CARBON FIBRE SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS

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SUMMARY: An experimental investigation of 7 monotonically loaded concrete beams was undertaken to evaluate the ability of carbon fibre fabric to reinforce shear deficient concrete members. Two methods of carbon fibre application were evaluated, a partial wrap and a full wrap. In addition to the experimental program, a strip model used to predict the load carrying capacity of concrete members reinforced in shear with composite materials was evaluated.

The experimental program showed that partial wraps of carbon fibre fabric, where the increase of load carrying capacity is dependent on the anchorage length of the carbon fibre, give small increases in ultimate load carrying capacity. It also showed that full wraps of carbon fibre fabric, where the anchorage problems of the carbon fibre are eliminated, provide large increases in ultimate load carrying capacity. The strip model approach was found to adequately predict the load carrying capacity of partially wrapped concrete members.

KEYWORDS: carbon fibre shear reinforcement, full wrap, partial wrap, shear deficient reinforced concrete elements, strip model method

1. INTRODUCTION

Composite materials have been applied successfully in the rehabilitation of many concrete components. Predominately, however, the strengthening has been for flexurally deficient concrete members. Limited research has been conducted on the use of composite materials for the strengthening of shear deficient concrete components. The research conducted to date in this area indicates potential, although many conflicting views exist as to the magnitude[1,2,3]. This paper highlights the findings of a pilot project [4] conducted to evaluate existing research and to focus future research.

2. TEST SPECIMENS

2.1 Beams

The test program involved the testing of 7 concrete beams (Table 1). The beams were designed to evaluate the performance of partial and full wraps (Figure 1). Beams 1-3 were designed with no internal shear reinforcement and Beams 4-7 were designed with the minimum steel shear reinforcing required by the Swiss concrete design codes (Table 3). Beams 1 and 4, with no carbon fibre wraps, were used as reference beams. The carbon fibre wraps were applied to the specimens as indicated in Table 3. The modulus of elasticity of the

concrete at the time of testing was 38,000 MPa and the concrete compressive cylinder strength was 46.4 (MPa).

Table 1. General beam characteristics

Parameter	Dimension	Beams
Height	400 mm	1-7
Width	200 mm	1-7
Length	2750 mm	1-7
Clear span	2250 mm	1-7
Long. tension reinforcement	2x26 mm bars, 1x20 mm bar	1-7
Long. compression reinforcement	2x14 mm bars	4-7
Cover	30 mm	1-7
Stirrups	2x6mm bars @ 150mm	4-7

Table 2. Sika Wrap Hex-230 C data

Sika Wrap Hex-230 C	
weight	230 g/m^3
thickness	0.13 mm
tensile design strength	3,500 N/mm^2
tensile modulus	230 kN/mm^2
failure strain	1.5 %

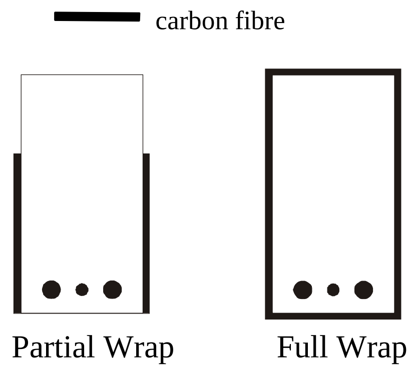

Figure 1. Cross sections of specimens with partial and full wraps

2.2 Carbon fibre

The carbon fibre fabric used was SikaWrap Hex-230C; a high strength uni-directional carbon fibre(Table 2). The resin used was Sikadur-330 LVP. All data was provided by Sika. No specific material tests on the used fabric were conducted.

The application of the carbon fibre was performed by Sika. The surfaces of the beams were ground to remove the first cement layer and expose the aggregates. This was done to ensure a good bond between the carbon fibre and the concrete. The glue was then mixed and applied to the surface so that the roughness was less than 1 mm. The resin was applied to the substrate in a quantity of 1.0 - 1.5 kg/m^2. The fabric was then placed on top of the resin coating and the resin was squeezed through the rovings of the fabric with plastic laminating roller.

3. TESTING

All specimens were monotonically loaded by a point load at one third of the clear span (Figure 2). Load cells were placed under the hydraulic jack and both reaction points to measure the applied load. Two LVDTs were placed at third points of the clear span of the beam to measure the deflections. Demec points were placed in a triangular configuration on the short span of the specimens, 150 mm apart, to measure the shear crack opening displacement (Figure 2). The triangular configuration was used so measurements could be

taken at a 60° angle to the horizontal and thus perpendicular to the shear crack. Measurements were only taken during the ascending branch of the load-displacement curves.

