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Applications of Fibber Reinforced Polymer Composites (FRP) in Civil Engineering

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Abstract: There is a growing concern with worldwide deterioration of traditional materials such as concrete, steel, and timber. Recently, attention has shifted to the use of fiber reinforced polymer composites (FRPs) as alternative materials. As FRPs are non-corrosive, high strength and modulus values compared to their density, light weight, acceptable deformability, tailored design and excellent formability enable the fabrication of new elements and the structural rehabilitation of the existing parts made of traditional materials. Furthermore, the resistance of FRP materials to corrosion means that they can be used to replace steel and reinforced concrete in situations when they would be exposed to corrosion. FRP therefore has wide application prospects in civil engineering ranging from reinforcing rods and tendons, wraps for seismic retrofit of columns and externally bonded reinforcement for strengthening of walls, beams, and slabs, to all-composite bridge decks, and even hybrid and all-composite structural systems. This paper is a review of the application of FRPs in civil engineering. Firstly, the paper will elucidate the basic information about FRP composites, including the definition, description of the components such as fibers and matrices. Then it pointed some fabrication processes, mechanical properties. Finally, it will focus on the application of FRP in civil engineering.

Keywords: *FRP, Composite, Reinforcement, Matrix, Rehabilitation.*

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1. Introduction:

Fiber-reinforced polymer composite materials (FRP) have hitherto been utilized predominantly in the aerospace and military industries, but for the last three decades there has been a growing awareness amongst civil engineers of the importance of the unique mechanical and in-service properties of these materials together with their customized fabrication techniques. In fact, this class of materials presents an immense potential for use in Civil Engineering, both for rehabilitation of existing structures and for the construction of new facilities (Lopez-Anido *et al.* 2000).

Polymer composites are multi-phase materials produced by combining polymer matrix with fillers and reinforcing fibers to produce a bulk material with properties better than those of the individual base materials. The matrix can be thermoplastics (Polypropylene, polyethylene, polystyrene, PVC (polyvinyl chloride) etc.) or thermosetting (Polyester, vinyl ester, epoxy resins etc.). Fillers are often used to bulk to the material, reduce cost, lower bulk density or to produce aesthetic features. Fibers are used to reinforce the polymer and improve mechanical properties such as stiffness and strength. High strength fibers of glass, aramid and carbon are used as the primary means of carrying load, while the polymer matrix protects the fibers and binds them into a cohesive structural unit. These are commonly called fiber-reinforced polymer composite materials (FRPs).

Advanced composite materials have found expanded use in aerospace, marine and automobile industries during the past few decades (1960 onwards) due to their good engineering properties such as high specific strength and stiffness, lower density, high fatigue endurance, high damping and low thermal coefficient (in fiber direction), etc. Recently, civil engineers and the construction industry have begun to realize potential of composites as strengthening material for many problems associated with the deterioration of infrastructures. Over the last decade, an increase in the application of FRPs has been seen in construction industry because of their good engineering properties. Further, these are being considered as a replacement to the conventional steel in reinforced concrete structures due to continuing drop in the cost of FRP materials. Various aspects of FRPC materials including guidelines for selection of polymer adhesives for concrete have been highlighted by ACI Committee-503 (1992) and Uomoto et al. (2002). Issues related to selection of materials have also been discussed by Karbhari (2001). Einde et al. (2003) and Bank et al. (2003) have presented a summary of applications of FRP material in civil engineering whereas general design guidelines for FRP application can be found in Bakht et al. (2000), ACI Committee 440 (2002) and Nanni (2003).

Use of FRP sheets for strengthening and rehabilitation of concrete structures has attracted considerable interest *(Nanni et al. 1993, Mufti at al. 2002, Hollaway et al. 2003, Mufti et al. 2003)*. First applications of composites were in the form of rebars and structural shapes. Later, FRP laminates were used for strengthening of concrete bridge girders by bonding them to the tension face of girder (Meier *et al.* 1992) as well as for retrofitting of concrete columns (Saadatmanesh 1994).

FRPs are available in the form of rods, grids, sheets and winding strands. Review of literature up to 1996 can be found in ACI Committee 440 (1996). Another general review on class of materials including FRPs used in civil construction was presented by Bakis et al. (2002). They divided the whole review into structural shapes, internal reinforcement, externally bonded reinforcement, bridge, standards and codes. A review on shear strengthening of RC beams with FRPCs was done Deniaud and Cheng (2001), Bousselham and Chaallal (2004). Review related to the bond-slip model for FRP sheet/plate bonded to concrete have presented recently by Lu et al. (2005) and review for upgrading of beam-column joints with FRP can be found in Engindeniz et al. (2005). A large volume of literature now exists on applications of FRPs in construction industry.

