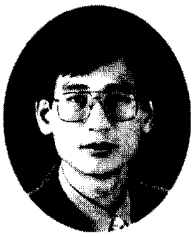
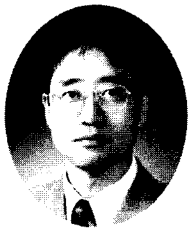
Strengthening Effect of R/C Beams with Different Strengthening Level





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ABSTRACT

This paper presents the behavior and strengthening effect of reinforced concrete rectangular beams strengthened using CFRP sheets with different strengthening level. In general, normally strengthened beams are failed by interfacial shear failure (delamination) within concrete, instead of by tensile failure of the CFRP sheets. The delamination occurred suddenly and the concrete cover cracked vertically by flexure was spalled off due to the release energy. The strengthened beams were stiffer than the control beam before and after reinforcement yielding. The ultimate load considerably increased with an increase of strengthening level, while the ultimate deflection significantly decreased. The tensile force of CFRP sheets and average shear stress of concrete at delamination failure were curvilinearly proportional to the strengthening level. Therefore, the increment of ultimate load obtained by strengthening was curvilinearly proportional to the strengthening level. The averaged horizontal shear stress of concrete at the interface ranges between $0.40\sqrt{f_{ck}}$ and $0.55\sqrt{f_{ck}}$ (in kg/cm^2) depending on strengthening level.

Keywords; strengthening effect, strengthening level, CFRP sheet, interfacial shear failure, delamination failure, ultimate load, ultimate deflection

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1. Introduction

Advanced composites are likely to play a significant role in future construction applications, particularly in the strengthening and rehabilitation of existing concrete structures. Deficiencies of the existing inventory of concrete structures range, on the one hand, from normal wear, and on the other hand, from insufficient detailing at the time of the original design to inadequate maintenance and rehabilitation measures. Therefore, rehabilitation alone will not bring these structures up to current standards. In this case, strengthening must also be considered(1).

Techniques such as external post-tensioning and epoxy-bonded steel plates have been used successfully to increase the strength of girders in existing bridges and buildings. High strength composite plates are used as an extension of the steel plating method, offering the advantages of composite materials such as immunity to corrosion, low volume to weight ratio, and unlimited delivery length thus elimination of the joints(2).

Fiber reinforced polymer (FRP) sheets or plates may be needed to improve the maximum load capacity and to reduce the vertical deflection at service of bridge structures. Also, their use tends to limit the width of cracks and improve their distribution in concrete beams. Composite plates usually are epoxy-bonded to the tension flange of girders, increasing both their strength and stiffness. The advantages of this strengthening technique include ease of application and elimination of the special anchorages otherwise needed in the post-tensioning method (3).

Carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) laminates appear at first to be the best (most economical) candidates for the external reinforcement of concrete structures. However, it is strongly believed that CFRP laminates offer the highest potential as a replacement of steel in typical strengthening applications. CFRP sheets combine the qualities of very high strength and high stiffness with outstanding fatigue performance. Moreover, CFRP sheets are durable under practically every types of environmental attack which may occur in or around concrete structures (4, 5).

The study of reinforced concrete beams strengthened in bending is described in this paper. Particularly, the strengthening effect of beams with different strengthening level was investigated in detail.

2. Experimental Program

The loading arrangement and cross sectional dimensions are shown in Fig. 1.

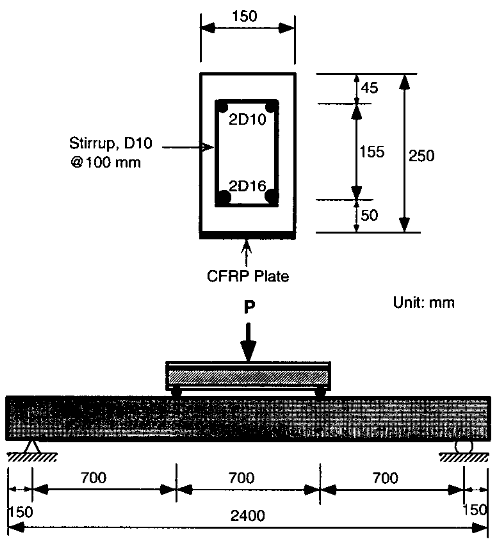

Fig. 1 Typical cross section and loading arrangement

The beams had 76% of maximum steel reinforcement ratio. For bending, the carbon fiber reinforced polymer (CFRP) sheets were glueded along the soffit of a beam as shown in the figure. The CFRP sheets were extended up to the supports.

