ADVANCED COMPOSITE MATERIALS IN BRIDGES AND STRUCTURES
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MATÉRIAUX COMPOSITES D'AVANT-GARDE POUR PONTS ET CHARPENTES
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INFLUENCE OF BOND ON ROTATION CAPACITY OF CONCRETE PRE-TENSIONED WITH AFRP

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ABSTRACT

The present study considers the flexural behaviour of concrete beams pre-tensioned with aramid fibre reinforced plastic (AFRP) tendons. AFRP materials are linearly elastic and do not yield. Hence, failure due to the tendons rupturing is brittle and sudden. However, failure due to concrete crushing is also deemed to be undesirable. The current work demonstrates how a high rotational capacity can be achieved using a composite made up of two brittle materials.

A series of small scale beams were cast using two types of AFRP or steel tendons. The influence of bond was investigated by testing beams with bonded tendons, unbonded tendons or partially bonded tendons. It was found that, unlike the bonded and unbonded beams, the beams with partially bonded tendons achieved both a high rotation capacity and a high ultimate load.

RÉSUMÉ

Le sujet de l'article porte sur la flexion des poutres en béton précontraint à l'aide de tendons en plastique renforcés de fibres (AFRP). Le matériau AFRP est caractérisé par une courbe contrainte-déformation linéaire élastique jusqu'à la rupture. Cependant, tout comme le béton, il cède brusquement, sans point d'écoulement, ce qui n'est généralement pas souhaitable. Néanmoins, il est démontré que l'on peut obtenir d'une poutre une capacité de flexion considérable tout en combinant deux matériaux relativement inflexibles.

Une série de poutres ont été coulées à petite échelle en utilisant 2 types de tendons AFRP ainsi que des tendons en acier. L'influence de l'adhérence des tendons au béton fut mesurée en comparant des poutres dont l'adhérence des tendons était totale, partielle ou nulle. Il appert que les poutres renforcées de tendons à adhérence partielle, contrairement au deux autres types de condition, démontrent une très bonne flexibilité tout en maintenant une charge de rupture élevée.

INTRODUCTION

The whole concept of reinforced and prestressed concrete design needs to be re-evaluated in the light of the properties of fibre reinforced plastic (FRP) reinforcement. In conventional design with steel reinforcement, beams are under-reinforced. With increasing loads, the steel yields, large deflections ensue and finally the concrete crushes. Concrete crushing is typically deemed to be a brittle mode of failure and hence should occur after the steel has yielded. With FRP materials, rupture of the tendons is also a brittle failure mode and hence undesirable. The concept of "ductility", defined as being the ability to do plastic work, is no longer applicable when referring to FRP materials.

From both a safety and serviceability point of view, a new definition which reflects the amount of deflection that occurs prior to the failure of a concrete beam prestressed with FRP materials is required. The nature of such a definition is in itself a subject of great debate. For the current work, the idea of a "rotation capacity" has been chosen as an indicator of the amount of deformation that occurs prior to collapse. The aim is to maximise the flexural rotation capacity of a beam pre-tensioned with AFRP through the control of bond.

The reported bond strengths between AFRP rods and concrete are in the order of 7-16 MPa depending on the type of AFRP, the bar diameter and the nature of the test (Makitani *et al.*, 1993, Khin *et al.*, 1994). Similar values for the bond strength have been obtained in the current work. With such high bond stresses there is an increased likelihood of a fully bonded tendon snapping at a crack location as a result of localised stress concentrations.

The question of whether FRP tendons should be bonded to concrete was first considered in a paper by one of the authors (Burgoyne, 1993) and in the present work, a series of beams with either bonded tendons, unbonded tendons or partially bonded tendons were cast and tested. For comparison purposes, beams with steel tendons were included in the bonded and unbonded test series.

Three different materials were used in the tests: two types of AFRP and steel (see Table 1). In addition, the surface characteristics of the tendons differed; one of the AFRPs was a braided rod whereas the surface of the second AFRP was formed during manufacturing by wrapping a spiral winding fibre around the tendon. The steel prestressing tendons were effectively smooth.

