Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 73/1/73/2 (1995)

Artikel: Behaviour of beams prestressed or strengthened with fiber reinforced plastic composites

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DOI: https://doi.org/10.5169/seals-55301

Behaviour of Beams Prestressed or Strengthened with Fiber Reinforced Plastic Composites

Comportement de poutres précontraintes ou renforcées avec des composites à fibres de carbone

Biegetragverhalten von Balken mit faserverstärkten Kunststoffen

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SUMMARY

Flexural behaviour of rectangular concrete beams prestressed with Carbon Fiber Reinforced Plastic (CFRP) tendons and beams externally strengthened by epoxy bonded CFRP laminates are investigated. Comprehensive test data is presented on the effect of carbon composites on the cracking behaviour, deflections, ultimate strength and failure modes. Theoretical analysis using a computer software is presented to predict the ultimate strength and moment-deflection behaviour of the beams.

RÉSUMÉ

La recherche présentée traite du comportement en flexion de poutres en béton à section rectangulaire précontraintes et renforcés par des fibres de carbone (CFRP) ou consolidées par des plaques collées à l'extérieur de la poutre. L'influence des composites à fibre de carbone sur le développement des fissures, les déformations, la résistance à la rupture et les modes de rupture a été étudiée au cours d'essais systématiques. Une méthode d'analyse numérique destinée à prédire la résistance à la rupture et la relation moment-flèche des poutres est présentée.

ZUSAMMENFASSUNG

Die vorliegende Untersuchung behandelt das Biegetragverhalten von Betonrechteckbalken, die mit Spanngliedern aus kohlenstoffaserhaltigem Kunststoff (CFK) vorgespannt oder mittels extern angeklebten CFK-Lamellen verstärkt wurden. Es werden umfangreiche Versuchsergebnisse zum Einfluss der Kohlenstoffverbundwerkstoffe auf das Rissverhalten, Durchbiegungen, Bruchfestigkeit und Versagensarten präsentiert. Zur Vorhersage der Tragfähigkeit und der Momenten-Durchbiegungsbeziehung wird ein Computerberechnungsprogramm eingesetzt.

1. INTRODUCTION

Corrosion of prestressing steel tendon is one of the major problems which affect the lifespan of bridges and other prestressed concrete structures, especially in coastal areas. Composite materials offer unique advantages, apart from high fatigue strength, in solving many practical problems in areas where conventional materials fail to provide satisfactory service life. Unlike steel, composites are unaffected by aggressive environmental conditions and have good corrosion-resistant property.

Carbon Fiber Reinforced Plastics (CFRP) represent an ideal alternative for prestressing steel and can also be used for repair and rehabilitation of damaged structural members. The main attributes of CFRP composites are high strength, lightweight, resistance to chemicals, good fatigue strength and non-magnetic and non-conductive properties. The limited information available on design, standards and evaluation criteria on CFRP prestressed / strengthened structures necessitates the need for further research in this field. This paper presents the experimental studies on flexural behavior of concrete beams prestressed / strengthened with CFRP tendons / laminates. The effectiveness of CFRP composites was assessed in terms of deflection, ultimate load and cracking, which were evaluated for a series of test beams. Theoretical analysis was also performed for prediction of load-deflection behavior of the beams.

2. RECTANGULAR BEAMS PRESTRESSED WITH CFRP TENDONS

2.1 Experimental Program

The CFRP prestressing tendon used in the study was carbon fiber composite cable (CFCC 1x7, 12.5Φ) composed of PAN type carbon fiber and resin [2]. The basic properties of CFCC tendons (CFCC 1x7, 12.5Φ) and shear stirrups (CFCC 1x7, 7.5Φ) are presented in Table 1. Four rectangular beams of dimensions 254 mm x 254 mm x 2490 mm were cast with minimum reinforcement based on the ACI code requirements. Two CFRP prestressing tendons were used with an eccentricity of 83 mm and pretensioned to a force of 185 kN. CFCC rectangular helicoidal hoops were used as the shear reinforcement. A prestressing bed facility was made use of for fabricating the specimens at Florida Atlantic University. Strain gages were installed at midspan on prestressing tendons to measure the deformation in cables during pretensioning. Load cells were placed at the dead ends of prestressing tendons and connected to a data acquisition system. The CFRP tendons were pretensioned to about100 kN (60% of breaking strength) and the anchorage loss was about 5% to 7%. The prestressing forces and concrete compressive strengths for the beams are presented in Table 2. The beams were tested after 28 days of casting over a simply supported span of 2440 mm (96 in).

