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A Review on “FRP Composites as a Substitute in Structural Engineering Design”

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ABSTRACT: Fiber reinforced polymer (FRP) composites are materials which are different from the steel reinforcement and recently been widely used in structural engineering design due to their various properties which makes them a high strength material. Apart from strength they also possess good stiffness, resistance to corrosion thereby being a durable material. In recent times they have been put to use in construction of new or in repair of existing structures like buildings, bridges, etc. Steel which is presently being used as reinforcing material to concrete structures is highly vulnerable to corrosion resulting in loss of serviceability of engineering structures. Most of the corrosion happens due to chloride attack. The analysis of causes of failures on German bridges shows that reinforcement corrosion initiated by chlorides makes up 2/3 of all the failures recorded in the bridge construction. In such an environment, fibre-reinforced polymer (FRP) reinforcement has evolved to be a prospective replacement of the traditional steel reinforcement. The paper presents a review on research and studies on various types of FRP composites, their properties and application in structural engineering design.

KEYWORDS: FRP Composites; properties of FRP composites, Structural design, Repair of structures

I. INTRODUCTION

Fiber-reinforced polymer (FRP) is a composite material made of a polymer matrix with strong and stiff fibre assemblies which act as the reinforcement. The fibres are of different materials like glass, carbon, paper, wood, aramid, plastic, etc. Among these the glass and carbon fibres have proven to being a strong and economical product. FRP composites possess a good dimensional stability, low thermal conductivity, electromagnetic transparency, impact resistance and low lifecycle costs. These are much lighter and also cheaper, faster, and easier to manufacture than cast aluminium or steel composite and hence have emerged as a supplementary and in some cases alternative material for producing reinforcing bars for concrete structures. For FRP composites to be used in structural engineering applications, it must possess good modulus of elasticity and uniform high ultimate strength. The fibres within should show very high uniformity in diameter and surface dimensions.

II. TYPES OF FRP COMPOSITS

The composites consist of two components: fibres and matrix. The fibres create 30% to 70% from the volume of the composite and 50% of its weight. Based on type of material, they are Carbon fibre, Glass fibre, Aramid fibres, Basalt fibres. Apart from these there are also various natural fibres which are being used recently.

2.1. Carbon fibre: Carbon is produced from a petroleum pitch, rayon, or polyacrylonitrile (PAN) precursor filaments. The carbon fibres possess a high tensile strength and modulus of elasticity and are not susceptible to aggressive environment and high temperatures. Carbon fibres of two types, one with high tensile strength (termed as HS fibres) and second with high modulus of elasticity (termed as HM fibres). Carbon fibres find significant application in structural engineering. However these fibres are much more expensive in comparison to glass and other fibres

2.2. Glass fibre: Glass fiber is obtained by extruding the molten glass from a furnace and cooling the filaments with water. The different types of glass fibres that are used in reinforced structures are: a) AR-glass – These are alkali resistant glass made with zirconium silicates. These are used in Portland cement substrates due to being resistant to the alkaline environment found in concrete. However these fibres are expensive. b) E-glass – This is the most commonly used fibre in the FRP composite industry for its strength and electrical resistance. It is made with alumina-calcium borosilicates. c) S-glass – These are high strength glass made with magnesium aluminosilicates

and used in applications wherein high strength, high stiffness, extreme temperature resistance, and corrosive resistance is needed.

E-glass is by far the most used and the least expensive one. Glass composites are used where higher stiffness of the carbon or aramid fibres is not required

2.3. Aramid fibres: Aramid fibres are synthetic fibres of low density, about 40% lower than glass density [1]. These are made from the polymer aromatic polyamide and have the best tensile strength to the density ratio. However, they are susceptible to UV light. Their strength and stiffness reduces when in contact with water especially in high humidity environments. Hence they need to be impregnated in an epoxy or vinyl ester matrix to protect them from moisture infusion. They are also painted or coated to protect from UV light

2.4. Basalt fibres: Basalt fibre is a continuous fibre produced through igneous basalt rock melt at about 1500 °C. It has a similar chemical composition as glass fibre but has better strength characteristics, and unlike most of the glass fibres, it is highly resistant to alkaline, acidic and salt attack, due to which it is a good prospect to be used for concrete, bridge and shoreline structures. Basalt fibres have high potential and are getting a lot of attention due to its high temperature and abrasion resistance. However, compared to FRPs made from carbon, glass and aramid fibre, its use in the civil infrastructure market is very low.

