Application of FRP bars as reinforcement in civil engineering structures

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Keywords

Steel, Reinforcement, Civil engineering

Abstract

This paper presents an overview and discusses the applications of fibre reinforced polymer (FRP) bars as reinforcement in civil engineering structures. Following a discussion of the science underpinning their use, selected case studies where FRP reinforcement has been used are presented. The use of FRP reinforcement is rapidly gaining pace and may replace the traditional steel due to its enhanced properties and cost-effectiveness. In addition, FRP reinforcement offers an effective solution to the problem of steel durability in aggressive environments and where the magnetic or electrical properties of steel are undesirable.

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DOI 10.1108/02630800210433837

Introduction

Concrete structures are conventionally reinforced with steel bars and prestressed with steel tendons. For structures subjected to aggressive environments (e.g. de-icing salts in bridges, marine structures, etc.), combinations of moisture, temperature and chlorides may result in the corrosion of reinforcing and prestressing steel, leading to the deterioration of concrete and loss of serviceability. This corrosion problem of steel rebar is the greatest factor in limiting the life expectancy of reinforced concrete structures. In some cases the repair costs can be twice as high as the original cost. In North America, this phenomenon has been exacerbated in parking garages and by the use of de-icing salts and significant fluctuations of temperature. In Canada, it is estimated that the cost of repair of parking garages is in the range of 6 billion dollars, and over 74 billion dollars for all concrete structures. The estimated repair cost for existing highway bridges in the USA is over 50 billion dollars, and 1-3 trillion dollars for all concrete structures. In Europe, steel corrosion has been estimated to cost about 3 billion dollars per year. Excessive corrosion problems also exist in Arabian Gulf countries (Benmokrane *et al.*, 1998). Deterioration in all types of reinforced structures is aggravated by excessive concentration of chlorides in construction materials, high humidity, temperatures, and marine exposure. Many environmental conditions (freeze/thaw, use of de-icing salts, moisture, chemical products, marine conditions) as well as mechanical overloads arising from ever-increasing traffic load, accelerate the corrosion process of steel rebar, thereby decreasing the life expectancy of these structures.

To increase the lifespan of reinforced concrete structures, government organisations, private industry and university researchers are seeking ways to avoid the corrosion problem and thereby eliminate, partially or totally, the burden of never-ending repair costs. One preferred solution, which has assumed the status of cutting-edge research in many industrialised countries, is the use of fibre reinforced polymer (FRP) rebars in concrete. The term FRP describes a

This work is a part of the RGC project CityU 02E. The authors acknowledge the financial support given by the Research Grant Council (RGC) of the Hong Kong Special Administrative Region.

group of materials composed of synthetic or organic fibres embedded in a resin matrix. The most common FRPs targeted to the construction industry are carbon FRP (CFRP), aramid FRP (AFRP), and glass FRP (GFRP). FRP composites can be produced by different manufacturing methods in many shapes and forms; the most popular ones for concrete reinforcement are reinforcing bars (rebars), prestressing tendons, pre-cured laminates/shells, and fibre sheets for lay-up installation. Commonly used FRP rebars have various types of deformation systems, including externally wound fibres, sand coating, and separately formed deformations. Rebars are commonly used for internal or near surface mounted (NSM) concrete reinforcement. FRP tendons have been used as pre-tensioned cables in prestressed concrete applications. FRP reinforcement may be used on beams and slab soffits to provide flexural strength, or on the sides of beams to provide shear strength, or wrapped around columns to provide confinement, ductility (a primary concern in seismic upgrades), and shear strength (Pries and Bell, 1987; Nanni, 1991). The main areas of application are marine environment structures, and structures wherein non-magnetic properties are important such as magnetic resonance imaging installations (Roll, 1991), and large transformer foundation pads. The bars are not susceptible to corrosion and have high tensile strength.

