FRPs in Reinforced and Prestressed Concrete Applications: Moving Forward

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Summary

The paper focuses on recent developments in the use of fibre reinforced polymers (FRPs) in reinforced and prestressed concrete applications. The influence of the FRP material properties on the design of concrete structures is considered and applications are discussed in conjunction with the structural function of the FRP reinforcement. The review includes examples of the practical implementation of the technology and addresses important durability issues.

A number of future considerations/research needs are identified and the requirement for the provision of standard, sustainable and cost-effective FRP solutions is highlighted. It is concluded that although there have been significant advances in our knowledge of the behaviour of FRP-concrete structures, the timeframe in which FRPs will no longer be considered as *new* materials remains ambiguous.

Keywords: fibre reinforced plastics, FRP, reinforcement, prestressing, concrete, durability

Introduction

For years the aerospace industry has used fibre composite sheets to form aircraft components but, to date, fibre reinforced polymers (FRPs) have not realised their potential in construction applications. Contributing factors include the perceived expense and a lack of confidence on the part of clients and designers.

As the initial cost of FRPs is higher than that of steel, it is clear that we need to look for applications where there are distinct advantages over conventional materials. For example, FRPs are light-weight and, for the most part, very durable. Hence, these materials fare well on the basis of lower construction and long-term maintenance costs.

The process of instilling confidence in clients and designers is more difficult to evaluate. Current world air traffic has reached a level of over 3 trillion passenger-revenue kilometres per year and the replacement age of passenger aircraft is on average between 20-30 years [1]. In the Airbus A320, FRP composites make up approximately 15% of the structure [2]. Growth in the use of high performance materials in the aerospace industry continues and an estimated 40% of an Airbus A380 will be manufactured using advanced composites and advanced metallic materials [3]. Yet the construction industry remains hesitant. The ongoing development of codes and guidelines will help to encourage use. However, even with the enormous potential of the technology, the integration of these novel materials into mainstream civil engineering remains a challenge.

In the following, FRP material developments and general design issues will be discussed. Reinforced and prestressed concrete applications, durability aspects and practical applications will be considered. In addition, future research needs will be examined and a number of conclusions drawn.

Material developments

The term, *fibre reinforced polymers* describes a group of materials composed of organic or inorganic fibres embedded in a polymer matrix. For many construction applications a material with a high strength and stiffness is required. Hence, the most commonly used reinforcing fibres are glass, aramid and carbon. To date, matrix materials have been primarily *thermoset* resins such as polyesters, epoxies and vinylesters. A review of these FRP material properties can be found elsewhere [4]. It is worth noting that FRPs are elastic and do not yield.

There have been developments in the use of *thermoplastic* matrix materials such as polypropylene and nylon. These are distinctly different from *thermosets* in that, when cured, thermosets are cross-linked and the reaction is irreversible. In contrast, thermoplastics are not cross-linked and thus, the reaction process is reversible upon heating and cooling [5]. One advantage of thermoplastic resin matrices is that a greater speed of production can be realised. For example, Winistoerfer [6] describes a pultrusion process for the manufacture of a unidirectional carbon fibre reinforced nylon tape where production speeds of 60 m/min were achieved.

As sustainability issues become increasingly important, the recycling possibilities of thermoplastic matrices are also expected to be attractive. Each year four billion plastic bottles enter the UK's domestic waste system and the vast majority are not recycled; 95% of these bottles are thermoplastic-based systems and could potentially be reused [7]. To address this issue, Cantwell investigated the properties of glass fibre/recycled polyethylene terephthalate (PET) laminates and concluded that recycled thermoplastics have significant potential as matrix materials [7]. A study on the use of recycled acrylonitrite butadiene styrene (ABS), a material obtained as the shredder residue from computer and monitor housings, came to a similar conclusion [8]. In the study, the performance of chopped glass fibre reinforced (25% by weight) virgin ABS, recycled ABS or virgin/recycled blended specimens was compared. Even though the tensile capacity (in the region of 60 to 70 MPa) and the tensile stiffness (between 6.5 and 6.7 GPa) of all the chopped fibre specimens were relatively low (at least for construction applications), the recycled polymers retained more than 85% of their virgin tensile, bending and compressive strength and stiffness properties. Furthermore, the incorporation of unidirectional fibres would help to increase the tensile strength and stiffness of the recycled composite.

Although promising, the long-term behaviour of fibre reinforced thermoplastic composites in infrastructure remains an area for further investigation. Particular concerns include the bond behaviour, the performance at high temperatures and creep (particularly above the glass transition temperature).

Recent fibre initiatives include a new high modulus PBO fibre with a tensile capacity of 5.8 GPa and a Young's Modulus of 280 GPa [9]. However, at least at the moment, these fibres remain expensive. Other investigations have considered the use of hybrid reinforcement. Hybrid systems include rods with particular fibre geometries (e.g. fibres braided around an internal core), and/or a combination of fibre types with different strain capacities [10], [11]. The motivation for using hybrid systems is either to combine more expensive fibres with cheaper fibres and/or to obtain a bi-linear load deformation plot. Although the load deformation plots of these hybrid systems often show an elastic portion and then a region where a relatively constant (or even increasing) load is sustained with large deformations, this behaviour does not necessarily indicate a ductile system. The energy put into these fibres is stored elastically, rather than being absorbed plastically, and so the energy is released when the fibres break. Hence, any system that relies on fibres rupturing at different stages, does not result in true ductility. In addition, the price for this 'pseudo-ductility' tends to be a loss in efficiency.

General design issues

As the properties of FRPs are fundamentally different from those of steel, the underlying assumptions of conventional design methods based on the use of steel reinforcing materials must be re-examined.

Three main aspects are highlighted in this section: code developments, the use of under- or over-reinforced sections and the bond behaviour.