2.5 Natural Fibres: Fibers extracted from the nature have emerged in the past decades aiming at replacing traditional high strength synthetic fibres to form a new class of natural fibre reinforced polymer (NFRP) composite. In the last few decades, many research groups in the world have developed promising materials, which are made of biodegradable fibres and polymers to form new types of bio-composites (or “green composites”), to replace conventional materials. In many countries, newly established policies have also encouraged business units to pay much attention to save energy and materials to sustain the life of our planets.

Natural fibres can be either animal-based or plant-based fibres. Cocoon silk, chicken feather, wool and spider silks are commonly used as animal-based fibres, which mainly target to biomedical applications such as implants. Plant-based fibres, including jute, hemp, sisal kenaf, coir, flax, bamboo and banana, are commonly mixed with polymers to form NFRP composites for making domestic products, of which cost and strength are the most concerning factors.

III. PROPERTIES OF FIBRES

The main functions of fibres are to carry the load and provide stiffness, strength, thermal stability and other structural properties to the FRP [3]. The matrix is responsible to distribute the loads to individual fibres [4] ensuring that the fibre position and alignment is not disturbed. It also protects the fibres from manufacturing damages, manipulation, harmful environment and all that is required to result in a durable FRP composite. The CFRP (Carbon), GFRP (Glass), AFRP (Aramid), Basalt fibres are presently dominating in civil engineering applications.. The properties of various kinds of fibres is shown in Table 1 [5]. Fig. 1 shows the stress-strain relation of the various kinds of the FRP composites in comparison with steel reinforcement [6].

Table 1: Properties of various kinds of fibre [5]

Properties	Carbon fibres		Glass fibres		Aramid fibres		Basalt fibres	Steel
	HS (High Strength)	HM (High Modulus)	E-glass	S-glass	Kevlar 29	Kevlar 49		
Density [kg/m ³]	1800	1900	2540	2530	1440	1440	2700	7850
Modulus of elasticity E [GPa]	230	370	72	89	83	124	90	200
Tensile strength [MPa]	2480	1790	3400	4600	2920	3600	4000	500
Extension [%]	11.00	0.50	2.12	1.93	3.50	2.90	2.25	2.50

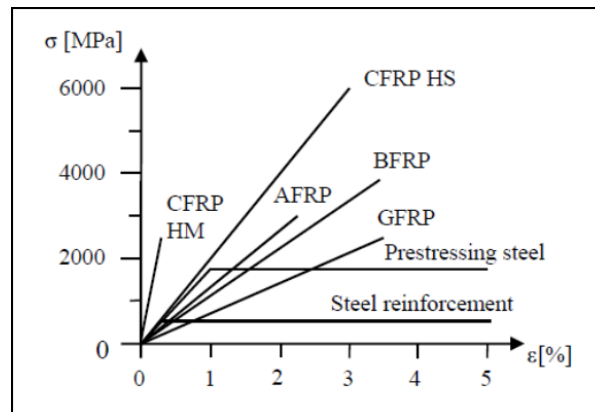


Fig. 1 Stress-strain diagram for the steel and FRP materials [6].

On the other hand natural fibres which are seen to be potential substitution of glass fibre are classified as renewable sources and can be extracted from the nature without damaging environment. The mechanical properties of the NFRP composites is shown in Table 2 [7]. It has been observed that they are comparable to glass fibre reinforced polymer (GFRP) composites [7]. Fig. 2 summarizes several key parameters that may affect the properties of composites made from Natural Fibres [7].

Table 2: Basic properties of natural fibres [7]

Fibre Type	Density (g/cm ³)	Tensile strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
Jute	1.3–1.5	200–770	20–55	2.0–3.0
Sisal	1.5	100–800	9–22	3.0–7.0
Kenaf	1.4–1.5	930	53	1.6
Coir	1.2	180	4–6	30
Flax	1.5	350–1040	28–70	2.0–4.0
Hemp	1.5	690	30–70	1.5–4.0
Bamboo	0.6–1.1	140–230	11–17	4.0–7.0