FRP reinforcement has widely been used as internal reinforcement in the new construction of civil structures or as NSM concrete reinforcement for increasing flexural and shear strength of deficient reinforced concrete (RC) members due to their versatility. This has made it necessary to create a comprehensive overview needed to justify their safe and economic use, which is the objective of this paper. Discussion on the applications of FRP reinforcement in civil engineering structures provides an insight to enhance the use of these techniques for productive use. The discussions are supported with real life case studies of civil structures where FRP reinforcement has successfully been used.

Application of FRP as flexural and shear reinforcement in concrete structures

FRP reinforcement is commonly used as internal or NSM concrete reinforcement when applied as flexural or shear reinforcement. The behaviour of concrete structures reinforced with FRP rebars as flexural or shear reinforcement is discussed in this section. The results of some experimental and analytical studies are also summarized here.

Internal reinforcement

FRP has much potential as longitudinal reinforcement in concrete structures susceptible to reinforcement corrosion and stressed primarily in bending. Examples of such structural components include bridge decks, footings, floor slabs, and wall type structures (abutments, stems, and wing walls). In these members, flexural strength is essentially provided by the longitudinal reinforcement. Since GFRP bars are made of brittle material, flexural failure of concrete members reinforced with FRP bar is thus expected to be of brittle type (Almusallam, 1997). Nawy and Neuwerth (1977) studied the flexural behaviour of simply supported beams. The results showed that the failure mode of most tested fibre glass reinforced beams occurred on the compressive side because compressive failure of concrete took place before the development of full capacity of FRP bars. Alsayed *et al.* (1995) reported that the FRP rebars have linear stress-strain relationship up to the failure point; the load-deflection curve for concrete beam reinforced with FRP rebars is thus expected to be dissimilar from that of reinforced with steel bars, as the beams reinforced with FRP bars may develop large displacements and eventually fail by crushing the concrete at the side before the FRP bar reaches its ultimate tensile strength. This may be attributed to the lower modulus of elasticity of FRP bars so they may not be effective if deflections instead of strength control the design (Petrina and White, 1995; Almusallum, 1997) but where the primary criterion and objective is to obtain the strength, FRP bars may be considered as the most effective solution. A preliminary study carried out on different shapes of locally manufactured GFRP bars by Balendran *et al.* (2000), showed that elliptical bars performed better than circular shaped bars. Masmoudi *et al.* (1998) carried out a series of tests on concrete beams reinforced with GFRP bars and found that the deflection was similar to both steel and FRP reinforced sections when the applied moment is less than

25 percent of the ultimate moment. They also reported that the crack width in FRP reinforced beam was three to five times that of identical beams reinforced with steel rebars. A recent experimental study carried out by Alsayed *et al.* (2000) suggested that the flexural capacity of the beams reinforced with FRP bars can be accurately predicted using the ultimate design theory. Ombres *et al.* (2000) performed an investigation on the flexural behaviour of FRP reinforced concrete one-way slabs. Cracking and deflection of FRP reinforced concrete structures were analysed both theoretically and experimentally. It was found that the stiffness of the GFRP reinforced concrete slabs is significantly lower than the steel reinforced members after cracking, resulting in larger crack widths and deflection, and the ultimate capacity of slabs increases with the amount of GFRP rebars. This is true, obviously, for the case in which the failure mode is compression-controlled (crushing of the concrete). It was also concluded that ultimate capacity, crack width and deflections can be predicted with acceptable accuracy using analytical models.

NSM reinforcement

The use of NSM FRP rods is a promising technology for increasing flexural and shear strength of deficient reinforced concrete (RC) members. Advantages of using NSM FRP rods with respect to externally bonded FRP laminates are the possibility of anchoring the reinforcement into adjacent RC members, and minimal installation time (Nanni *et al.*, 1999). Furthermore, this technique becomes particularly attractive for flexural strengthening in the negative moment regions of slabs and decks, where external reinforcement would be subjected to mechanical and environmental damage and would require protective cover that could interfere with the presence of floor finishes. Tensile and bond tests on commercially available carbon FRP deformed rods for application as NSM reinforcement were carried out by De Lorenzis and Nanni (2001). Three full-size beams, one control beam and two beams strengthened in shear with NSM FRP rods, were tested. Results of shear tests were compared with the predictions of a simple design approach, showing reasonable agreements, so it may be concluded that this is an effective technique to enhance shear capacity of RC beams.

