



## Structural Behavior of Reinforced Concrete Deep Beams Using Carbon Fibers

Byungwan Jo, Gyesam Lee and Youngjin Kim

*Hanyang University, Korea*

### ABSTRACT

Static load tests for reinforced concrete deep beams strengthened with carbon fiber sheets and plates were carried out to investigate the structural behavior and the strengthening effect of carbon fiber on the R/C deep beams. Test results show that the crushing of compression strut for the unstrengthened specimen is changed to the group of several diagonal cracks at mid-depth within the shear span of strengthened specimen.

Consequently, it is appropriate to strengthen the R/C deep beam with carbon fibers in perpendicular to the expected fracture mode, which obtained by the nonlinear structural analysis, which cause the improvement of ultimate fracture load.

### 1. INTRODUCTION

The repair and strengthening of structurally deteriorated reinforced concrete deep beams, which have a span to effective depth ratio( $l/d$ ) less than 5, are required to provide satisfactory resisting strength and serviceability.

Deficiencies are usually the result of deterioration caused by service age and exposure to adverse environments, unexpected design load brought about by a growing society.

As a result, different repair and strengthening techniques have been successfully developed to strengthen a deteriorated structure. Historically, reinforced concrete members have been repaired by additional beams, external post tensioning.

In recent years, with the development of strong structural adhesion, epoxy bonded steel plates have been extensively used to strengthen concrete structures. The first recorded case was in Durban, South Africa, in 1964, to strengthen concrete beams in an apartment complex<sup>(1)</sup>. However, as a result of corrosion problems in steel plates, the applications of flexible carbon fiber sheets, wrapped around the sides and bottom face of concrete members are emerging technology to increase their shear and flexural strength. These fiber sheets, with a high strength-to-weight ratio, make it particularly suited to reinforcing material for concrete structures. Many researchers have studied fiber sheets on the general slender concrete beams<sup>(2)</sup>.

However, relatively few studies have been conducted on the concrete deep beams, which shows compression strut failure connecting between a loading point and supports, rather than flexural failure of a slender beam. Major concern of this paper was placed on the strengthening effect of fiber sheets and plates wrapped on the concrete deep beams.

## 2. STRUCTURAL BEHAVIOR OF REINFORCED CONCRETE DEEP BEAM

The major concern of deep beams is placed on the shear capacity, which would usually fail in shear at the ultimate limit state. Shear failures in deep beams are not the same as shear failures in the regular slender concrete beams with the inclined shear cracks at a distance of approximately  $d$ (effective depth of beam) from the support points.

A large part of the applied load in a deep beam would be transferred to the supports directly through the compression struts formed straight between load point and support points. Struts are formed straightly between load point and support points. A simple strut-and-tie analogy<sup>(1)-(2)</sup> for this mechanism is shown in Fig. 1.

In these cases, the longitudinal steel reinforcement can normally be considered as part of the main tension tie. From these strut-and-tie analogies, it can be seen that failures in deep beams may occur in the following modes. 1) crushing of the concrete in the nodal zone below a load point or above a support point; 2) yielding of the main longitudinal reinforcement that leads to flexural failure; 3) crushing of a concrete compression strut; 4) diagonal splitting failure along a compression strut.

With good design and detailing practice, the first two failure modes are likely to occur. The third and fourth failure modes are our major concerns to be strengthened with carbon fiber sheets and plates.

## 3. TEST SPECIMENS

A total of eight reinforced concrete deep beams were cast, with the main steel reinforcement 4-D25 to prevent bending failure. This flexural steel ratio was close to the maximum steel ratio( $0.75 P_b$ ) allowed under the current ACI code (318-95).