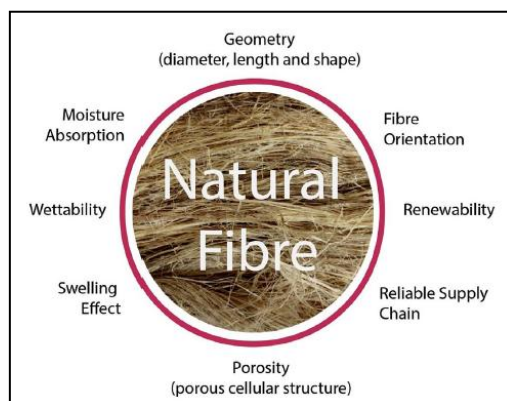


Fig. 2. Key factors that affect the mechanical properties of natural fibre composites (Ref: [7])

IV. FRP COMPOSITES IN STRUCTURAL ENGINEERING

FRP composites are used in structural engineering design due to their various properties which makes them a high strength material. Apart from strength they also possess good stiffness, resistance to corrosion thereby being a durable material. FRP composites are alternative to steel reinforcement especially in aggressive environments, mainly due to

their high corrosion resistance. With evolution of various techniques like pultrusion, resin transfer molding, filament winding and semi-automated manufacturing of large components, it is now possible to manufacture FRP economically. Studies have shown that with proper design, FRP composites can be used to supplement the conventional structural materials and produce a cost effective design.

The emerging field of renewal engineering may best describe the role of FRP composites in civil engineering. The renewal of the structural inventory, which is depicted in Fig. 3 [8], can be divided into (1) rehabilitation, including the applications towards repair, strengthening and retrofit of structures; and (2) new construction with all FRP solutions or new composite FRP-concrete systems.

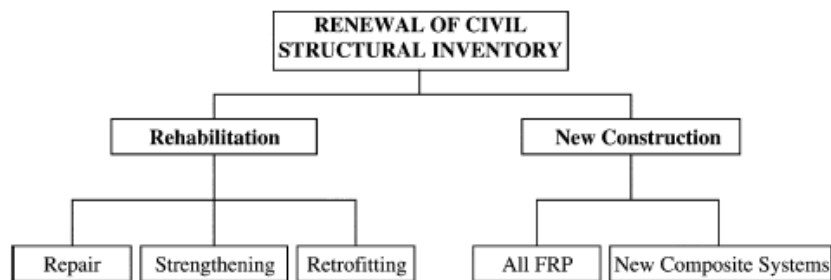


Fig 3: Use of fiber reinforced polymer composites in civil engineering [8]

4.1 Post strengthening Post-strengthening is done whenever the structure has to support greater magnitudes of loads than the values for which they were designed. Furthermore, during the process of modernization of buildings, individual supports and walls may be removed, thus leading to a redistribution of forces and the need for local strengthening. In such situations the method of bonded reinforcement may represent an attractive solution since it can be achieved with relatively small impact on the structure. Furthermore, the existing clearance limits to bridges are not affected.

4.2 New Composite Systems New lightweight structural concepts utilizing FRP shells and tubes to form new structural systems are now being invented to use FRP-Concrete composite systems in construction of lightweight bridge systems. These innovative FRP-Concrete composite systems due to their simplification in construction and excellent short- and long-term structural characteristic finds application in repair of constructed facilities like, strengthening of walls and slabs, shear strengthening, flexural strengthening, slab strengthening. A more detailed study can be found in [8]. It also finds application in structural replacement-new bridge systems.

4.2a) Carbon shell system (CSS): The first modular FRP-concrete composite structural system consisting of concrete filled carbon shells has been developed at UCSD [9] and is schematically shown in Fig. 4. This system creates new structural elements by using prefabricated filament-wound carbon/ epoxy thin shells filled on-site with concrete. The shell acts as both longitudinal as well as circumferential reinforcement. It also acts as a formwork for the concrete core. The concrete provides compression force transfer, stabilizes the thin shell against buckling and provides anchorage of connection elements. The design of the carbon tubes consists of carbon fibers in the longitudinal tube direction (+ or - 10 degree from the member longitudinal axis due to manufacturing limitations) and hoop fibers (90 degrees) in the transverse direction. Circumferential ribs are provided on the inside of the carbon shell for full force transfer between the concrete infill and the shell. The concept is suitable for both columns and girders.

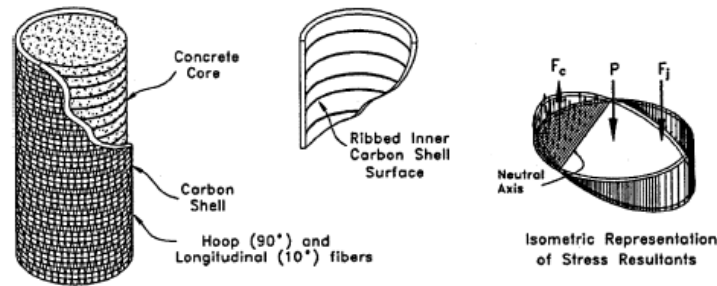


Fig. 4: Concrete filled Carbon Shell System (CSS) [8].

