Composites in Constructions, Figueiras et al (eds), © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 858 7

Strengthening of Reinforced Concrete Beams with Carbon FRP

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ABSTRACT: Seven concrete beams reinforced internally with steel and externally with carbon fiber-reinforced polymer (FRP) laminate applied after the concrete had cracked were tested under four-point bending. Results show that FRP is very effective for flexural strengthening. As the amount of steel increases, the additional strength provided by the carbon decreases. Compared to a beam reinforced *heavily* with steel only, the beams reinforced with both steel and carbon have adequate deformation capacity, in spite of their brittle mode of failure. Clamping or wrapping of the ends of the FRP laminate combined with adhesive bonding is effective in anchoring the laminate.

1 INTRODUCTION

The use of fiber-reinforced polymer (FRP) composites for the rehabilitation of beams and slabs started about 15 years ago with the pioneering research performed at the Swiss Federal Laboratories for Materials Testing and Research or EMPA (Meier, 1987). FRP composites, used in the repair of beams and slabs as external tensile reinforcement, increase the strength (ultimate limit state) and the stiffness (serviceability limit state) of the structure. Repair with FRP is thus motivated by requirements for earthquake strengthening, higher service loads, smaller deflections, or simply to substitute for deteriorated steel reinforcement. Unfortunately, the increase in strength and stiffness is sometimes realized at the expense of a loss in ductility, or capacity of the structure to deflect inelastically while holding a load close to its capacity. Brittle failure is oftentimes caused by debonding or anchorage failure, which occurs in the majority of tests of beams strengthened for flexure (64 % according to a survey by Bonacci, 1996). In only 22 % of the tests surveyed, rupture of the FRP was achieved, with the rest of the beams failing in shear or compression.

The issues addressed in this paper are:

1. What is the flexural strength enhancement provided by FRP laminate?
2. Is the flexural behavior of concrete beams reinforced with steel and carbon sufficiently ductile?
3. How effective is clamping or wrapping in enhancing anchorage?

2 EXPERIMENTAL DESIGN

A series of seven beams were tested (Table 1; beam 10, which has a balanced steel ratio, was not tested but was used in calculations). Shear and bearing steel reinforcement were provided in ample amount to ensure that failure occurred by flexure only (Figs. 1 and 2).

2.1 *Test set-up*

The beams were cast with the compression side up but were tested upside down (tension side up) for ease of repair, under four-point loading (Fig. 1). An array of eight LVDTs (linear variable differential transformers) placed evenly over the sides of the beam and supplemented with strain gages on the concrete, steel and carbon measured the strain profile of the beam at midspan (Figs. 1 and 2). Three additional LVDTs measured the deflections of the beam at the ends and midspan.

2.2 *Externul strengthening*

In most cases, strengthening and repair were performed with the application of carbon laminates shortly after the first flexural cracks appeared, at about 1/3 of the ultimate moment of the (virgin) beam reinforced with steel only. For beams 4a and 4b, repair occurred at a higher ratio of the ultimate moment of the virgin beam (68 % and 52 %, respectively), as might occur in lightly reinforced beams.

Table 1 Beam Properties

Beam	b mm	h mm	d mm	f_c MPa	A_s mm²	ρ_s / ρ_b %	f_y MPa	A_L mm²	M_R/M_V %	Anchor
4a	152	460	415	42.3	253	11	430	60.9	68	clamp
4b	152	457	413	42.7	253	11	433	I22	52	d.wrap*
5	156	460	414	42.3	400	I8	500	00.9	34	wrap
6	152	457	410	41.5	568	25	453	00.9	36	clamp
7 N	152	457	408	41.9	774	35	469	60.9	35	clamp
8 N	157	460	400	42.0	1019	46	404	60.9	31	wrap
9	159	457	405	42.8	1290	5s	453	0	---	---
10	152	457	403	42.8	1639	73	453	0	---	---