2. Fiber reinforced polymer composites (FRP):

For An FRP is a specific type of two-component composite material consisting of high strength fibers embedded in a polymer matrix. The mechanical and physical properties are clearly controlled by their constituent properties and by the micro-structural configuration. While the fibers are mainly responsible for strength and stiffness properties, the polymeric matrix contributes to load transfer and provides environmental protection. In addition, fillers are used to reduce the cost and sometimes to improve performance, imparting benefits as shrinkage control, surface smoothness and crack resistance. Additives and modifiers ingredients can expand the usefulness of the polymeric matrix, enhance their processability or extend composite durability.

The reinforcing of a low modulus polymeric matrix with high strength and modulus fibers utilizes the viscoelastic displacement of the matrix under stress to transfer the load to the fiber; this result in a high strength, high modulus composite material. The aim of the combination is to produce a two phase material in which the primary phase, that determines stiffness, is in the form of fibers and is well disperse and bonded and protected by a weak secondary phase, the polymeric matrix (Hollaway and Head 2001).

2.1 Reinforcing Fibers:

The fibers provide the strength and stiffness of an FRP. Because the fibers used in most structural FRP applications are continuous and are oriented in specified directions, FRPs are orthotropic, and they are much stronger and stiffer in the fiber direction(s). According to Halliwell (2000), the functional requirements of fibers in a composite are:

i. High modulus of elasticity to give stiffness
ii. High ultimate strength
iii. Low variation of strength between individual fibers
iv. Stability during handling
v. Uniform diameter

Generally fiber can be used in different ways, with the performance changing for each (Cripps 2002):

- The highest performance in terms of strength and stiffness in one direction comes from unidirectional composites, when fibers are parallel and give their maximum possible performance in this single direction,
- By arranging the fibers in a weave or mat, strength can be gained in more directions, although the limit strength is reduced,
- By chopping the fibers into short lengths and arranging them randomly, equal strength is achieved in all directions. This is generally the cheapest technique, used for the least structurally demanding cases.

Many different types of fibers are available for use, and all have their respective advantages and disadvantages. In civil engineering applications, the three most commonly used fiber types are glass, carbon (graphite), and to a lesser extent, aramid (Kevlar). The suitability of the various fibers for specific applications depends on a number of factors including the required strength, the stiffness, durability considerations, cost constraints, and the availability of component materials.

2.1.1 Glass fibers:

Glass fibers are commonly produced by a process called direct melt, wherein fibers with a diameter of 3 to 25 microns are formed by rapid and continuous drawing from a glass melt. Glass fibers are used for the majority of composite application because they are cheaper than the others. There are different forms known by names like E-glass (the most frequent used), S-glass (is a stringer and stiffer fiber with a greater corrosion resistance), R-glass (is a higher tensile strength and modulus and greater resistance to fatigue and aging) and AR-glass (an alkali-resistant glass used to reinforced concrete). The main characteristics of glass fibers are their high tensile strengths and moderate elastic modulus. Glass fibers are, also, excellent thermal and electrical insulators. Glass fibers are particularly sensitive to moisture, especially in the presence of salts and elevated alkalinity, and need to be well protected by the resin systems used in the FRP. Glass fibers are also susceptible to creep rupture and lose strength under sustained stresses.

2.1.2 Carbon fibers:

Carbon fibers are produced by a process called controlled pyrolysis, wherein one of three potential precursor fibers is subjected to a complex series of heat treatments (stabilization, carbonization, graphitization, and surface treatment) to produce carbon filaments with diameters in the range of 5-8 microns. The resulting fibers can have properties that vary widely, and so several classes of carbon fibers are available, differentiated based on their elastic moduli: Standard: 250-300 GPa, Intermediate: 300-350 GPa, High: 350-550GPa, Ultra-High: 550-1000 GPa. Although considerably more expensive than glass fibers, carbon fibers are beginning to see widespread use in structural engineering applications such as pre-stressing tendons for concrete and structural FRP wraps for repair and strengthening of reinforced concrete beams, columns, and slabs. Their steadily increasing use can be attributed to their steadily decreasing cost, their high elastic moduli and available strengths, their low density (low weight), and their outstanding resistance to thermal, chemical, and environment effects, they do not absorb moisture. Carbon fibers are an ideal choice for structures which are weight and/or deflection sensitive.

