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The use of FRP as embedded reinforcement in concrete

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ABSTRACT: The increased use of FRP in construction is largely driven by the requirement for more durable solutions than steel for those applications subjected to the most severe environmental conditions. Adoption of FRP as embedded reinforcement in new structures has, however, been much slower than for other applications such as repair and strengthening. This is due to a number of factors including cost, availability (especially of bent bars), structural performance, lack of design guidance, and its own durability in highly alkaline environments such as that found in concrete. On-going research around the world has addressed, and continues to address, these various areas of concern. This Paper summarizes the research contributions made by the University of Sheffield over the past decade to this huge worldwide effort.

1 INTRODUCTION

For more than a century steel bars have been used as reinforcement in RC structures to compensate for the low tensile strength of the concrete. Although steel reinforcement is generally manufactured and used in straight lengths, it is readily cold formed in to 2-d and 3-d shapes for use in more complex structural elements and critical structural connections.

Nevertheless, when concrete structures come into contact with carbonic acid, resulting from the carbon dioxide present in the atmosphere, or are exposed to chloride rich environments, such as those created by the presence of seawater or the frequent use of deicing salts, steel reinforcement is susceptible to corrosion. Corrosion of the reinforcement can lead to premature deterioration of the mechanical performance of the structure and subsequent failure.

At present, corrosion of steel reinforced concrete structures is considered to be the most significant factor in limiting the life expectancy of RC structures in North America, Europe, the Middle-East and other parts of the world. In Europe alone, the annual cost of repair and maintenance of the infrastructure is estimated to be over €30 billion and, in the United States, the overall costs associated with damage due to reinforcing steel corrosion have been estimated at about $80 billion (Federal Highway Administrator 1997).

Over the past thirty years, different measures have been taken to combat the corrosion problem. These have included the specification of increased concrete cover, the introduction of additives and inhibitors to make the concrete more impermeable and non-conductive, and the use of different types of reinforcing materials such as stainless steel and epoxy coated steel bars. Research data, however, have shown the long-term performance of epoxy coated steel rebar to be questionable, while stainless steel, which exhibits excellent corrosion resistance, is too expensive for wide scale use (Federal Highway Administration, 2000). The on-going requirement for more durable structures is therefore the key driving force behind the introduction of advanced composites in the construction industry as reinforcing material for concrete.

Manufactured from a combination of mineral fibres within a polymeric matrix, fibre reinforced polymer (FRP) reinforcing bars display excellent resistance to environmental factors such as freeze-thaw cycles, chemical attack and temperature variations. Above all, composites can be engineered to be highly corrosion resistant providing a highly durable reinforcement material for increasing the design life of new concrete structures.

While composite materials have proven to possess superior mechanical properties and have been used extensively in the aerospace, automobile and defence industries, civil engineers are beginning only now to gain confidence and experience in applying this technology to the construction industry.

2 FRP PRODUCTS FOR CONCRETE STRUCTURES

The mechanical characteristics of FRP reinforcement are different in many respects from conventional steel reinforcement and depend very much on the type of fibres and resins used. Carbon, glass and aramid fibres, impregnated with a resin matrix, are the basic components for the manufacture of composite

Figure 1. Examples of various types of FRP reinforcement.

Table 1. Advantages and disadvantages of FRP reinforcement.

Advantages	Disadvantages
Higher strength to self-weight ratio (10–15 times greater than steel)	Higher raw material cost and relatively poor availability
Excellent fatigue characteristics (carbon and aramid FRPs only)	Lower elastic modulus (except some Carbon FRPs)
Excellent corrosion resistance and electromagnetic neutrality	Glass FRP reinforcement suffers from stress corrosion
Low axial coefficient of thermal expansion	Lack of ductility; durability issues in alkaline environments

reinforcement. Due to the non-structural contribution made by the resin, as well as its relatively high cost, a maximum fibre to resin volume fraction is always desirable. However, the maximum fibre content that can be achieved in practice is normally below 70% resulting in bars with an equivalent elastic modulus well below that of the constituent fibres.