*diagonal wrap

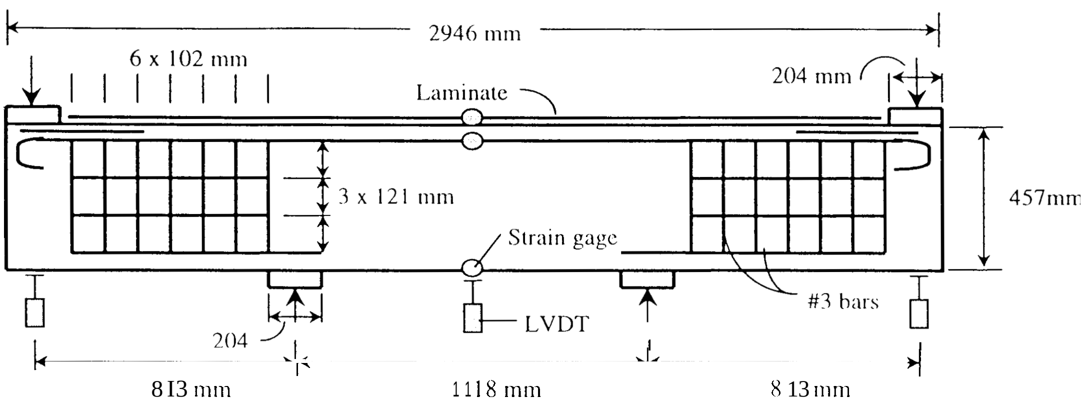


Fig. 1 Beam reinforcement and test set-up

External strengthening followed the procedures recommended by the manufacturer. The carbon laminate was subsequently covered with a heating tape and left undisturbed to cure for 24 hours. Prior slant-shear tests had shown that these curing conditions achieved the same results as would seven days at room temperature. Tables 2 and 3 show relevant material properties.

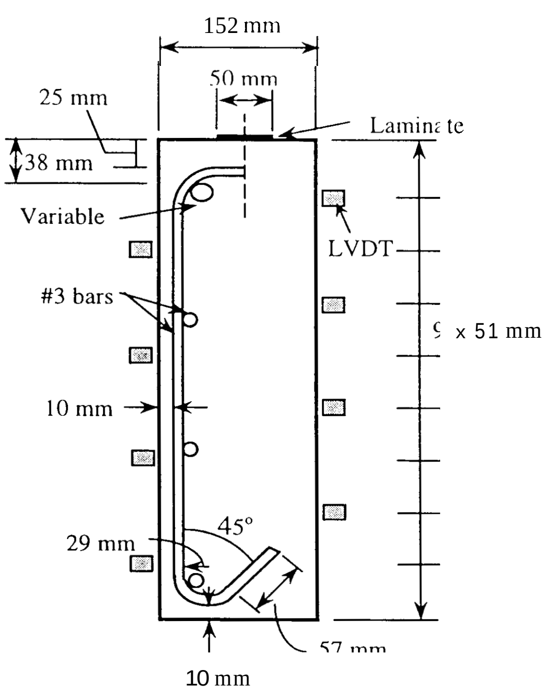


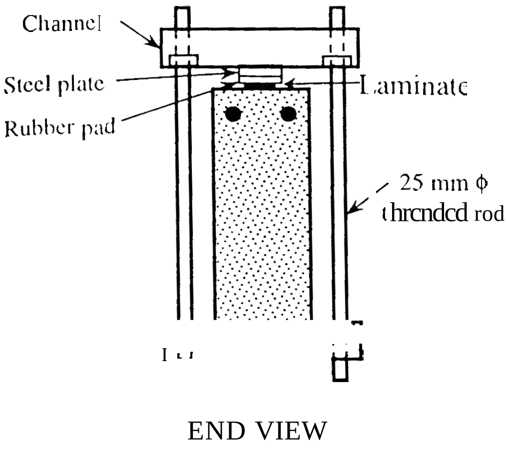
Fig. 2 Beam cross-section showing stirrups at shear span and LVDTs at midspan

Table 2 Properties of carbon laminate (from manufacturer)

Tensile strength	2400 MPa
Modulus of elasticity	155 GPa
Fiber volume content	> 68 %
Thickness	1.2 mm
Width	50 mm
Ultimate strain	1.9 %

Table 3 Properties of adhesive (from manufacturer)

Bond strength, concrete-concrete	22.0 MPa (2 day, dry cure) 21.3 MPa (14 day, moist cure)
Tensile strength (7 days)	24.8 MPa
Shear strength (14 days)	24.8 MPa
Ultimate strain (7 days)	1 %