2.1.3 Aramid fibers:

Aramid fibers are manufactured from a synthetic compound called aromatic polyamide in a process called extrusion and spinning. In this fiber, molecular chains are aligned and made rigid by means of aromatic rings linked by hydrogen bridges. Their main characteristics are high strength, impact resistance due to their energy absorbing capacity properties, moderate modulus and low density. In addition, FRPs manufactured from aramid fibers have low compressive and shear strengths as a consequence of the unique anisotropic properties of the fibers. The fibers, themselves, are susceptible to degradation from ultraviolet light and moisture but exhibit resistance to acids and alkalis.

2.1.4 Basalt fibers

Basalt fibers are materials obtained by melting crushed volcanic lava deposits. Basalt fibers have better physical and mechanical properties than glass fibers, but are significantly cheaper than carbon fibers. Their main advantages are fire resistance, significant capability of acoustic insulation and immunity to chemical environments.

Table 1 illustrates typical properties of the different types of fibers and steel, showing their strength, modulus and density.

Table 1*: Range of properties for fibers for FRP composites*

Fiber type	Density (Kg/m³)	Tensile strength (GPa)	Elastic Modulus (GPa)
Glass	2.46 – 2.58	2.4 – 3.5	72 – 87
Carbon	1.74 – 2.20	2.1 – 5.5	200 – 500
Aramid	1.39 – 1.47	3.1 – 3.6	58 – 130
Basalt	2.65 – 2.80	4.2 – 4.8	89 – 110
Steel	7.85	480 – 700	200

Other fibers that are now in the development phase for use if FRP products for structural engineering include ultrahigh-molecular-weight polyethylene fibers and polyvinyl alcohol fibers. Natural fibers, such as sisal, flax and bamboo, have been used only in experimental applications to produce FRP products. However, it is expected that they will become more important in the construction industry due to their sustainability and recyclability (Bank 2006).

2.2 Matrix:

The matrix is the binder of the FRP and plays many important roles. Some of the more critical functions played by the matrix are:

- To bind the fibers together
- To protect the fibers from abrasion and environmental degradation
- To separate and disperse fibers within the composite
- To transfer force between the individual fibers and
- To be chemically and thermally compatible with the fibers.

According to Hollaway and Head (Elsevier 2001), the requirements for a good FRP matrix are the following:

i. Wet out the fiber and cure satisfactory in the required conditions
ii. Bind together the fibers and protect their surface from abrasion and environmental ageing
iii. Disperse the fibers as separate them in order to avoid any catastrophic propagation of cracks
iv. Transfer stresses to the fibers efficiently
v. Be chemically and thermally compatible with fibers
vi. Have appropriate fire resistance and limit smoke propagation
vii. Provide good aesthetic finish (color and surface).

There are several different polymer matrices which can be utilized in FRP composites, but in construction industry only a relatively small number are actually used. According to their nature, there are two major types of polymers, which determine the methods of manufacturing and the properties of the composite: (i) thermoplastic and (ii) thermosetting. The first FRP were all based on thermosetting polymers and, besides the fact that thermoplastic have seen rapid growth in recent years, thermosetting is yet the most used in Civil Engineering applications (ACI 440R 1996).

2.2.1 Thermoplastic Matrix

Thermoplastics are polymers composed of long-chain molecules that are held together by relatively weak Van der Waals forces, but that have extremely strong bonds within individual molecules. These polymers can be amorphous, which implies a random structure with a high concentration of entanglement, or crystalline, with a high degree of molecular order (Cowie 1991). In these materials, the molecules are free to slide over one another at elevated temperatures, and so thermoplastics can be repeatedly softened and hardened by heating and cooling without significantly changing their molecular structure. The semi-crystalline polypropylene and nylon are especially popular as matrices.