CODE DEVELOPMENTS

There have been a number of key advances in the development of guidelines and codes for the use of FRP reinforcement for concrete. Documents such as The Institution of Structural Engineers Interim Design Guidance [12], the Japanese Ministry of Construction Guidelines of FRP Reinforced Concrete Building Structures [13] and the American Concrete Institute ACI-440 document [14] are devoted to the use of passive FRP reinforcement for concrete. The remit of the Fédération Internationale du Béton (fib) Task Group 9.3 includes both reinforced and prestressed concrete structures. Similarly, publications such as the Japanese Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials [15], the Canadian Highway Bridge Design Code [16] and the proposed Canadian Standards Association document CSA-S806, Design and Construction of Building Components with Fibre Reinforced Polymers (publication date late 2001) [17] consider both reinforced and prestressed FRP reinforcement. Such documents will do a great deal to encourage designers to consider advanced materials for concrete reinforcement.

It is recognised that for the use of FRPs to grow, both standardisation and the ongoing development of design guidelines are essential. This represents a particular challenge to code writers since the use of FRPs is a relatively recent initiative. Furthermore, there remains a certain dichotomy in the code development for new technologies. On one hand, codes by their nature tend to be conservative. On the other hand, if FRPs are penalised with excessively stringent safety factors, the economics of using FRPs will be adversely affected. It will be therefore important to re-evaluate early guidelines to reflect the knowledge and confidence gained through increasing standardisation, research, usage and applications.

DESIGN PHILOSOPHY – TO UNDER OR OVER REINFORCE SECTIONS?

Steel-reinforced and prestressed concrete structures are designed to be under-reinforced. With increasing load, the steel yields, large deformations ensue and finally failure is due to concrete crushing. The behaviour is ductile. In the case of FRP reinforced structures, both the failure of the tendon and concrete crushing are brittle failure modes.

It is likely that FRP reinforced structures will be designed to be over-reinforced. The behaviour in the concrete is therefore critical and a greater understanding of the concrete compressive failure strain and the failure limits on the rotation at a concrete hinge is required. Possible means of enhancing the strain capacity by confining the concrete compression zone will be addressed in a later section.

BOND BEHAVIOUR

When used as internal reinforcement for concrete, the bond at the interface between an FRP rod and concrete is of the utmost importance. The bond behaviour will have a direct influence on both the serviceability and ultimate limit states.

A significant amount of work has been devoted to this aspect and a comprehensive review paper was published in 1995 [18]. An important conclusion was that greater insight into the mechanism of FRP-concrete bond was necessary and that the bond mechanisms were likely to differ from those of steel.

FRP manufacturers have tried to improve the bond by providing surface deformations in the outer resin layer, wrapping fibres around the rod surface, coating the rods with sand, using braiding techniques or forming twisted rods. However, one of the big problems with the diversity and number of available FRP profiles is that the bond characteristics of each type of rod will be different. Numerous possible bond slip laws for FRP reinforcement have been proposed [19] but it is clear that for any particular rod, the material properties, geometric configuration and surface profile will have a significant influence on the bond properties.

Passive versus prestressed reinforcement

In general, the Young's modulus of commonly used FRPs is lower than that of steel. Hence, in concrete with passive FRP reinforcement, serviceability limits will often control the design of a member. Prestressed concrete takes greater advantage of the high strength and strain capacity of the FRP materials and represents a more efficient use of the technology [20]. Nevertheless, passive reinforcement may be cost-effective where aspects such as the light-weight or non-magnetic properties of FRPs are important, or for structures subjected to severe exposure conditions such as bridge decks in countries where deicing salts are used extensively.

In the following, both reinforced and prestressed concrete applications will be considered with respect to the structural function of the FRP reinforcement.

Passive reinforcement for concrete

LONGITUDINAL TENSILE REINFORCEMENT

As discussed, serviceability limits will often dictate the design of a reinforced concrete member with internal FRP tensile reinforcement. In particular, deflection criteria and crack width limits are of importance.

In ACI 318 (for concrete structures with conventional steel reinforcement), short-term deflections are calculated by considering Branson's equation for an effective moment of inertia [21]. A similar approach has been used in the ACI 440 document (for concrete structures with FRP reinforcement) except that factors have been included in the formulae to account for the different modulus and also the different bond conditions of FRP bars [14]. Other approaches have considered sub-dividing the length of a beam into cracked and uncracked sections and then considering the relevant second moment of areas [22], [23].

The crack widths of FRP reinforced beams are likely to be greater than those of an equivalent steel reinforced structure. However, unlike steel, which is susceptible to corrosion, FRPs are durable. Hence, a limit on the maximum crack width is more a case of aesthetics. The Japanese Recommendation is that, for structures in public view (without steel reinforcement), the allowable crack width should be less than 0.5 mm [15].

The use of FRP reinforcement will potentially result in a smaller concrete contribution to the shear resistance of a beam. The reasons are two-fold. In the first instance, the dowel strength of FRPs can be relatively low: for GFRP it was estimated to be between 7.5% and 14% of the ultimate tensile strength [24]. Secondly, since the FRP modulus of elasticity can also be fairly low, larger shear cracks are expected which will result in a reduction of the shear resistance due to aggregate interlock. The concrete contribution to the shear capacity of the member would be reduced accordingly.

SHEAR STIRRUPS

FRPs stirrups can be formed in a number of ways. The most common method for thermoset FRPs is to wrap the pultruded material in its uncured state around a mandrel with the requisite stirrup dimensions. A continuous hoop spiral is then formed and, after curing, the spiral can be cut into individual stirrups. Another means is to filament wind thermoset resin impregnated fibres around a mandrel but with a very steep fibre angle. The box section is left to cure and the stirrups are formed by slicing the cured box into thin sections [25]. However, there have been problems with this method when aramid fibres are used as there is difficulty in cutting through the cured section.

An alternative to these processes is the in-situ manufacture of stirrups using a method similar to resin transfer molding (RTM) [26]. In this system, a bundle of uni-directional fibres are covered with a plastic tube. The fibre bundle is flexible and can be formed into almost any shape. Once the requisite shape is obtained, a thermoset resin is injected in the space between the fibres and the tube. The resin cures and hardens to form a rigid stirrup. However, it is not clear what the influence of the smooth outer tube will be on the performance of the stirrup as internal shear reinforcement for concrete.