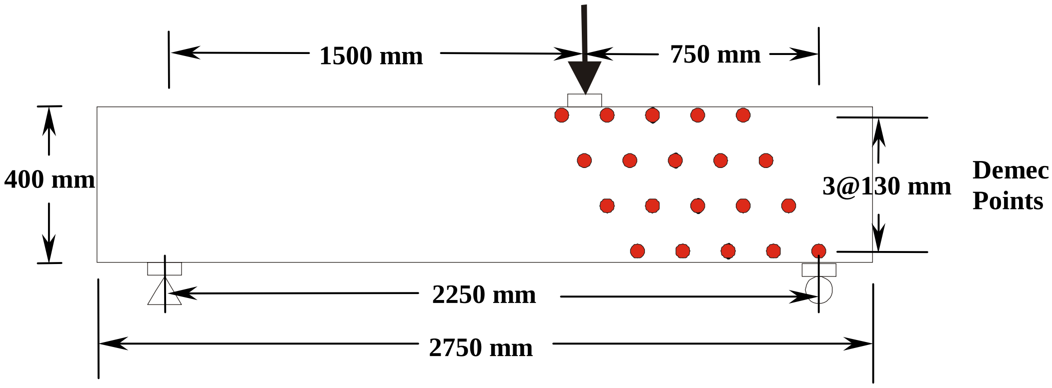

Figure 2. Static system and location of demec points

4. TEST RESULTS

4.1 Loads and Deflections

The test results show that the partial carbon fibre wraps increased the load carrying capacity of the beams only marginally (Table 3). The test results also show that full carbon fibre wraps increased the load carrying capacity of the specimens dramatically. A load increase of 73 percent and 39 percent was observed for Beams 3 and 6, respectively. Beam 6 failed in flexure. All other specimens failed in shear.

Table 3. Shear reinforcement and load information

Beam	Shear Reinforcement			Load Information	
	Internal stirrups	Partial Wrap	Fully wrap	Ultimate Load (kN)	% increase above reference beams
1				279	0
2		X		316	13
3			X	482	73
4	X			365	0
5	X	X		401	10
6	X		X	506	39*
7	X	X		414	13

* Beam #6 failed in flexure

The application of both the partial wrap and the full wrap showed no change in the initial stiffness of the specimens. In the beginning of the tests the deflection of the test specimens was due to flexure and the carbon fibre wraps were not designed to contribute to the flexural performance of the specimens. The carbon fibre wraps did increase the stiffness towards the end of the experiments, when the deflections were increasingly due to the opening of the shear crack (Figures 3 and 4). The increase in stiffness was more prominent for the beams without internal shear reinforcement. The apparent difference in the stiffness of Beam 1, and Beams 2 and 3, is due to the more flexible beam supports used for the testing of Beam 1 and the corresponding systematic measurement error.