2.2.2 Thermosetting Matrix

Thermosetting polymers are also long-chain molecules built from monomers, but for these materials the molecular chains are cross-linked through primary chemical bonds. Thus, thermosets cannot be reversibly softened and will deteriorate irreversibly at elevated temperatures. These are usually made from liquid or semi-solid precursors which harden irreversibly; this chemical reaction is known as cure and on completion, the liquid resin is converted to a hard solid by chemical cross-linking which produces a tightly three-dimensional network of polymer chains. Almost exclusively, thermosets are currently used in structural engineering applications. These polymers generally have good thermal stability at service temperatures, good chemical resistance, and display low creep and relaxation properties in comparison with most thermoplastics. However, because it is difficult to reversibly soften thermosets, FRP components made from thermosets matrices must be bent or formed during the manufacturing process. This may become a problem in some specific applications. For example, FRP reinforcing bars for concrete that incorporate thermosetting polymer resins cannot be bent on site, and research is currently underway to develop satisfactory thermoplastic matrices for these specialized applications.

Three specific types of thermosetting resins are commonly used in the manufacture of infrastructure composites: polyester resin, epoxy resin and vinylesters resin.

2.2.2.1 Polyester Resin:

Polyesters are the most widely used polymers in the manufacture of FRP components for infrastructure applications due to their relatively low cost and ease of processing (these resins cure at ambient temperatures). Numerous specific types of polyesters are available for use, with varying degrees of thermal and chemical stability, moisture absorption, and shrinkage during curing.

2.2.2.2 Epoxy Resin:

Epoxies are often used in wet lay-up applications of FRP plates and sheets because of their ability to cure well at room temperature and owing to their outstanding adhesion (bonding) characteristics. Epoxies have high strength, good dimensional stability, relatively good high-temperature properties, strong resistance to chemicals (except acids), and superior toughness. Epoxies, however, cost significant more than polyesters or vinylesters

2.2.2.3 Vinylester Resin:

Vinylesters have similar mechanical and in-service properties to those of the epoxy resins and equivalent processing techniques to those of the unsaturated polyesters. Vinylesters are resistant to strong acids and alkalis, which is one reason that they are commonly used in the manufacture of FRP reinforcing bars for concrete (the environment inside concrete is highly alkaline). They also offer reduced moisture absorption and shrinkage as compared with polyesters. Vinylesters cost slightly more than polyesters.

2.3 Fabrication of FRP Composites:

There is a wide variety of techniques by which FRP composites can be fabricated, although there are differences between the techniques available for thermosetting and thermoplastic, due to their intrinsic different properties. Table 2 presents the commonly used process for fabrication of FRP composites applied in Civil Engineering, heir principles and typical applications (Cripps 2002).

Table 2*: Fabrication processes of FRP composites*

Pultrusion	Tightly packed tows of fibers, impregnated with polymer, are pulled through a shaped heated die to form aligned, continuous sections geometry. Solid and hollow profile section may be produced with a high fiber content and high degree of fiber alignment. Off-axis fibers may also be introduced, if required. Pultruded shapes and concrete reinforcing bars and tendons; I beams and other sections.
Filament Winding	The process involves winding fibers over a mandrel which rotates while a moving carriage laying down the reinforcement in the desired pattern. The orientation of the fibers can also be carefully controlled so that successive layers are plies or oriented differently from the previous layer. Cylindrically symmetric structures such as hollow and vessels. The process of wrapping in retrofit strengthening is an adaptation of the process.
Compression and Transfer Moulding	Compression moulding of thermosetting moulding compounds in dough with chopped glass fibers (DMC) or sheets with longer fibers (SMC). Simple or complex decorative panels.
Matched-die Moulding and Autoclave	Large panels and relatively complex open structural shapes are constructed by hot-pressing shets of pre-impregnated fibers or cloths between flat or shaped platens, or by pressure autoclaving to consolidate a stack of prepreg sheets against a heated, shaped die. Composite reinforced with chopped-strand mat or continuous-filament mat reinforcements may also be press-laminated. Laminates and retrofit strengthening sheets.

Continuous Sheet Production	Chopped strand mat or chopped strands are impregnated with resin and sandwiched between two layers of film on a moving belt. The sandwich passes through guides tha form the corrugated or other desired profile. Corrugated plates.
Resin Transfer Moulding and Vacuum-assisted resin transfer moulding	Pre-catalysed resin is pumped under low pressure into a fiber perform, which is contained in a closed and often heated die. The preform may be made of any kind of reinforcement, but usually consists of woven cloths or continuous-fibers mats. Structural components with varying shapes and degrees of anisotropy/orthotropy, e.g. cladding and roofing panels, shell structures and bridge decks.
Contact moulding by hand lay-up or spray-up	Open mould methods, where fiber continuous strand mat and/or other fabrics such as woven roving are placed manually in the mould and each ply is impregnated with brushes and rollers. The product must also be built by spraying through a gun which simultaneously delivers short fiber and pre-catalysed resin. Fabrication one-off structures, small number of large components.

