THE USE OF ARAMID FIBRE REINFORCED PLASTICS AS PRESTRESSING TENDONS FOR CONCRETE

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The use of continuous fibre reinforcing materials (CFRMs) as concrete reinforcement is a potential solution to the current problems associated with the corrosion of steel reinforcement. In addition, the high strength of these materials means that CFRM tendons are particularly well suited to prestressed concrete applications.

The current study investigates the flexural behaviour of concrete prestressed with aramid fibre reinforced plastics (AFRPs). A particular focus was the influence of the bond between the AFRP and concrete on the flexural response of a beam.

INTRODUCTION

In 1992, the UK Department of Transport banned the use of grouted steel post-tensioned tendons because of fears of tendon corrosion. Although the new recommendations regarding grouted steel post-tensioning will help to mitigate the possibility of steel corrosion, proper detailing and workmanship are essential and the regular inspection and maintenance of the steel tendons remains problematic. The current problems of corrosion of steel reinforcement in concrete are widespread and the construction industry needs to evaluate possible alternatives.

One possibility is the use continuous fibre reinforcing materials (CFRMs) as concrete reinforcement. CFRMs are strong, light-weight, non-magnetic and for the most part non-corrodable. The term CFRM includes both fibre ropes and fibre reinforced plastics (FRPs). Fibre ropes are made up of continuous strands which can be either twisted, braided or parallel lay. In the case of parallel lay ropes, the fibres are usually protected by an outer polythene sheath. Although the ropes are well suited as either external post-tensioning or internal unbonded tendons, they cannot be used as bonded concrete reinforcement since the fibres are free to move relative to each other. In FRPs, the continuous fibres are embedded in a resin matrix. The matrix transfers the load between the outer and inner fibres and hence where it is necessary to bond the CFRM to concrete, FRPs are appropriate. The current work considers the use of FRPs as concrete reinforcement.

In the construction industry, the most commonly used FRPs are carbon fibre reinforced plastics (CFRPs), glass fibre reinforced plastics (GFRPs) and aramid fibre reinforced plastics (AFRPs). Typical stress-strain curves can be seen in Fig. 1. Unlike steel, FRPs are purely elastic materials. They do not yield and hence failure of FRP materials is brittle and sudden. This property has important repercussions on the structural behaviour of concrete structures reinforced or prestressed with FRPs. The current work investigates some of these ramifications and demonstrates how the disadvantages can be overcome.

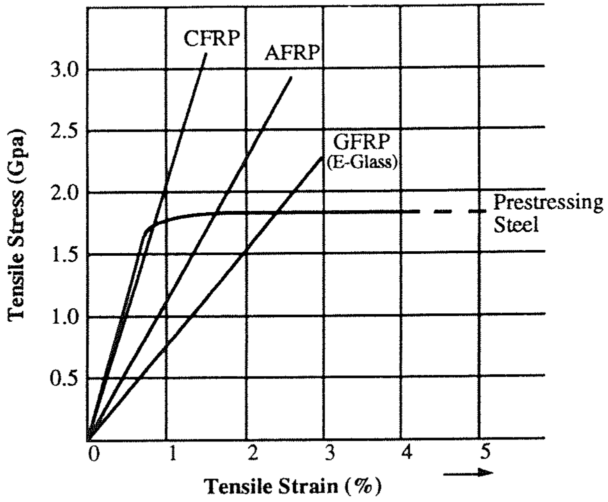

Figure 1 : Schematic stress strain curves

THE USE OF ARAMID FIBRE REINFORCED PLASTICS PRESTRESSING TENDONS

The focus of this work was the use of AFRPs as prestressing tendons for concrete. This particular area was chosen for the following reasons:

Choice of material

AFRPs, CFRPs and GFRPs were considered as possible prestressing materials and all three categories of materials were evaluated on the basis of cost, strain at failure, durability and availability (in the UK). Due to the high cost of the CFRP and concerns about the long-term durability of the GFRPs, the AFRPs were deemed most suitable (see Table 1).