This paper summarises the results of the experimental programme. The implications of this work on the current design philosophy for the use of AFRP tendons in pre-tensioned concrete applications are discussed.

Table 1: Tendon Properties

	Braided AFRP	Spiral Wound AFRP	Steel Wire
Modulus of Elasticity (GPa)	68.0	54.0	220.0
Ultimate Strain (%)	2.2	3.8	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	Vinylester	N/A
Surface Characteristics	Braided	Spiral winding	Smooth

* measured value

EXPERIMENTAL PROGRAMME

A total of fifteen pre-tensioned (100x200x2800mm) concrete beams were cast and tested. The program was divided into series of tests, an overview of which can be seen in Table 2. The testing included beams with either AFRP or steel tendons which were bonded, unbonded or partially bonded.

Pre-tensioning details

Because of the low transverse strength of FRP materials, the tensioning and gripping of FRP tendons has been identified as a problem. Although pre-tensioned applications eliminate the need for permanent anchorages, a gripping mechanism was still required in the short-term.

The tensioning system used was based on the results of a previous study (Harada *et al.*, 1993) in which an expensive cement anchoring system was developed. In the current work, a similar concept was applied and the AFRP tendons were coupled to prestress wire using expansive cement couplers. Details of this system can be found elsewhere, (Lees *et al.*, 1996). Although the use of the expansive cements couplers added an extra stage to the casting process, the system proved very successful and none of the tendons failed in the anchorages during tensioning.

Table 2: Experimental Results

Beam	Prestress (kN)	f_{cu} (MPa)	f_{ct} (MPa)	P - Cracking Load (kN)	P - Ultimate Load (kN)	Failure Mode
SB1	42.5	67.8	3.1	6.7	10.4	conc
SB2	44.4	70.9	3.1	6.5	10.1	conc
TB1	30.7	58.5	3.0	5.2	8.0	tendon
TB2	31.0	58.5	3.0	5.0	8.0	tendon
FB1	28.0	68.5	3.2	4.6	7.8	tendon
SUB1	49.9	60.8	3.9	6.8	9.8	conc
SUB2	46.3	65.6	3.7	6.5	9.6	conc
TUB1	28.4	60.3	3.3	4.7	6.2	conc
FUB1	29.8	60.3	3.3	4.7	6.3	conc
TPB1*	29.3	56.0	3.4	4.7	7.0	conc
TPB2*	29.3	56.3	3.1	4.5	7.8	tendon
FPB1*	29.1	56.0	3.4	4.4	7.4	conc
FPB2*	30.5	56.3	3.1	4.8	7.4	tendon
TAB1*	29.1	58.0	3.2	4.5	6.4	conc
FAB1*	30.1	58.0	3.2	4.9	7.9	tendon/conc

Notes: Each beam is identified by a series of letters and a number. The first letter indicates the type of tendon material, the next set of letters identify the extent to which the tendon was bonded to the concrete and the number is used to distinguish between several beams of the same type. The key is as follows:

S = 5mm steel prestress wire
T = 4mm deformed AFRP rod
F = 3.7mm braided AFRP rod

B = fully bonded
UB = unbonded
PB = partially bonded
AB = adhesive bonded

conc = concrete crushing
tendon = tendon rupture

* indicates an 8mm crack inducer at centerline of beam.

The tendons for each beam were tensioned individually to approximately 70% of their ultimate strength using a hand-powered jack. In order to have similar prestress levels in both types of AFRP beams, the deformed AFRP beams contained two tendons whereas the braided AFRP beams contained three (see Fig. 1).

During the course of the experiments there were two cases where an AFRP tendon failed during jacking at a load far below the manufacturer's assured load. One possibility might be that the tendon had been damaged during handling but none was observed prior to stressing. However, there is no conclusive explanation for the premature failures and hence the need for proper care and due regard for safety during the stressing of FRP tendons is of the utmost importance.