2.4 Mechanical Properties of FRP Composites:

The mechanical properties of an FRP depend on a number of factors including:

- The relative proportions of fiber and matrix
- The mechanical properties of the constituent materials (fiber, matrix, and any additives)
- The orientation of the fiber within the matrix, and
- The method of manufacture.

The Young’s modulus and tensile strength of composites are lower than that of fibers alone. The volume fraction of fibers normally ranges between 50-65%. Thus each FRP composite has its own typical mechanical characteristics which make it suitable for a given structural application. Glass fibers are considerably cheaper than carbon fibers but some forms of this fiber tend to be very sensitive to the alkaline environments of concrete. Glass fibers also have a lower elastic modulus than carbon fibers. A comparison of mechanical properties of FRP with steel is provided in Table 3 (Mufti 1991).

***Table 3**: Typical comparative properties of FRP and steel.*

Material	Tensile Strength (MPa)	Modulus of Elasticity (MPa)
Glass-Epoxy	1050	55000
Carbon-Epoxy	1500	180000
Aramid-Epoxy	1400	76000
Steel	400-1000	200000

Regardless of the type of fibers employed, FRP materials have similar stress-strain behavior: linear elastic up to final brittle rupture when subject to tension, which means that they do not possess the ductility that steels have, and their brittleness limit the ductile behavior of RC members strengthened with FRP composites. Nevertheless, when used to provide confinement for concrete, these materials can greatly enhance the strength and ductility of columns.

Polymeric resins are used both as the matrix for the FRP and as the bonding adhesive between the FRP and the concrete. The latter function is of particular concern here, as weak adhesives can cause interfacial failures. Epoxy resins are generally used when the bonding function of resins is of crucial importance, as in the flexural and shear strengthening of beams. Present-day epoxy resins are so strong that interfacial failures generally occur in the concrete, particularly as the concrete in the structure to be strengthened is comparatively weak.

Some commonly available FRPs used in concrete reinforcing applications, and their respective properties, are listed in Tables 4 and 5. Table 6 provides a comparison between various types of FRPs and conventional reinforcing materials for concrete. From this data it is evident that both glass and aramid FRPs have moduli that are considerably less than steel in the pre-yield zone, but that carbon FRPs have moduli that are comparable to, or even higher than, steel in some cases. Also evident from the data is the fact that FRPs have ultimate strengths that can be many times greater than steel.

2.5 Environmental Durability:

FRP materials are increasingly being used in civil engineering applications such as reinforcing rods and tendons, wraps for seismic retrofit of columns, externally bonded reinforcement, composite bridge decks, and even hybrid and all composite structural systems. Since FRP are still relatively unknown to the infrastructure system planner, there are heightened concerns related to the overall durability of these materials, especially as related to their capacity for sustained performance under harsh and changing environmental conditions under load (Karbhari 2007).

Table 4: *Selected properties of typical currently available FRP reinforcing products*

Reinforcement Type	Designation	Diameter (mm)	Area (mm²)	Tensile Strength (MPa)	Elastic Modulus (GPa)
Deformed Steel	#10	11.3	100	400*	200
V-ROD CFRP Rod	3/8	9.5	71	1431	120
V-ROD GFRP Rod	3/8	9.5	71	765	43
NEFMAC GFRP Grid	G 10	N/A	79	600	30
NEFMAC CFRP Grid	C 16	N/A	100	1200	100
NEFMAC AFRP Grid	A 16	N/A	92	1300	54
LEADLINE™ CFRP Rod	Round	12	13	2255	147

*specified yield strength

Table 5: *Selected properties of typical currently available FRP strengthening systems**

