論文 Experimertal Study on Shear Strength of Reinforced Concrete Beams Strengthened with Continuous Carbon Fiber Sheet

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ABSTRACT: Based on the test of eleven simply supported beams, this paper evaluates the shear strength of reinforced concrete beams strengthened by continuous carbon fiber sheet (CFS). The main experimental factors are width and spacing of CFS strips, and number of layers of CFS etc.. The experimental results indicate that CFS can obviously increase the shear strength of these specimens. Based on the test, a simplified design formula is proposed in this paper.
KEYWORDS: carbon fiber sheet, shear strength, strengthening

1. INTRODUCTION

Physical aging, chemical corrosion, unreasonable design and construction will result in the repair or reinforcement of the reinforced concrete structures. Compared with the existing methods, strengthening of the structures by continuous carbon fiber sheet (CFS) has many advantages of excellent mechanical strength and deformation property, convenience to use, low weight, non-dimensional increase, and immunity to corrosion. The CFS-strengthening technique has attracted many researchers and engineers today in the world.

Based on the test of eleven simply supported beams, this paper evaluates the shear strength of reinforced concrete beams strengthened by continuous CFS.

2. EXPERIMENTAL INVESTIGATION

Eleven specimens were divided into two groups. All the beams were rectangular cross-section with the dimensions of 150mm×250mm. The span of the specimens was 2200mm, and the clear span was 2000mm. The diameter and spacing of the stirrups in Group I were 4mm and 150mm, and those in Group II were 6mm and 240mm. The ratio of stirrup in these two groups were 0.112% and 0.158%, respectively.

The control specimens of this test were BVI-1, BVII-1 and BVII-5, which were not strengthened by CFS. The strengthening conditions of other beams are given in Table 1. Fig. 1 shows the details of the longitudinal and transverse reinforcements, geometric dimensions used in the construction of the specimens. The mechanical properties of concrete, reinforcement, CFS and epoxy are listed in Table 2, Table 3, Table 4 and Table 5, respectively.

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Table 1 Strengthening condition of specimens

Group	No.	Strengthening condition		
		Layers of CFS	Width of CFS strips A (mm)	Spacing of CFS strips B (mm)
I	BVI-1	-	-	-
	BVI-2	1	30	120
	BVI-3	1	30	100
	BVI-4	2	30	100
	BVI-5	1	30	80
II	BVII-1	-	-	-
	BVII-2	1	30	100
	BVII-3	2	30	120
	BVII-4	1	30	60
	BVII-5	-	-	-
	BVII-6	1	50	100

Table 2 Mechanical properties of concrete

Group	Cubic compressive strength f_{cu} (MPa)	Axial compressive strength f_c (MPa)	Modulus of elasticity E_c (MPa)
I	25.5	20.5	2.88×10^4
II	17.5	14.2	3.18×10^4

Table 3 Mechanical properties of reinforcement

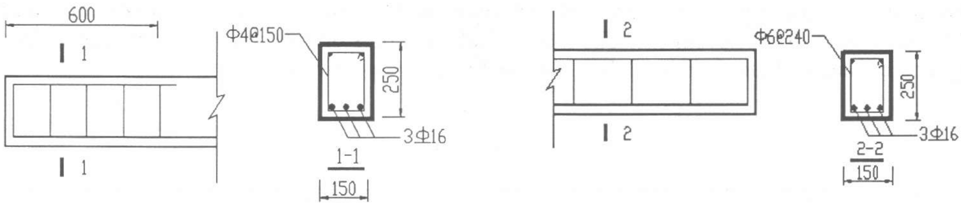
Type	Nominal yield strength f_y (f_{yv}) (MPa)	Ultimate strength f_u (MPa)	Modulus of elasticity E_s (MPa)
Φ6	410.6	557.9	1.974×10^5
Φ8	368.3	481.8	1.938×10^5
Φ10	242.2	356.7	2.04×10^5

Table 4 Mechanical properties of CFS

Calculating thickness (mm)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Density (g/cm^3)
0.121	1800	2.2×10^5	1.76