4.2 b) Hybrid tube system (HTS): Another modular FRP bridge system has been developed based on pultrusion and hand lay-up of a carbon/ glass hybrid material system [9]. The hybrid tube system (HTS) beam-and-slab bridge proposes the use of hollow E-glass/ carbon hybrid beams that are connected along their tops with a polypropylene fiber reinforced concrete deck system. A parametric study of a hybrid tube bridge system was performed by evaluating the maximum simply supported span length of the system under a set of allowable design criteria for service and factored loads. The bridge system under consideration consisted of seven transversely spaced HTS girders supporting a 13-m wide road surface. The results of the parameter study as shown in Fig. 5, indicates that the deflection under live load governs the design, which is common for FRP structures.

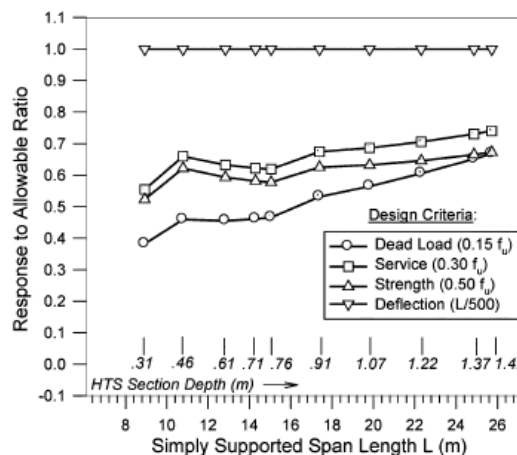


Fig. 5: Hybrid tube bridge system characterization studies [8].

V. CRITERIA FOR SELECTION OF FRP

Corrosion of the steel in outdoor applications is a major concern in civil engineering field. Ladner et al. [10] observed ‘small traces of rust’ on unprimed as well as primed bonded steel plates even after only 3 years exposure to weathering. The rust became more extensive during the course of the test and after 15 years exposure the areas had grown to 10 mm in diameter.

For structural work of bridges, steel plates have other disadvantages. During renovation work, only a limited number of mechanized lifting machines are available. At places like the interior of box girders, or where lifting steel by mechanized means is not suitable or possible, the strengthening plate would have to be carried by hand to the point of installation. Consequently, due to handling limitations on site, the steel plates are rarely longer than 6-8 m; however, if the strengthening work involves greater plate lengths, a butt-joint system must be used. This type of joint cannot be welded since the welding temperatures would destroy the adhesive bond; consequently butt-jointed steel plates have to be formed from single shear lap joints. If steel plates were replaced by high strength fibre composites, a relatively thin component could be delivered to the building site in rolls of lengths in excess of 300 m. Compared to steel plates, the bonding technique is greatly simplified [11]. Table 3 lists criteria which specifically relate to the use of composite materials as a post-strengthening material for structures and applies particularly to prestressed laminates.



Table 3 Qualitative comparison between E-glass, Aramid and H-T carbon fibres [11]

Criterion	Fibre composite laminates made of		
	Carbon	Aramid	E-glass
Tensile strength	very good	very good	very good
Compressive strength	very good	inadequate	good
Modulus of elasticity	very good	good	adequate
Long term behaviour	very good	good	adequate
Fatigue behaviour	excellent	good	adequate
Bulk density	good	excellent	adequate
Alkaline resistance	very good	good	inadequate
Price	adequate	adequate	very good

From Table 3, it is clear that the tensile strength of carbon, aramid and E-glass is very good. However these fibres differ in their compressive strength. Although most of structures made of concrete require additional strengthening to absorb tensile stresses, there may be regions which are normally stressed in tension but which may also be subjected to compressive stress depending upon the load distribution. In these situations bonded steel plates are not acceptable as they will peel off. Aramid fibre reinforced polymers would also fail due to their poor compressive strength. Deuring [12] has shown that carbon fibre reinforced composites (CFRP) do satisfy the compressive requirement.