A further production method, for FRPs with a thermoplastic matrix, is to form a stirrup by locally heating a straight bar and bending the bar into the required shape [27]. The fibre alignment at the bends is an issue in both the RTM and thermoplastic systems.

A loss of efficiency when using FRP stirrups has been observed due to the stress concentrations in the corners of the stirrups. This reduction appears to be a function of the ratio of the bend radius to bar diameter. An equation based on a regression analysis of results including carbon, aramid and glass fibre specimens suggests that for r/d ratios of 3, 5 and 7 tensile strengths of approximately 45%, 55% and 65% that of the straight tensile strengths would be achieved. However, it is noted that the fibre type, resin material and bending method will all affect the results [15]. These factors were further highlighted where it was found that for a bent bar to achieve 50% of the tensile capacity, a minimum r/d ratio of 4 was required for GFRP stirrups and one type of CFRP stirrup whilst an r/d ratio of at least 7 was required for another type of CFRP stirrup [28]. Again, differences in the fibre alignment at the bends would be a contributing factor.

A further issue is the appropriate analysis of reinforced concrete beams with FRP stirrups. Since the materials are elastic, the strain in the stirrup is important and traditional plastic methods such as the truss analogy are not valid. Nevertheless, to date, the analysis methods proposed for code implementation tend to be based on the truss analogy. However, in the equation for the stirrup contribution, the steel yield stress is replaced with the strain in the FRP multiplied by the Young's Modulus of the FRP material. For example, the strain in the FRP stirrup is limited to 0.0025 in the IstructE guidelines [12] or 0.002 in ACI 440 (although there is a further limit on the stress in the stirrup to ensure premature failure in the bend portion does not occur) [14].

One of the few existing analysis methods that considers the actual average stresses and strains in reinforced concrete is the Modified Compression Field Theory [29]. Although this theory is only applicable for cross-sections away from disturbed regions, it has been found to give good predictions for the shear behaviour of beams with internal FRP reinforcement [30], [31].

LONGITUDINAL COMPRESSION REINFORCEMENT

Kobayashi and Fujisaki found that the compressive capacities of carbon, aramid and glass FRPs were approximately 30-50%, 10% and 30-40% of the tensile strengths respectively [32]. Therefore, in many cases, it is unlikely that the use of FRPs in compression will be a viable application of these materials. Indeed the ACI 440 recommendations suggest that the strength of FRP rods in compression should be ignored [14]. Nevertheless, if an engineer seeks to design a structural member solely with FRP reinforcement, or when load reversals are expected, there may be cases where the FRP is required to carry compressive forces.

CONFINING REINFORCEMENT

As discussed, the behaviour of the concrete in the compressive zone is of the utmost importance if structures with FRP reinforcement are designed to be over-reinforced. If the concrete is confined in the compressive zone then a more ductile failure can be achieved (see Figure 1).

It has been shown that by including FRP spirals in concrete compression specimens, an enhancement of the concrete compressive strain capacity can be realised [33], [34]. The enhancement is a function of the pitch, geometry, diameter and stiffness of the spiral.

The concept was applied in the design of a cable stayed footbridge in Denmark (see Figure 2). The Herning Footbridge deck was reinforced partly with CFRP and partly with stainless steel reinforcement. In addition, the deck was prestressed with unbonded prestressed CFRP tendons and the horizontal component of the CFRP stay cable forces. The CFRP reinforced section of deck was designed to be over-reinforced and additional CFRP stirrups were placed in the compression zone to provide confinement to the concrete. Significant compressive strains and rotations would therefore be expected prior to failure due to concrete crushing [35].

Other applications for FRP confining reinforcement would be hoop ties in columns [36] and for sustaining bursting stresses that are prevalent in anchorage zones in prestressed concrete [37].

2-DIMENSIONAL GRID REINFORCEMENT FOR SLABS

Matthys and Taerwe tested a number of concrete slabs with 2-dimensional FRP grid reinforcement in one-way bending [38]. They found that in order to ensure an adequate stiffness for deflection control, higher reinforcement ratios and/or section depths were required. For the most part, deflection control was more critical than crack control but, as would be expected, the cracking was influenced by the bond characteristics of the CFRP grid.

For FRP grid-reinforced slabs with a similar strength to that of a steel-reinforced reference slab, the punching load was lower. However, when an FRP-reinforced slab was designed to have a similar cracked stiffness to that of the reference steel-reinforced slabs (as will be necessary for serviceability reasons), the punching shear resistance was comparable [39]. Again, the bond behaviour was important.

The fibre placement at the joints is a further consideration and CFRP grid joints with a woven pattern, a cross ply arrangement or a combined layout (a mix of cross ply layers and layers placed to form a cruciform geometry where the fibre tows did not cross through the joint) have been investigated [40]. The fibre orientation at the joints resulted in different joint stiffnesses and led to differences in the deflection behaviour of concrete slabs reinforced with FRP grids.

OTHER STRUCTURAL FORMS

The use of profiled FRPs to function as combined stay-in place formwork and reinforcement has been considered. Circular FRP tubes have been proposed to act jointly as formwork and confining reinforcement for columns [41], [42] and standard pultruded double T-sections with a continuous base have been tested for use as formwork/reinforcement for beams [43].

Prestressed longitudinal reinforcement for concrete

Prestress cables can be in the form of FRP tendons or fibre ropes. FRP tendons have been used both as bonded or unbonded tendons whereas fibre ropes are used solely as *unbonded* internal or external stressed tensile elements.

PRETENSIONED AND POST-TENSIONED TENDONS; GENERAL CONSIDERATIONS

One issue in the use of post-tensioned tendons is the anchorage. Stress concentrations in the anchorage can lead to premature failure. It is therefore important to consider not only the capacity of a tendon but also the load rating of the actual tendon with anchorage system. At the moment, many of the tendon anchorages tend to be proprietary and a particular system is used for a particular type of prestress tendon. Typical anchorage systems include cast or mechanical wedging systems. In the case of the former, it is likely that the tendon would be cut to length and the anchorages attached to the tendon prior to delivery to site. An overview of some of the available anchorage systems for FRP tendons can be found in a paper on ground anchors [44]. A system for anchoring aramid fibre ropes has also been described elsewhere [45].