Concreting, striking and detensioning

The beams were cast immediately after the stressing of the tendons. By this stage, primarily due to the high short-term relaxation of AFRPs, the stress in the tendons had dropped to approximately 66% of their ultimate capacity.

Rapid hardening Portland Cement was used to obtain a high strength at an early age and because of the low water cement ratio (0.36), a superplasticiser was added to the mix to improve workability. The concrete cube strength, f_{cu}, was in the order of 60 MPa at 7 days. The average concrete tensile strength, f_{ct}, was 3.3 MPa at 7 days and was measured by testing modulus of rupture specimens.

The concrete for the beams was mixed in the laboratory and was placed by hand in 100 mm layers. After each layer was placed, the concrete was vibrated externally using an electric hammer on the formwork. Internal vibration of the concrete was not considered because of the danger of damaging the FRP tendons.

Testing

Testing was carried out seven days after casting. A four point loading configuration was chosen (see Fig. 2) and the load was applied using two 10 tonne hydraulic jacks (100 mm extension) bearing against a spreader plate. The beams were pin jointed at one end and supported on a roller at the other. Prior to testing, portal gauges were attached along the length of the beam in order to measure the strains at set positions and LDVT's were used to measure the displacements of the beam (see Fig. 3). Strain hoops to measure slip were connected at either end of the tendons and load cells were placed under the jacks.

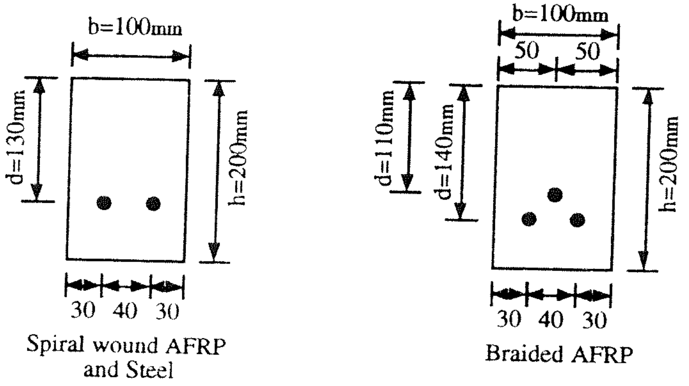

Figure 1: Beam Cross Sections

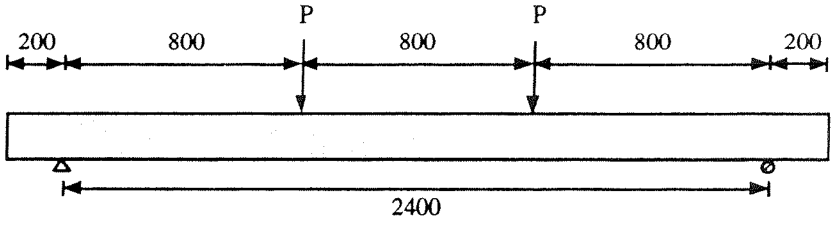

Figure 2: Loading Arrangement

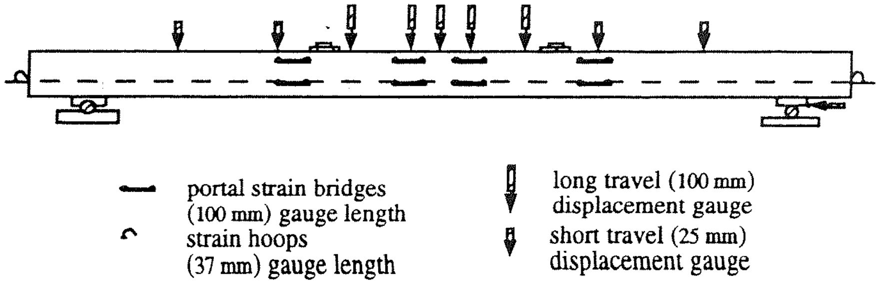

Figure 3: Experimental Gauging

EXPERIMENTAL RESULTS

A summary of the experimental results can be found in Table 2 and Figures 4,5. The main findings of each series of tests are detailed below.

