

Guest editorial comment

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Non-ferrous reinforcement

Traditionally, concrete structures have been reinforced with steel bars or prestressed with steel wires or strands. Generally, embedded steel is very durable, the concrete providing a suitable alkaline environment. However, for structures in highly aggressive environments, the protection afforded by the concrete is often insufficient to ensure the necessary service life for the structure. In addition to attempts to improve the quality of the concrete itself, there are a number of approaches for protecting the steel directly, such as by means of epoxy coating or the use of cathodic protection. A further alternative is to replace the steel completely by a material that will, hopefully, be more durable. One such option, which has great potential, is the use of fibre-reinforced plastics (FRPs), which consist of continuous fibres, generally of glass, carbon or aramid, set in a suitable resin to form a rod or grid. These materials are well accepted by the aerospace and automotive industries and are starting to find applications in the construction industry.

The mechanical properties of FRPs are chiefly determined by the amount and type of fibre, while the durability will be a function of both the resin and the fibre. The strength of FRP reinforcement will tend to be between that of high-yield reinforcing steel and prestressing strand (say 1000 N/mm^2 for glass fibres and 1500 N/mm^2 for carbon fibres) but the stiffness will generally be significantly lower (say 45 kN/mm^2 for glass fibres and 150 kN/mm^2 for carbon fibres). All FRP materials have a straight line response to failure with no plasticity.

The most common method for manufacturing FRP rods is pultrusion, in which the fibres are drawn off storage containers in a controlled pattern, are impregnated with resin and then drawn through a heated die which sets and cures the resin. One limitation at present is that thermoset resins are generally used and, hence, once fully cured, rods cannot be bent into the range of shapes currently used with steel. Thus 'specials' are required. Spiral reinforcement, either circular or rectangular in form, is produced by some Japanese manufacturers along with two- or three-dimensional grid. Other manufacturing techniques are being developed in which resin-impregnated fibres are wound on to suitable man-

drels to producing closed shapes, such as shear links. As an alternative, thermoplastic resins are being developed, which would allow the fully cured material to be bent.

Demonstration structures

A number of demonstration projects have been built around the world. Initially, because of concerns about the lower stiffness of FRP in comparison with steel, most structures were prestressed, with conventional steel for the secondary reinforcement. A number of highway bridges have been built in Japan, North America and Europe, starting with one in Dusseldorf in 1987. More recently, FRP reinforcement has been used for a wide range of reinforced concrete applications including footbridges, marine structures, retaining walls, cladding panels and non-magnetic structures, such as beneath sensitive hospital equipment.

Design

Much experimental work has been carried out, and simple design methods are being developed in a number of countries, modifying existing design codes for steel-reinforced structures. The Japanese Ministry of Construction has published draft guidelines for design, the Canadian Bridge Code will shortly have a chapter dealing with FRP, and guidance is being prepared by the American Concrete Institute. All the proposed approaches are broadly in agreement. Modifications to BS 8110 have been developed within EUROCRETE, an international collaborative research project partly funded by the European EUREKA scheme, and are now being validated by the Institution of Structural Engineers. The most significant points are summarized below.

Flexure

For beams in flexure the basic principles are independent of the type of reinforcement used. However, as FRP does not yield, the simple design equations given

in codes are no longer applicable. It is likely, because of the high strength and relatively low stiffness of FRP, that failure will be by compression of the concrete and not rupture of the reinforcement.

Shear

The lower stiffness of FRP means that the contribution of the tensile reinforcement to the shear capacity of the cross-section is reduced. The design equation for the permissible shear stress needs to be modified to include an effective area of reinforcement, based on the modular ratio. The contribution of the links needs to be determined at a limiting strain.

Cracking

It will be necessary to control crack widths from considerations of aesthetics and, possibly, watertightness in some structures. Preliminary studies have shown that the current crack width formulae should be equally applicable to FRP, but may need some modification to take account of the different bond properties.

Deflections

Deflections are likely to be higher than for equivalent steel-reinforced units. However, comparisons made with the approach in BS 8110 show satisfactory agreement with the response of FRP-reinforced beams, indicating that deflections can be estimated with reasonable accuracy.

Columns

FRP rods have low compressive strengths in comparison to their tensile capacities. Thus the guidelines recommend that the contribution of compressive reinforcement in columns should be ignored. (Several studies have looked at the effect of FRP hoop reinforcement or FRP wrapped round columns. The confinement leads to significant increases in the failure load and the failure strain. A major programme of work is under way at Southampton University in this area.)

Fire

Fire will be a significant design consideration for some types of structures. However, it is an area that has received very little attention. Fire testing by the composites industry is concerned with spread of flame and the emission of toxic gas. For embedded reinforcement the prime concern will be the temperature rise at the surface of the bar. Once this reaches the temperature at which the resin starts to soften, the bond will weaken and the fibres will cease to act compositely.

Health and safety considerations

For embedded reinforcement there would appear to be no health and safety worries. During fixing the surface layer of the FRP may contain loose fibres

which may cause irritation, and some people may experience a dermatological reaction to the resin. Thus, gloves should be worn when handling bars. When cutting bars the normal precautions to avoid inhaling dust should be taken.

Costs

Currently the cost of FRP rods is expected to lie between that of epoxy-coated steel and stainless steel (say 2–8 times normal black bar). For reinforced concrete cast *in situ* this increased first cost can only be justified in the basis of whole life costing for structures in aggressive environments. For precast units, reduced covers may lead to significant weight reductions and hence savings in handling and transport costs. Basically, potential users of the materials must be encouraged to consider the true total costs and not just the material costs.

Durability

Probably the single most important aspect of the use of FRP as reinforcement is the durability of the material when embedded in concrete. Glass fibres and some resins are degraded by the highly alkaline environment. Work has concentrated on the development of alkali-resistant glass (AR glass) or the use of carbons or aramids, but little attention has been paid to the resin. Currently manufacturers are, for commercial reasons, reluctant to disclose the details of the materials used. Criteria by which the durability may be assessed are urgently needed. Considerable work needs to be carried out to develop acceptance criteria.

Quality control

For the production of FRP reinforcing rods in the quantities required for construction and to the required quality, tighter control of the manufacturing process is required. The key areas include:

- all raw materials to conform to national or international standards
- visual tests to ensure uniformity
- tests on small samples cut from the composite
- dimensional checks
- stiffness and strength checks on the completed product, at regular intervals during the production run.

Though the final item is intended mainly for compliance purposes during production, the data would also be used to determine the characteristic or guaranteed properties. The method of determining the properties will control the partial safety factors used in design.

The way forward

The experimental work and demonstration projects worldwide have shown that FRP reinforcement is a viable, and cost effective, alternative to steel in certain circumstances. However, the construction industry is extremely conservative, probably with justification when one considers the long time-scales involved. There are a number of significant aspects that have to be demonstrated before the materials can be accepted with confidence, including:

- durability of FRP embedded in concrete
- the ability to produce material of a consistent quality
- the ability to produce suitable reinforcement shapes
- the ability to produce large quantities of materials.

All are essential if the materials are to move forward from their present position as products of a cottage industry to one in which their true potential can be realized.