Pretensioned internal tendons have the advantage that the long-term anchorage is provided through the bond between the FRP tendon and concrete. However, as discussed earlier, the bond mechanisms are potentially different from those of steel and are dependent on the FRP and the surface profile. This was highlighted in an investigation of the transfer bond stresses of small diameter (approximately 4 mm) braided and spiral wound aramid FRP bars [46]. Based on the experimental results, the inferred bond shear stress of the braided bar was a maximum at the beam end and decreased over a length of 515 mm (although a distance of less than 200 mm was required to transfer 95% of the force). In contrast, the spiral wound bar seemed to exhibit a locking behaviour and indeed the predicted bond stress increased over a distance of approximately 50 mm. The long-term integrity of the bond is important and again the relevant values for the particular tendon must be considered.

Creep rupture is a cumulative damage effect and is a function of the sustained stress during the lifetime of the structure. The time to creep rupture is a function of the initial stress, the type of fibre and matrix, the alkaline environment and the temperature [47]. GFRP is particularly susceptible to deterioration under high stress levels and alkaline environments and is therefore not recommended for use in pretensioned or cement based grouted post-tensioned applications [16].

INTERNAL BONDED PRESTRESSED TENDONS FOR CONCRETE

The bond between the tendon and concrete will have significant effects on the behaviour of a FRP prestressed concrete beam. When a tendon is fully bonded there will be a strain concentration in the section of tendon that spans a crack. If the FRP tendon has a high bond strength then only limited debonding will occur on either side of the crack location. As the crack displacement takes place over a short length of tendon, high tendon stresses develop and only limited rotations can occur before the tendon will snap. There is thus a high ultimate moment capacity, but a low rotational capacity.

The other extreme is to use unbonded tendons. Large rotations can occur at crack locations but, since the tendon is unbonded, only a few cracks form in the concrete. The beam is therefore predisposed to a failure in the concrete due to the large rotations that occur at a limited number of concrete hinges. Such beams exhibit large rotations but a low ultimate moment capacity.

The alternative is to use tendons that are partially bonded to the concrete. Partial bonding allows for some bond breakdown on either side of a crack and enables a designer to optimise both the ultimate load and the rotation capacity requirements. The principle was demonstrated by testing in flexure a number of small scale pretensioned concrete beams with aramid FRP tendons [48]. Beams with fully bonded, unbonded or partially bonded tendons were considered. Partial bonding was achieved by either using tendons that were intermittently bonded and unbonded along the length of the tendon (partial bond 1) or by using tendons with a limited bond capacity (partial bond 2). The study showed that by carefully designing the bond parameters, beams with both a high rotation capacity and a high moment capacity can be obtained (see Figure 3).

The importance of bond between a tendon and concrete was further highlighted in an investigation of the influence of combining unbonded CFRP tendons with passive stainless steel reinforcement [49] and also in one of the few studies on continuous beams [50]. In the latter study, Maissen tested a two-span continuous beam with prestressed CFRP tendons and the behaviour was compared with that of a similar beam with a steel tendon. The passive reinforcement in the hinge regions was the same in both cases and the ultimate capacity of the CFRP and steel tendons similar. It was noted that the CFRP beam exhibited higher rotations and a higher ultimate load capacity than the steel prestressed beam. A key factor was that, in the CFRP beam, the bond between the CFRP wires and the grout was rather weak. This enabled some debonding to take place at crack locations. In addition, since there was a significant strain capacity in excess of the initial prestress, failure did not occur immediately after the formation of the first hinge. Hence, although there were fewer cracks than in the steel prestressed beam, quasi-elastic hinges formed and large loads and rotations were achieved.

When using stressed FRP tensile reinforcement, the contribution of the tendon to the shear resistance of a beam through dowel action is an issue. As the tendons are highly anisotropic, there is potentially a propensity for the tendon to rupture at an inclined crack. Combined shear and tensile stresses may reduce the component of force that is available for carrying tensile stress and this should be considered in design [51].

A system has been proposed where CFRP tendons with a relatively low prestress level are cast into concrete prisms and then used as precast, pretensioned reinforcing elements [52]. The prestressed prisms are cast into rectangular beam sections and used as tensile reinforcement. Beams containing 42×42×2350 mm long prisms prestressed to a level of 13.5 MPa exhibited smaller deflections and crack widths than those of equivalent beams with passive CFRP reinforcement (at a load of approximately 40% of ultimate, the deflections were four times smaller and the crack widths three times smaller). A further advantage is that the prisms can be pre-fabricated. However, whether the prisms will prove feasible for longer tendon lengths is questionable as handling and installation difficulties may arise

EXTERNAL UNBONDED PRESTRESSED TENDONS FOR CONCRETE

The corrosion of the steel tendons plagued early attempts at external prestressing. In particular, smoke from steam locomotives corroded the bars of the first externally steel prestressed concrete bridge (Dischinger's bridge at Aue, 1936) [53]. Protection of external steel tendons remains a challenge and the excellent durability characteristics of non-metallic tendons will be an asset. Furthermore, as the tendons are external to the structure, the monitoring and testing of the tendons is greatly facilitated.

Aramid fibre ropes have been used in both new construction and also to upgrade existing structures [54]. A study by Leung considered beams with the novel combination of external prestressed aramid fibre ropes and internal FRP spiral confinement hoops in the compression zone [33].

A further innovative post-tensioning system has been proposed by Winistoerfer where layers of thin carbon-nylon tape are wrapped around pin anchors [6]. The outer-most tape layer is fusion bonded (nylon is a thermoplastic) to the next outer-most layer but the inner layers remain non-laminated. In this way, the through thickness stress concentrations that are prevalent in the bends of laminated sections (see section on shear stirrups) are reduced. Furthermore, as the tendon forms a closed loop, the tendon anchorage system is self-contained.