Application of FRP as axial reinforcement

This section describes the behaviour of concrete structures reinforced by FRP rebars as axial reinforcement. The FRP reinforcement is used as axial reinforcement in concrete columns. The results of some experimental and analytical studies are also summarized here.

Compressive capacity of FRP bars

The compressive strength of glass, carbon and aramid FRP bars were 55 percent, 78 percent and 20 percent of their tensile strengths, respectively (Wu, 1990). Kobayashi and Fujisaki (1995) reported similar reductions in strength. These researchers conducted materials tests on FRP bars, as well as FRP reinforced columns tests under monotonic and reversed cyclic loading. The bars were made out of carbon, aramid and glass fibres. The material tests were conducted on FRP bars subjected to externally applied compression while the bars were embedded in concrete. They reported that the compressive capacity of glass, carbon and aramid FRP bars were 30 percent, 30 to 50 percent and 10 percent of their tensile capacities, respectively. The same bars were subjected to incrementally increasing axial tension-compression reversals. They were subjected to either ten or 30 cycles at each load level. Aramid and glass FRP reinforcement were affected significantly by the cyclic loading developing only 20 to 50 percent of their monotonic compressive capacities before failure. Carbon FRP did not show any significant effect by the cyclic loading. In all cases the bars failed in compression and the tension capacity was affected by reversed cyclic loading. The researchers also tested small-scale concrete columns with a 200 mm square section and 650 mm height under uniaxial compression. The columns were reinforced by grid type carbon FRP. The hoops consisted of glass, aramid or carbon FRPs. The results indicated that the strain compatibility was maintained up to the crushing of the concrete. The columns developed their concentric capacities at about 0.25 percent to 0.4 percent compressive strain. The FRP continued straining up to 1.0 percent to 1.8 percent in compression, beyond the peak column load, before they failed in compression. It was suggested that the concentric capacity of FRP reinforced concrete columns could be computed conservatively by ignoring the contribution of FRP and using the gross area of column section multiplied by 85 percent of concrete strength.

FRP reinforced columns under concentric and eccentric loading

The behaviour of FRP reinforced concrete columns under concentric and eccentric loading by testing small-scale specimens was investigated by Paramanantham (1993). The FRP longitudinal and tie reinforcement were produced by pultrusion and were made of vinyl ester resin and E glass fibres. A total of 15 FRP reinforced concrete blocks were tested to investigate the concentric capacity of specimens as affected by tie spacing and bar buckling. The tie spacing used was 100mm, 150mm and 200mm. It was concluded that the concentric capacities of specimens were very similar, though those with 100mm spacing showed better control of bar buckling while developing slightly improved strength. The FRP bars were able to contribute to the load carrying capacity by developing stresses corresponding to a strain of 0.03. This constituted about 20 to 30 percent of the ultimate strength of FRP. An additional 16 columns were tested under eccentric loading. The columns under eccentric loading were subjected to different axial force and bending moment combinations. They all developed compression crushing as the failure mode. The experimental results were compared with a moment axial force interaction diagram derived analytically based on standard plane section analysis. The comparison showed that the experimental strength values were consistently higher than those computed analytically, except for four columns, which showed slightly lower capacities.

Comparison between steel and FRP reinforced columns

A comparative study was conducted by Alsayed *et al.* (1999) between steel and FRP reinforced concrete columns. The researchers tested 450mm by 150mm rectangular columns, with a 1,200mm column height, under concentric compressing. A total of 15 columns were tested with different combinations of steel and glass FRP reinforcement, including all FRP reinforcement columns. The longitudinal FRP reinforcement consisted of 15.7mm diameter re-bars and FRP ties consisted of 6.35mm diameter bars. The results indicated that the FRP reinforcement resulted in approximately 10 percent reduction in concentric column capacity as compared to steel reinforcement. The analytical expression commonly used to compute concentric capacities of columns with steel reinforcement was found to produce reasonable values for FRP reinforced columns when the effect of longitudinal FRP was accounted for at the crushing strain level of concrete.