The modulus of elasticity of the strengthening material plays a major role in its selection or suitability to be used for strengthening works. For example, in case of steel plate, if the plate is not prestressed before being bonded, it would not relieve the stresses because only stiff plates are able to relieve the stresses in the existing internal steel reinforcement. As per Table 3, CFRP has better modulus of elasticity than Aramid and E-glass fibre composite laminates. It also means that fibre composite laminates made of aramid and glass fibre reinforced composites must be thicker than CFRP laminates to achieve the same tensile stiffness if they have to be used. Since the infrastructure structures have large spans so using GFRP composites would make their handling difficult at the construction site.

The results shown in Table 3 clearly indicate that carbon fibre reinforced polymer composites most closely fulfil requirements for the post strengthening of structures.

VI. CARBON FIBRE REINFORCED POLYMER COMPOSITES

Carbon fiber reinforced polymer composites (CFRP) are finding particular importance in market for retrofitting of structures like bridges which are highly susceptible to deterioration due to corrosion especially in coastal environment. CFRP with its low density also finds application in places other than those of corrosive environment. CFRP materials due to their light weight are easy for handling on site and thus require less manpower [11]. CFRP consists of noncorrosive tensile elements composed of a large number of parallel carbon fibre filaments in an epoxy resin. The light weight carbon fibre composites combine the qualities of a high tensile strength with an outstanding fatigue performance. The laminates are durable under practically every type of environmental attack which may occur in or around concrete structures. All this points along with recent decrease in price of CFRP composites makes them an economical choice in structural engineering application.

6.1 Strengthening of structures with unstressed and stressed CFRP laminates: Post-strengthening with CFRP composites needs to be done such that its failure of structure is always that of an under-reinforced type which means it should fail during yielding of the steel reinforcing bars before a compressive failure of the concrete. Yielding of the steel bars should not occur before reaching the serviceability (design) loads.

Kaiser [13] investigated a 2 m span beam (2.00 length x 0.300 width x 0.250 depth) under fatigue loading. The existing steel reinforcement consisted of two rebars of 8 mm diameter in the tension and in the compression zones. This beam was post strengthened with a glass/carbon fibre hybrid composite having dimensions 0.3 by 200 mm and the test was executed with unrealistically high steel stresses. The aim of the test was to gain insight into the failure mechanism after a complete failure of the steel reinforcement; it was surprising to observe how much the hybrid laminate could withstand after failure of the reinforcement.

Fatigue test was performed by EMPA on a beam of 6.00 m span under realistic loading conditions. A 32 % increase in load carrying capacity was observed upon strengthening the beam by bonding a CFRP composite plate. Figure 6 [11] shows cross section of the beam/ girder on which test was performed. The beam carried a load of 815 kN upon post

strengthening with a CFRP laminate 200 wide and 1mm thick. Without post strengthening it carried a load of 610 kN. The CFRP laminate used in this test was not pre-stressed. The test was also performed with a pre-stressed CFRP so that a comparative result be obtained. The results showed that the upon strengthening the beam with a CFRP (50% pre-stressed), the beam achieved the same 815 kN load at only 50% deflection to that when strengthened with an unstressed CFRP. Hence it could be concluded that in some cases it can be advantageous to provide additional prestressing to the flexure-strengthening laminates as in this way the serviceability of the structure can be improved and the shearing of the laminates due to the shear failure of the concrete in the tension zone can be avoided [12]. The typical load vs deflection relationship observed in this test for this beam is shown in Figure 7. [11]

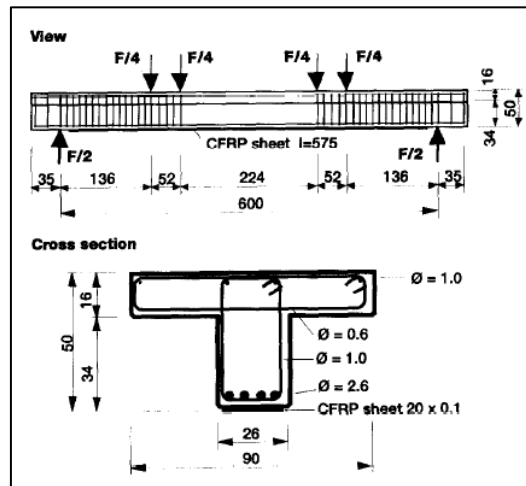


Figure 6; View and cross-section of test girder (measurements in cm) (Ref [11])