FRP System	Fiber Type	Weight (g/m²)	Thickness (mm)	Tensile Strength (MPa)	Tensile Elastic Modulus (GPa)	Strain at Failure (%)
Fyfe Co. LLC (www.fyfeco.com)						
Tyfo SHE-51	Glass	930	1.3	575	26.1	2.2
Tyfo SCH-35	Carbon	-	0.89	991	78.6	1.3
Mitsubishi (www.mitsubishichemical.com)						
Replark	Carbon	200	0.11	3400	230	1.5
Replark 30	Carbon	300	0.17	3400	230	1.5
Replark MM	Carbon	-	0.17	2900	390	0.7
Replark HM	Carbon	200	0.14	1900	640	0.3
Sika (www.sika.com)						
Hex 100G	Glass	913	1.0	600	26.1	2.2
Hex 103C	Carbon	618	1.0	960	73.1	1.3
CarboDur S	Carbon	2240	1.2-1.4	2800	165	1.7
CarboDur M	Carbon	2240	1.2	2400	210	1.2
CarboDur H	Carbon	2240	1.2	1300	300	0.5
Degussa Building Systems (www.wabocorp.com)						
MBrace EG 900	Glass	900	0.35	1517	72.4	2.1
MBrace CF 530	Carbon	300	0.17	3500	373	0.94
MBrace AK 60	Aramid	600	0.28	2000	120	1.6

*Additional information can be obtained from the specific FRP manufacturers

Table 6: *Comparison of typical approximate properties for reinforcing materials for concrete***

Property	Steel Rebar	Steel Tendon	GFRP Rebar	CFRP Tendon	AFRP Tendon
Tensile Strength (MPa)	483-690	1379-1862	517-1207	1200-2410	1200-2068
Yield Strength (MPa)	276-414	1034-1396	N/A	N/A	N/A
Tensile Elastic Modulus (GPa)	200	186-200	30-55	147-165	50-74
Ultimate Elongation (%)	>10	>4	2-4.5	1-1.5	2-2.6
Compressive Strength (MPa)	276-414	N/A	310-482	N/A	N/A
CTE* (10^{-6}/°C)	11.7	11.7	9.9	0	-1 – 0.5
Specific Gravity	7.9	7.9	1.5-2.0	1.5-1.6	1.25

**FRP materials are continually being developed with better properties. The properties given are circa 2000.
*coefficient of thermal expansion (CTE)materials.

Although FRP have been successfully used in the industrial, automotive, marine and aerospace sectors, there are critical differences in loading, environment and even the types of materials and processes used in these applications. Several evidences provides substantial reason to believe that if appropriately designed and fabricated, these materials can grant longer lifetimes and lower maintenance costs than equivalent structures fabricated from conventional materials (Karbhari 2007).

FRP materials used in civil infrastructure are exposed to a variety of environmental that may act individually or may be synergistic in nature. According a recent study undertaken to identify critical gaps in durability of composites to be used in civil engineering applications (Karbhari *et al.* 2003), seven factors were distinguish, namely:

i. Moisture/solution
ii. Alkali
iii. Thermal, including cycling and freeze-thaw
iv. Creep and relaxation
v. Fatigue
vi. Ultraviolet radiation
vii. Fire.

3. Applications:

Over the last decade there has been significant growth in the use of FRP composites as constriction material in structural engineering. These materials have proven themselves to be valuable for use in the construction of new buildings and bridges and for the upgrading of existing structures (Bank 2006).

3.1 Rehabilitation:

Majority of rehabilitation works consist of repair of old deteriorating structures, damage due to seismic activities and other natural hazards. Structural strengthening is also required because of degradation problems which may arise from environmental exposure, inadequate design, poor quality construction and a need to meet current design requirement. Therefore, structural repair and strengthening has received much attention over the past two decades throughout the world (Karbhari *et al.* 2003). Therefore, there is an urgent need for development of effective, durable and cost-efficient repair, strengthening and retrofit materials and methodologies (Hollaway and Head 2001).

Generally, FRP composites can be utilized for structural rehabilitation in the following situations (Bakis *et al.* 2002):

- Deficiencies at the design stage, including: design errors, inadequate factors of safety, use of inferior class materials and poor construction quality.
- Change of use, in service, namely, increased safety requirements (upgrading of structural design standards), modernization that causes redistribution of stresses and increase of the applied load.
- Ageing of materials that compromise the load capacity of the structure: for example concrete degradation in hostile marine or industrial environments.
- Accidents, as fire or seismic events.

There are two possible alternatives to restore a deficient structure to the required standard; these are complete or partial demolition and rebuild, or beginning of a programme of strengthening (ACI 364.1R 1994).