Confining effects of spiral FRP reinforcement

The confining effects of spiral FRP reinforcement on square and circular specimens were investigated by Taniguchi *et al.* (1993). The specimens had either 150mm square or 150mm diameter circular cross-sections. All the specimens were 300mm in height. The transverse FRP reinforcement was manufactured from carbon fibres, resulting in either 5mm diameter strands or 5.3mm diameter bars. It was concluded that FRP transverse reinforcement was effective as confinement reinforcement when used with sufficiently small pitch. Leung and Burgoyne (2001) investigated compressive behaviour of concrete confined by aramid fibre spirals. Circular concrete cylinders with single spiral and rectangular concrete specimens with two interlocking spirals were investigated. It was found that the behaviour of confined concrete is influenced not only by the concrete strength, but also by the spiral leg spacing and the degree of interlocking. Concrete cylinders with close spacing and a high degree of interlocking gave higher strength and ductility.

FRP reinforced frames

A half scale model of a three-storey FRP reinforced concrete frame was designed, built and tested by Fukuyama and Masuda (1995). The frame was subjected to lateral load reversals at the third storey mid height level. The frame had two 3.5m spans and 1.8m storey height. The main reinforcement in the beams, columns and slabs were braided aramid fibre bars with 67 kN/mm^2 elastic modulus. The bars were coated with silica sand to improve their bond characteristics. The columns had 350mm square cross-section with 20mm longitudinal bars, each having 90-mm^2 area. Initial cracking was observed near the column base at 0.5 percent lateral drift. These cracks were essentially flexural cracks, and progressively increased within the potential hinging region up to 2 percent drift ratio. At this deformation level the column concrete started to crush. The overall resistance of the frame continued to increase up to 5 percent lateral drift. It was reported that lateral drift under ultimate limit state and maximum crack width under serviceability limit state controlled the design. It was concluded that FRP reinforced frames could be designed and built without much difficulty, but additional research was needed to establish many aspects of these structures.

Bond behaviour of FRP reinforcement

Bond is of primary importance in reinforcement as it is the means for the transfer of stress between the concrete and the FRP reinforcement in order to develop composite action. The bond behaviour influences the ultimate capacity of the reinforced element as well as serviceability aspects such as crack width and crack spacing. Among the many different types of bond tests reported in the literature, the most common are the direct pullout test and the beam pullout test (Nanni *et al.*, 1995a, b). It is generally believed that the beam pullout tests are more representative of the bond behaviour in real members.

Research indicates that the bond strength of FRP reinforced concrete depends on several factors, such as the surface deformation of the rod, the ratio of surface area to cross-section of the rods, the thickness and the shear strength and shear modulus of the rod's surface layer (FIP Commission, 1992). The bond between FRP reinforcement and concrete also depends on the friction due to surface roughness of FRP rebars, the mechanical interlock of the FRP rebars against the concrete, the chemical adhesion, the hydrostatic pressure against the FRP rebars due to the shrinkage of hardened concrete and the swelling of FRP rebars due to temperature change and moisture absorption (Makitani *et al.*, 1993). Ehsani *et al.* (1997) carried out bond tests using pullout specimens and beam specimens with GFRP bars in normal weight concrete and observed that the bond behaviour of GFRP bars depends on the bar type and manufacturing process. They also found that the embedment length increased with tensile capacity of GFRP bars, and the ultimate bond stress and slip values were larger for direct pullout specimens than for beam pullout specimens. Tighiouart *et al.* (1998) performed bond tests using pullout specimens and beam specimens with GFRP bars and steel bars, and reported that the steel bars gave higher bond strength than GFRP bars. They also proposed a new model for the bond-slip relationship. The bond properties of FRP reinforcing bars at different temperatures were studied by Katz *et al.* (1999) and greater sensitivity to high temperatures was seen in FRP rebars, in which the bond relies mainly on the polymer treatment at the surface of the rod. Katz (2000) also studied the effect of cyclic loading on the bond mechanism of FRP to concrete. The results indicated a reduction in the bond strength after cyclic loading.