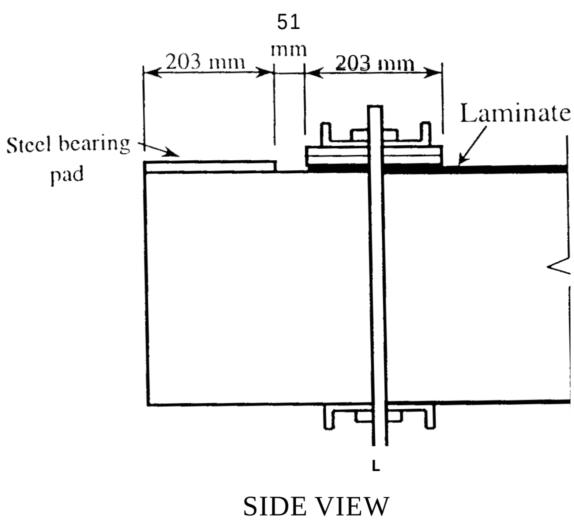


Fig. 3 Clamping of ends of laminate

2.3 *Anchorage*

The carbon laminate was 2440 mm long and covered the middle of the tension face, leaving gaps of 51 mm between it and the load bearing plate at each end. For beams 4a, 6 and 7N, clamps torqued to 400 N·m applied compressive forces estimated (from thread geometry and estimated friction coefficient) to be between 15 kN and 25 kN onto the end 200 mm of the laminate (Fig. 3).

For the other beams, carbon fabric wraps 200 mm in width were used to anchor the carbon laminate. For beam 4b, six layers of wrap were placed diagonally at each end. For beams 5 and 8N, two layers of wrap were used, diagonally at one end, and transversely at the other (Fig. 4). Tables 4 and 5 show relevant material properties.

Table **4** Properties of carbon wrap (from manufacturer)

Tensile strength	960 MPa
Ultimate strain	1.33 %
Thickness	0.33 mm
Modulus of elasticity	73.1 GPa
Strength /width	3.16 kN/cm/layer
Mass /area	230 g/m^2

Table 5 Properties of impregnating resin (from manufacturer)

Tensile strength	30 MPa
Ultimate strain	1.5 %

3 THEORETICAL PREDICTION

A computer program was developed to calculate the moment and curvature of concrete beams under constant moment, with internal steel and external carbon reinforcements. For a given value of compression depth c, the program assumes a value of concrete compressive strain at the extreme fiber ε_{cM} from which it calculates beam curvature, strains, stresses and forces in the concrete, steel and carbon reinforcements. These calculations assume that plane sections remain plane, concrete follows a parabolic stress-strain curve and the carbon is installed at a given bending moment. If force equilibrium is not satisfied, a new value of ε_{cM} is assumed

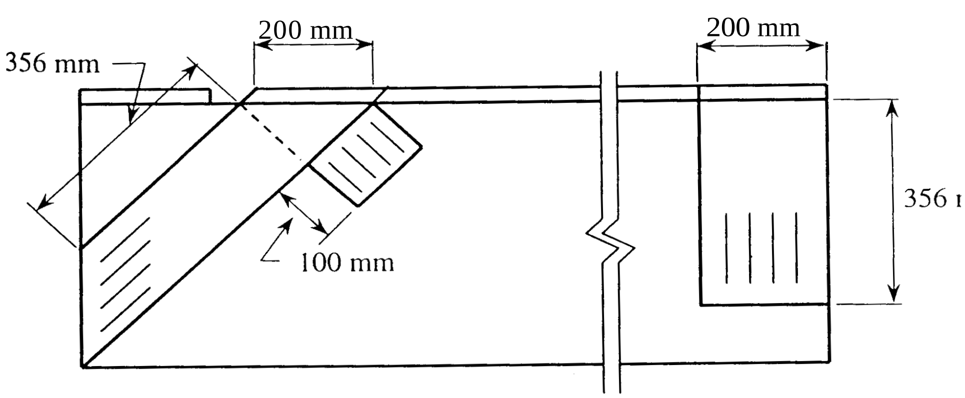


Fig. **4** End wraps

and the iteration repeated. On the other hand, if force equilibrium is satisfied, a new value of c is assumed and the iteration repeated. The program stops when concrete crushes or the carbon ruptures. In addition, the ultimate moment and curvature of steel reinforced concrete (RC) beams were calculated by the current ACI 318-99 method, which assumes a concrete rectangular stress block.

4 RESULTS

Strain profiles at midspan measured with LVDTs and strain gages allowed the calculation of the beam curvature and also of the tensile strain on the concrete surface at repair (from linear extrapolation). That value is then added to the actual measured strain of the laminate. If there is no slip, the modified laminate strain would fall on a straight line with the other strains measured at midspan. In general, the measurements showed a roughly linear profile (plane sections remain plane).