Table 5 Mechanical properties of epoxy

Compressive strength (MPa)	Tensile strength (MPa)	Shear strength (MPa)	Modulus of elasticity (MPa)
50～60	15～18	20	(5～6)$\times10^3$



Group I **Group II**

Fig. 1 Dimensions and reinforcement of the specimens

Before the test, all sides in the shear span area of the specimens were sanded to obtain a rough surface, and then the surface was cleaned. A coat of epoxy consisting of thoroughly mixed resin and hardener was applied. The CFS, previously cut to the required dimensions, was positioned on the prepared surface, and a resin coat was applied. Using a thin and soft plastic plate, the CFS was gently pressed along the fiber direction to remove any air bubbles. A similar procedure was repeated while wrapping additional layers. After the CFS was bonded, seven-day resin curing was needed.

The loading condition of this experiment is illustrated in Fig.2.

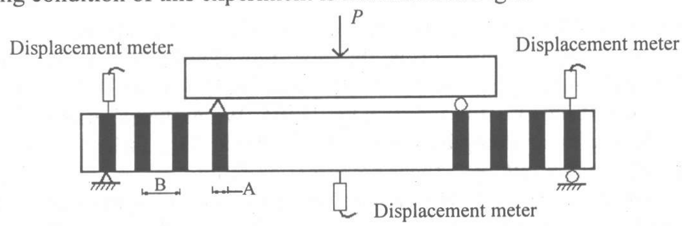


Fig. 2 Loading condition

3. TEST RESULTS AND DISCUSSION

3.1 SHEAR STRENGTH

Table 6 Experimental results

No.	Shear/span ratio λ	Ratio of stirrup ρ_{sv}	Cracking load (kN)	Shear capacity (kN)	Increase*
BVI-1	2.27	0.112%	90	150	-
BVI-2	2.27	0.112%	100	175	16.7%
BVI-3	2.27	0.112%	100	180	20.0%
BVI-4	2.27	0.112%	100	190	26.7%
BVI-5	2.27	0.112%	110	185	23.3%
BVII-1	2.27	0.158%	70	135	-
BVII-2	2.27	0.158%	80	150	11.1%
BVII-3	2.27	0.158%	80	160	17.0%
BVII-4	2.27	0.158%	90	170	25.9%
BVII-5	3.64	0.158%	80	90	-
BVII-6	3.64	0.158%	90	125	38.9%

*: It is compared to control beams BVI-1, BVII-1 and BVII-5, respectively.

As shown in Table 6, wrapping CFS strips increased the shear strength, including cracking load and ultimate shear capacity, of reinforced concrete beams. The increase effect of wrapping CFS strips was more remarkable after diagonal cracks appeared. It indicated that CFS strips could directly work as tensile rods to increase the shear strength. Based on the data analyzing, some regularities are found as follows:

(1) The strengthening effect of CFS on shear strength of specimens is better if the spacing of CFS strips decreases. For example, the shear strength of specimens BVI-2, BVI-3 and BVI-5, with CFS strip spacing of 120mm, 100mm and 80mm, increased by 16.7%, 20.0% and 23.3%, respectively. And in Group II, decreasing of the spacing from 100mm (BVII-2) to 60mm (BVII-4) resulted in increasing of the shear strength from 11.1% to 25.9%.

(2) The strengthening effect is more remarkable with the increase of CFS strips layers. Both beam BVI-3 and beam BVI-4 had similar strengthening conditions that the width of CFS strips was 30mm and spacing of the strips was 100mm. The shear strength of BVI-3, strengthened by one layer of CFS strips, was 180kN, while that of BVI-4, strengthened by two layers of CFS strips, slightly increased to 190kN. In Group II, BVII-5, strengthened by two layers of CFS strips with

spacing of 120mm, had the shear capacity of 160kN, which was greater than that of BVII-2 strengthened by one layer of CFS strip with spacing of 100mm.

In the process of analyzing the experimental data, it was found that the strengthened beam with CFS of smaller spacing was better than that of CFS strips with more layers when the quantity of CFS kept constant. For the specimens strengthened by one layer of CFS, the failure mode was that CFS strips ruptured in the position along the diagonal cracks. And when the specimens were strengthened by two layers of CFS, the failure mode was that CFS strips peeled off from concrete. The strain of CFS in the second failure mode was from 5000 μ to 6000 μ, smaller than that in the first failure mode. So the CFS in second failure mode could not work adequately.