Within the scope of rehabilitation of concrete structures, it is essential that differentiation is made between repair, strengthening and retrofit terms which are often erroneously used interchangeably (Hollaway and Head 2001):

- In “repairing” a structure, the FRP composite is used to fix a structural or functional deficiency such as a crack or a severally degraded structural component.
- The “strengthening” of structures is specific to those cases wherein the addition or the addition or application of the FRP composite would enhance the existing designed performance level.
- The term “retrofit” is used to relate to the seismic upgrades of facilities.

3.1.1 Repair and Strengthening:

***Figure 1**: Repair and strengthening.*

Repair with FRP composites has been used successfully on concrete, timber, metal and masonry structures. The predominant role of concrete as a structural construction material simulated the application of FRP composite in repairing of concrete structures, namely, bridges and large structural elements (Guideline No. 03742, 2006, Documents Scientifiques et Techniques, 2001).

The basic FRP strengthening technique, which is most widely applied, involves the manual application of either wet lay-up or prefabricated systems by means of cold cured adhesive bonding. Common in this techniques is that the external reinforcement is bonded onto the concrete surface with the fibers as parallel as practically possible to the direction of principal tensile stresses. Besides the basic techniques, several special techniques have been developed, namely the automated wet lay-up wrapping (of columns or chimneys, for example), use of pre-stresses FRP (to close open cracks in bridge decks, for example) (FIB Bulletin 14 2001). Near-surface mounted (NSM) technique may also be thought as a special method of reinforcement of concrete structures. In the NSM method, grooves are first cut into the concrete cover and the FRP reinforcement, usually a laminate strip, is bonded therein with appropriate groove filler, typically epoxy paste or cement grout.

3.1.2 Seismic Retrofit:

The problem of structural deficiency of existing constructions is especially acute in seismic regions, as, even there, seismic design of structures is relatively recent. The enhancement of confinement in structurally deficient concrete columns in seismically active regions of the world has proven to be one of the most significant applications of FRP materials in infrastructure applications (FIB Bulletin 35 2006).

Seismic retrofit of reinforced concrete structures, namely bridges, using conventional steel techniques, whilst effective, has been found to be time consuming, cause significant traffic disruption, rely on field welding and is susceptible o corrosion. Additionally, many of the methods increase the stiffness and strength capacity of the columns putting adjacent structural elements at risk from higher transmitted seismic forces. The use of FRP composites in this application (figure 2), not only provides a means of confinement, without the associated increase in stiffness, but also enables the rapid fabrication of cost effective and durable jackets with little traffic interference.

Figure 2*: Seismic retrofitting of a bridge with FRP composites.*

3.2 Concrete Structures Reinforced with Fiber Composites:

Concrete reinforced with fiber reinforced polymer (FRP) materials has been under investigation since the 1960’s. The predominant role of concrete as a construction material and the problems associated with corrosion of steel reinforcement stimulated the development of fiber composites for internal (ACI 440.1R 2003, FIB Bulletin 40, 2007) and external (FIB Bulletin 14, 2001, ACI 440.2R 2002) reinforcement of concrete and pre-stressing cables and tendons (ACI 440.4R 2004). Unstressed FRP reinforcement has been developed in a number of forms including ribbed FRP rod similar in appearance to deformed steel reinforcing bar, undeformed E-glass and carbon fiber bar bound with polyester, vinylester or epoxy resin, E-glass mesh made from flat FRP bars and prefabricated reinforcing cages using flat bars and box sections (Gowripalan 1999). Stressed FRP reinforcement is also available, usually consisting of bundles of rods or strands of fiber-reinforced polymer running parallel to the axis of the tendon. These are used in a similar fashion to conventional steel tendons (Gowripolan 2000).

The durability performance of FRP reinforcements is considered by some (Gowripalan 1999, Ko *et al.* 1997) to offer a possible solution to the problem of corrosion of steel reinforcement, a primary factor in reduced durability of concrete structures. Other reported advantages of FRP rebar include enhanced erection and handling speeds (Cowie 1991) and suitability to applications which are sensitive to materials which impede radiowave propagation and disturb electromagnetic fields.

3.2.1 FRP bars, rods and grids:

The use of FRP reinforcing bars and grids for concrete is a growing segment of the application of FRP composites in structural engineering for new construction (FIB Bulletin 40, 2007). For an effective reinforcing action, it is necessary to develop bond strength between FRP and concrete. This is attained in FRP rod by having various types of deformation systems, including exterior wound fibers, sand coatings and separately formed deformations.