FRP materials can be manufactured by using different techniques such as pultrusion, filament winding, moulding, braiding and manual lay-up and can be produced in various shapes. As for conventional steel reinforcement, however, non-ferrous composite materials are usually manufactured in the form of rebars, sheets, grids and links (Figure 1).

Composites can be engineered to meet the specific demands of each particular application and their overall performance and characteristics depend on the choice of materials (fibre and resin matrix), the volume fraction of fibre, fibre orientation and fabrication method. Furthermore, in order to enhance the bond characteristics of FRP reinforcing bars in concrete, several techniques are employed including the introduction of surface deformations, sand coating, over-moulding a new surface on the bar, or a combination thereof.

The main advantages and disadvantages of these advanced composite materials compared to steel are listed in Table 1.

High strength, light weight and low modulus of elasticity, together with the fact that FRP bars, unlike steel, do not display plasticity, are the key properties that differentiate the performance of these materials.

3 INTERNATIONAL RESEARCH EFFORT AND THE DEVELOPMENT OF GUIDELINES

The first research committee on Continuous Fiber Reinforcing Materials (CFRM) was established in 1989 by the Japan Society of Civil Engineers (JSCE). The work of this Committee was published in Japanese in the form of a State-of-the-Art report in 1992 addressing various issues such as applications, design guidelines, durability and test methods. The part of this first publication that dealt with design considerations was translated into English and published in 1993. Since the development of design guidelines was seen as crucial if the use of CFRM was to be encouraged, the work of the Committee focused specifically on this issue and fuller design recommendations were subsequently published in Japanese in 1996 and then in English in 1997.

Research activity in Canada on the use of FRP as reinforcement for concrete also began in 1989. The Canadian Society of Civil Engineers created a technical committee to study the use of advanced composite materials in bridges and structures. The efforts of this committee resulted in the publication of a State-of-the-Art report in 1991 (Mufti *et al.*) and lead to design recommendations that were published in February 1998 (Canadian Highway Bridge Design Code). The Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada), was established in 1995 largely to provide civil engineers with smarter ways to build, repair and monitor structures using high-strength, non-corroding, fibre reinforced polymers and fibre optic sensors. Within this framework, two design manuals, which deal with various aspects of reinforcing and strengthening concrete structures, were published in 2001 (ISIS Canada).

Mainstream FRP research in the U.S.A. and Europe commenced in 1991. In January of that year, the American Society of Civil Engineering sponsored a conference on Advanced Composites Materials in Civil Engineering Structures and in November, the 5-year BRITE/EURAM Project, “Fibre Composite Elements and Techniques as non Metallic Reinforcement for

Concrete", funded by the Commission of the European Communities, began in Europe (Taerwe, 1997).

Also in 1991, the American Concrete Institute (ACI) formed Committee 440, Fibre Reinforced Polymer Reinforcement, whose efforts lead to the publication of a State-of-the-Art report in 1996 (American Concrete Institute). This report was followed by the publication of their recommendations for externally bonded with FRP systems (American Concrete Institute 2002) and the design and construction of concrete reinforced with FRP bars (American Concrete Institute, 2003).

In December 1993, the EUROCRETE project (Clarke *et al*, 1996) began in Europe. This pan-European research programme was established with the aim of developing durable FRP reinforcement for concrete. Although many fundamental areas of research were progressed, one of the main objectives was the development of suitable design guidelines. Much of the work done by the task group that dealt with this particular issue is included in an interim guidance, which was published in 1999 by the British Institution of Structural Engineers.

The EU TMR Network, ConFibreCrete, was established in 1997 with the aim of developing guidelines for the design of concrete structures, reinforced, prestressed or strengthened with advanced composites. The Network comprised 11 teams from 9 different European countries and its work was closely linked to the work of the *fib* Task Group 9.3, FRP Reinforcement for Concrete Structures, which was established late in 1996. An outcome of the ConFibreCrete project was a bulletin on externally bonded FRP reinforcement for RC structures published through the International Federation of Concrete, *fib* (*fib* Task Group 9.3, 2001). These guidelines concern mainly flexure, shear and confinement, but they also deal with other issues such as execution, quality control, durability and environmental effects. A further bulletin dealing with state-of-the-art knowledge on FRP materials and their use in RC and PC structures is in the final stages of preparation and is expected to become available in 2005.