Table 1 Basic characteristics of CFCC

Form, Size	Diameter	Effective section area	Breaking strength	Tensile strength	Tensile modulus	Elongation
CFCC1x7 12.5Φ	12.7 mm	76.0 mm^2	167 kN	2.20 GPa	141 GPa	1.6%
CFCC1x7 7.5Φ	7.4 mm	30.4 mm^2	60 kN	1.96 GPa	130 GPa	1.6%

The load points were 533 mm (21 in) apart from the center of the span for Beam-1 and 280 mm (11 in) for the other beams (Fig. 1). Four vibrating wire strain gages were mounted on the concrete beams along the depth at midspan. Dial gages were set up to measure deflections at midspan, support and tendon slip. Static load was applied in 5 to 10 kN increments and monitored by a load cell connected to System 4000 data acquisition system. Concrete strains, midspan and support deflections, and tendon slip were recorded at regular load intervals together with crack pattern.

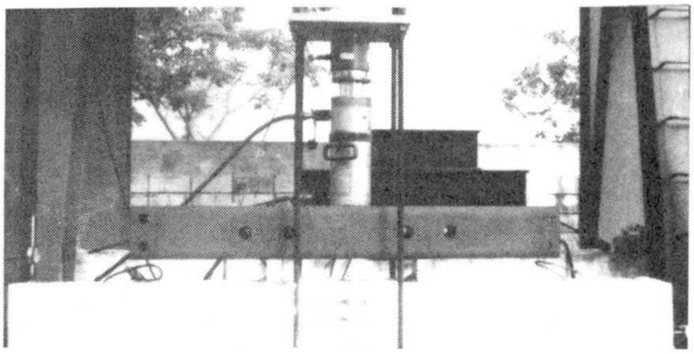

Fig. 1 Typical beam test setup

Table 2 Specimen characteristics

Beam no.	Prestressing force kN	Ratio f_i/f_u percent	Anchorage loss percent	Concrete strength MPa
Beam-1	183.7	55.0	6.1	60.6
Beam-2	185.6	55.6	6.6	75.2
Beam-3	188.8	56.5	5.0	53.3
Beam-4	187.1	56.0	4.8	47.9

2.2 Results and Discussions

The ultimate flexural strengths of beams compare well with the predicted values based on the conventional theory for PC beams with prestressing steel tendons (Table 3). Beam-1, with a larger pure bending region, failed by diagonal tension at a lower moment value. The first crack moments for all the beams were lower than the predicted values. The moment vs. deflection of all the beams show the typical bilinear behavior (Fig. 2). Crack propagation in all the beams was similar. The first initial crack was observed under the load points at a load of about 57 kN. Then new cracks formed between the load points symmetrically. When the applied load reached 70% of the ultimate value, more cracks developed beyond the load points perpendicular to the line of principal stress. Some cracks appeared at the tendon level when the applied load reached 80% of the ultimate value. Beam-1 failed by diagonal tension all of a sudden and the other beams failed by tendon rupture with sufficient warning.

Table 3 Test results

Beam number	First crack moment (kN-m)		Ultimate moment (kN-m)		Maximum deflection (mm)	Failure mode
	Experimental	Theoretical	Experimental	Theoretical		
Beam-1	27.4	36.2	50.0	65.9	23.1	DT
Beam-2	26.3	36.8	68.1	66.8	33.0	F
Beam-3	27.2	34..8	66.5	65.3	27.2	F
Beam-4	28.2	37.1	66.6	64.8	23.6	F

No tendon slips were observed in all the beams. The strain distribution across the depth was essentially linear. The upward neutral axis shift was observed with increasing load. When the load reached its ultimate value, the compression zone was about 50 mm from the top.