Prestressing versus non-prestressed reinforcement

FRPs are characterised by a relatively low modulus of elasticity and serviceability conditions often control the design of FRP reinforcement. However, the costs of FRPs are typically 3-4 times that of steel (using a cost per unit strength ratio). Hence, use as reinforcement, where the FRP is subjected to fairly low stress levels, is not as economically viable as when the FRP is used as prestressing tendons.

TABLE 1 - Evaluation of tendon materials

Material	Cost	Strain at Failure	Durability	Availability
CFRP	H	L	H	L
GFRP	L	M	L	M
AFRP	M	M-H	M	M
STEEL	L	M-H	L	H

Notes: Grading is relative for the three materials - H = High, M = Medium, L = Low

One problem with using FRPs as prestressing tendons is the difficulty in finding suitable permanent anchorage systems. The transverse strength of FRPs is low (typically 1/10th of the longitudinal strength) and stress concentrations generated in the anchors can lead to the premature failure of a tendon. However, this is not prohibitive since pre-tensioned applications eliminate the need for long-term anchoring systems; the development of long term anchorages for post-tensioning systems is an active field of study.

FLEXURAL BEHAVIOUR OF PRESTRESSED FRP BEAMS

The rotation capacity of FRP beams

The linear elastic behaviour of FRPs has a significant effect on the flexural response of a concrete beam prestressed with FRPs. A major point of debate is the question of, and even the definition of, *ductility*. Failure of a beam due to *either* concrete crushing *or* the tendons rupturing will be brittle. Ductility, defined as the ability to do plastic work, is difficult to achieve.

For determinate and indeterminate structures prestressed with steel the formation of plastic hinges, either in the span or over the supports, ensures that large deformations occur. For most structures, the most important safety feature is *not* the occurrence of plastic hinges but the fact that significant rotations take place prior to failure allowing the redistribution of moments. Thus, from a safety point of view, the performance criteria for FRP prestressed structures should be based on the amount of deformation that occurs before failure; whether or not these deformations take place due to plastic *or* elastic work is irrelevant. It is accepted that this philosophy is not applicable to structures where there is a requirement for energy to be absorbed, for example, structures subjected to earthquake loading.

For the current work, the concept of a rotation capacity has been chosen as a measure of the deformation that occurs prior to failure in structures prestressed with FRP tendons. The aim was to determine the influence of the bond between the FRP tendon and concrete on the rotation capacity of a beam. This question of the importance of the bond was first raised by one of the authors in 1993, (Burgoyne (1)).

The influence of bond

Before cracking occurs, the strains in the concrete are small, and fairly uniform over the length of the beam, so the degree of bond has relatively little effect on the behaviour of the beam. However, once cracking occurs in the concrete, the amount of bond can have a significant effect.

Beams with bonded tendons must have the same change in strain in both the tendon and the concrete, by definition, except at the crack locations. Away from the crack, the tendon and the concrete act as a composite, both carrying some of the tension; at the crack, the tendon must be carrying all the tension. This implies that the tendon strain will be higher at the crack position than elsewhere. It also implies that there must be some breakdown of bond on either side of the crack otherwise the tendon would have to have infinite strain at the crack. If the tendon can yield, (as for steel tendons), the increased strain does not cause a problem; the tendon carries its yield load and the ultimate moment capacity can be calculated in the conventional way (Fig. 2a). However, if the tendon cannot yield, it will snap as soon as the strain reaches a limiting value. The result will be a high moment capacity, since the tendon reaches its failure load, but limited rotation capacity. Some debonding must take place on either side of the crack, but the bond strengths that have been reported for FRPs are very high (Khin *et al.* (2), Makitani *et al.* (3)), so the curvature will remain low (Fig. 2b).