(3) The greater the span/depth ratio is, the more remarkable the strengthening effect is. This regularity could be approved by specimens BVII-4 and BVII-6. For BVII-4, the shear/span ratio was 2.27 and the shear strength could increase by 25.9%. When the experimental factor of BVII-6 was changed to 3.64, the shear strength increased by 38.9% and the failure mode was also changed from brittle diagonal- tension failure to shear-compression failure.

(4) The strengthening effect is more remarkable when the strength of concrete is higher. The strengthening conditions of specimens as BVI-3 and BVII-2 are the same. The failure of BVII-2, with the axial compressive concrete strength of 14.2MPa, began with the shear failure of concrete at the fabric-concrete interface and the CFS strain was still small (about 6500 μ). In this case, the CFS of BVII-2 did not work adequately. As a contrast, concrete strength of BVI-3 was 20.5MPa, leading to CFS rupture with the stain of CFS was greater than 9000 μ .

3.2 LOAD-DEFLECTION CURVES

The load-deflection curves are illustrated in Fig. 3. It can be seen that wrapping a beam with CFS strips results in an increase in stiffness and deformation capability of the beam. The increased effect will be more obvious when the shear/span ratio is increased or the ratio of stirrup is decreased. Based on the research results of others, we think there are two reasons. One is that the increase could be contributed to direct effect of CFS strips on stiffness. On the other hand, the use of CFS strips could limit the development of diagonal cracks, which indirectly increases the stiffness of the beam.

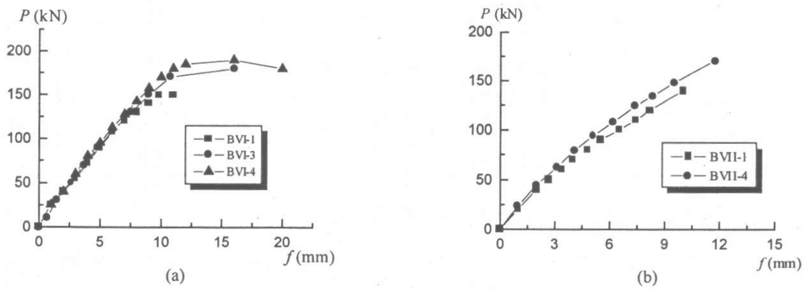


Fig. 3 Load-deflection curves

3.3 STRAIN OF CFS AND STIRRUP

Fig. 4 illustrates the strain development of CFS and stirrup in the strengthened beam BVII-2, and the positions of the strain gages are shown in Fig. 5 respectively.

As shown in Fig. 4, CFS strains were greater than strains of the stirrup. This trend was observed for the entire load range. In the pre-cracking stage, slightly lower strains in stirrup than in CFS were observed and the strain difference would be remarkable after diagonal cracking.

4. DESIGN METHOD

As other researches shown, this paper also thinks that the CFS contribution to shear strength