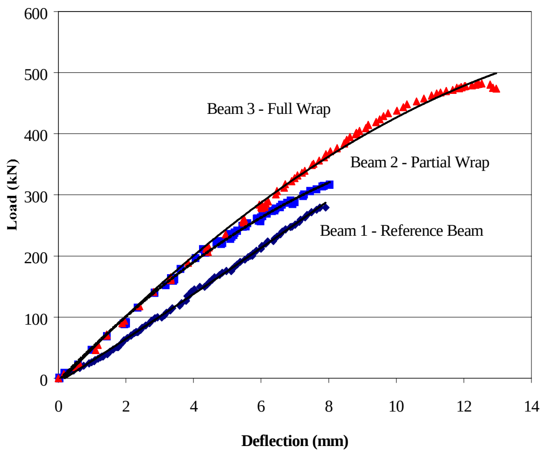

Figure 3. Loads versus deflections for specimens without internal stirrups

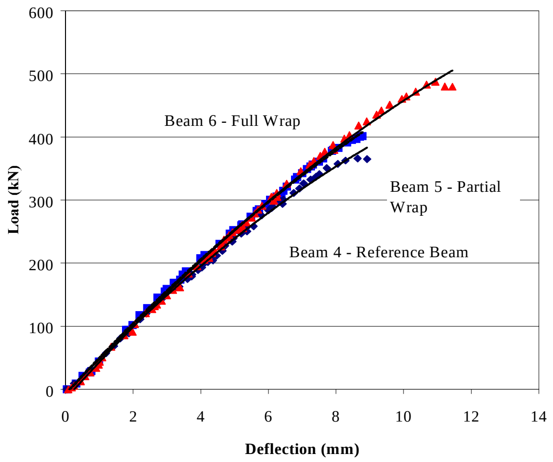

Figure 4. Loads versus deflections for specimens with internal stirrups

4.2 Shear crack opening

The shear cracks formed at an angle of approximately 30º to the horizontal. The measured crack opening along the length of the shear crack is shown in Figure 5 for all of the specimens. The vertical line indicates the beginning of the carbon fibre patches for specimens 2, 5 and 7. The carbon fibre patches crossed the shear crack from 267 mm to 800 mm (Figure 6). Beam 1 had the largest crack opening because it was the only specimen with an absence of shear reinforcement (both stirrups and wraps). As can be seen from Figure 5 the application of carbon fibre, both in the form of a patch and a full wrap, reduces the crack opening displacement. It is interesting to note that the maximum crack opening displacement was located near the middle of the crack length and diminished towards either end. The reason for the closure of the crack opening near the top and bottom of the specimen may be explained by the horizontal compression force due to flexure and the dowel effect of the reinforcement, respectively.

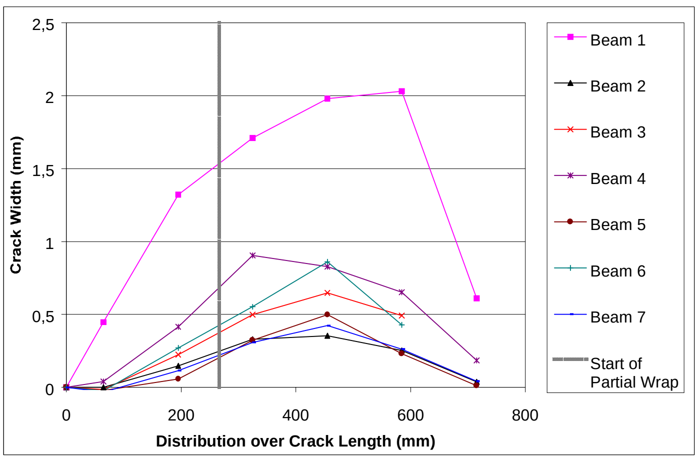

Figure 5. Measured shear crack opening at 60 degrees from the horizontal

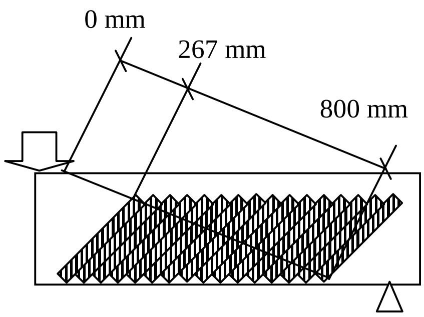

Figure 6. Measurement of shear crack length

5. PREDICTION EQUATIONS

In addition to the test program a recently proposed method [1] to predict the load carrying capacity of members reinforced with carbon fibre was evaluated, using test results from the three partially wrapped specimens in this test series, called hereafter the MCS test series.

5.1 Strip model

Alexander and Cheng [1] proposed a strip model to predict the additional load carrying capacity gained by concrete beams with the addition of carbon fibre sheets. In this model the strains in the carbon fibre were assumed to increase linearly from the bottom of the shear crack to the top of the shear crack (figure 7). This strain distribution was selected to correspond with the strains measured in the vertically oriented carbon fibre of their test specimens. The proposed strip model was based on 8 strips crossing the shear crack (figure 7).

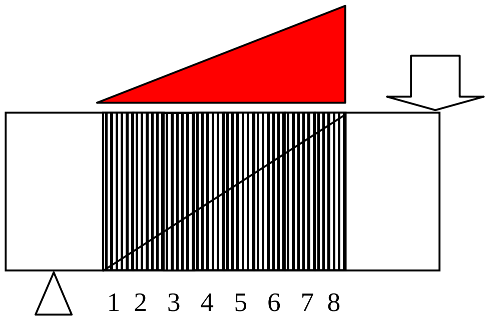

Figure 7. Vertical orientation of carbon fibre strips and assumed strain distributions [1].

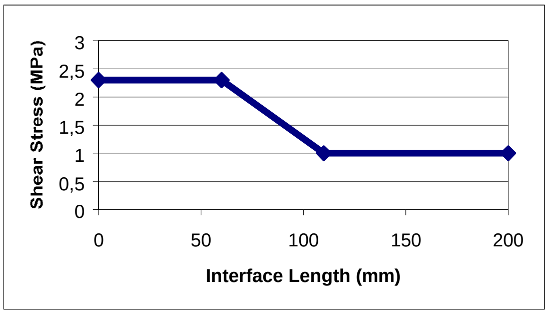

Figure 8. Shear stress versus carbon fibre interface length [1].