The slender RC beams behaved in expected fashion under flexural loading. As load increased, flexural cracks increased in number, width and depth. Shear cracks and flexural-shear cracks also appeared, propagating diagonally from the loads to the supports. The widest cracks, and oftentimes the ones that proved critical, started as flexural cracks opposite the loads, then propagated vertically over the entire depth of the beam due to a combination of flexure and vertical shear. There was considerable *vertical shearing displacement* at these cracks, causing the laminate to start debonding where it intersected with the cracks (Beam 4b, 5, 7, 9).

Beam 4a (clamped): Failure was initiated by debonding of the carbon laminate, which slipped 12 mm at one end. Examination of the failure surface after the load had been removed showed shear failure at the concrete level, with the glue line and the carbon remaining intact. Shortly after debonding failure of the carbon laminate, *a horizontal shear failure plane also appeared at the level of the steel reinforcement.* No sign of concrete crushing was observed.

Beam 4b (wrapped): Failure was due to concrete crushing. Wide 45° shear cracks were observed, but there was no anchorage failure nor delamination. Both observation and calculation showed there was no slipping of the carbon laminate.

The agreement between experimental data and theoretical prediction is reasonable (Fig. 5). The theoretical model correctly predicts failure by concrete crushing but ignores concrete in tension, and consequently is less stiff than the measurements at low values of moment, before concrete cracks. From the linear strain profile and the reasonable agreement between measured and calculated moment-curvature, there appears to be full strain compatibility of the carbon laminate with the concrete up to ultimate concrete crushing.

Beam 5 (wrapped): Wide flexure-shear cracks extended vertically above the North load. The transverse wrap at the South end ruptured at one edge of the beam, causing the carbon laminate to debond abruptly. There was no sign of concrete crushing.

Beam 6 (clamped): At midspan, on the compressive face, concrete spalled and showed severe distress towards the end of the test. The carbon laminate then failed explosively and showed evidence of

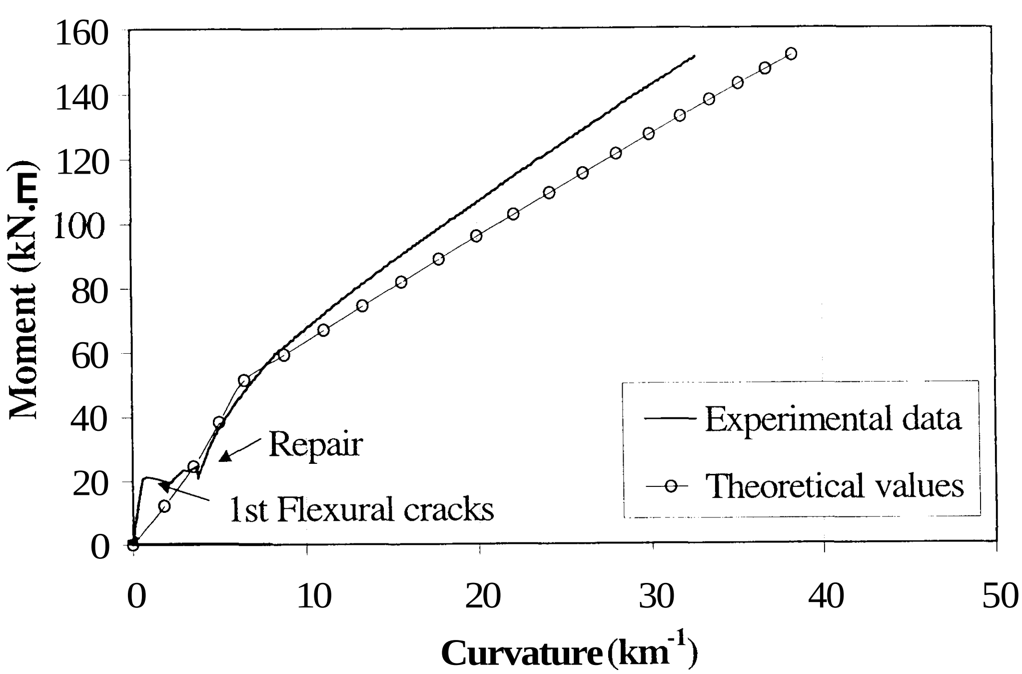


Fig. 5 Curvature vs. moment (beam 4b)

interlaminar slip (about I2 mm) *within the thickness* of the laminate itself when clamps were removed. Wide vertical cracks extended over the depth of the beam above the loads, and a horizontal crack covered the plane of steel reinforcement. When the failed beam was removed from the test machine by lifting it at its ends, these three major cracks connected and the central, rectangular portion of the beam, fell off.