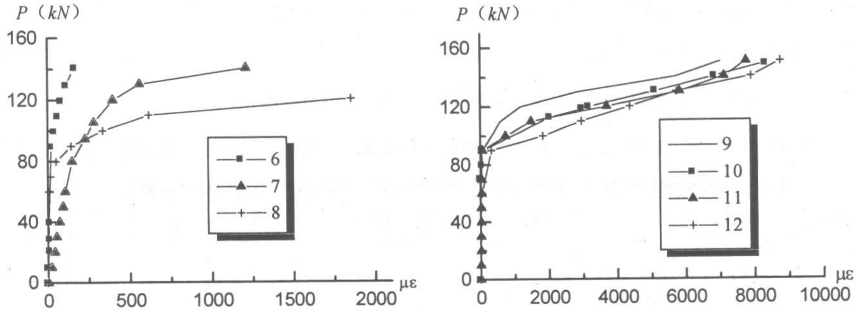


Fig. 4 Strain development of CFS and stirrup in BVII-2

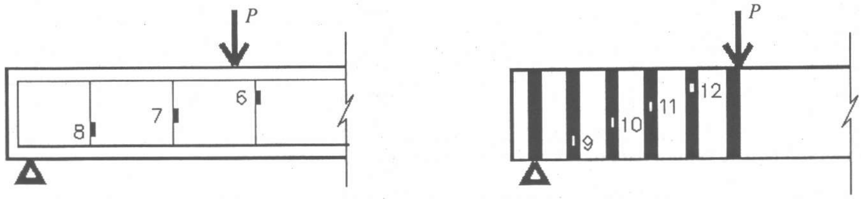


Fig. 5 Positions of electric strain gages

is in analogy with steel stirrups, assumes a limiting CFS strain. The National Code for Design of Concrete Structures of China takes the following equation as shear strength design formula.

$$V \leqslant V_{cs} \tag{1}$$

where

V ——shear force at section;

V_{cs}——shear strength contribution from concrete and stirrup;

$$V_{cs} = 0.07 f_c b h_o + 1.5 f_{yv} \rho_{sv} b h_o \tag{2}$$

According to the experiment and the design formula provided by China code, the design method of shear strength of beams strengthened with continuous CFS is proposed as follows:

$$V = V_{cs} + V_{cfs} = 0.07 f_c b h_o + 1.5 f_{yv} \rho_{sv} b h_o + \alpha_{cfs} \beta f_{cfs} \frac{A_{cfs}}{s_{cfs}} h_o \tag{3}$$

where

V_{cfs} ——shear force carried by CFS, which indicates the composite effect of CFS on the shear strength of the beam;

α_{cfs} ——coefficient of CFS for shear reinforcement, which has the relationship with strength of concrete, shear span/depth ratio and the quality of wrapping CFS. It is provisionally taken as 0.7 in this paper.

f_{cfs} ——tensile strength of CFS strips;

β ——reduction coefficient for tensile strength of CFS strips. In this paper it takes as 2/3 or 1/2, in the case of wrapping one layer or two layers of CFS, respectively.

A_{cfs} ——total area of CFS strips in the same section of the beam;

s_{cfs} ——spacing of CFS strips;

b, h_o ——width and effective height of cross-section of the beam;

The comparison of calculating results with Eq.3 and experimental data is list in Table 7.

Table 7 Comparison of calculating results and experimental data*

No.	V_{cs} (kN)	V_{cfs} (kN)	V_{cal} (kN)	V_{test} (kN)	V_{test}/V_{cal}
BVI-1	59.35	0	59.26	75	1.27
BVI-2	59.35	11.18	70.44	87.5	1.24
BVI-3	59.35	13.42	72.68	90	1.24
BVI-4	59.35	20.13	79.39	95	1.20
BVI-5	59.35	16.77	76.03	92.5	1.22
BVII-1	51.68	0	51.68	67.5	1.31
BVII-2	51.68	13.42	65.10	75	1.15
BVII-3	51.68	16.77	68.45	80	1.17
BVII-4	51.68	22.36	74.04	85	1.15

*: The diagonal tensile failure data of BVII-5 and BVII-6 are excepted.

The average value, standard deviation and coefficient of variation of the ratio of experimental data and calculating results are 1.22, 0.05 and 0.05, respectively. These values are close to the calculating indexes of China code, which indicates that the design method proposed in this paper can meet the engineering requirements. However, because of the insufficient experimental data, two coefficients, α_{cfs} and β, in Eq.3 are provisionally taken as constant according to the experiment. So, it should carry out further researches on how to reasonably determine the two coefficients.

5. CONCLUSIONS

Based on test and theoretical analyses, the paper obtained the following conclusions:

(1) Strengthening with continuous CFS can obviously increase the diagonal cracking strength and the ultimate shear strength of reinforced concrete beams. The CFS-strengthening technique is useful.

(2) The CFS contribution to shear strength is in analogy with steel stirrups. The strengthening effect will be better with the width of CFS strips being wider, the spacing of CFS strips being smaller or the wrapping layers of CFS being more. Moreover, when the quantity of CFS keeps constant, the strengthening program, with the spacing of strips being smaller, is better.

(3) Strengthening a reinforced concrete beam with CFS strips can increase the stiffness of it.

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