Durability

The long-term durability of FRPs remains a difficult issue to address. The design life of a typical civil engineering structure is between 50-100 years, yet the use of FRPs in construction is a relatively recent initiative. Thus, only a limited amount of long-term data exists.

Researchers have proposed carrying out accelerated tests to extrapolate long-term data from short-term test results [55]. In a typical accelerated test, the materials are subjected to elevated temperatures and/or highly alkaline solutions and the time to failure is monitored. These relatively short tests are then used to infer the lifetime of the material. Although accelerated tests can produce valuable results, there is a concern that they do not always accurately reflect the environment of the materials under service conditions. In particular, the actual deterioration mechanisms may differ from those prevalent in the accelerated tests. Kinloch [56] aptly highlights the possible contradiction (albeit when referring to the accelerated testing of adhesives) by posing the question, *When did boiling an egg ever produce a chicken?*

Fibre composites tend to be more durable than bare fibres. For example, Uomoto [57] found that after the immersion of bare carbon, aramid and glass fibres in a NaOH solution at 40° C for 120 days, the fibre strength retention was 95%, 92% and 15 % respectively. Similar tests on 6 mm round CFRP, AFRP and GFRP rods showed a strength retention of 100%, 98% and 29% respectively. However, if we rely on the resin to protect the fibres and to act as a load transfer medium, then the durability of the resin also takes on great importance. Tests by Benmokrane *et al* showed that the durability of GFRP bars with a vinylester resin was much better than that of a bar with a polyester matrix [58]. Another study determined that polyester resin was unsuitable for long-term stressed concrete applications [59].

Serious concerns have been raised about the suitability of GFRP in alkali environments such as concrete e.g. [57], [60]. Even bars of alkali resistant (AR) glass fibres in either vinylester or polyester matrices have been found to deteriorate when subjected to alkaline conditions [61]. After the immersion of the AR bars in an alkaline solution (ph12) of $Ca(OH)_2$ at 25°C for 6 months, strength losses of 20.8% for the 10 mm polyester bars and 12.7% for the 10 mm vinylester bars were recorded. Higher losses were noted at higher temperatures. Bars were also embedded in concrete beams and subjected to a deicing salt solution for a period of two years. When tested in flexure, the losses were 29.5% and 31% for the 10 mm AR polyester and vinylester bars respectively.

Some authors e.g. [59], [62] have suggested GFRP can be suitable for use as internal reinforcement for concrete (with appropriate safety factors) but this remains a moot point. One innovative way to mitigate the exposure of the glass fibres to an alkaline environment is to use a non-alkaline cement material [63].

Cracking of concrete may occur due to thermal incompatibilities between certain FRP rods and concrete. The longitudinal thermal expansion coefficients for aramid, carbon and glass are around -6×10^{-6} / °C, 0 / °C, 10×10^{-6} / °C respectively [15]. However, the transverse coefficient of thermal expansion can much higher. Matthys *et al* carried out a study of thermal cracking of AFRP bars in concrete and found that an increased cover was required to mitigate this effect [64]. A later study by Sen *et al* considered both thermal and moisture effects and suggested that the moisture uptake of the fibre and matrix was the more critical factor [65]. The research showed that the high moisture absorption limit for AFRP made the material particularly susceptible to inducing detrimental cracking in concrete.

A great deal of research is being carried out on durability issues and in 1998 a conference devoted to the Durability of Fiber Reinforced Polymer (FRP) Composites for Construction was held in Sherbrooke, Canada. The conference papers covered a wide range of topics (some of which have been referred to in this section) and included a general overview of research that considered the resistance of glass, aramid and carbon fibres to alkalis, water and UV effects [66]. Aspects such as possible bond deterioration, freeze-thaw behaviour, performance at high temperatures and long-term deflections are also important. A further review paper on durability issues can be found elsewhere [67].

It appears that differences in the test methods, resins, fibre properties, fibre coatings, fibre layout and manufacturing processes will all influence the measured durability characteristics. There is an urgent need to quantify these influences in order to obtain results that are reliable, repeatable and consistent.

Applications

A summary of a number of recent applications in Europe, Japan, USA and Canada has been highlighted in special journal issues devoted to advanced composite materials. Readers are referred to a recent Structural Engineering International issue on advanced materials [68] and annual issues of Concrete International under the heading of *FRP*

Around the World [69] and *Fiber Reinforced Polymer Reinforcement* [70]. Applications discussed range from the use of CFRP tendons as bridge cables in Switzerland to CFRP shear stirrups in bridge decks in Canada [68], from carbon fibre prestressed piles in the USA to GFRP shotcrete reinforcement for underground petroleum storage facilities in Japan [69] and from GFRP reinforced barrier walls in Canada to bridge beams with internal CFRP prestressed tendons in the USA [70].

Future considerations/Research needs

There is an increasing focus on quantifying the economics and cost/benefit aspects of FRP reinforcing systems e.g. [71]. Savings in terms of construction, installation and long-term maintenance costs are expected to offset a higher initial cost. However, many projects are tendered on a lowest first-cost basis and a low priority is given to maintaining a structure throughout the design lifetime. A further obstacle is that savings in items such as long-term maintenance are difficult to calculate and heavily dependent on assumed interest rates.

With a greater use of FRPs it is expected that economies of scale will contribute to reducing the cost of the materials. The establishment of optimal supply chains will also play a role in the overall economics. There is an additional question regarding whether it is more important to establish the market share for FRPs rather than each manufacturer focussing on their individual product. This aspect is connected to a growing awareness of the need for standardisation within the FRP market. At the moment, each particular company produces and markets their particular product. However, there can be great variations in parameters such as the FRP constituent materials and manufacturing methods which hinders the extrapolation of one set of test results to another product [72].

Sustainable development is of paramount importance and the energy requirements in the production of the constituent materials, the manufacture and installation of the FRP reinforcement and ultimately the disposal of the materials will be an issue. In using FRPs we are seeking to provide long-term solutions, thus methods of ascertaining the condition (or for that matter even the location!) of FRP bars embedded in concrete are required. Structural monitoring systems where fibre-optic Bragg gratings are attached to FRP tendons may provide long-term data on the in-situ performance of FRP reinforcement [73]. However, these systems rely on continuous monitoring and are not widespread.