The most recent effort in trying to address some of the fundamental problems of using FRP in reinforced concrete in Europe is the 2 year CRAFT RTD project, CurvedNFR, which commenced in June 2003. This project aims to develop materials, methodology and manufacturing processes for a low cost, curved FRP rebar (CurvedNFR, 2003).

The University of Sheffield, having taken a key role in the Eurocrete project and having recently coordinated the ConFibreCrete Network, has had an ongoing involvement in FRP research in Europe. The main focus of its work has been to undertake fundamental research to support the development of design guidelines.

Although great strides have been made in research dealing with the use of FRPs in RC structures since its inception in 1989, there remains much work to be done. For example, internationally accepted codes of practice for FRP materials are still required and there are many specific research problems that remain to be more fully investigated, such as shear behaviour of FRP RC elements, detailing of FRP reinforcement and a unified design philosophy in general.

4 THE USE OF FRP IN THE CONSTRUCTION INDUSTRY

FRP products have made a dramatic entry into the construction industry over the past 20 years and, since demonstration projects were first constructed in the late 80's and early 90's, the interest in these materials has increased exponentially. The main reasons behind the rapid growth of the use of FRPs in construction were firstly related to the light weight of the reinforcing products and their electromagnetic neutrality. The earliest commercial applications were for non-magnetic or radio-frequency transparent reinforcement for advanced transport systems, specialised defence applications and structures housing magnetic resonance imaging medical equipment. Nowadays, the crucial need to find durable and cost effective solutions to the problem of corrosion in RC structures is perhaps the stronger driver responsible for the rapidly increasing interest in the use of advanced composite materials as reinforcement in concrete around the world.

The number of applications worldwide has increased substantially during the last decade and, although externally bonded applications of FRP reinforcement for the strengthening and rehabilitation of existing structures predominate, the use of FRP as internal reinforcement for newly built structures is receiving more and more attention.

When FRP reinforcement is specified for use in new concrete structures, durability is generally the primary concern. Because of its relatively high cost, the use of advanced composites is typically only likely to replace steel reinforcement in those applications where the superior corrosion resistance properties of FRP are required. For these special applications, FRP can be competitive with other corrosion resistant products such as stainless steel and epoxy coated reinforcement. Although these existing corrosion resistant products only account for about 3–4 % of the total reinforcement market, in Europe alone this represents about 0.5 million tonnes per year (Euro-Project Ltd. 1997). Even a relatively modest share of this corrosion resistant market coupled with the other niche markets where electro-magnetic neutrality or high strength are identified as key issues, is very attractive to the composites industry.

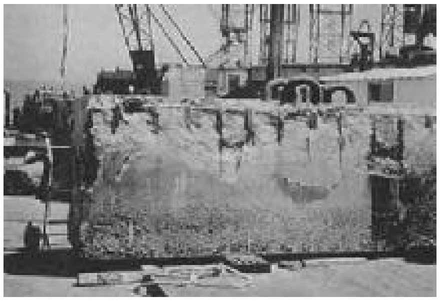

Figure 2. Damaged fender support beam, Qatar (courtesy EUROCRETE project).

Figure 3. FRP reinforced post and panel fencing around a transmitter (courtesy EUROCRETE project).

4.1 *Durability*

Currently, in Europe, more money is spent each year on repairing and strengthening existing structures than on new construction. A large proportion of this expenditure on the rehabilitation of existing infrastructure is incurred in resolving problems of reinforcement corrosion in concrete structures. When steel corrodes, it expands locally resulting in additional stresses accumulating in the concrete. These stresses are capable of cracking the concrete near the surface, allowing much faster ingress of water and corrosive chemicals ultimately resulting in spalling of the concrete cover (Figure 2).