Before application of the glued-on CFRP sheets, all beams were pre-loaded to about 60% of their ultimate design load, 4.7 ton (46 kN). This is to simulate actual condition of cracked reinforced concrete beams at the time the strengthening system is applied.

2.1 Test Parameters

Table 1 Test parameter and variables

Beam I.D	No. of CFRP sheet	Steel Reinforcement	Stirrups
CF0	0	2D16 (3.97 cm^2) $\rho = 0.76\rho_{max}$ $= 1.31\%$	D10 @100 mm (1.43 cm^2) $\rho_v = 0.95\%$
CF1	1		
CF2	2		
CF3	3		
CF4	4		
CF6	6		

As presented in Table 1 different number of CFRP sheets was selected as a test parameter to investigate the strengthening effect of different strengthening levels. A total of six beams were tested and observed. Of six beams, a control beam was tested and compared with CFRP glued-on beams having different strengthening levels. Beams CF0 was control beam with one fourths of maximum steel reinforcement ratio. Stirrups were sufficiently provided to prevent possible shear failure alllowed for the beam in accordance with the ACI Code [(6)].

2.2 Preparation of Test Beams

2.2.1 Concrete

The test beams were supplied by a precast concrete manufacturer, according to the design specifications. Portland Type-I cement, natural sand, and crushed aggregates with a maximum size of 25 mm were used for the concrete. The target strength of the concrete was 210 kg/cm^2 (20.6 MPa). The averaged compressive strength of the concrete cylinder at time of testing for each beam was about 180 kg/cm^2 (17.6 MPa).

2.2.2 CFRP Sheets

For strengthening of the test beams, the CFRP sheets (trade named, Forca Tow Sheet)were applied with the corresponding epoxy adhesive. The properties of the materials are summarized in Table 2.

Table 2 Properties of CFRP sheet

Properties	FTS-C1-20
Tensile strength, kg/mm, kg/mm^2 (N/mm, Pa)	39,4355 (386, 3479)
Tensile modulus, kg/mm^2 (MPa)	23500 (0.23)
Elongation, %	1.5

2.2.3 Reinforcing Bars

The steel reinforcing bars used had a diameter of 16 mm (D16) and 10 mm (D10) were of Grade 40 (SD40) and 30 (SD30) correpsonding to a minimum yield strength of 4000 kg/cm^2 (392 MPa) and 3000 kg/cm^2 (294 MPa), respectively, with a tensile modulus of 2.04×10^6 kg/cm^2 (2.02×10^5 MPa). The actual yield strengths obtained from direct tension tests were 4324 kg/cm^2 (424 MPa) and 3150 kg/cm^2 (309 MPa) for D16 and D10 bars, respectively.

D16 and D10 bars were used for the tension and compression reinforcing steels, respectively. Also, D10 bars were used for the stirrups.

2.2.4 Preparation of Concrete Surface

For the preparation of concrete surface to be glued on, the disk grinding method was recommended by the system supplier. The concrete surface was ground enough to remove laitance and show the open texture of the aggregates. After grinding, the dust was removed by brushing and vacuum cleaning. The surface to be coated with the epoxy resin was even (level) without any roughness or formwork marks larger than 0.04 in. (1.0 mm).

2.2.5 Gluing CFRP Sheet

The CFRP sheets were cut to proper lengths using a sharp blade. The CFRP sheet or plate was wiped with a clean cloth before starting application in order to remove soiling as well as carbon dust. The adhesive components were mixed according to the technical data sheet provided by the system supplier. The primer and epoxy adhesive were applied using a roller similarly to the commercial specifications. The use of a hard roller was tried to press the CFRP sheet into the adhesive.

