an anisotropic material. The placement of the fibers in relation to the principal strain direction must be considered. It is worth noting that only full wrapping scheme around the element's cross section would provide increased torsional capacity, so that the tensile forces carried by the FRP on each side of the cross section may form a continuous loop (Figure 6-6).

Figure 6-6: Forces carried by the FRP reinforcement



7 AXIAL COMPRESSION, TENSION AND DUCTILITY ENHANCEMENT

Until the early 1990s, constructing an additional reinforced concrete cage and installing grout injected steel jackets were the two common methods adopted for strengthening of a deficient RC column (Ballinger et al. 1993). Steel jacketing is more effective than caging, because the latter results in substantial increase in the cross-section area and self weight of the structure. Both methods are however, labor intensive and sometimes difficult to implement on site. In recent years, using FRP composites as a technique to strengthen RC columns has replaced steel jacketing.

Several experimental studies on concrete confined with FRP (Saadatmanesh et al. 1994, Nanni and Bradford 1995, Picher et al. 1996, Matthys et al. 1999, Candappa, 2000) have been carried out which confirm using FRP as a method of strengthening. Current analytical and numerical research (Mirmiran and Shahawy 1997, Saadatmanesh et al. 1994, Matthys et al. 1999, Lokuge et al., 2004) aims at defining the constitutive behavior of FRP-confined members. The most common form of FRP column strengthening involves the external wrapping of FRP sheets / straps.

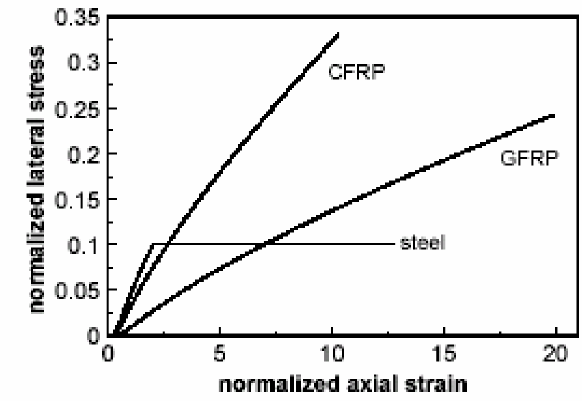
The strengthening of RC columns using steel or FRP jacketing is based on the well-established fact that lateral confinement of concrete can substantially enhance its axial compressive strength and ductility. In seismic problems, strengthening or retrofitting techniques are based on increasing the confinement pressure in either the potential plastic hinge region or over the entire member (e.g. Chai et al. 1991). In the field of design of FRP jackets extensive experimental work has been conducted by Seible et al. (1995), and numerical and analytical work by Monti et al. (2001), with the task of identifying suitable design equations that optimize the FRP jacket thickness as a function of the desired upgrading level. It should be emphasized that usually the increase in strength is not as significant as that in ductility. A recent review on the issue of upgrading through confinement may be found in Triantafillou (2001).

7.1 Axial Compression

Strength enhancement can be achieved by using steel confinement as well as FRP confinement. However FRP-confined concrete behaves differently from steel-confined concrete. Therefore already established design guidelines for steel confined concrete columns cannot be applied for FRP confined columns. As shown in Figure 7-1, the confinement actions provided by steel and FRP wrapping are different. This behavior is due to the linear behavior (without any yield points) of carbon fiber composites. After the initial linearly elastic phase, steel displays a yielding plateau. Therefore after reaching the maximum stress corresponding to yielding, the confining pressure remains constant. In the contrary, FRP wrapping continues to provide continuously increasing confining pressure until it fails (elastic behavior).

In designing the FRP strengthening system for columns, it is necessary to estimate the strength enhancement of concrete due to FRP composite confinement. This confining action depends on the strain in FRP composite which is same as the lateral strain of concrete (lateral dilation). Therefore the passive confining pressure provided by the externally bonded FRP composites depends on the lateral dilation of concrete. Therefore constitutive model for concrete which can predict the lateral dilation of concrete is ideal in estimating the passive confining pressure provided by the FRP composite. The concrete material model proposed by Lokuge et al., (2004), meets the above mentioned requirements. Moreover that model has been validated to give comparable results for the experimental test results reported by Candappa (2000) for concrete confined by FRP.