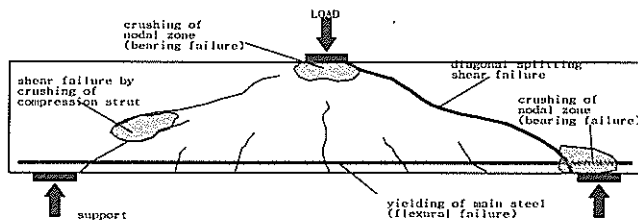
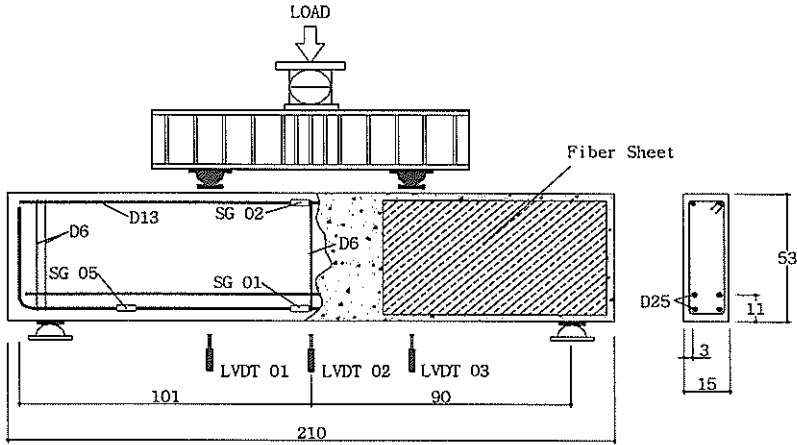


Fig. 1. Strut-and-tie analogy



**Fig. 2. Dimensions and test setup of an unstrengthened deep beam**

Stirrups 3-D6 to hold the compression steel reinforcements in position and to stimulate the shear failure were used. Beam sketch, dimensions 15cm × 53cm × 210cm (W×H×L) and test setup were shown in Fig. 2.

Material properties of concrete and steel are given in the Table 1.

A total of three reinforced concrete deep beams without a carbon-fiber strengthening were cast. Pilot tests were conducted to investigate the structural behavior of unstrengthened deep beam, such as an initial cracking load, failure load and crack patterns.

Strengthened deep beams with carbon fiber sheets and plates which are placed in a resin matrix are used in the aerospace and automotive fields because of their high strength to weight ratio, durability, and ability to form complex shapes. Carbon fibers have a high elastic modulus and high strength in tension, material properties of carbon fiber sheets, plates and epoxy were given in Table 2.

Strengthened specimens were made from carbon fiber sheets and plates in a resin matrix wrapped around the web and tension flange of R/C deep beam (pilot specimen) to increase their flexural and shear strengths.

**Table 1. Material properties**

Concrete	Compressive strength	240 $kg/cm^2$
	Max. Aggregate size	20 $mm$
	Slump	13 $cm$
Steel	Reinforcement yield stress	3000 $kg/cm^2$
	Young's modulus	$2.1 \times 10^6$ $kg/cm^2$

**Table 2. Material properties of carbon fiber and epoxy**

Material	Property	
Carbon Fiber Sheet	Tensile Strength ( $kg/cm^2$ )	46,000
	Weight ( $g/m^2$ )	300
	Specific Gravity	1.82
	Ultimate Elongation (%)	1.5
	Thickness ( $mm$ )	1.2
Carbon Fiber Plate	Width ( $mm$ )	50
	Thickness ( $mm$ )	1.2
	Cross sectional area ( $mm^2$ )	60
	Modulus of Elasticity ( $N/mm^2$ )	155,000
Epoxy	Tensile Strength ( $MPa$ )	552
	Ultimate Elongation (%)	2
	Modulus of Elasticity ( $MPa$ )	27,800

This study initially tried to isolate three sets of variables:

The effect of two different carbon fibers (sheets and plates)/epoxy systems, and three different fiber orientations (vertical, horizontal, and inclined), and two different anchorages (fiber anchor and bolt anchor).

Each beam was designated in a way to reflect the experimental variables involved in that beam. C and S denote carbon fiber sheets and plate, V, H, and I refer to vertical, horizontal, and inclined fiber orientations respectively. Ac and B denote fiber anchor and bolt anchor to avoid debonding failure of carbon fibers on the concrete faces.

Table 3. summarizes names of all test specimens based on experimental variables.