Durability of FRP reinforcement

The increasing use of fibre-reinforced composites in civil engineering applications requires a thorough understanding of the durability of such materials when exposed to harsh environments. To accomplish this task, long-term durability studies of the behaviour of these materials in aggressive field conditions is important. A primary cause of deterioration of FRPs is the diffusion of moisture and other corrosive solutions into the matrix, which can damage the matrix as well as the fibres. Therefore, moisture absorption and associated changes in material properties must be discussed. Here are some studies, which have been conducted to investigate the durability of FRP bars in solutions that simulated exposure to civil engineering environments.

Tannous and Saadatmanesh (1999) studied the durability of GFRP bars in corrosive chemical treatment in order to simulate exposure in the field. The results showed significant loss in mechanical properties such as ultimate tensile strength, ultimate strain, and elastic modulus after the durability tests. Similar durability studies on GFRP rebars were conducted by Katz and Berman (2000), Pisani (1998), Kumahara *et al.* (1993) and Sen *et al.* (1993). They reported that the mechanical properties of GFRP bars when subjected to alkaline or high temperature environment decreased significantly. Kumahara *et al.* (1993), for example, found a reduction of about 20 percent in the tensile strength of GFRP rods at a temperature of 250°C, which was much above the glass transition temperature of the resin.

However, studies have shown serious durability problems in FRP bars made from E-glass in environments with high alkalinity such as in concrete (Katsuki and Uomoyo, 1995). An alternative glass fibre that could potentially improve the durability of FRPs in this type of environment is the alkali resistant (AR) glass. Currently, AR glass fibres are used for various purposes in civil engineering. For example, short AR glass fibres have been used in the construction of wall panels for high-rise buildings in the USA because of their light weight and durability (Sen *et al.*, 1993). Micelli *et al.* (2001) reported that GFRP bars manufactured with a thermoplastic resin showed good durability after an accelerated ageing test. However, they observed a significant loss of tensile strength with GFRP bars made with a polyester matrix after accelerated ageing. The accelerated ageing regimes recommended by Micelli *et al.* (2001) and simulated aggressive environments recommended by Tannous and Saadatmanesh (1999) are useful methods to study the effects of these on the different types of FRP bars.

Selected case studies of FRP reinforcement applications

FRP reinforcement has been used in many countries. The application of these materials is wide including commercial and residential buildings, civil engineering and marine structures. Brief case studies of the diverse applications offered by FRP reinforcement are presented below.

FRP reinforcement applications in USA

MRI foundation pad at St Francis Medical Centre, Grand Island

GFRP rebar was used to fabricate Magnetic Resonance Imaging (MRI) foundation pad at St Francis Medical Centre, Grand Island (Busel, 2000). The use of GFRP Rebar for MRI facilities in hospitals has been ongoing for several years. Due to the magnetic transparency of the rebar, any transient magnetic fields will not be reflected by the reinforcement used in the concrete and negatively affect the quality of the MRI image. Numerous installations throughout the USA have incorporated GFRP bars including in the Gonda Building at the Mayo Clinic in Rochester, Minnesota.

Pierce Street Bridge, Lima, Ohio

This project was originally scheduled to rebuild completely with steel reinforcing bars, but the Pierce Street Bridge in Lima was redesigned to accommodate a FRP rebar reinforced bridge deck to prevent the salt-induced corrosion and deterioration which caused the reconstruction in the first place. Utilization of composite bars in place of steel rebar resulted in a 2 percent increase in the total cost of the bridge, but this was readily accepted by the state of Ohio and the city of Lima because the inherent corrosion resistance will reduce scheduled maintenance on the bridge over its lifespan (Busel, 2000).