Figure 7-1: Comparison of confinement actions of steel and FRP materials (FIB Bulletin 14, 2001)

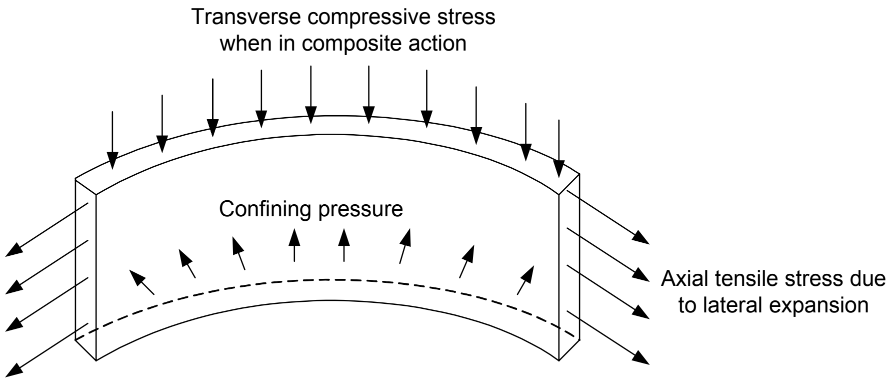


The maximum confining pressure provided by FRP composites is related to the amount and strength of FRP and the diameter of the confined concrete core. However, the ultimate strength of the confined concrete is closely related to the failure strain of the FRP wrapping reinforcement. As the FRP is subjected to tension in hoop direction, eventual failure occurs when its hoop tensile strength is reached. Many researchers (Lorenzis 2001) have noted that the strain measured in the confining FRP at rupture is in many cases lower than the ultimate strain of FRP tested for tensile strength. The recorded hoop strains corresponding to rupture had a range of 50 to 80% of the failure strain obtained in the tensile tests (Xiao and Wu 2000). This reduction is due to the following reasons:

- The triaxial state of stress of the wrapping reinforcement. The quality of the execution
- If the surface preparation for FRP application is not good enough, some part of the circumferential strain is used to stretch the fibers. Moreover, fibers may be damaged at improperly rounded edges or local protrusions
- The curve shape of the wrapping reinforcement
- Size effects when applying multiple layers

Figure 7-2 shows the concept of composite action, where the FRP jacket provides longitudinal load carrying capacity as well as lateral confinement (it undergoes both longitudinal and lateral strains). This behavior depends on the fiber arrangement and bond interface characteristics. The ultimate stress and strain are reduced with a possibility of micro-buckling and de-lamination. Therefore failure of the member occurs at a lower circumferential strain than in case of no composite action. In case of no composite action, the FRP jacket is subjected to lateral strain only and fails due to either fiber collapse or de-lamination between plies. This failure takes place at a circumferential strain lower than the ultimate strain.

Figure 7-2: Triaxial state of stress in FRP jackets



Depending on the loading condition (axial loading, shear and bending) the load-carrying capacity of the column should be calculated according to appropriate confinement models.

7.2 Tensile Strengthening

FRP composites can be used to provide additional tensile strength to concrete members. It depends on the design tensile strength of FRP and the ability to transfer stress into the substrate (Nanni et al. 1998). The tensile strength contribution of FRP can be directly calculated using Hooke's law because of its linear-elastic behavior.

7.3 Ductility

The collapse of and severe damage to many buildings and bridges in recent earthquakes have highlighted the need for the seismic retrofit of seismically inefficient structures. Most of the structural failures during recent earthquakes were attributed to poor column behavior. Figure 7-3 shows three photos of column failures during Kobe 1995 earthquake. These failures are due to inadequacy of confining reinforcement and bad detailing, which resulted in improper confinement. In concrete structures, the ability to withstand strong earthquakes depends mainly on the formation of plastic hinges and their capability of energy absorption and dissipation without a major loss of strength capacity. Within the plastic hinge, all the inelastic deformations are assumed to occur. The region outside the hinge is assumed to remain elastic at all times.