FRP reinforcement represents a valid alternative for structures vulnerable to corrosive environments and has many possible applications in structures in or adjacent to the sea, in or near the ground, in chemical and other industrial plants and in places where good quality concrete can not easily be achieved.

Furthermore, the use of FRP reinforcement allows the concrete cover needed to protect the reinforcement to be reduced. This results in thinner sections of lower weight and has particular benefits in precast elements such as cladding panels.

Figure 4. Magnetic levitation train track in Japan.

Figure 5. Prestressed FRP cables used in a ribbon bridge in Japan.

4.2 *Electromagnetic neutrality*

Steel reinforcement is usually avoided when magnetic neutrality is required and in many applications, especially for the mobile telecommunications and defence industries, this can be a big concern. As a demonstration project in the Eurocrete Project, concrete posts and fence panels reinforced with FRP reinforcement were used to provide a secure boundary for a telecommunication facility (Figure 3).

Other possible applications include bases of large motors, hospital buildings containing magnetic resonance scanning equipment, power transmission towers and magnetic levitation systems such as the MAGLEV (Figure 4).

4.3 *High strength*

One of the more important properties of FRPs is the very high strength that can be developed, allowing a reduction in the area of reinforcement needed in certain applications. However, since high strength in the reinforcement can only be developed when accompanied by high strain, this property can only be fully exploited in prestressed concrete elements (Figure 5). Furthermore, when FRP is adopted for prestressing, considerably lower losses occur than those associated

Figure 6. FRP ground anchors.

with conventional steel tendons due to the lower elastic modulus of the FRP material. However, because of the stress corrosion that affects FRP materials, particularly glass fibre based products, only carbon and aramid are likely to be appropriate for applications in this field.

In addition, FRP cables can be used in cable stay bridges and in other anchoring applications such as ground anchors or rock bolts (Figure 6).

5 FRP IN REINFORCED CONCRETE: STRUCTURAL CONSIDERATIONS

Figure 7 shows the generic mechanical properties of FRP reinforcement according to the type of fibres used in their manufacture.

FRP products are characterized by perfectly elastic behaviour up to failure and can develop higher tensile strength than conventional steel in the direction of the fibres. This anisotropy, however, seriously affects the shear strength, which is very low, compared to the tensile strength, and depends on the properties of the matrix and orientation of the fibres. The elastic modulus of FRP materials used in construction generally varies between 20% of that of steel for glass fibres to 75% of that of steel for carbon fibres.

Although FRP materials, in general, have a low compressive strength, due to the low buckling strength of the individual fibres, this is not usually a major concern since, in the majority of civil engineering applications, FRP is predominantly used only in tension.

Due to the particular mechanical properties of the reinforcement, and especially due to their lack of ductility, FRP RC structures are normally governed by brittle modes of failure generally considered to be undesirable. Based on these considerations, both the construction techniques and the design philosophy need to be carefully reassessed (Pilakoutas, 2000). The behaviour of FRP RC members in flexure, shear and bond is therefore briefly examined and various approaches for the design of RC elements with FRP reinforcement are considered and commented upon.

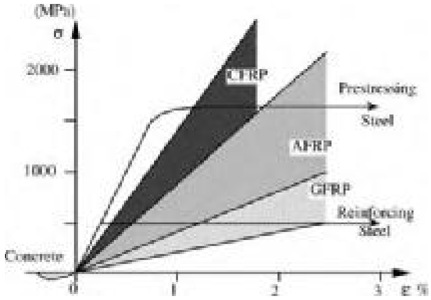

Figure 7. Stress–strain characteristics for concrete and reinforcing materials.

5.1 *Design philosophy*

Work at Sheffield (Pilakoutas *et al*, 2002) has looked at the issue of a suitable design philosophy and has arrived at a new approach. During this work it was revealed that the current partial safety factor approach does not lead to uniform safety levels and often results in conservative designs with larger than necessary amounts of reinforcement. In addition, the margins between the flexural mode of failure and the other modes of failure are quite variable and the designer has no reliable means of assessing them.