With unbonded or external tendons, the tendon is free to slide relative to the concrete. The strain increase in the tendon due to the displacement is failure uniformly distributed along the length of the tendon. Large rotations can be realised since the concrete can have a large strain at a few crack locations, while the tendon has a low strain over its whole length, compatibility between the two

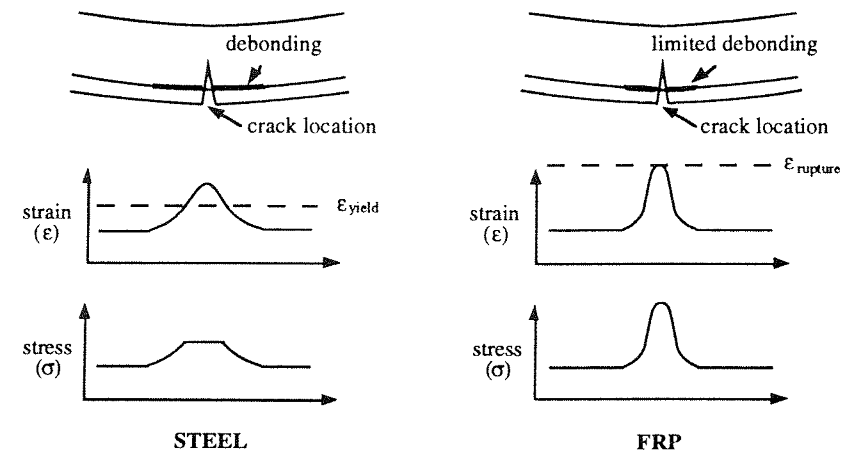

Figure 2 : Debonding at crack location

only being necessary in an overall sense. The corollary is that since the tendon strain, and hence stress, are low, the moment capacity is reduced.

The idea of partial bond is thus to obtain the best of both worlds. There should be sufficient bond to allow the tendon to achieve its full strength, but not too much so that the tendon can achieve high strains over a reasonable length before failure. Partial bonding can be achieved in two ways; by intermittently bonding and debonding sections of tendon, or by coating the tendon by a resin of known, low shear strength. Both a high ultimate load capacity and high rotation can then be achieved (Fig. 3).

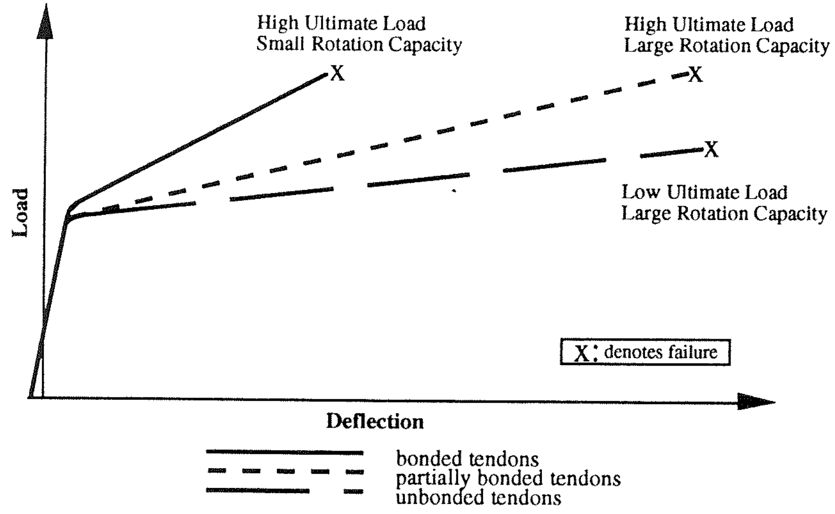

Figure 3 : Schematic load deflection curves

TABLE 2 - Tendon properties

	Braided AFRP	Spiral Wound AFRP	Steel Wire
Modulus of Elasticity (GPa)	68.6	54.0	220.0
Ultimate Strain (%)	2.2	3	4.2*
Manufacturer's Assured Load (kN)	15.7	22.7	35.4*
Tendon Diameter (mm)	3.7	4	5
Fibre Type	Kevlar 49	Technora	N/A
Resin Matrix	Epoxy	Vinyl ester	N/A
Surface Characteristics	Braided	Spiral winding	Smooth

* measured value

EXPERIMENTAL PROGRAMME

An experimental programme was carried out in order to investigate the influence of the bond between the AFRP tendons and the concrete on the flexural behaviour of a beam. Two AFRP materials were considered in the experimental programme; a braided rod composed of Kevlar 49 fibres in an epoxy matrix and a spiral wound bar manufactured using Technora fibre in a vinyl ester matrix (see Table 2). For comparison purposes beams with steel prestressing tendons, which were effectively smooth, were included in the study. One of the variables in the programme was the different bond characteristics of each of the three tendons.