Kennedy Mansion Seawall Renovation, Port Kennedy, Pennsylvania

This project performed renovations to the Kennedy mansion seawall for the new owner. The seawall is a massive curved-face non re-entrant faced wall that is 58m long and 5m high. It is located on the beach of the Atlantic Ocean generally around 2.4m from the water at low tide. At high tide and in storms, the waves will crash against the seawall. The seawall had severely deteriorated with numerous cracks, spalls, and evidence of corrosion of steel rebar. Composite rebar was exclusively used in the rehabilitation of this seawall. It was more expensive than steel reinforcement, but not subject to corrosion-attack by seawater. The total renovation cost (including engineering and permit fees) was $180,500. The use of composite reinforcing instead of steel for this job added only 3 percent in total cost. Life cycle cost for FRP rebar showed a significant cost savings over the projected life of the structure (Busel, 2000).

Culvert bridge in the City of Rolla, Phelps County, Missouri

A culvert bridge was constructed using precast concrete boxes reinforced entirely with glass FRP rods (Nanni, 2000). The new bridge replaced a deteriorated steel pipes culvert bridge on Walker Avenue in the City of Rolla, Phelps County, Missouri. The 36ft (11m) wide bridge consisted of 18 precast concrete boxes arranged in two rows, nine boxes per row. A crew from the city public work department installed the boxes and the bridge was opened to traffic on 13 October 1999. Each box segment is 5ft (1.5m) wide and 5ft (1.5m) deep with a wall thickness of 6in (150mm) and is reinforced with a mesh of No. 2 GFRP rods. The precast units were manufactured by Scurlock Industries of Springfield, Missouri using a dry cast process. Long-term monitoring of the new culvert bridge is also being performed over the course of three years using fibre optic sensors that were attached to the FRP rebars at different locations prior to casting. Test results indicate that FRP reinforcement techniques are effective in increasing the flexural capacity of the concrete sections.

Buffalo Creek Bridge, McKinleyville, West Virginia

This is the first bridge in the world to use FRP rebars in the construction of a bridge deck (Busel, 2000). Advantages provided by the use of composite rebar include corrosion resistance to deicing salts and the caustic environment of concrete. The bridge is owned by the West Virginia Department of Transportation, Division of Highways. The project to use composite rebar in the bridge deck was a joint effort between the Division of Highways, the Federal Highway Administration, and West Virginia University Constructed Facilities Centre.

G270 and J857 bridges strengthened with near surface mounted FRP rods, Missouri

Bridge G270 is located on Route 32 in Iron County, Missouri (Mayo *et al.*, 1999). A reinforced concrete bridge was strengthened and tested to failure. The bridge was built in 1922 and consisted of three simply supported decks made of 460mm thick solid reinforced concrete slabs with an original roadway width of 7.6m. Each simply supported deck spanned 8m and was supported by two abutments and two bents. Each bent consisted of two piers connected at the top by a RC cap beam. The piers had a 0.6m × 0.6m square cross-section and were supported by 1.2m × 1.2m × 0.75m square spread footings. In general, the condition of the bridge was good. Two of the three bridge decks were strengthened with externally bonded reinforcement. The first was strengthened using externally bonded carbon FRP sheets and the second using NSM carbon FRP rods. The decks were tested to failure under static load. The piers, originally designed for gravity loads, were seismically upgraded using NSM carbon FRP rods, as well as jackets made of unidirectional carbon or glass FRP sheets. All strengthening work was carried out on the bridge while in service. Bridge upgrading was rapid with no interruption of traffic flow.

Similar to Bridge G270, Bridge J857, located on Route 72 in Phelps County, Missouri, was strengthened in August of 1998 while in service (Alkhrdaji *et al.*, 1999). The three-span structure had a roadway width of 7.6m with each deck spanning 8m. One of the three solid RC decks was strengthened using NSM, FRP rods. The NSM reinforcement consisted of 11mm sandblasted CFRP rods. Strengthening to approximately 130 percent of the existing nominal moment capacity was desirable in order to upgrade the bridge decks for heavy truck loading. Once the bridge was decommissioned, each of the three decks was tested to failure by applying quasi-static load cycles. For the deck with NSM rods, failure was initiated by the rupture of some CFRP rods at the location of the widest crack. This deck exhibited the highest failure load, corresponding to an increase in moment capacity of 27 percent over the unstrengthened deck. Two columns were also strengthened with NSM-CFRP rods to increase their flexural capacity. The rods were mounted on two opposite faces of the columns and anchored 380mm into the footings.