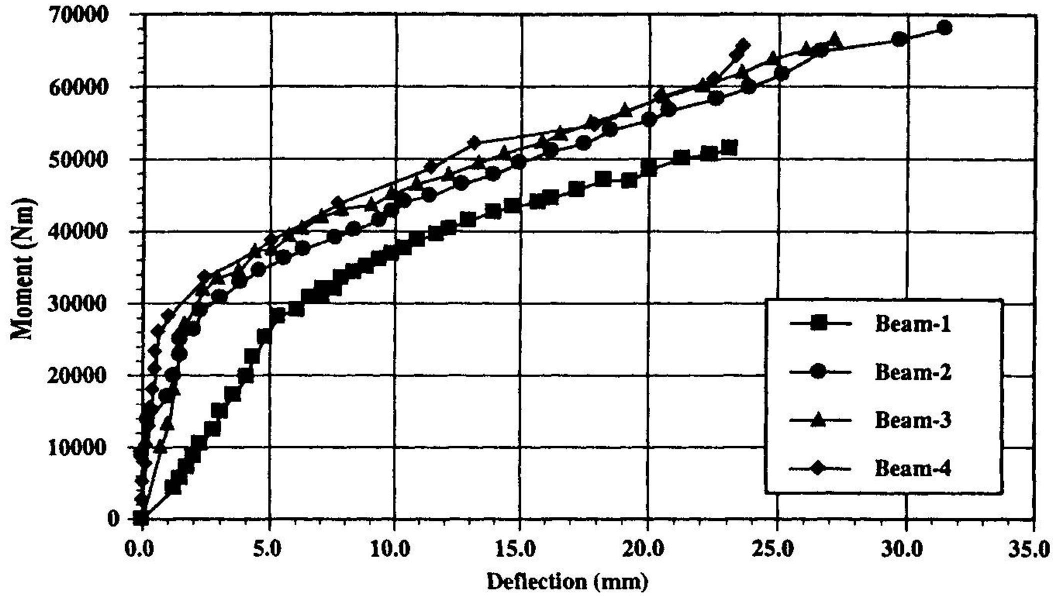

Fig. 2 Moment vs. deflection

3. RECTANGULAR BEAMS STRENGTHENED BY CFRP LAMINATES

3.1 Experimental Program

Six reinforced concrete rectangular beams were cast with minimum steel reinforcement according to ACI 318-89 code provisions (Fig. 3). One layer of CFRP laminate was bonded to one reinforced concrete beam. Two reinforced concrete beams bonded with two layers of CFRP laminates and another two with three layers of CFRP laminates were prepared for testing and the remaining beam was used as the control beam. Carbon fiber prepreg laminate with a tensile strength of 2,758 MPa and tensile modulus of 141 MPa was used in the study. The two-part epoxy resin consisted of a main resin and a curing agent with a mixing ratio of 2:1. The cured adhesive had a tensile strength of 60 MPa. The CFRP laminates were bonded to the tension face of the beams following the procedure detailed in ref. 3. The beams were tested under two-point static loading over a simple span of 2438.4 mm (8 ft.). Deflections were measured at midspan, support and section at 609.6 mm (2 ft.) from midspan. Strains and deflections at various locations, crack patterns and the applied load were recorded for every load increment till the ultimate load capacity of the beam.

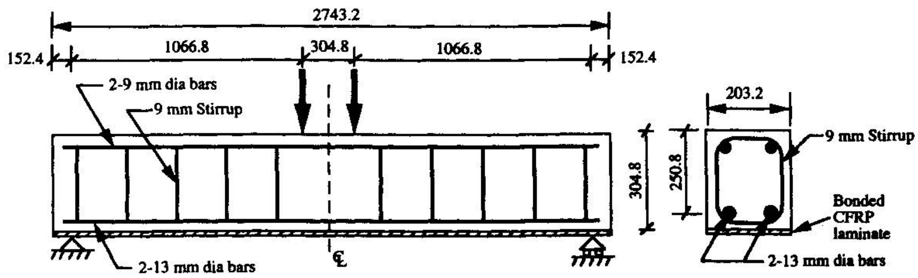

Fig. 3 Reinforcement details of rectangular beam

Note: All dimensions are in mm

3.2 Theoretical Analysis

The determination of ultimate strength of the beams based on ACI method needs modification since the fiber reinforced plastics have no definite yield plateau. Hence, a computer program has been developed to perform flexural analysis of rectangular sections with single or multiple FRP reinforcement layers. The program is based on the stress-block factor approach [4] considering the linear-elastic stress-strain properties of FRPs and parabolic stress-strain relationship of concrete.

3.3 Results And Discussions

A significant increase in the moment capacity can be observed for the beams bonded with laminates over and above the control beam (Fig. 4). All the beams show a significant decrease in the ultimate deflection, indicating that the stiffening effect of the CFRP laminates reduces the structural deformation until failure. A considerable increase can be observed in load carrying capacity of the laminated beams over the control beam at ultimate load stage (column [2] of Table 4). The ratio of experimental to theoretical ultimate load values (column [4]) can be seen to decrease with the number of laminates, which indicates the prediction of higher stiffness for the laminated beams by the program. The load factors, which are the ratios of experimental ultimate loads to the theoretical service loads (column [6]), decrease with increasing number of laminates; however, the values are significantly greater than unity which indicates the CFRP laminate restraining effect.