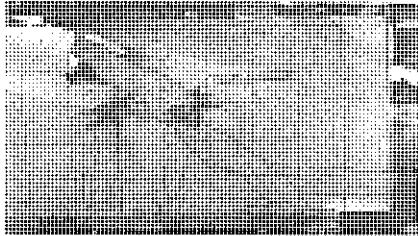
**Table 3. specimen names and experimental variables**

Specimen	Fiber Type	Fiber Orientation	Anchorage
C-V2-W	Sheets	Vertical	-
C-H2-Ac		Horizontal	Fiber anchor
C-I2-W		Inclined	-
S-I2-B	Plates	Inclined	Bolt anchor
S-I2-S		Inclined	-

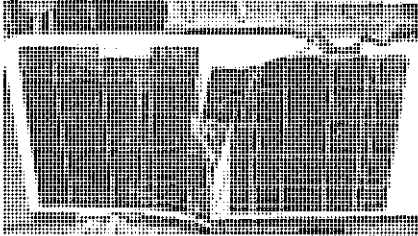
11 specimens were tested to failure as simply supported beams under two symmetrical point loads with a total span of 1800mm and a ratio of shear span to depth 1.25. The beams were loaded at a rate of 1mm/min and in increments of 1 ton. Midspan deflection and deflections under the point loads were recorded at each load increment using linear variable displacement transducers (LVDTs). To determine levels of strain for concrete, reinforcing steel, and fiber sheets, eight (2, 3, 3 respectively) strain gauges were installed as shown in Fig. 2.

#### 4. TEST RESULT

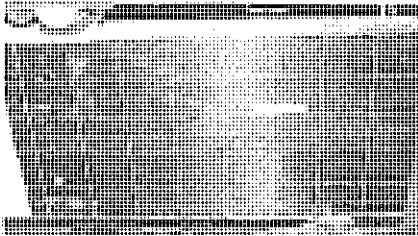
For pilot specimen, as the load increased, an initial crack, which occurred at the mid-depth web, propagated to connect load points and supports, which was called "compression strut", rather than the diagonal shear cracks at the slender beams as shown in Fig. 3.



(a) Pilot



(b) C-V2-W



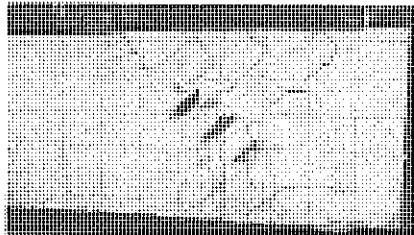
(c) C-H2-Ac



(d) C-I2-W



(e) S-I2-B



(f) S-I2-S

Fig. 3. Failure aspect of specimens

The load versus central deflection at mid-span was shown in Fig. 4, compared to that of finite element analysis. The sudden change in the slope of the curves showed the point at which the initial crack occurred.

Test results show that an initial crack occurs at a load 26~32 ton, equivalent to about 55~60 percent of the failure load 49 ton. Table 4. also showed the range of improvement provided by the carbon fiber strengthening. All beams exhibited similar range of initial cracking load (about 29 ton) regardless of strengthening variables. However, the strengthened beam showed greater ultimate (fracture) strength than the pilot beam, estimated 40% of strengthening effects before the beam abruptly failed. This was due to the peeling of the carbon fibers form the concrete.