2.3 Data Acquisition and Test Procedure

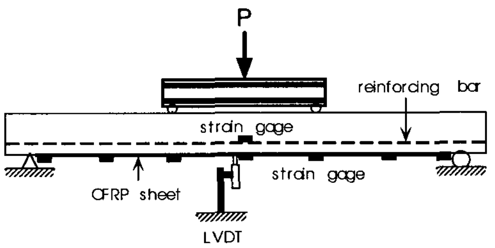

Fig. 2 Instrumentation layout

Fig. 2 shows the instrumentation layout for the tests. A computer-aided data acquisition system was used to measure load and deflection as well as strains of the steel reinforcing bars and CFRP sheet. Each test beam was loaded monotonically up to failure by hydraulic loading machine. The following data were obtained by the data acquisition system: (1) load from the loading machine, (2) deflection from the LVDT at mid span, (3) strains of the reinforcing bars at midspan, (4) strains of the CFRP sheet at the middle and both sides of span.

3. Analysis and Discussion of Test Results

Relevant test results are summarized in Table 3.

Table 3 Summary of test results

Beam I.D	CF0	CF1	CF2	CF3	CF4	CF6
No. of CFRP Sheets	0	1	2	3	4	6
Failure Mode*	T.F	I.S.F	I.S.F	I.S.F	I.S.F	I.S.F
Ultimate Load, ton (kN)	9.49 (93)	11.36 (111)	12.89 (126)	13.49 (132)	13.62 (133)	13.92 (136)
Ultimate Deflection, mm	27.4	15.5	13.5	12.7	12.0	12.0
CFRP Tensile Force,ton (kN)	-	3.55 (35)	5.93 (58)	6.86 (67)	7.06 (69)	7.53 (74)
Shear Stress of Conc., kg/cm^2 (MPa)	-	-	5.65 (0.55)	6.53 (0.64)	6.72 (0.66)	7.17 (0.70)

* T.F : Tensile Failure of CFRP sheets
I.S.F : Interfacial Shear Failure of concrete

3.1 Failure Mode and Behavior

In their failure modes, Beam CF1 was failed by the tensile failure of CFRP sheet and Beams CF2, CF3, CF4, and CF6 were failed by interfacial shear failure of the concrete (delamination) just above the epoxy adhesive. After the delamination, the concrete cover already cracked was ripped off. On the other hand, the reference beam, Beam CF0, was failed by compression failure of the concrete in the top flange long after yielding of the steel reinforcing bars, which is a typical failure mode in conventional under-reinforced concrete beams. The CFRP sheets in the strengthened beams inhibited the growth of large cracks which occurred in the reference beam by helping the distribution of small cracks with small crack spacing.

In Beam, CF1 failed by the tensile failure of CFRP sheet, the glued CFRP sheet was ruptured by strip (Fig. 3). In this failure mode, unlike the beams that failed by interfacial shear failure of concrete, there were no pieces of concrete cover spalled off from the beam. From these test results, it can be stated that the tensile failure of CFRP sheet is likely to occur when strengthening level is low. In Table 3, the tensile force calculated at failure of the CFRP sheets was found to be only about 60% of its failure stress in tension, implying that there was stress concentration and possible dowel action in crack faces.

Fig. 3 Tensile failure of CFRP sheet in Beam CF1

In other cases, interfacial shear failure of concrete is more likely to occur between the surface of concrete and the CFRP laminates.

In Beams CF2, CF3, CF4, and CF6 which failed by interfacial shear failure of concrete, the glued-on CFRP sheet was delaminated along the interface between concrete and CFRP sheet as shown in Fig. 4. The epoxy adhesive on the CFEP sheet tore out the concrete just above the interface. The delamination occured in the shear span and the concrete cover in the constant moment span was ripped off. When the delamination occurred on one side of the beam, the impact energy released from the tensioned CFRP sheet splitted off the concrete cover already cracked vertically by flexure along the longitudinal reinforcing bars in the constant bending moment zone (Fig. 4).

Strengthening with CFRP sheets inhibited the growth of the crack already developed before applying CFRP sheets.

