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Steel–CFRP Composite (CFRP Laminate Sandwiched between Mild Steel Strips) and It's Behavior as Stirrup in Beams

Faris Abbas Jawad Uriayer, and Mehtab Alam

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Abstract**—**In this present study, experimental work was conducted to study the effectiveness of newly innovated steel-CFRP composite (CFRP laminates sandwiched between two steel strips) as stirrups. A total numbers of eight concrete beams were tested under four point loads. Each beam measured 1600 mm long, 160mm width and 240 mm depth. The beams were reinforced with different shear reinforcements; one without stirrups, one with steel stirrups and six with different types and numbers of steel-CRFR stirrups. Test results indicated that the steel-CFRP stirrups had enhanced the shear strength capacity of beams. Moreover, the tests revealed that steel-CFRP stirrups reached to their ultimate tensile strength unlike FRP stirrups which rupture at much lower level than their ultimate strength as werereported in various researches.

Keywords**—**Steel-CFRP Composite, Stirrups, Concrete Beams, Shear Span.

I. INTRODUCTION

DIFFERENT types of FRP bars are available for main flexural reinforcements. Along with these longitudinal reinforcements, FRP rod stirrups in the shape of U, closed, and T types are also used depending on their specific application in different beam geometry and section types [6], [9].Various test results indicated that FRP stirrups can resist only about 30%–80% of their tensile strength whose reduction rate was largely dependent on the types of FRP bars and on the ratio of radius of bend to stirrup diameter [1]-[5], [7]. In this research, innovative steel-CFRP stirrups were developed and their applicability and effectiveness in resisting shear force were experimentally observed. Test results indicated that the steel-CFRP stirrups enhanced the shear strengthcapacity of beams.Moreover, the tests revealed that steel-CFRP stirrups reached to their ultimate tensile strength unlike FRP stirrups which ruptures at much lower level than their ultimate strength aswere reported in various researches.

II. EXPERIMENTAL PROCEDURE

Three materials were used to prepare the stirrups. They are as follows:

1. CFRP (SikaWrap®-300C); Woven carbon fibre fabric.
2. Adhesive (Sikadur®-330); 2-part epoxy impregnation resin.
3. Steel strips.

The mechanical properties of these materials as reported by manufacturer are listed in Table I.

III. BEAMS AND STIRRUPS

Two types of stirrups were manufactured (handmade):

A. U-Shaped

Two steel strips were cut and bent to the required shape of a stirrup. According to the instructions of manufacturer, CFRP layers were pasted on outer face of one of the two. By using parallel clamps, the second one was glued tightly to the first one, Fig. 1 (a). Two types of U-shaped stirrups were prepared, one with two layers of CFRP and the second with five layers of CFRP.

B. D-Shaped

The same procedure was used to prepare two identical C-shaped parts to make a D-shaped stirrup. Two layers of CFRP were sandwiched for each part. The two parts were assembled by overlapping them at the top and bottom sides. Steel wire was used to tie each other tightly, Fig. 1 (b). A total of 8 beams were cast, Fig. 2 shows type and number of stirrups used in the shear spans of these beams. The first character in the identification of a beam refers to the type of stirrup material (N: no stirrups, S: steel stirrups and C: composite stirrups), the next subscript numeral to either the width of composite stirrup or the diameter of steel stirrup,

(a) (b)

Fig. 1 Types of stirrups

Faris Abbas Jawad Uriayer is Research Scholar at the Department of Civil Engineering, Jamia Millia Islamia, New Delhi, India (e-mail:faj_1964@yahoo.com).

Mehtab Alam, Professor, is with Department of Civil Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi, India.

International Science Index, Civil and Environmental Engineering Vol:7, No:1, 2013 waset.org/Publication/1559

TABLE I
PROPERTIES OF MATERIAL

Material	SikaWrap®-300C	Sikadur®-330	Steel strip
Tensile strength (MPa)	3900	30	388
Tensile E-modulus(MPa)	230000	4500	150000
Elongation at break	1.5%	0.9%	30%
Thickness (mm)	0.166	-	1.5

the following character to the shape of stirrup U or D as illustrated in Fig. 1, the next digit for the number of CFRP layers used and the last digit for the number of stirrups used in shear span. All beams have cross-sectional dimensions 160mmx240mm, length of 1600mm and distance between roller supports of 1400mm Fig. 3. Three different types of steel-CFRP stirrups were considered (two types of U-shaped stirrups, width of each was 10mm and one type of D-shaped with width of 16 mm).