Bonded beams

The bonded beams were characterised by a good crack distribution; failure, in the case of the AFRP beams, was due to the tendon rupturing, as expected. Although a fairly high ultimate load was achieved, the beams had a limited rotation capacity.

Unbonded Beams

The unbonded beams were constructed to exactly the same specification as the bonded ones, except that a central length of the tendon was debonded. The central debonded length of tendon could slide relative to the concrete and therefore the strain in this section of tendon at a given load was lower than that of a bonded tendon. As a result, the rotation capacity was increased. However, only one major crack occurred in the beam and failure was due to the concrete crushing at the crack location, at a lower load capacity.

Partially bonded beams

The partial bond was achieved in one of two ways; either by providing intermittent bond with staggered bonded and unbonded lengths of tendon (beams PB1 & PB2 in Table 2) or by coating the surface of the tendons with a resin with a known low shear strength (beams AB1 in Table 2). For the intermittently bonded beams, the lengths of the bonded regions were designed so that the as the force on one side of the bonded region became excessive, the bond would break down and the load would then be shed to the adjacent unbonded region. The partially bonded tests were extremely successful. Multiple cracks formed and, in all of the beams, rotation capacities similar to the unbonded beams were achieved. With the exception of one beam, the ultimate capacities in all cases were significantly higher than the unbonded beams and for two of the partially bonded beams (TPB2, FAB1), the ultimate capacity was as high as that of the bonded beams.