The amount of shear transferred to the carbon fibre is governed by two parameters, 1) the shear strength of the concrete, and 2) the interface length between the concrete and the carbon fibre; the anchorage or development length. Alexander and Cheng determined the shear stress – interface length transfer capacity experimentally. The shear stress - interface length determined by Alexander and Cheng is shown in figure 8. The concrete in their test program had a compressive strength of 43 MPa.

As the load demand on the carbon fibre is increased, the load in each of the selected strips is increased in relation to their assumed strains. When the load demand in one of the strips exceeds its carrying capacity, (the interface length of the strip multiplied by the possible shear stress transfer indicated in figure 8), this strip fails and the load is subsequently redistributed to the remaining strips. This is continued until the remaining strips can no longer carry the required load and all of the remaining strips fail.

5.2 Modifications to the strip model

A number of modifications to this model were made in order to use the strip model to predict the behaviour of the specimens tested at MCS. The predominant reason for this was the orientation of the carbon fibres. The carbon fibre on the MCS specimens was oriented at 45 degrees to the horizontal to increase the anchorage length. In addition to this the carbon fibre on the MCS test specimens was applied to only the bottom 2/3^{rds} of the height of the partially wrapped specimens simulating application to a T-beam. The carbon fibre applied to the specimens tested by Alexander and Cheng was applied over the entire height.

These differences mean that the strain distribution in the carbon fibre was different in the two test series. The strain distribution assumed for the MCS test series is shown in figure 9. This strain distribution was chosen to correspond with the crack width openings measured on the 6 specimens with shear reinforcement (figure 5).

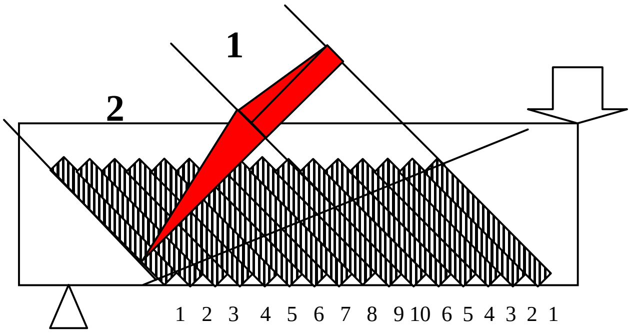

Figure 9. Assumed strain distribution MCS test series

With the use of the new strain distribution the theoretical prediction equations change from those suggested by Alexander and Cheng [1] to:

$$y_{x1} = \frac{D_1}{3} \cdot \frac{x_1}{\sum_{i=n_1}^{n_1} i - \sum x_{F1}} + \frac{2 \cdot D_1}{3} \cdot \frac{1}{n_1} \quad (5)$$

$$y_{x2} = \frac{D_2 \cdot x_2}{\sum_{i=n_2}^{n_2} i - \sum x_{F2}} \quad (6)$$

where: $$\varepsilon_{x1\max} = \varepsilon_{x2\max} \quad (7)$$

and:

$_1$	= top portion of partial wrap (figure 9)	n	= number of effective strips
$_2$	= bottom portion of partial wrap (figure 9)	x	= strip number
D	= portion of load carried by all strips	x_F	= failed strip number
ε_{xmax}	= strain in highest numbered strip	y_x	= portion of load carried by strip

The shear stress versus interface length relationship was also modified as the average compressive strength of concrete used in the MCS test specimens was 46.4 MPa, 3.4 MPa higher than that used in the test series conducted by Alexander and Cheng. This was modified using the square relationship between the shear strength of the concrete and the concrete strength as suggested by Alexander and Cheng.

With the exception of these changes, the strip model was used as proposed by Alexander and Cheng. The difference between the maximum load possible in each strip, an upper bound value as calculated by the strip model method (solid line), and the actual load in each strip is shown graphically in figure 10 for all steps[4].