IV. MATERIAL PROPERTIES (BEAMS)

The average 28 day compressive strength from three cylindrical specimens of 150mm diameter and 300mm height was 31MPa. Five deformed steel bars were used aslongitudinal reinforcement on tension face in two layers, three bars of diameter 16mm in lower layer and two bars ofdiameter 10mm in upper layer. Effective depth was 184mm. Three deformed steel bar, two with diameter of 16mm and one with diameter of 12mm were used as top bars in the same layer for holding stirrups. The beam was designed to ensure that the shear failure of beams would happen first. Yield strength for all deformed flexure bars was 550MPa.

V. LOADING AND MEASUREMENTS

Fig. 3 shows the loading arrangement for four-point loading system. All specimens were loaded by a testing machine with the capacity of 300kN under static load. The tests were conducted on beam specimens at displacement control rate of 2 mm per minute. Vertical deflections at the mid span were measured by linear variable differential transducer.

Fig. 2 Configuration and names of beams

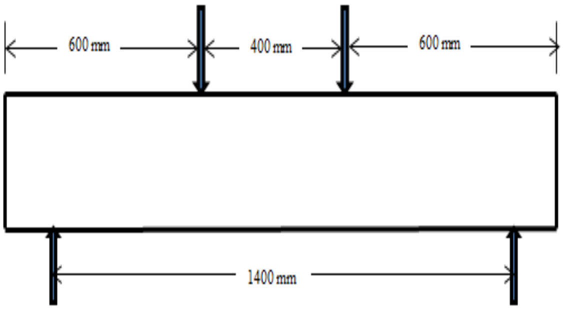

Fig. 3 Arrangement of loading system

VI. LOAD-DEFLECTION CURVES AND FAILURE MODES

Fig. 4 shows load deflections curves of all beams tested in this experiment. For all specimens, flexural crack occurred first near the mid span, followed by the shear cracks, one of which further widened and grew to a major diagonal crack, leading to an abrupt shear failure of the beam. The abrupt failure was accompanied with a sudden widening of the width of major diagonal crack. It is clear that the widening in the width of diagonal crack refer to the rapture of CFRP laminates of shear stirrups. After the rupture of CFRP laminate, only steel component of the stirrup(s) carried the shearing load. Having raptured of CFRP, the deflection continued and this steel strained reaching to the necking phenomenon and finally ruptured, Fig. 5. It could be seen from Fig. 4 that there was a resemblance in the behavior of all beams including the beam reinforced with steel stirrups till the peak load that caused the shear failure.After reaching to the ultimate load, curves declined abruptly for all beams reinforced with steel-CFRP stirrups due to the rupture of CFRP laminate, while for beams reinforced with steel stirrups the load descended gradually

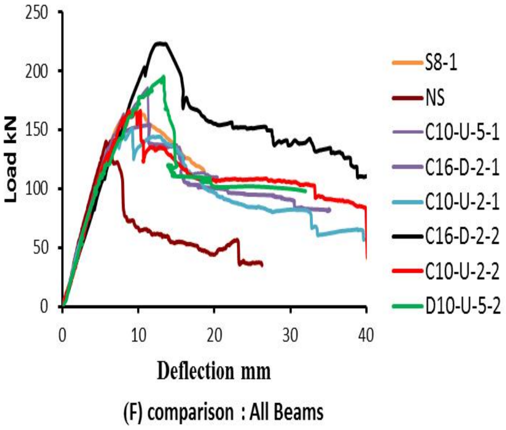

Fig. 4 Load Deflection curves

International Science Index, Civil and Environmental Engineering Vol:7, No:1, 2013 waset.org/Publication/1559

Fig. 5the necking phenomenon of steel strips

VII. Beams Strength

It can be seen from Fig. 4 that all beams transversely reinforced with stirrups exhibited higher strengths than the NS beam. The strength values ranged between 1.07-1.59 times the strength of NS, Table II. Compared to strength of S_8-1, the strength values for beamswere 0.9, 0.98 and 1.10 times of strength value of S_8-1 for beams C_{10}-U-2-1, C_{16}-D-2-1 and C_{10}-U-5-1 respectively, while they were 0.98, 1.10 and 1.32 times of strength ofS_8-1 for C_{10}-U-2-2, C_{16}-D-2-2 and C_{10}-U-5-2 respectively,

VIII. Ultimate Stresses and Efficiency Factor

A. Ultimate Stresses of Stirrups

Table III shows experimental and theoretical strength values of stirrups. The stirrup stress at failure was determined based on the difference between the measured shear force at failure, and the shear force contributed by the concrete as measured at the initiation of the first shear crack [4]. To calculate theoretical strength values of stirrups, ultimate tensile load of stirrups $(A_s f_y)$ was calculated according to modified formula presented by [8].