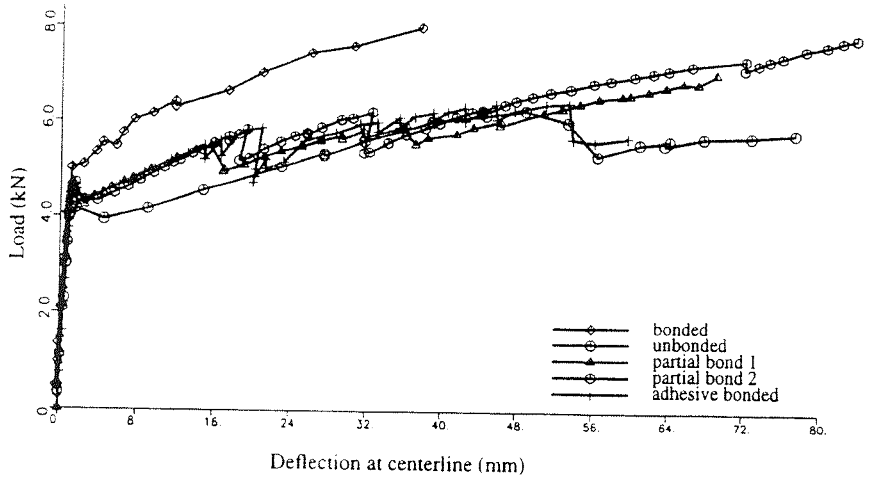

Figure 4: Load deflection curves for beams with spiral wound AFRP tendons

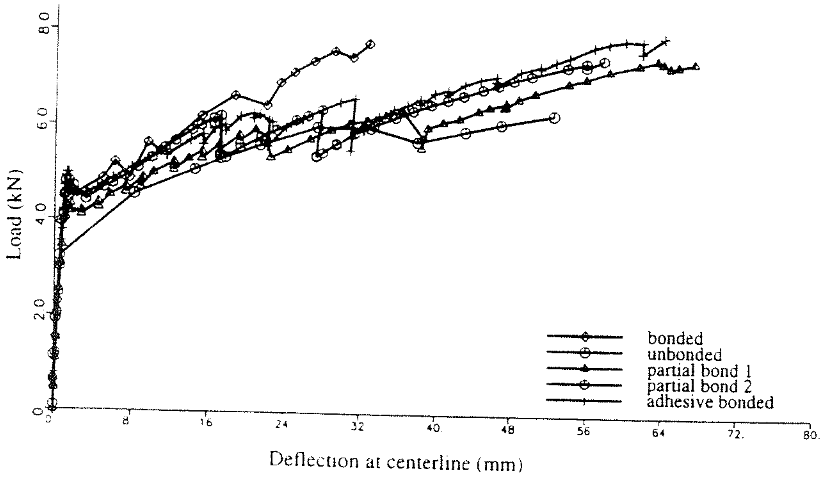

Figure 5: Load deflection curves for beams with braided AFRP tendons

DISCUSSION

Although the complete analysis of the tests presented in this work is still in progress, several initial observations can be made.

The ultimate capacities of the beams with bonded FRP tendons were accurately predicted using conventional strain compatibility design methods. During testing, a noticeable curvature was observed through the constant moment region which also indicated that a strain compatibility approach was applicable. Failure was due to the FRP tendons rupturing.

In both the unbonded and partially bonded beams the flexural cracks acted as hinge locations and the sections of the beam connected by the hinges behaved as rigid blocks. In the unbonded beams only one crack occurred and hence the behaviour of the beams could be equated to that of two rigid blocks connected at a central hinge point. The beams failed due to concrete crushing at this hinge point, as a result of the high localised strain in the concrete.

The response of the partially bonded beams was that of a *series* of rigid blocks connected by hinges and the formation of the multiple cracks was a crucial element in ensuring the enhancement of the rotation capacity of these beams (see Fig. 6). Furthermore, the development of the cracks was intrinsically connected to the extent and distribution of the bond along the tendon. After first cracking, the occurrence and location of the second crack was a function of the magnitude of force which the tendon could transmit to the concrete through the bonded sections. If this force was less than a critical value, then second cracking did not occur.

From the experimental results, it can be seen that the concept of partial bond has far-reaching implications in the flexural design of concrete beams pre-tensioned with FRP tendons. By controlling the bond at particular locations along the beam, the designer can optimise both the ultimate capacity and the rotation capacity of a beam. If this idea could be extended to post-tensioned structures through a judicious choice of grout, the same principle would apply.

Although this is an encouraging result, there remain many outstanding questions. The effects of limited bond on the shear capacity of the beam are unknown and more work needs to be done on quantifying the long-term integrity of the bond between the concrete and the AFRP.

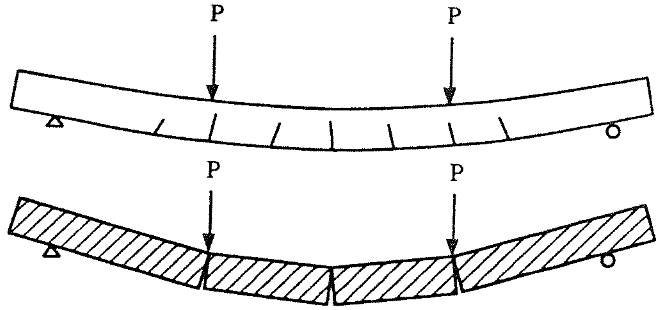

Figure 6: Schematic comparison of bonded and partially bonded beams

CONCLUSIONS

The following conclusions can be made on the basis of the experimental results presented in this paper:

1) The extent and distribution of bond along the length of a FRP tendon has a significant influence on the flexural response of a beam.

2) The beams with bonded FRP tendons were characterised by a good crack distribution and a high ultimate moment capacity. Failure was due to tendon rupture with a limited rotation capacity.

3) In the beams with unbonded FRP tendons, there was only one major crack and failure occurred due to concrete crushing after a significant rotation had taken place. The ultimate capacity was lower than that of the bonded beams.

4) In several of the partially bonded beams the combination of a high rotation capacity and a high ultimate load was realised. Multiple cracks formed during testing.

5) The concept of controlling the bond to enhance the performance of a beam in flexure was applied successfully. This promising result could provide a future design basis for concrete prestressed with FRP materials.

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