It is preferable to design structures with strong columns and weak beams with plastic hinges forming in the beams and not in columns. However, it may not always be possible to design structures like this, and hinges may develop in columns. Therefore the possibility of plastic hinge formation at concrete column ends demands a sufficient level of ductility to safeguard the structures in seismic areas. Therefore in performing a structural analysis for earthquake loadings, it is of great importance to design columns with sufficient level of ductility in order to minimize the chances of a possible failure.

Figure 7-3: Column failures in Kobe 1995 earthquake (EQE 1995).

Using steel reinforcement is the traditional method of increasing ductility. Recent advances in FRP technology have proven that FRP composites can be used to increase the ductility of concrete columns. Methods of improving ductility using FRP composites are described here in brief (Triantafillou 2001).

The purpose of seismic retrofit of RC columns is to achieve a sufficient level of deformation ductility to dissipate seismic energy before one of the failure modes becomes critical. The displacement ductility factor or the curvature ductility factor has been commonly used to quantify the ductility of the seismic performance of a structure. In order to achieve a target displacement ductility factor, μ_Δ, it is possible to find the thickness of the FRP jacket. The method is explained in FIB Bulletin 14, 2001 and is as follows.

Equivalent plastic hinge length Lp for a given column is calculated based on the yield stress and diameter of longitudinal rebars.

From Lp and μ_Δ the curvature ductility factor $\mu_\Phi = \Phi u / \Phi y$ is established.

Curvature ductility factor $\mu_\Phi = \Phi u / \Phi y$. Φy is the yield curvature and it may be found from moment-curvature analysis of the cross section, whereas Φu is the maximum curvature and it may be obtained (again from section analysis) in terms of the ultimate concrete strain.

Therefore ultimate concrete strain can be established and an appropriate confinement model can be used to determine the required FRP thickness.

Japanese researchers (Mutsuyoshi et al. 1999) have used a different method in estimating the displacement ductility factor for FRP confined columns. They have found that displacement ductility factor is related to the shear capacity Vu, and to the moment capacity Mu of the member after retrofitting.

8 USE OF FRP BARS AS PRIMARY REINFORCEMENT

Providing steel reinforcement in reinforced concrete structures is a commonly and traditionally used method to resist the tensile stresses. However, these steel bars can corrode due to various reasons. Improper design and workmanship, cover insufficiency can lead to cracking of concrete and adverse environmental conditions can ultimately lead to corrosion of steel bars. Corrosion of steel reinforcement in concrete structures (chloride ion or chemical corrosion) result in deterioration of the structures, costly maintenance and repair and reduction of the service life of the structure. Limited life span of reinforced concrete structures has been addressed in the past and a necessity arises to investigate methods of prevention of corrosion or use of non-corrosive reinforcement.

Fiber Reinforce Polymer (FRP) bars have been identified as a prospective substitute for steel reinforcement as FRP materials are nonmetallic, non-corrosive and they have a high tensile strength and are light weight. The commonly used FRP bars are CFRP, GFRP and AFRP. Apart from using FRP instead of steel reinforcement, it has been proposed that they can be used as steel pre-stressing tendons in pre-stressed concrete structures (ACI 440R 1996). It is reported that FRP is used in situations where electrical or magnetic transparency is required (FRP Reinforcing Bar web site). FRP bars have been identified as a promising solution to the corrosion problems associated with steel reinforcement in concrete structures. They can be used in marine structures, parking structures, bridge structures under adverse environmental conditions and where magnetic fields are present.

Standards and design guidelines for the provision of FRP bars in concrete structures for bridges and buildings have been prepared recently (ACI 440H 2000; CSA 2000; ISIS-Canada, 1998 and 2001, CEM, 2002).

Fiberglass rebar may be a suitable alternative to steel reinforcing as shown in CEM (2002):

- Architectural Concrete: cast stone, architectural cladding, balusters, column facades, window lentils, architectural pre-cast elements, hand railing, and statuary and fountains, etc.
- Concrete exposed to de-icing salts in: bridge decks, railroad grade crossings, median barriers, parking garage elements, and salt storage facilities, etc.
- Concrete exposed to marine salts in: seawalls, water breaks, buildings & structures near waterfront, aquaculture operations, and floating marine docks, etc.
- Concrete used near electromagnetic equipment such as: MRI rooms in hospitals, airport radio & compass calibration pads, and concrete near high voltage cables, transformers, substations, etc.