The significance of the nature and degree of bonding was ascertained by designing, casting and testing a series of beams with either bonded tendons, unbonded tendons or partially bonded tendons. Although the beams were pre-tensioned, many of the same principles apply to post-tensioned structures. A brief summary of the experimental procedure and an overview of the experimental results follows. A more comprehensive overview can be found elsewhere (Lees and Burgoyne (4)).

Experimental procedure

The beam dimensions were 200x100x2800mm and a high early strength concrete (approximately 60 MPa at 7 days) was used. The beams were tested in flexure using a four point loading configuration (see Fig. 4). The prestress levels in the tendons at the time of testing was about 65% of the manufacturer's assured load.

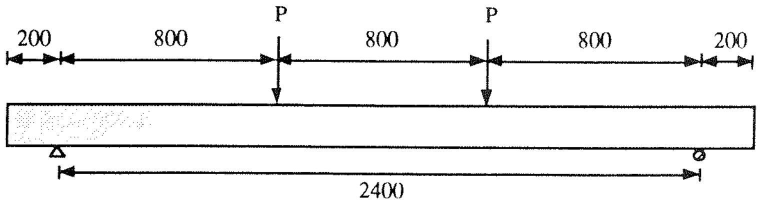

Figure 4 : Loading arrangement

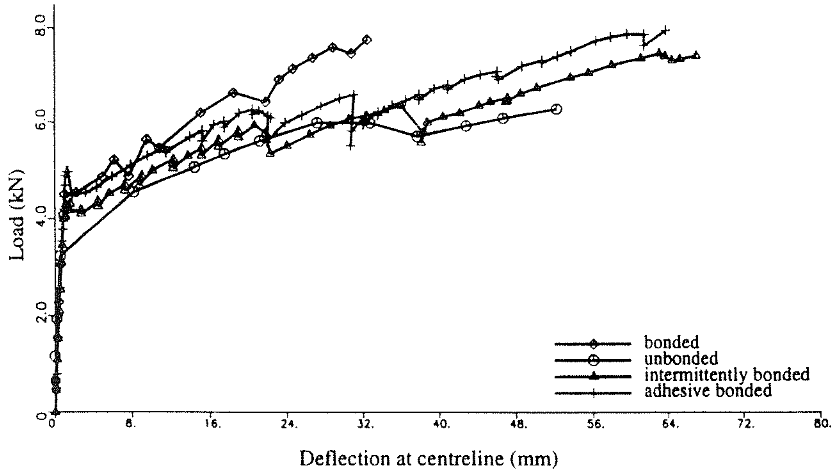

Figure 5 : Experimental load deflection curves for beams with braided AFRP tendons

The experimental load deflection curves for the beams with braided AFRP tendons can be found in Fig. 5; similar trends were noted for the spiral wound AFRP beams. The following observations can be made.

- The FRP bonded beams failed due to the tendons rupturing. There was extensive cracking but the beams had a limited rotation capacity.
- The unbonded FRP beams failed due to concrete crushing at an ultimate load which was 25% lower than that of the bonded beams. Only a single crack occurred in the constant moment region and the deflection of the beam was similar to that of two rigid blocks connected by a central hinge. Nevertheless, the rotation capacity was approximately twice that of the bonded beams.
- In the majority of the partially bonded FRP beams, both the rotation capacity and the ultimate load were high. Multiple cracks formed during testing and with the exception of one beam, all the ultimate loads were significantly higher than the equivalent unbonded beams.