Technology transfer between industries will be beneficial and there is much to be gained in learning from the experience in the marine, offshore and aerospace industries.

FRPs are reaching a critical stage of development. As with any innovation, there are still questions to be answered. Furthermore, it is wrong to advocate FRPs as the only viable reinforcing material for concrete. There will be applications where FRPs provide a superior solution but equally there will be cases where other materials are more appropriate. The foundations for the widespread implementation of FRPs already exist; all that remains is the necessary vision to implement the technology.

References

1. Airbus, Global market forecast 2000 - 2019. 2000: Airbus Industrie, France. AI/CP390.0031/00.
2. Bölkow L. Ein Jahrhundert Flugzeuge - Geschichte und Technik des Fliegens. 1990: VDI-Verlag GmbH, Düsseldorf. *(in German).*
3. Airbus. Feature - A3XX: Engineering a new way to fly, Airbus Letter September 2000. 4 January 2001. http://www.airbus.com/
4. Soudki KA. FRP reinforcement for prestressed concrete structures. *Progress in Structural Engineering and Materials* 1998; **1**(2): 135-142.
5. Hull D. An introduction to composite materials. 1981: Cambridge University Press.
6. Winistoerfer AU. Development of non-laminated advanced composite straps for civil engineering applications. Department of Engineering, University of Warwick, PhD Thesis, 1999.
7. Cantwell WJ. The fracture behavior of glass fiber/recycled PET composites. *Journal of Reinforced Plastics and Composites* 1999; **18**(4): 373-387.

8. Vijay PV, GangaRao HVS, & Bargo JM. Mechanical characterization of recycled thermoplastic polymers for infrastructure applications. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridge and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 53-60.

9. Toyobo. PBO fiber. 4 January 2001. http://www.toyobo.co.jp/e/seihin/kc/pbo/

10. Tamuzs V & Tepfers R. Ductility of non-metallic hybrid fiber composite reinforcement for concrete. In: L. Taerwe, (ed). *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of Second International RILEM Symposium (FRPRCS-2)*. Ghent, Belgium: 1995. E&FN Spon. 18-25.

11. Somboonsong W, Ko FK, & Harris HG. Ductile hybrid fiber reinforced plastic reinforcing bar for concrete structures: Design methodology. *ACI Materials Journal* 1998; **95**(6): 655-666.

12. IStructE. Interim guidance on the design of reinforced concrete structures using fibre composite reinforcement. 1999: The Institution of Structural Engineers, London.

13. Sonobe Y, *et al.* Design guidelines of FRP reinforced concrete building structures. *Journal of Composites for Construction* 1997; **1**(3): 90-115.

14. ACI-440H. Guide for the design and construction of concrete reinforced with FRP bars. 2000: American Concrete Institute.

15. JSCE. Recommendation for design and construction of concrete structures using continuous fiber reinforcing materials. Concrete Engineering Series 23. 1997: Japan Society of Civil Engineers.

16. Bakht B, *et al.* Canadian bridge design code provisions for fiber-reinforced structures. *ASCE Journal of Composites for Construction* 2000; **4**(1): 3-15.

17. Cheung MS & Wiseman A. Development of Canadian standard for building construction using FRP composites. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridge and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 841-848.

18. Nanni A, Bakis CE, & Boothby TE. Test methods for FRP-concrete systems subjected to mechanical loads: State of the art review. *Journal of Reinforced Plastics and Composites* 1995; **14**: 524-558.

19. Cosenza E, Manfredi G, & Realfonzo R. Behavior and modeling of bond of FRP rebars to concrete. *ASCE Journal of Composites for Construction* 1997; **1**(2): 40-51.

20. Burgoyne CJ. Rational use of advanced composites. In: *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third International Symposium (FRPRCS-3)*. Sapporo, Japan: 1997. Vol. 1. Japan Concrete Institute. 75-88.

21. ACI-318-95. Building code requirements for structural concrete (318-95) and commentary (318R-95). Fourth Printing ed. 1998: American Concrete Institute.

22. Faza SS & Gangarao HV. Pre- and post-cracking deflection behaviour of concrete beams reinforced with fibre-reinforced plastic bars. In: K.W. Neale and P. Labossiere, (eds). *Advanced Composite Materials in Bridges and Structures*. Montreal, Canada: 1992. The Canadian Society for Civil Engineering. 151-160.

23. Razaqpur AG, Svecova D, & Cheung MS. Rational method for calculating deflection of fiber reinforced polymer reinforced beams. *ACI Structural Journal* 2000; **97**(1): 175-184.

24. Michaluk CR, Rizkalla SH, Tadros G, & Benmokrane B. Flexural behavior of one-way concrete slabs reinforced by fiber reinforced plastic reinforcements. *ACI Structural Journal* 1998; **95**(3): 353-365.

25. Duranovic N, Pilakoutas K, & Waldron P. Tests on concrete beams reinforced with glass fibre reinforced plastic bars. In: *Procs of Third International Symposium on Non-metallic (FRP) Reinforcement for Concrete Structures*. Sapporo, Japan: 1997. Vol. 2. Japan Concrete Institute. 479-485.

26. Sugiyama T, *et al.* Development of continuous fiber flexible reinforcement. In: C.W. Dolan, S.H. Rizkalla, and A. Nanni, (eds). *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, SP188*. Baltimore, USA: 1999. ACI International. 13-22.

27. Currier J, Fogstad C, Walrath D, & Dolan C. Bond development of thermoplastic FRP shear reinforcement stirrups. In: *3rd Materials Engineering Conference*. San Diego: 1994. 592-597.

28. Shetata E, Morphy R, & Rizkalla S. Fiber reinforced polymer reinforcement for concrete structures. In: C.W. Dolan, S.H. Rizkalla, and A. Nanni, (eds). *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, SP188*. Baltimore, USA: 1999. ACI International. 157-168.

29. Vecchio FJ & Collins MP. The modified compression-field theory for reinforced concrete elements subjected to shear. *ACI Journal (March-April)* 1986; **83**(2): 219-231.