Figure *8-1* shows use of GFRP rebars in construction of Sierrita de la Cruz Creek Bridge, RM1061 Amarillo Texas.

Figure 8-1: Use of GFRP rebars in construction of Sierrita de la Cruz Creek Bridge, RM1061 Amarillo Texas (Aslan FRP, 2004)

8.1 Applications of FRP bars

FRP bars have been originally applied as non-magnetic or radio-frequency transparent reinforcements for magnetic resonance imaging (MRI) medical equipment and for specialized defense applications. FRP composite rebar application has emerged about twenty five years ago. Deterioration of the concrete structures has lead US, Europe and Japan to investigate FRP composite rebar as an alternative to steel reinforcement. According to ACI 440H, the Japanese lead in this field, with more than 100 demonstration projects reported in the literature. Publication of ACI440.1R-01 Guide for the Design and Construction for Concrete Reinforced with FRP bars paved the way for practicing engineers to use this newly developed FRP bars.

8.2 Design Considerations

A direct substitution of FRP reinforcing bars instead of steel bars is impossible due to many differences in the mechanical properties of the two materials. Fiber reinforced polymer bars are anisotropic materials. Factors such as type and volume of fiber and resin, fiber orientation and quality control during the manufacturing play a major role in the mechanical characteristics.

- FRP composites show a linear elastic behavior until failure and no ductility. This is contrary to the steel which shows yielding.

- ACI Committee 440 recommends a minimum amount of FRP rebar. The concrete will be the weak link and the member will fail in concrete crushing in compression. At this stage FRP will still hold a good tensile strength. In traditional steel reinforcement design, steel yielding prior to crushing of concrete is ensured by provisions in standard design codes.

- Another major difference is that serviceability will be more of a design limitation in FRP reinforced members than in steel reinforced members. Due to its lower modulus of elasticity, deflection and crack width will affect the design. Deflection and crack width serviceability requirements will provide additional warning of failure prior to compression failure of the concrete.

- Service limits in FRP reinforced concrete elements such as deflection, crack width and crack spacing are directly influenced by the bond properties of the reinforcement in concrete.

- FRP reinforced concrete member is normally designed based on its required strength and then checked for serviceability and ultimate state criteria (e.g., crack width, deflection, fatigue and creep rupture endurance).

9 SUMMARY OF THE STRENGTHENING TECHNIQUES

Table 9-1 presents summary of strengthening techniques, which are covered in this report. The type of FRP, design actions and special need of each technique are also tabulated.

Table 9-1: Summary of strengthening techniques

Strengthening Method	Design Action	Type of FRP	Special Considerations
Wet lay up of FRP sheets to the tension zone of the soffit of a beam or slab	Flexural strengthening	Sheets or strips	De-bonding
Attaching prefabricated FRP sheets to the tension zone of the soffit of a beam or slab	Flexural strengthening	Sheets or strips	De-bonding
The different types of wrapping schemes to increase the shear strength of a beam or column	Shear strengthening	Sheets	Direction of fibres
Automated winding of wet fibers under a slight angle around columns or other structures,	Shear and axial compression strengthening	Sheets	Equipment availability
Attaching prestressed FRP strips to the tension zone of the soffit of a beam or slab	Flexural strengthening	Strips	Anchorage
Fusion-bonded pin-loaded straps	Flexural and shear strengthening	Pin-loaded Straps	Equipment availability
In-situ fast curing using heating device	Flexural strengthening	Strips	-
Prefabricated U or L shape strips for shear strengthening	Shear strengthening	Strips	Direction of fibres
Bonding FRP strips inside concrete slits	Flexural strengthening	Strips	Crack initiation
FRP impregnation by vacuum to the tension zone of the soffit of a beam or slab	Flexural Strengthening	Strips	Equipment availability
Prefabricated FRP shells or jackets for the confinement of circular or rectangular columns	Axial compression strengthening and ductility enhancement	Sheets	Confining pressure will be different to that of steel
FRP wrapping for axial compression strengthening and ductility enhancement	Axial compression strengthening and ductility enhancement	Sheets	Confining pressure will be different
FRP wrapping for torsional strengthening	Torsional strengthening	Sheets	Direction of fibres

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