Beam 7N (clamped) and beam 9 (no carbon): Failure was due to concrete crushing. In addition, two wide cracks occurred above the loads, one propagating vertically, the other diagonally and connecting to the crushing zone. For beam 7N, tapping with a coin showed some evidence of debond of the carbon laminate opposite the loads, but there was no wholesale debond or delamination.

Beam 8N (wrapped): Failure was due to concrete crushing. The wraps held, although concrete diagonal shear cracks were visible underneath. The critical crack started out as flexural crack, opposite one of the loads, then propagated at 45 ° towards midspan where it joined with the concrete crushing zone. The carbon laminate debonded locally at its intersections with the critical crack, but there was no overall debond.

5 CONCLUSIONS

1. The application of carbon FRP laminates is very effective for flexural strengthening of reinforced concrete beams, provided proper anchorage of the laminate is ensured. In one case (beam 4b), the strengthened beam was 3.33 times stronger than the unrepaired beam, whose capacity can be calculated by the ACI method. As the amount of steel reinforcement increases, the additional strength provided by the carbon FRP external reinforcement decreases (Table 6). The same FRP reinforcement more than doubled the strength of a lightly reinforced beam (11 % of balanced ratio), but only increased by 19 % the strength of a moderately reinforced beam (46 % of balanced ratio).

2. Compared with the curvature of a beain with a steel reinforcement ratio of 75 % of the balanced ratio (maximum allowed), beams reinforced with steel and carbon have adequate deformation capacity (from 1.43 to 1.87 as niuch), in spite of their brittle failure mode (Table 6).

3. Clamping or wrapping combined with adhesion is effective in anchoring the FRP laminate. A diagonal wrap with six layers anchored the carbon laminate to a strain of 1.11 % (or 58 % of rupture) without slip. Since beam 4b failed by concrete crushing, it is not known how much more effective this wrap would have been. However, a transverse wrap with two layers failed at a (flexural) laininate strain of 0.826 % (or 43 % of rupture, beam 5). On the other hand, clamping and adhesion anchored the laminate to a strain of 1.14 % (or 60 % of rupture, beam 4a). Designers should keep in mind that debonding of the laminate usually starts where there is significant shearing displacement across diagonal or transverse cracks.

6 NOTATION

A_L	cross sectional area of carbon laminate
A_s	area of steel flexural reinf'orcement
b	beam width
c	compression depth
d	beam depth
f_c	concrete cylinder compressive strength
f_y	yield strength of steel flexural reinforcement
h	beam height
M_R	moment at repair
M_u	ultimate moment of tested beam
M_V	ultimate moment of virgin beam
ε_{cM}	compressive strain on concrete extreme fiber
ε_{LM}	maximum laminate strain (at beam failure)

Table 6 Results
(experiments were unique, therefore uncertainties in the results could not be established)

Beam	M_V kN·m	M_u kN·m	M_u / M_V	ε_{LM} 10^{-3}	ϕ_V km^{-1}	ϕ_u km^{-1}	ϕ_u / ϕ_{Vb}	ρ_s / ρ_b %	Failure Mode	Anchor
4a	44.0	93.5	2.13	10.07	113	30.6	1.75	11	debond	clamp
4b	45.0	151	3.36	9.88	111	32.6	1.86	11	crush	d.wrap
5	80.1	117	1.46	6.62	62.2	25.0	1.43	18	debond	wrap
6	99.2	148	1.49	7.80	46.9	24.6	1.41	25	slip	clamp
7 N	136	179*	1.32	6.23*	33.6	29.5*	1.69	35	crush	clamp
8 N	172	204	1.19	6.10	26.7	25.3	1.45	46	crush	wrap
9	207	213	1.03		22.2	19.0	1.09	58	crush	---
10	252				17.5		1.00	73	---	---

* calculated

ρ_b balance ratio of steel flexural reinforcement
ρ_s ratio of steel flexural reinforcement
ϕ_u ultimate curvature of tested beam
ϕ_Y calculated ultimate curvature of steel RC beam
ϕ_{Yb} calculated ultimate curvature of RC beam with balanced steel reinforcement

7 ACKNOWKLEDGMENTS

The authors thank Frank Davis for overall assistance with the tests and the SIKA Corporation for supplying Carbodur laminates, Sikadur 30 adhesive, Sikawrap Hex 230 C and Sikadur 330 impregnating resin.

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