30. Fam AZ, Rizkalla SH, & Tadros G. Behavior of CFRP for prestressing and shear reinforcements of concrete highway bridges. *ACI Structural Journal* 1997; **94**(1): 77-86.

31. Stratford TJ. The shear of concrete with elastic FRP reinforcement. Department of Engineering, University of Cambridge, Cambridge, UK, PhD Thesis, 2000.

32. Kobayashi K & Fujisaki T. Compressive behavior of FRP reinforcement in non-prestressed concrete members. In: L. Taerwe, (ed). *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of 2nd International RILEM Symposium (FRPRCS-2)*. Ghent, Belgium: 1995. E&FN Spon. 267-274.

33. Leung HY. Aramid fibre spirals to confine concrete in compression. Department of Engineering, University of Cambridge, Cambridge, PhD Thesis, 2000.

34. Mutsuyoshi H, Taniguchi H, Kita T, & Machida A. Ductility improvement of PC members reinforced with FRP. *Concrete Library of JSCE, No 22* 1993(December): 117-128.

35. Christoffersen J, Hauge L, & Bjerrum J. Footbridge with carbon-fibre-reinforced polymers, Denmark. *Structural Engineering International* 1999; **4**: 254-256.

36. Saatcioglu M & Sharbatdar K. Use of FRP reinforcement in concrete columns. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridges and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 363-370.

37. Choi M-C & Ibell TJ. Anchorage zones for FRP-prestressed concrete. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridge and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 111-118.

38. Matthys S & Taerwe L. Concrete slabs reinforced with FRP grids. I: One-way bending. *ASCE Journal of Composites for Construction* 2000; **4**(3): 145-153.

39. Matthys S & Taerwe L. Concrete slabs reinforced with FRP grids. II: Punching resistance. *ASCE Journal of Composites for Construction* 2000; **4**(3): 154-161.

40. Engel RS, Croyle MG, Bakis CE, & Nanni A. Deflection of reinforced concrete beams reinforced by fiber reinforced polymer grids with various joint designs. In: C.W. Dolan, S.H. Rizkalla, and A. Nanni, (eds). *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, SP188*. Baltimore, USA: 1999. ACI International. 75-85.

41. Yamakawa T, Satoh H, & Zhong P. Seismic performance of hybrid reinforced concrete circular columns confined in aramid fiber reinforced polymer tube. In: C.W. Dolan, S.H. Rizkalla, and A. Nanni, (eds). *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, SP188*. Baltimore, USA: 1999. ACI International. 1089-1102.

42. Lillistone D & Jolly CK. Concrete-filled fibre reinforced plastic circular columns. In: *Composite Construction - Conventional and Innovative*. Innsbruck, Austria: 1997. IABSE. 759-764.

43. Hall JE & Mottram JT. Combined FRP reinforcement and permanent formwork for concrete members. *ASCE Journal of Composites for Construction* 1998; **2**(2).

44. Benmokrane B, Xu H, & Nishizaki I. Aramid and carbon fibre-reinforced plastic prestressed ground anchors and their field applications. *Canadian Journal of Civil Engineering* 1997; **24**: 968 - 985.

45. Brown IF. Abrasion and friction in parallel-lay rope terminations. Department of Engineering, University of Cambridge, Cambridge, UK, PhD Thesis, 1997.

46. Lees JM & Burgoyne CJ. Transfer bond stresses generated between FRP tendons and concrete. *Magazine of Concrete Research* 1999; **51**(4): 229-239.

47. Budelmann H & Rostásy FS. Creep rupture behavior of FRP elements for prestressed concrete - Phenomenon, results and forecast models. In: A. Nanni and C.W. Dolan, (eds). *Fiber-Reinforced-Plastic Reinforcement for Concrete Structures - International Symposium, SP138*. Vancouver, Canada: 1993. American Concrete Institute. 87-100.

48. Lees JM & Burgoyne CJ. Experimental study of influence of bond on the flexural behaviour of concrete beams pre-tensioned with aramid fiber reinforced plastics. *ACI Structural Journal* 1999; **96**(3): 377-385.

49. Campbell TI, Rizkalla NS, & Tung DP. Hybrid FRP/stainless steel reinforcements for pretensioned concrete beams. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridge and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 201-208.

50. Maissen A. Concrete beams prestressed with carbon-fibre-reinforced-polymer cables. *Structural Engineering International* 2000; **2**: 117-120.

51. Park SY & Naaman AE. Dowel behavior of tensioned fiber reinforced polymer (FRP) tendons. *ACI Structural Journal* 1999; **96**(5): 799-806.

52. Svecova D & Razaqpur AG. Flexural behavior of concrete beams reinforced with carbon fiber-reinforced polymer (CFRP) prestressed prisms. *ACI Structural Journal* 2000; **97**(5): 731-738.

53. Virlogeux MP. External prestressing: From construction history to modern techniques and technology. In: A. Naaman and J. Breen, (eds). *External Prestressing in Bridges, SP-120*: 1990. American Concrete Institute. 1-60.

54. Burgoyne CJ. Advanced Composites in Civil Engineering in Europe. *Structural Engineering International* 1999; **4**: 1-7.

55. Gerritse A. Assessment of longterm performance of FRP bars in concrete structures. In: B. Benmokrane and H. Rahman, (eds). *Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, Procs of 1st International Conference*. Sherbrooke, Canada: 1998. 285-297.

56. Kinloch AJ. Adhesives in engineering. *Proceedings of the Institution of Mechanical Engineers* 1997; **211**(Pt G): 307-335.

57. Uomoto T. Durability of FRP as reinforcement for concrete structures. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridges and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 3-17.

58. Benmokrane B, Rahman H, Ton-That M-T, & Robert J-F. Improvement of the durability of FRP reinforcements for concrete structures. In: B. Benmokrane and H. Rahman, (eds). *Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, Procs of 1st International Conference*. Sherbrooke, Canada: 1998. 571-585.