In the proposed approach, the main aim was to arrive at a design that has a predetermined safety level (a probability of failure of 10^{-6}) and for which the failure mode hierarchy could be selected by the designer at the design stage. This unified approach has been proposed since it enables new materials to be introduced as they are developed without the need for re-writing the design guide each time. Hence, as a result, the engineer not only selects whether, for example, concrete crushing, bond failure or shear failure is to be the dominant mode of failure for design purposes, but also the secondary failure mode. This approach will always ensure the desired safety level in a structure without undue conservatism.

To demonstrate this approach, the work at Sheffield has resulted in a proposal for a new set of partial safety factors for use with the Eurocrete bar. For this particular bar, the predominant mode of failure is chosen to be by concrete crushing, hence only relatively modest partial safety factors are imposed on the reinforcement material itself.

The above work has highlighted the problem that the use of high safety factors does not necessarily improve the safety of elements and can have the opposite effect by leading to failure in an undesirable mode.

5.2 *Flexure*

When dealing with FRP RC structures, the amount of reinforcement to be used depends on the stiffness

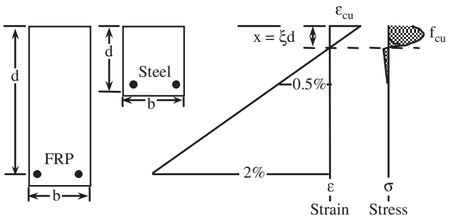

Figure 8. Strain distribution for a glass FRP RC section.

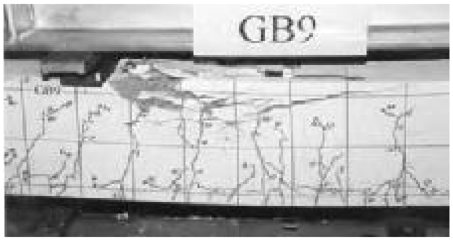

Figure 9. Deflection and cracking in FRP RC beams.

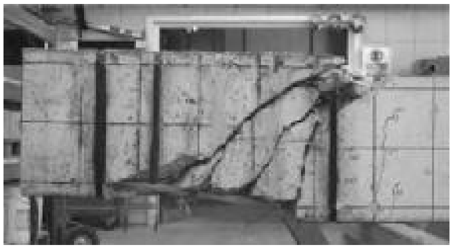

Figure 10. Shear failure of an FRP RC beam.

and strength of the composite material. For FRP reinforcement, the strength to stiffness ratio is an order of magnitude greater than that of steel and this greatly affects the distribution of stresses along the section. Hence, when considering a balanced section, as usually desired in steel RC design, the neutral axis depth for the equivalent FRP RC section would be relatively small and close to the compressive face. Moreover, due to the lower elastic modulus of FRPs, section depth will also need to be increased if deflections are to be maintained at a similar level, as shown in Figure 8. For such a section this implies that a larger proportion of the cross-section is subjected to tensile stress and that the compressive zone is subjected to a greater strain gradient. Hence, for a similar cross-section as that used for steel RC, much larger deflections and crack widths are to be expected, Figure 9.

Figure 11. Shear fracture surface of slab SCS1 after failure.

Furthermore, anchoring of the FRP rebars becomes more difficult due to the high strains developed in the tensile reinforcement.

If all the other modes of failure are avoided, flexural failure can be reached either by crushing of the concrete in compression or by rupture of the FRP reinforcement in tension.

Although both modes are brittle and undesirable, the approach currently adopted by most researchers in the field is to accept that FRP RC sections will be over-reinforced and that the ultimate failure will be by concrete crushing rather than by reinforcement failure.