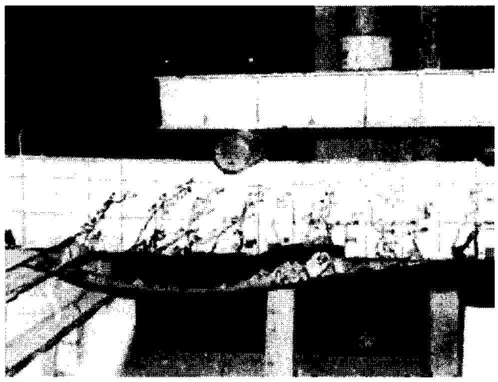

Fig. 4 Interfacial shear failure of concrete in Beam CF3

Fig. 5 compares the load-deflection curves of the reference beam with those of the strengthened beams with different strengthening level. As shown in the figure, the ultimate load considerably increased with an increase of strengthening level, while the ultimate deflection at CFRP sheet failure significantly decreased. The strengthened

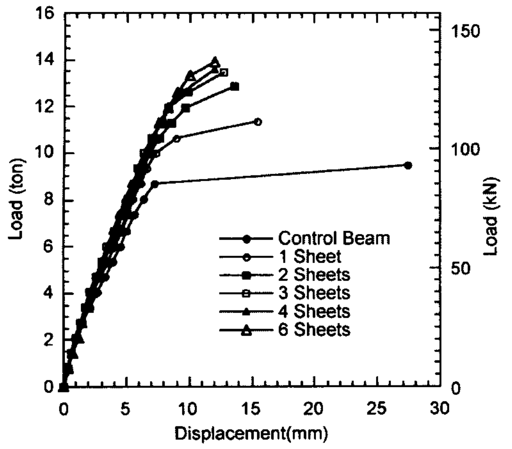

Fig. 5 Load-deflection curves

beams were stiffer than that of the reference beam before and after reinforcement yielding. Therefore, the deflections at service load was considerably reduced.

3.2 Influence of Strengthening Level

In the parametric study, several noteable findings were observed. As shown in Fig. 6, the ultimate load capacity curvilinearly increased with an increase of the strengthening level. The slope of the ultimate load-strengthening level curves, i.e., the strengthening effect, rapidly decreased with the strengthening level. This fact implies that the maximum strengthening effect can be achieved by gluing three or four of CFRP sheets. However, this conclusion should be further confirmed experimentally in beams with different steel reinforcement ratio and different concrete strength.

The ultimate deflection of strengthened beams curvilinearly decreased as the strengthening level increased (Fig. 7). This lower ductility is one of disadvantages of beams strengthened using CFRP sheet. However, the strengthened beams had, after failure or delamination of the CFRP sheets, a minimum loading capacity and ductility which were almost same as those of the reference beam, in spite of the fact that the concrete cover in the constant moment zone was severely damaged.

From Fig. 6, it is infered that the tensile force at failure of the CFRP sheets curvilinearly increased with the strengthening level. In the Table 3, the tensile force was

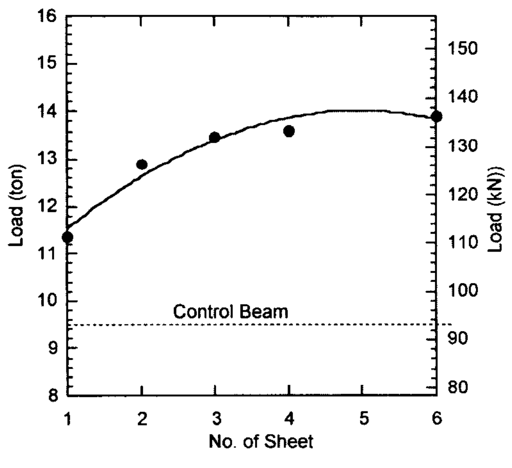

Fig. 6 Relationship between ultimate load and strengthening level

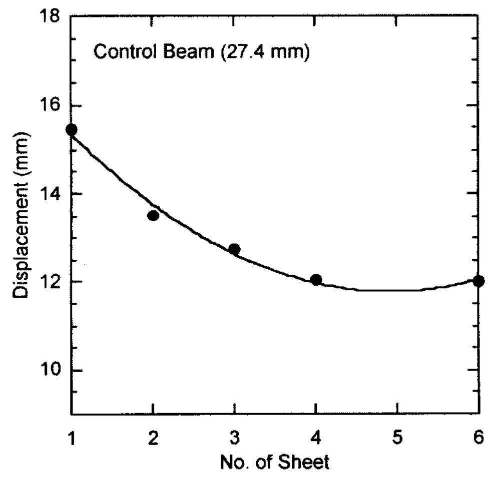

Fig. 7 Relationship between ultimate deflection and strengthening level

obtained from the following equation:

$$T = \frac{\Delta M}{(h - \frac{a}{2})} \qquad (1)$$

Where ΔM is the difference in moment capacity (observed experimentally) between the strengthened beam and the reference beam, taken as the average of the moments at yielding and failure, h is the total depth of the beam and a is the depth of compression block, assumed to be 0.2h.

It seems that the contribution of the shear resistance of concrete to the strength of the interface, curvilinearly increases with an increase of strengthening level (Fig. 8). The shear stress at the interface between the CFRP sheets and the concrete at delamination failure, was calculated from the tensile force, T, assuming horizontal shear stresses are equally distributed over the shear span. This leads to the following equation:

$$\tau_{ch} = \frac{T}{wL_a} \qquad (2)$$

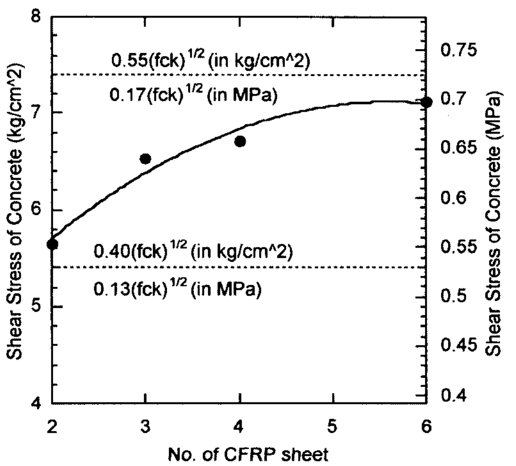

Fig. 8 Average shear stress of concrete at delamination failure

where, w is the width of the CFRP sheet or contact area, and L_a is the distance from the loading point to the end of the CFRP sheet.

As shown in Fig. 8, the average horizontal shear stress of concrete at the interface ranges between $0.40\sqrt{f_{ck}}$ and $0.55\sqrt{f_{ck}}$ (in kg/cm^2) depending on strengthening level. This resisting shear stress in low strength concrete is higher than that in high strength concrete proposed by Naaman and Park [(7)].

4. Conclusions

This investigation dealt with the strengthening effect of reinforced concrete rectanglular beams strengthened using glued-on carbon fiber reinforced plastic (CFRP) sheets. Based on the observation and analysis of the experimental test results the following conclusions can be drawn.

(1) The strengthening technique using externally bonded CFRP sheets or plates can significantly improve the ultimate loading capacity of reinforced concrete beams. The strengthening effect was curvilinearly proportional to the strengthening level. Therefore, the maximum strengthening effect can be achieved by gluing three or four of CFRP sheets in this test. However, However, this conclusion should be further confirmed experimentally in beams with different steel reinforcement ratio and different concrete strength.

(2) In general, normally strengthened beams were failed by interfacial shear failure (delamination) within the concrete, while, lightly strengthened beams were failed by

tensile failure of CFRP sheet.

(3) The strengthened beams are stiffer than the reference beam before and after reinforcement yielding. Therefore, the deflections at service load were considerably reduced.

(4) Strengthening with CFRP sheets can inhibit the growth of large cracks by helping distribution of many small cracks. However, these small cracks may reduce the bond strength of concrete.

(5) The ultimate deflection of strengthened beams rapidly decreased and seemed to approach to a constant value as the strengthening level increased.

(6) The average horizontal shear stress of concrete at the interface ranges between $0.40\sqrt{f_{ck}}$ and $0.55\sqrt{f_{ck}}$ depending strengthening level.

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