The Walters Street Bridge, central Missouri

A short-span FRP-reinforced concrete bridge in central Missouri is another application of the use of FRP materials in bridge construction (Stone *et al.*, 2002). The Walters Street Bridge is a pre-cast concrete panel bridge reinforced with both GFRP and CFRP reinforcing bars. It was designed according to the American Concrete Institute's document *Guide for the Design and Construction of Concrete Reinforced with FRP Bars* (ACI, 2001) to meet the load and deflection requirements of the American Association of State Highway and Transportation Officials. Carbon FRP as tensile reinforcement, and glass FRP as shear reinforcement, were utilized in this bridge construction.

FRP-reinforced concrete bridge in St James, Missouri

One current example of the use of FRP in new construction involves the FRP-reinforced

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Volume 20 · Number 2 · 2002 · 62–72

concrete bridge in St James, Missouri (Nanni, 2000). In this bridge, instead of the traditional steel reinforcement, FRP bars are used in the pre-cast panels of the multi-panel bridge. The pre-cast panels are 300mm deep and 860mm wide. The bridge consists of nine panels having an overall width of 7.8m and a length of 7.3m. Both carbon and glass FRP bars were used as reinforcement for the panels.

Carl Sagan pedestrian bridge, Ithaca, New York
The Carl Sagan pedestrian bridge in Ithaca, New York, was constructed in May 2000 (Busel, 2000). The bridge consists of two 12.8m span rail beams supporting a bridge deck 2.4m wide and 140mm thick, without any shear reinforcement. The deck is made of pre-cast reinforced concrete panels of variable cross-section reinforced with 12mm FRP rebars.

FRP reinforcement applications in Canada

Wotton Bridge, Quebec
Wotton Bridge, located in the county of Wotton, Quebec (Canada), was constructed using FRP composite bars in collaboration with the Ministry of Transportation of Quebec (Busel, 2000). The bridge is a slab-girder type with four main girders simply supported over a span of 30m.
The deck is a 200mm thickness concrete slab continuous over three spans of 2.65m each. The deck has an overhang of 1.15m on each side. Pre-tensioned pre-cast concrete beams with I-shaped cross-section were used as main girders. Half of the bridge, including bridge barriers and sidewalks, was reinforced with sand-coated FRP bars. Glass FRP bars (16mm) were used in all directions except in the short direction at the bottom where carbon FRP bars (3mm – 9.5mm) were used. The FRP bars withstood typical on-site handling problems during fabrication of the FRP reinforcement mesh and also during concrete pouring, which lasted
only two hours for the whole bridge deck ($55.0m^3$). The construction crew reacted positively saying that more FRP bars could be handled and placed in less time due to their light weight. Plastic bits were spaced at 1.0m apart in both directions to support the FRP bars and maintain a clear concrete cover of 25mm at the bottom and 65mm at the top.

Joffre Bridge, Quebec
The province of Quebec accepted the challenge of constructing the first bridge using CFRP reinforcement (Benmokrane *et al.*, 1998). A portion of the concrete deck slab was reinforced with FRP reinforcing bars. The bridge, located over the Saint-Francois River in Sherbrooke, consists of five spans (26m to 35m). The distance between steel girders is 3.7m that constitute the highest span using FRP reinforcement. A portion of the traffic barrier and the sidewalk were GFRP reinforcement. Over 180 instruments (fibre optic sensors, vibrating wire strain sensors, and electrical strain gauges) were installed at critical locations in the concrete slab deck and on the steel girders in order to identify the structural behaviour and the performance of the FRP reinforcement with time and under traffic and environmental conditions. The bridge was opened to traffic on 5 December 1997.