5.3 *Cracking deformation*

Work by Zhao (1999) at the University of Sheffield has lead to the conclusion that, provided the FRP bars have good bond characteristics, then the crack widths in RC members can be calculated by existing equations that use the strain in the reinforcement as the basis for the calculation. However, the British Standard equation was found to be non-conservative and a modification has been proposed. Regarding short-term deflection calculations, the same work has concluded that existing equations such as those adopted by the ACI can be used directly without modification for the accurate prediction of deflections. The same applies to calculations for long-term deformation when the approach used is based on the fundamental properties of the materials.

5.4 *Shear and punching shear*

Shear transfer in RC beams relies on the tensile and compressive strength of concrete as well as the tensile properties of the longitudinal and, when provided, the transverse reinforcement. In most cases, failure due to shear (Figures 10 and 11) is brittle in nature and, therefore, should be avoided.

All of the shear-resisting mechanisms provided by conventional steel RC elements, such as aggregate interlock, tooth bending and dowel action, are expected to be affected when using FRP reinforcement due to the higher strains that are generally mobilised in the reinforcement. The mechanical properties of the longitudinal reinforcement significantly affect the amount of concrete in compression and the overall deflections. Larger deflections and the absence of plasticity in the reinforcement always lead to a brittle failure and not much dowel strength is expected from the more flexible, anisotropic FRP materials. Furthermore FRP links cannot generally develop their full tensile potential also due to their anisotropic properties resulting in premature failure at the corners.

An important aim of researchers working in this field has been to provide simplified design equations to enable FRP reinforcement to be used in practice. This has resulted in the development of modification factors for inclusion in existing predictive code equations. This approach, although not ideal, has the perceived advantage that code committees are more likely to accept such modifications than they are to adopt fundamental changes to the underlying design philosophy. The proposed modifications of existing code equations are based on the fundamental principle that, assuming perfect bond, the concrete section experiences forces and strains that are independent of the type of reinforcement utilised. Hence, if a design using FRP reinforcement maintains the same strain as when conventional steel is used ($\varepsilon_{FRP} = \varepsilon_s$) and the same design forces are developed ($F_{FRP} = F_s$), then that design, by definition, will lead to the same safe result. Based on this assumption, an equivalent area of steel (A_e) is introduced to evaluate the concrete shear resistance by multiplying the actual area of FRP reinforcement (A_{FRP}) by the modular ratio of FRP to that of steel, as shown in Eqs. (1) and (2) (for example Nagasaka *et al*, 1989).

$$F_{FRP} = \varepsilon_{FRP} \cdot E_{FRP} \cdot A_{FRP} = \varepsilon_s \cdot E_s \cdot A_s = F_s \tag{1}$$

$$A_e = A_{FRP} \cdot \frac{E_{FRP}}{E_s} \tag{2}$$

When the shear force applied to a RC member exceeds the shear strength of the concrete itself, shear reinforcement is required. According to the proposed modifications, the required amount of FRP shear reinforcement is determined by limiting the maximum strain that it can develop. In some formulations, a maximum limit of 0.0025 (0.002 according to the ACI Committee 440 (2003) and the Canadian Standard Association (1996)), which is the value that corresponds to the yield strain of conventional steel bars, is suggested (for example Institution of Structural Engineers, 1999). By imposing this limit, however, FRP links will only be stressed to a fraction of their potential and thus the benefits of using such materials are not taken to their maximum mechanical and economic advantage (see for example Figure 12).

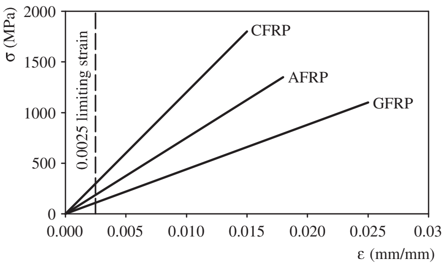

Figure 12. Limiting strain according to current design recommendations to include the use of non-ferrous reinforcement.

Experimental tests carried out on FRP RC beams at the University of Sheffield and by other researchers (Duranovic, 1997, Tottori and Wakui, 1993) have provided evidence that the restrictions imposed by the current modifications to design code equations on the value of maximum allowable strain that can be developed in FRP reinforcement are unnecessarily conservative (recorded values of up to 10,000 microstrain being reported).