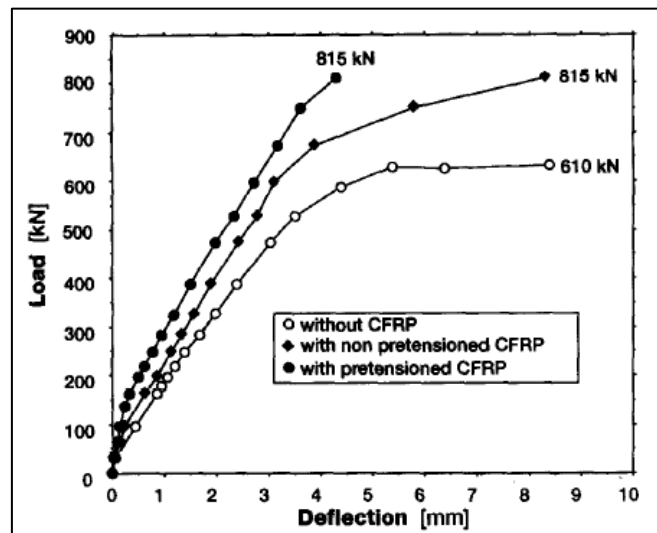


Figure 7 Load-deflection curves for the girder type shown in Figure 6 (Ref: [(11)])

6.2 Implementing pre-stressed CFRP laminates for strengthening shearing force areas. Most of the structures requiring rehabilitation need strengthening not only for increasing its flexural resistance but also for increasing shear resistance. As in case of bridges, its strengthening can be done by relieving the inner shear stirrup along with supplementing the stirrup with a prestressed CFRP laminate. Doing so, the cracks developing due to shear may be eliminated or reduced significantly.

Methods allowing the effective strengthening of the shearing force areas without using steel are being developed. One such method of strengthening of the beam is shown in Figure 8. A component of stressed advanced composite material is used along the inner stirrup reinforcement. This can be braided or unidirectional in form. The prestressing material is wrapped around the cross-section on one side and is anchored in the compression zone on the opposite side with the

modulus of elasticity and geometry so chosen so as to minimize the loss of tensioning force due to creep of the element to be strengthened and the relaxation of the prestressing material.

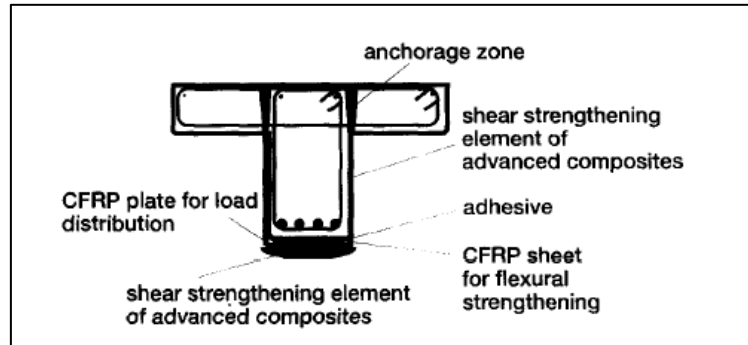


Figure 8: Schematic sketch of cross-section of end anchorage system for pretensioned laminates. (Ref: [11])*

*The same system can be used for shear strengthening

6.3 Safety considerations in design using CFRP: EMPA recommends that the post-strengthening of a structure should not be more than 50%. Therefore, after an accidental failure of the post strengthening of the beam, a residual factor of safety of approximately 1.2 would remain and the collapse of the structure could be avoided.

VII. SUMMARY AND CONCLUSION

As far as structural works like small residential blocks or multi-storied buildings with beams spanning less than 5m are concerned steel seems to be the favourite material. However, use of FRP composites with thin fibres find a place in interior decoration works. In bigger projects, where cost control is critical part of overall project, the advantages of FRP composites make them attractive for use in structural engineering applications. They are lighter and economical in comparison to traditional reinforcing materials. Innovative FRP/ concrete bridge systems, such as the concrete filled carbon shell system (CSS) and the hybrid tube system (HTS) effectively use FRPs for new construction by combining them with conventional materials of concrete and steel. In applications where corrosion, length of strengthening component and handling on construction sites play dominant roles, for example bridges, multi-storey parking spaces, railway stations and specialized industrial structures, fibre composites can be used efficiently.

The disadvantages of the FRP composites are high initial costs, their susceptibility to mechanical damage and fire, inability to bend in the field, longer load transfer lengths, poor shear strength and low strain to failure. Due to other differences in the physical and mechanical behaviour of the FRP materials versus steel, unique guidance on the construction of concrete structures reinforced with FRP bars is needed. [14]

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