59. Clarke JL & Sheard P. Designing durable FRP reinforced concrete structures. In: B. Benmokrane and H. Rahman, (eds). *Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, Procs of 1st International Conference*. Sherbrooke, Quebec, Canada: 1998. 13-24.

60. Sen R, Mariscal D, & Shahawy M. Durability of fiberglass pretensioned beams. *ACI Structural Journal* 1993; **90**(5): 525-533.

61. Tannous FE & Saadatmanesh H. Durability of AR glass fiber reinforced plastic bars. *ASCE Journal of Composites for Construction* 1999; **3**(1): 12-19.

62. Devalapura RK, Greenwood ME, Gauchel JV, & Humphrey TJ. Evaluation of GFRP performance using accelerated test methods. In: B. Benmokrane and H. Rahman,

(eds). *Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, Procs of 1st International Conference*. Sherbrooke, Canada: 1998. 107-116.

63. DeRoover C, *et al.* A new non-alkaline cement material reinforced by glass fibres (IPC) for the construction of bridges. In: J.L. Humar and A.G. Razaqpur, (eds). *Advanced Composite Materials in Bridge and Structures, 3rd International Conference*. Ottawa, Canada: 2000. The Canadian Society for Civil Engineering. 429-436.

64. Matthys S, DeSchutter G, & Taerwe L. Influence of transverse thermal expansion of FRP reinforcement on the critical concrete cover. In: M. El-Badry, (ed). *Advanced Composite Materials in Bridges and Structures, 2nd International Conference*. Montreal, Canada: 1996. The Canadian Society for Civil Engineering. 665-672.

65. Sen R, Carpenter W, & Snyder D. Finite element modeling of fiber reinforced polymer pretensioned elements subjected to environmental loads. *ACI Structural Journal* 1999; **96**(5): 766-773.

66. Malvar LJ. Durability of composites in reinforced concrete. In: B. Benmokrane and H. Rahman, (eds). *Durability of Fiber Reinforced Polymer (FRP) Composites for Construction, Procs of 1st International Conference*. Sherbrooke, Canada: 1998. 361-372.

67. Hamilton-III HR & Dolan CW. Durability of FRP reinforcements for concrete. *Progress in Structural Engineering and Materials* 2000; **2**(2): 139-145.

68. SEI. *Structural Engineering International, Journal of the International Association for Bridge and Structural Engineering (IABSE)* 1999; **9**(4).

69. ACI. FRP around the world. *Concrete International* 1999; **21**(10).

70. ACI. Fiber reinforced polymer reinforcement. *Concrete International* 1998; **20**(6).

71. Hastak M & Halpin DW. Assessment of life-cycle benefit-cost of composites in construction. *ASCE Journal of Composites for Construction* 2000; **4**(3): 103-111.

72. Scalzi JB. Will FRP composites ever change bridge engineering? *Concrete International* 2000; **22**(4): 56-58.

73. Maaskant R, *et al.* Fiber-optic Bragg grating sensors for bridge monitoring. *Cement and Concrete Composites* 1997; **19**: 21-33.

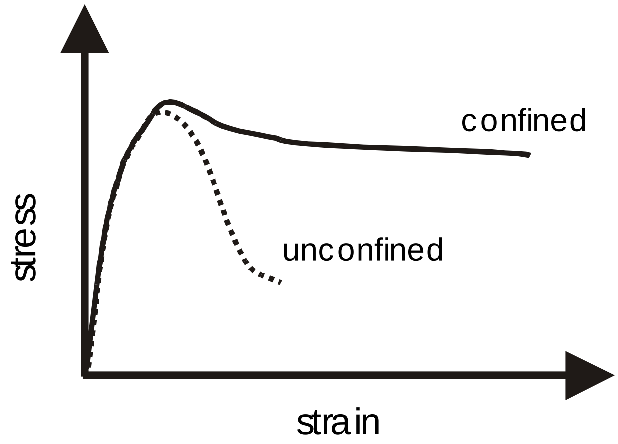

Figure 1 – Schematic diagram of compressive stress-strain curves for confined and unconfined concrete

Figure 2 – Photo of Herning Footbridge (*Courtesy of COWI Consulting Engineers*)

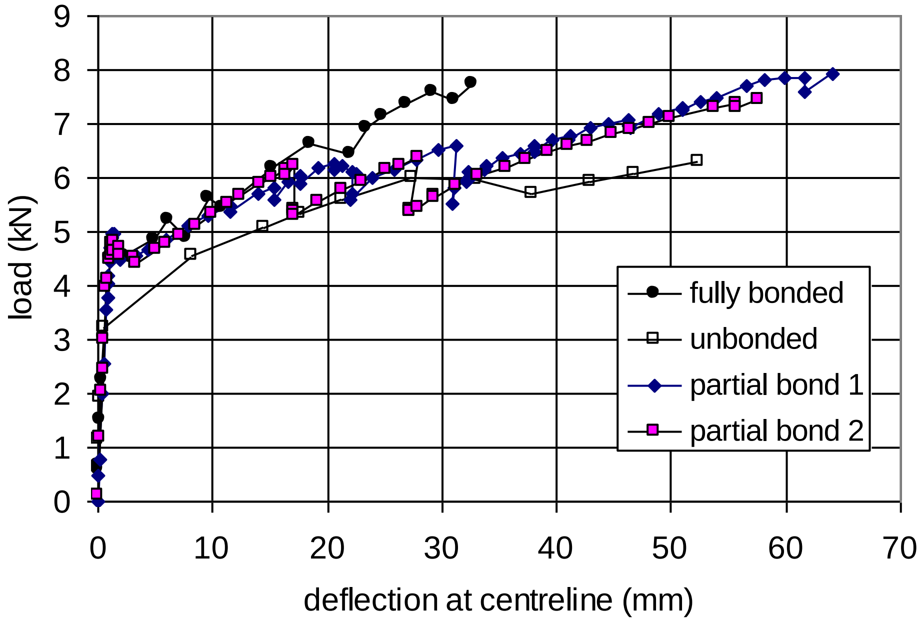

Figure 3 – Influence of bond on load-deflection behaviour