Such a tendency was also observed during a series of tests focusing on punching shear and shear by El-Ghandour *et al* (2003) and Guadagnini *et al* (2003) respectively.

5.5 *Bond of FRP bars*

Bond between concrete and FRP reinforcing bars is a fundamental aspect of the composite action of FRP reinforced concrete and accordingly, needs to be adequately understood before FRP materials can be accepted widely in the construction industry.

In flexural structural elements, splitting of concrete in the tension zone is the most likely mode of bond failure. This type of failure is substantially different and more dangerous than the pull-out mode, since it happens at a much lower bond stress level and the residual bond strength of the reinforcing bar decreases rapidly to zero.

The bond splitting behaviour of FRP bars in concrete is expected to vary from that of conventional steel bars due to their lower modulus of elasticity, lower shear strength and stiffness in the longitudinal and transverse directions, and the high normal strains expected before failure. However, despite the fact that a lower maximum bond strength is expected from FRPs, the more ductile nature of the bonding mechanism can lead to a better distribution of the bond stresses and, hence, lead to reduced anchorage lengths.

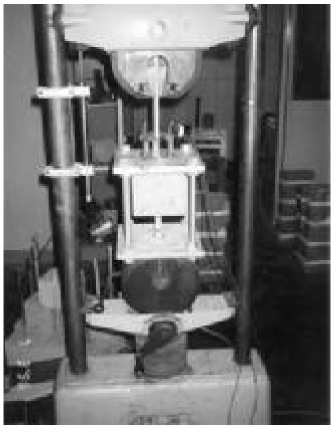

Figure 13. Pull-out test arrangement.

In order to investigate the bond behaviour of carbon and glass FRP bars in concrete, two major experimental series of tests were undertaken at the University of Sheffield (Achillides and Pilakoutas, 2004) as part of the EUROCRETE project. These included pull-out tests and beam tests.

In the pull-out tests, several parameters were examined such as the nature of the fibres, the diameter, shape and deformations of the bars, the embedment length and concrete strength. The pull-out test arrangement adopted is shown in Figure 13.

Beam testing was necessary to improve understanding of the splitting mode of failure. In fact, under flexural load conditions, splitting of concrete in the tension zone rather than pull-out is the most common mode of bond failure.

Pull-out tests are therefore useful for determining the pull-out bond strength, whilst beam tests offer a more realistic assessment of bond strength in structural applications.

The carbon FRP bars used in the beam tests developed a bond strength of more than 4 MPa. This is comparable to the bond strength of deformed steel bars and substantially higher than that of the glass FRP bars (3 MPa). However, in the pull-out tests, they produced similar results. This comparatively lower bond strength of glass FRP bars in the beam tests may be attributed to their higher deformability in the longitudinal direction which seems to play an important role in inducing the splitting mode of failure. Unexpectedly, splices with both carbon and glass EUROCRETE bars developed better bond characteristics than for single anchorage bars.

In general, the experimental results indicate that FRP reinforcing bars interface satisfactorily with the concrete matrix. Their bond behaviour depends on various factors, the full influences of which will need to be evaluated before the formulation of any design formulae. Attention has to be focused on the high deformability of FRP bars that seems to play an important role in the splitting mode of failure in concrete members.

As a step in the direction of increasing current knowledge of the bond properties of FRP bars and bond performance in concrete elements, an international round robin test (*i*RRT, 2002) programme was recently organised by the ConFibreCrete research network (1997) working together with the *fib* Task Group 9.3 and ISIS, Canada.

The *i*RRT was designed with the following objectives in mind:

1. To assess the merits of simple tests for material characterization.
2. To specify a standard methodology for determining relevant parameters such as average maximum bond strength and average maximum pull out load for FRP bars embedded in concrete. A uniform presentation of experimental data will facilitate comparison of the results and will enable the assessment of the reliability and replicability of the specified tests.
3. To generate a comprehensive database that will be made available to the scientific community. This will enable code committees to compare the bond strength developed by various types of FRP bars predicted by design relationships with an extensive set of test results and will assist researchers in evaluating the validity of their analytical and mechanical models.