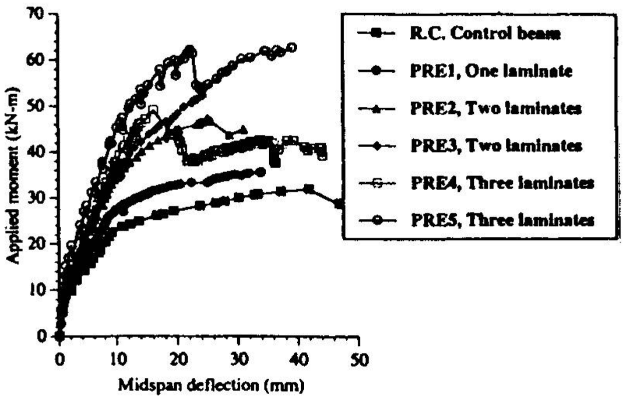

Fig. 4 Effect of CFRP laminates on deflection

The prediction of higher ultimate capacity by the program can be attributed to the assumption of perfect bond between the concrete and CFRP laminates. The CFRP laminate strains at ultimate load predicted by the program were significantly higher than the experimental values [5]; this indicates the higher tensile force developed by the laminates and higher ultimate capacity and the corresponding service load than those observed from the experiments. The control beam exhibited widely spaced cracks, whereas the beam with CFRP laminates showed cracks at relatively close spacings. All the beams with CFRP laminates failed by crushing of concrete with a significant increase in the flexural capacity. Longitudinal splitting of the CFRP laminate preceded debonding before complete failure of the beam. For a beam with two CFRP laminates (Fig. 5), although the theoretical curve exhibits a higher ultimate moment and higher stiffness, it compares well with the experimental curve. The strain-compatibility method seems to give accurate results, although more precise predictions could be made with better idealization of the bond between laminate and concrete and the failure criterion.

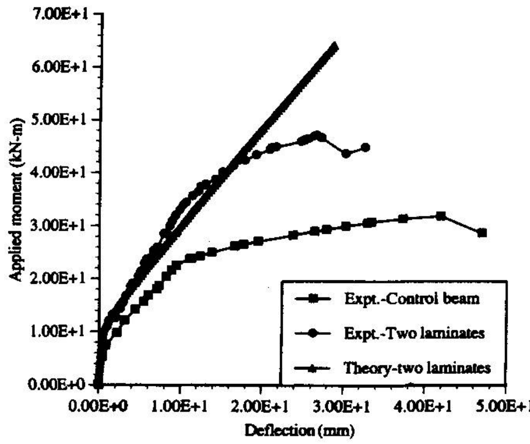

Fig. 5 Moment deflection behavior of control beam and beam with two CFRP laminates

Table 4 Experimental and theoretical loads

Beam number	Number of CFRP laminates	Exptl. ultimate load UL (kN) [1]	Factor of increase F_{UL} [2]	Theor. ultimate load (kN) [3]	[1] / [3] [4]	ACI 318 service load (kips) [5]	[1] / [5] [6]
S5-STL	-	59.793	1.000	53.632	1.115	26.721	2.238
S5-PRE1	1	66.603	1.114	97.225	0.685	49.798	1.338
S5-PRE2	2	88.422	1.479	120.356	0.735	62.044	1.425
S6-PRE3	2	97.923	1.638	140.817	0.695	72.875	1.344
S6-PRE4	3	91.967	1.538	163.059	0.564	84.650	1.086
S6-PRE5	3	116.214	1.944	163.059	0.713	84.650	1.373

4. CONCLUSIONS

The flexural strength of concrete beams prestressed with CFRP tendons could be predicted using conventional theory. The moment-deflection characteristics of the CFRP pretensioned beams show typical bilinear behavior. The failure mode indicates brittle behavior, which needs further study. The addition of bonded CFRP laminates to reinforced concrete beams results in a significant reduction in deflections and crack width with a substantial increase in the ultimate flexural capacity. The computer program based on ACI strain compatibility method gives a good estimate of the nominal moment strength and corresponding curvatures and deflections.

5. ACKNOWLEDGMENTS

This research work is based on a project funded by Itochu Corporation, Japan (Dr. M. Arockiasamy, Principal Investigator) and another funded by the Florida Department of Transportation (WPI # 0510641, Dr. Mohsen Shahawy, Technical Coordinator and Dr. M. Arockiasamy, Principal Investigator). Thanks are due to Dr. S. E. Dunn, Professor and Chairman, Department of Ocean Engineering, and Dr. C. S. Hartley, Dean, College of Engineering, Florida Atlantic University for their continued interest and encouragement. Grateful acknowledgments are due to the cooperation and assistance from the staff at the Structures Research Center, FDOT, and the Graduate Research Assistants at the Center for Infrastructure and Constructed Facilities, Florida Atlantic University.

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