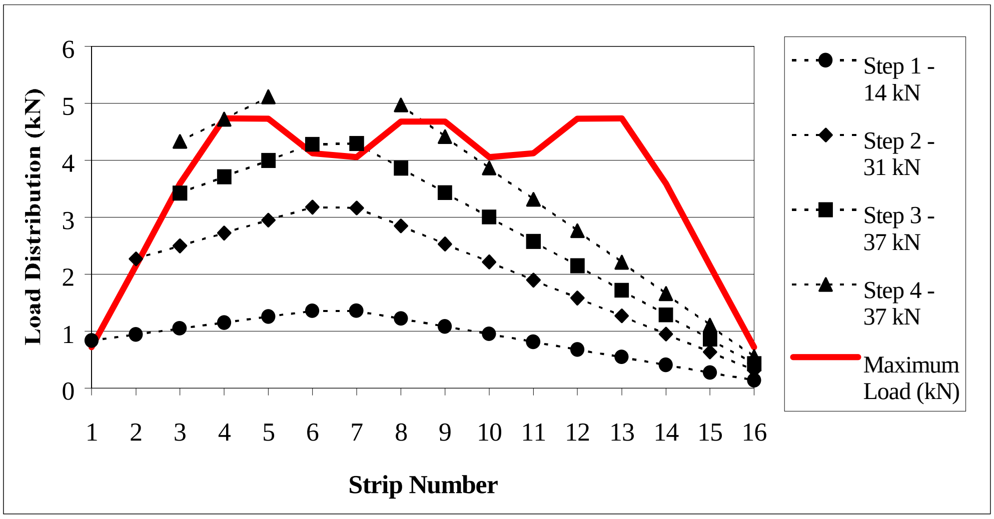

Figure 10. Load distribution in the carbon fibre at different load levels (the strip numbers are labelled starting from the top of the shear crack)

The strip model predicts the ability of the carbon fibre to transfer force directly across the shear crack. Since the carbon fibre on the MCS test specimens was oriented at 45 degrees and, as predicted by the strip model, can transfer 37 kN of load across the shear crack up per side, the actual increase in load carrying capacity of the specimen is *37 x sin(45) x 2 = 52 kN.*

5.3 Predictions versus measured values

As the strip model method is for partial wrapped specimens, there are only three comparisons possible with the experimental results of the MCS test series (table 5).

Table 5. Predictions of shear contributions from CFRP sheets using the strip model

Beam	$V_{u,o}$ (kN)	$V_{frp,sm}$ (kN)	Predicted ultimate load $V_{frp,sm} + V_{u,o}$ (kN)	$V_{u,frp}$ (kN)	Measured contribution of FRP $V_{u,frp} - V_{u,o}$ (kN)	Ratio $(V_{frp,sm} + V_{u,o})/V_{u,frp}$
2	279	52	331	316	37	1.05
5	365	52	417	401	36	1.04
7	365	52	417	414	49	1.01

where:

$V_{u,o}$ - ultimate shear load of reference beams
$V_{frp,sm}$ - predicted contribution of FRP using the strip model
$V_{u,frp}$ - ultimate shear load of beams strengthened with FRP

As can be seen in table 5, the strip model in combination with the measured values for concrete contribution predicted the ultimate load of the reinforced beams very well. The strip model only slightly overestimated the ultimate loads (within 5 percent for all three beams).

There are two possible reasons for this slight overestimation. The first is that the shear stress versus carbon fibre - interface length curve used was not correct for the carbon fibre used in the MCS test series. If the curve used underestimated the ability of the concrete to transfer the load to the carbon fibre then the predicted loads would under estimate the carbon fibre contribution to the total load.

The second possibility is because the contribution of the steel and the concrete was determined experimentally using a reference beam. Because concrete is not a homogeneous material the strength of the concrete and therefore the strength of the concrete beams vary from specimen to specimen. It is possible that this variability contributed to the overestimation of the contribution of the carbon fibre. This is corroborated by the fact that Beams 5 and 7 had slightly different ultimate loads even though they were designed the same.

6. CONCLUSIONS

1) The MCS test series showed that carbon fibre patches, where the load carrying capacity is dependent on the anchorage length of the carbon fibre, give small increases in ultimate capacity (i.e. smaller then 15 percent).
2) The MCS test series showed that by wrapping specimens in carbon fibre large increases in load carrying capacity are possible (Beam 3 had a 73 percent increase. Beam 6 had a 39 percent increase and failed in bending).
3) The comparison of the MCS test results with the research of Alexander and Cheng [1] showed that the strip model adequately predicts the ability of the carbon fibre to increase the load carrying capacity of the beam. The predictions of the ultimate load carrying capacities of the beams were within 5 percent of the measured values.
4) The strip model method is very dependent on the concrete properties. A shear stress versus carbon fibre - interface length curve should be determined for each test series. The variation of the concrete must be considered when evaluating the results.
5) Future research should focus on the transfer mechanism between concrete and composite materials.

7. REFERENCES

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