FRP reinforcement applications in UK

Fidgett footbridge, Chalgrove, Oxfordshire
Fidgett footbridge was the first concrete footbridge in the UK and probably in the whole of Europe to be fully reinforced with glass FRP rods (Clarke and O'Regan, 1995; Clarke *et al.*, 1996). It consists of a slab 5m long by 1.5m wide with a depth of 300 mm. Reinforcement consists of 13.5mm diameter rods at 150mm centres in both directions at the top and bottom surfaces. The slab was pre-cast, with a 40 N/mm^2 concrete, in March 1995 and installed in May 1995, on mass concrete abutments. Vibrating wire strain gauges were cast into the concrete and fibre optic sensors fitted to the slab. The bridge was fitted with glass FRP handrails. The completed structure was load tested to 1.25 times the design load in accordance with British Standard (BS: 8110) and then monitored during the following year.

Bowler's Copse Footbridge, Wendlebury, Oxfordshire
Bowler's Copse Footbridge is a 4.6m span footbridge (Clarke and Waldron, 1996). It uses the Super cover Concrete system developed by South Bank University. The bridge is reinforced with normal steel reinforcement, but with the cover increased to 88mm. GFRP reinforcement is then used within the thick cover area to reduce crack widths. There is 30mm cover to the GFRP

reinforcement. Another layer of GFRP bars was used below the top surface to cope with early thermal cracking.

FRP reinforcement applications in other countries

Oppegaard Footbridge, Oppegaard, Oslo, Norway

The bridge, with a span of 9.5m, crosses a small stream on the golf course. It is mainly intended for pedestrians but is also required to carry a tractor and trailer, giving an imposed load of 5.3 tonnes. The structure consists of two concrete beams with a timber deck spanning between them. Each beam is in the form of a shallow arch with a horizontal tie to provide stability and to reduce the shear reinforcement requirements. The beams are reinforced with glass FRP straight rods. The shear links were formed from thermoplastic glass FRP. The horizontal tie was pre-stressed with tendons, consisting of continuous Kevlar fibres in a polyethylene sheath. The beams were precast in May 1996 and installed on the previously cast abutments in June 1996 (Grostad *et al.*, 1997).

Fender Support Beam, Qatar

This is owned by Qatar Fertiliser Company and is a private location, with no public access. The fender support beam is one of 48 on the loading facility; the other 47 are conventionally reinforced with steel. The support beam, which is one of the EUROCRETE case studies, is approximately 7.9m long, 1.4m wide and 1.5m deep. It is reinforced with glass FRP pultruded rods at the top and bottom, with shear links formed from thermoplastic glass FRP. The unit was fabricated in May 1996 and installed in June 1996 (Grostad *et al.*, 1997).

Construction of the "soft-eye" for the Tunnel Boring Machine, Bangkok, Thailand

GRRP was used in the construction of the "soft-eye" opening for the Tunnel Boring Machine (TBM) as part of the Bangkok Metro Rapid Transit Authority. Contractors using TBMs have realized substantial benefits from the use of GFRP rebar when used as temporary reinforcing in soft-eye applications. Due to the low shear strength of GFRP bars, a TBM can pass directly through concrete reinforced with GFRP Rebar. TBMs cannot pass through traditional steel reinforced concrete and require expensive, dangerous and time-consuming work to pass through walls in temporary earthworks. The use of GFRP rebar in this application has proven itself in several applications in Bangkok and Hong Kong (Busel, 2000).

Concluding remarks

This paper has presented an insight into the application of FRP reinforcement in the civil and structural engineering industry. From the wide range of applications that have been successfully carried out over the past few years, it can be concluded that FRPs have found a particularly attractive niche in application as reinforcement. In addition, FRP reinforcement offers an effective solution to the problem of steel durability in aggressive environments and where the magnetic or electrical properties of steel are undesirable. They also appear to be suitable where the weight of the reinforcement required is a disadvantage. Using FRPs allows a drastic cut down of the overall weight of the elements and facilitates handing and installation procedures. Application of FRP reinforcement may not be suited for every case but does provide practitioners with an additional effective tool to upgrade or build new reinforced concrete structures. Research and development is continuing to refine the design methods, installation procedures, and quality control tests to provide the construction industry with science-based procedures. In the interim, a judicious use of FRP reinforcement can provide substantial benefits.

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