FRP reinforcing bars and grids for concrete with both glass and carbon fibers are produced by a number of companies in USA, Asia and Europe (ACI 440R 2007). Their use has become recurrently and is no longer confined to demonstration project as in the past. Applications have become routine for certain specialized environments, namely in bridge decks and in underground tunnels.

3.2.2 FRP cables for prestressing and poststressing applications:

Composite cable applications in the infrastructure are used in the construction of suspension and stay cables for bridges, pre-stressed tendons for various concrete structures and external reinforcements for structural beams. All these applications require materials that incorporate high tensile strength and, in addition, require characteristics such as corrosion resistance and light weight (Hollaway 2003).

Corrosion of steel pre-stressing tendons can lead to the concrete degradation and the deterioration of structural integrity. In cable-stay applications, both corrosion and fatigue make the replacement of conventional cables a significant life cost. FRP composites have good corrosion, durability and fatigue characteristics and therefore the utilization of these materials does make good engineering sense.

The initial cost of the cables is higher than their competitors but this must be weighed against reduced transportation and handling costs, reduces maintenance and the anticipated longer useful life for individual stay cables and for concrete structures pre-stressed with FRP composite cables.

FRP cables are unidirectional reinforced structural elements made from glass, aramid or carbon fibers embedded in the polymer matrix. Different shapes exists, such as bars, cables, rectangular strips and braided reinforcement.

Carbon fiber and aramid cables are used for pre-tension and post-tension concrete, however glass fiber cables are not recommended for pre-tension due to the low resistance to alkaline environments (Susana Cabral-Fonseca 2008).

3.3 New FRP Civil Structures:

A small number of new load bearing civil engineering structures have been made predominantly from FRP materials over the last three decades. These include compound curved roofs (Hollaway 2002) pedestrian and vehicle bridges decks (FHWA 2002*)* energy absorbing roadside guardrails (Bank and Gentry 2000), building systems, modular rooftop cooling towers (Barbero and GangaRao 1991), access platforms for industrial, chemical and offshore (Hale 1997), electricity transmission towers, power poles, power pole cross-arms and light poles and marine structures such as seawalls and fenders (Weaver 1999).

FRP pultruded structures profiles have been used in a significant number of structures to data, including pedestrian bridges, vehicular bridges, building bridges, building frames, cooling towers, walkways and platforms, etc. (Susana Cabral-Fonseca 2008).

4. The future:

The future holds unlimited promise for the use of FRPs in structural engineering applications. One of the most exciting recent advances is the development of smart materials and smart structures. Smart are those in which sensors are installed to continuously monitor the performance of the structure throughout its lifetime. Recently, FRP materials have been developed which include fiber-optic sensors (FOS) as part of their internal structure. These FOS can be used to measure variations in strain and temperature within the structure itself, and can provide information to engineers on its short and long-term performance. These materials can be considered an emerging technology, although several smart structures have already been built in Canada and are currently under observation. Smart structures and materials will undoubtedly become more important and widespread in the future. Figure 3 gives an example of a smart structure in Canada: the Taylor Bridge near Winnipeg (Fitzwilliam 2006).

Figure 3*: Taylor Bridge near Winnipeg in Canada*

5. Conclusions:

The application of FRPs in civil infrastructures is not uncommon anymore in many European and North American countries, and some Asian countries like Japan, China etc. FRP is now widely used in strengthening of existing structures and repair of building and bridges that were damaged, shows that this technique, in many cases, may be a superior alternative to traditional techniques both from technical and economical perspectives. So, it is very clear that the volume of repair and retrofit works with FRPs will increase substantially in the future. For new structures, the application of FRPs is very promising and will depend on the ability to compete with the conventional materials (e.g. steel and concrete). Lightness, structure and easy workability are three very positive aspects of FRP materials. However, design standards is a big factor, also FRPs exhibit anisotropic behaviour and their mechanical characteristics may be affected by the quantity and orientation of fiber reinforcement, temperature, environmental conditions and so on. The material costs of the FRP composites are several times more than that of the conventional materials. However, the life-cycle cost, including fabrication, application, protection and projected maintenance costs, is comparable and can be less than that of conventional materials. In the longer term, the challenge is to prepare a new generation of architects and civil engineers to utilize the full potential of FRP materials. This requires systematic education and training in the design and manufacture of FRPs for the construction industry.

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