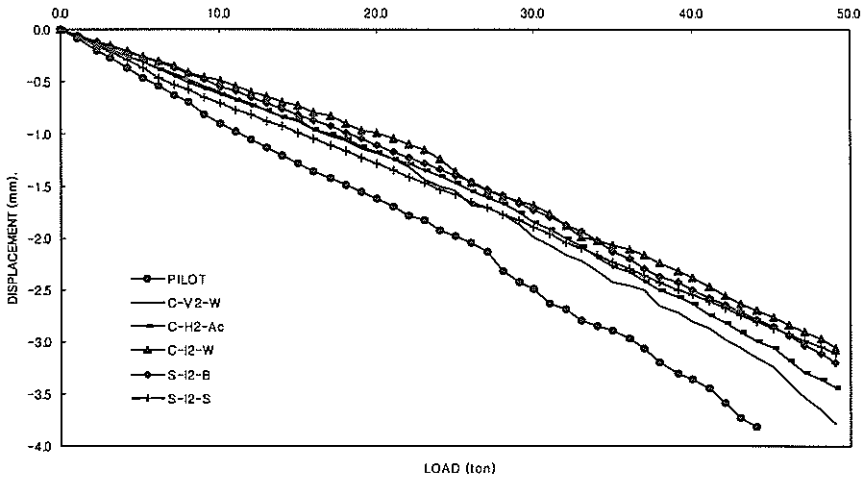


Fig. 4. load-deflection curves

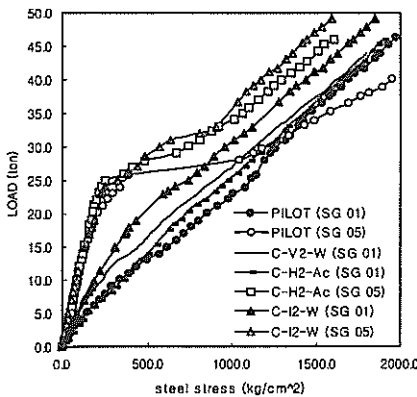


Fig. 5. load-steel stress curves  
(carbon fiber sheets)

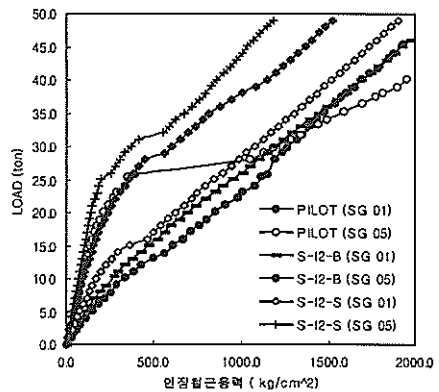


Fig. 6. load-steel stress curves  
(carbon fiber plates)

**Table 4. Strengthening Effect**

Specimens	$P_{cr}$ (ton)	$P_{max}$ (ton)	Strengthening Effect (%)
Pilot	26	49	-
C-V2-W	27	50.10	0.04
C-H2-Ac	26	53.16	6.53
C-I2-W	32	72.11	44.51
S-I2-B	29	62.17	24.59
S-I2-S	32	74.25	44.80

For specimen S-I2-S, the initial cracks occurred between carbon fiber plates and the at the plate end, propagated to loading points, and peeled to failure.

For specimen S-I2-B, the fatal crack propagated in three dimensions tearing a diagonal piece out of the web in the region of constant shear between the load and the support. It was due to the anchorage failure of inclined, short fiber plates with anchor bolts at the ends, compared to those of S-I2-S. Consequently, it is not necessary to provide additional anchor bolts on the strengthened beam with the carbon fiber plates, if not satisfactory anchorage system. For C-V2-W beam, vertical fiber orientation had showed less resistance to failure and more brittle fracture those of horizontal fiber orientation failure properties of each beam were given in Fig. 5.

## 5. CONCLUSIONS

Based on the experimental investigation, following conclusions can be made.

1. There was little difference in the initial cracking load between the various forms of carbon fibers used. The rigidity until the crack occurs was approximately same in each specimen, however, after the crack occurrence, there was a difference in the ultimate failure load. The most significant differences in behavior of reinforced concrete deep beams strengthened with carbon fibers were mainly due to various fiber orientations, anchorage and web coverages.
2. Diagonal "compression-strut" crack of unstrengthened pilot beams was changed to the group of several diagonal cracks at mid-depth within the shear span of strengthened specimen and exhibited more ductile failure mode with increased stiffness in the webs and tension face.
3. The inclined fiber orientations perpendicular to the expected compression- strut crack showed a smaller increase in strength and stiffness, the mode of failure was more ductile and preceded by warning signs such as snapping or peeling sound.
4. The specimen strengthened with additional anchor bolts showed better performance. Since carbon fibers were well anchored at the side and bottom, so that no peeling-off occurred.

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