DISCUSSION

A schematic representation of the crack patterns of the beams can be found in Fig. 6. It can be seen that the extent of cracking is inherently connected to the amount of force transferred from the tendon to the concrete. In the beams with bonded tendons, multiple cracks formed. However, the rotation capacity was restricted by the limited extent of debonding on either side of the crack.

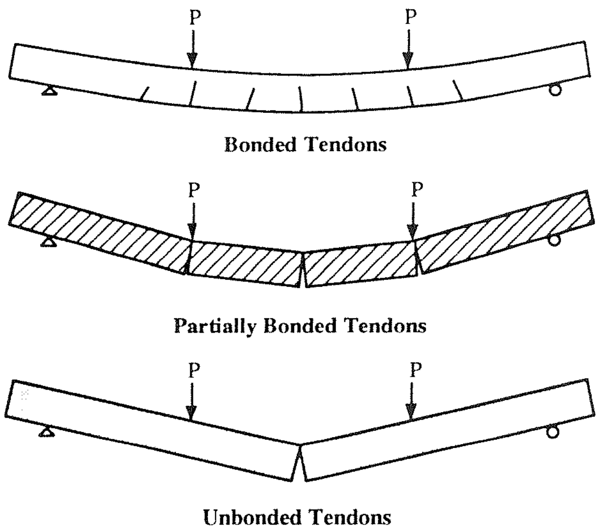

Figure 6 : Beam rotation

In contrast, the intermittently bonded beams were designed so that as the tendon force on one side of a bonded region became excessive, the bond would break down and the force would be transferred to the adjacent unbonded length of tendon. The sequence of events was crucial; the integrity of the bond had to be sufficient to induce multiple cracks in the beam and consequently multiple locations at which rotations could occur. However, as the load was increased to a level approaching the ultimate capacity, the bond would break down so that lengths of tendon became unbonded and large rotations occurred.

Where the tendons were coated with a resin, a similar phenomena was apparent. The magnitude of the resin shear strength was an essential factor in the behaviour of the beam. Again, it was necessary for a sufficient force to be transferred through bond in order to generate tensile stresses in the bottom face of the concrete beam and for multiple cracking to take place. With increased loading, the rate of change in the force in the tendon along the beam exceeded the shear strength of the resin and the tendon effectively became unbonded for further load increments. Significant rotations at the crack locations were then possible.

The principle of limited bond can be extended to post-tensioning and the coating of the tendons with a resin of known shear strength could be used to optimise the flexural behaviour of a post-tensioned beam. The choice of resin requires a certain amount of consideration. If the shear strength of the resin is too high, the bond will not breakdown and the rotation capacity will be limited. If the shear strength is too low, the bond breaks down prior to the occurrence of multiple cracking and the beam will fail due to concrete crushing at a limited number of hinge locations. A corollary of this concept is that a judicious choice of grout could also be used as a means to limit the bond. By choosing a grout with a particular shear strength, the bond breakdown between the FRP tendon and the grout could also be prescribed at various stages of loading.

CONCLUSIONS

1) The use of CFRMs as concrete reinforcement is a potential solution to the current problems associated with steel corrosion. AFRPs are particularly well suited for use as prestressing tendons.

2) Ductility, defined as the ability to do plastic work, is difficult to achieve using FRPs. An alternative indicator of the amount of deformation that occurs prior to failure is necessary and the concept of a rotation capacity is proposed.

3) The extent and distribution of the bond between the AFRP and concrete along the length of the tendon significantly affects the flexural response of a beam

4) The experimental results indicate that both a high rotation capacity and a high ultimate load can be achieved by controlling the bond between the AFRP tendon and concrete. The nature of the intermittent bond and the shear strength of the resin were crucial factors in the resulting behaviour of the beams.

5) The successful application of the principle of partial bonding implies that through a judicious choice of grout and/or FRP coating, designers have the ability to optimise the flexural behaviour of beams prestressed with FRP tendons.

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