Other indirect benefits that will result from this exercise are an increased familiarization with the range of FRP products available in the global market and a heightened awareness of the international efforts aimed towards the development of design guidelines and standardised tests to ensure reliable, replicable research.

The tests have now been concluded and the reports from the various laboratories are currently being compiled.

6 SHAPING: THE FUTURE OF FRPs

Although FRPs are already quite extensively adopted in various sectors of the construction industry (e.g. strengthening and repair of existing structures), their use as internal reinforcement for concrete is limited only to specific structural elements and does not extend to the whole structure. The reason for the limited use of FRPs as internal reinforcement can be partly related to the lack of commercially available curved or shaped reinforcing elements used for shear reinforcement or complex structural connections.

Most of the shaped steel reinforcing bars currently used in concrete structures are provided pre-bent and cut in the factory according to design specifications. These may be supplemented by a small quantity of special one-off shapes bent directly on site. Whether bending occurs on site or at the factory, conventional steel reinforcing bars have a major advantage since, due to their elastoplastic behaviour, they can be easily formed by cold bending, and hence, most detailing needs can be easily met speedily at very low cost.

The high production costs that are associated with the manufacturing of FRP curved elements, however, have generally reduced the interest in using FRPs for these types of applications. In addition, various studies have shown that the mechanical performance of bent portions of composite bars are reduced dramatically under a combination of tensile and shear stresses and that the maximum tensile strength that can be carried through the bend can be as low as 40% of the maximum tensile strength of the equivalent straight bar (Ehsani *et al*, 1995, Morphy *et al*, 1997). This phenomenon can become an issue whenever non-straight unidirectional composite elements are used in structural applications since premature failure can occur at the corner portion of the composite. The reduction in the strength of the composite, therefore, needs to be carefully taken into account since it has a major influence on the maximum value of strain that can be safely sustained by the reinforcement. To date, this reduction in strength has been quantified using empirical models such as that proposed by the Japanese Concrete Institute, which is described by Eq. (3) (JSCE, 1996). In this equation, the strength of the bent bar, f_{fb}, is expressed as a function of the uniaxial tensile strength, f_{fu}, the bar diameter, h, and the bend radius, r.

$$f_{fb} = \left(0.05\frac{r}{h} + 0.3\right) f_{fu} \leq f_{fu} \qquad (3)$$

All of these issues are being addressed in the 2 year CRAFT RTD project CurvedNFR (2003), funded by the European Commission. This was established with the aim of developing materials, methodology and manufacturing processes for low-cost, curved fibre reinforced plastic (FRP) rebars. The project partnership includes 8 small specialist industrial partners and 3 research providers across 6 European countries. Of many candidate materials being considered, thermoplastic resins that may be retrospectively softened and bent by the application of heat seem to offer a promising solution at this early stage of this project.

7 CONCLUSIONS

Although FRP materials have fundamentally different mechanical characteristics than steel, the design of FRP RC elements can be based on the same fundamental principles as far as flexural design, shear design, cracking and deflections are concerned. However, a different philosophy of design is needed which addresses the issue of safety at a more fundamental level.

FRP materials offer 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 highly suited for the manufacture of non-structural precast elements where the combined self weight of the reinforcement and concrete necessary to provide adequate cover is a major disadvantage. Using FRPs can allow a drastic reduction in the overall weight of these elements and facilitates cheaper handling and installation procedures.

FRP reinforcement will never totally replace steel reinforcement in RC structures but is likely to find increasing use in niche applications where its particular chemical, physical and mechanical properties lead to more practical or economic structural solutions.

Despite the extraordinary progress made to date in the use of these advanced composite materials as embedded reinforcement in concrete, many aspects of their structural behaviour still require further detailed examination before their full potential can be exploited in new construction.

ACKNOWLEDGMENTS

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