$$\mathrm{P_{ult.}} = (\mathrm{f_y} \cdot \mathrm{A_S} + \textstyle\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{A_{CFRP,i}} \cdot \mathrm{E_{CFRP}} \frac{\varepsilon_{\mathrm{u \cdot CFRP}}}{\sqrt{\mathrm{i}}}) \tag{1}$$

where f_y and A_S =yield stress and cross section area of steel strips: $A_{CFRP,i}$, E_{CFRP}, $\varepsilon_{u \cdot CFRP}$ = cross section area of one layer of CFRP, modulus of elasticity and ultimate strain of CFRP respectively while$i$ represents number of layer of CFRP used. From Table III, good convergences could be seen between experimental and theoretical values of ultimate tensile stress of stirrups.

B. Efficiency Factor

Effectiveness of single steel-CFRP stirrup in shear span of beams, was estimated by the efficiency factor $(\emptyset_E)$ used by [5].

$$\emptyset_E = \frac{V_S}{V_{S.S06}} X \frac{(A_S . f_y)_{S06}}{A_v . f_{fu}} \tag{2}$$

where, *Vs*, *S06* and *Vs*=experimentally measured shear forces carried by steel stirrups of 6 mm diameter and by other stirrups, respectively. $(A_s . f_y)_{s06}$=yield strength of steel stirrup of 6.0 mm diameter; and $A_v . f_{fu}$= ultimate tensile strength of steel-CFRP stirrup. In this present study the diameter of steel stirrups was 8 mm. The efficiency factor represents the relative effectiveness of the stirrups in resisting shear compared to that of the steel stirrup with 8.0 mm diameter. If the value of $\emptyset_E$ is equal to 1.0, then the steel-CFRP stirrups might be regarded as effective as steel stirrups in using its material strength.

From Table IV, the efficiency factor for three beams reinforced with one of steel-CFRP stirrup in shear span is higher than one ranging between (1.0 -1.34).

The results indicated that the newly innovated steel-CFRP stirrups enhanced the shear strength of beams after reaching to their capacity without any reduction value, Table III and Table IV.

TABLE II
DETAILS OF STIRRUPS USED TO REINFORCE BEAMS

Name of beams	Max. Load kN	Max. Load /140	Max. Load /168	Displ. at Max. Load mm	Beam Shear Capacity kN
NS	140	1.00	-		70
S_8-1	168	1.20	1.00	9.54	84.00
C_{10}-U-2-1	151.18	1.07	0.90	9.13	75.59
C_{16}-D-2-1	164	1.17	0.97	11.54	82
C_{10}-U-5-1	185.6	1.32	1.10	11.12	92.80
C_{10}-U-2-2	166	1.18	0.99	10.26	83.00
C_{16}-D-2-2	223	1.59	1.32	12.77	111.5
C_{10}-U-5-2	195	1.39	1.16	13.16	97.5

TABLE III
COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL VALUES OF ULTIMATE STRESS OF STIRRUPS

Name of beams	Beam shear Capacity kN	Load causing Initial shear crack kN	Exp. Shear Resistance of Stirrups kN	Theoretical Shear Resistance of stirrups$A_s f_y . d/S$ kN
NS	70	60	-	-
S_8-1	84	50	34	40.48
C_{10}-U-2-1	75.57	45	30.57	27.6
C_{16}-D-2-1	82	45	37	44.16
C_{10}-U-5-1	92.8	52	40.8	40.48
C_{10}-U-2-2	83	37.5	45.5	41.41
C_{16}-D-2-2	111.5	54	57.5	66.2
C_{10}-U-5-2	97.5	48	49	60.7

* The value of $A_s f_y$, ultimate tensile strength, was calculated according to (1).

TABLE IV
EFFICIENCY FACTOR OF BEAMS

Name of beams	Experimental shear forces carried by stirrup (kN)	shear strength of Steel stirrups $(A_s . f_y)_{s08}$ (one leg) (kN)	Ultimate tensile strength of steel-CFRP stirrups$A_v . f_{fu}$ (one leg) (kN)	Efficiency factor $(\emptyset_E)$
S_8-1	34	27.5		1
C_{10}-U-2-1	30.75	-	18.77	1.34
C_{16}-D-2-1	37	-	30.0	1.0
C_{10}-U-5-1	40.8	-	27.5	1.2

IX. CONCLUSION

In this research, innovative steel-CFRP stirrups were developed and their applicability and effectiveness in resisting shear force were experimentally observed.Three types of steel-CFRP stirrups were manufactured manually, U-shaped of two types and D-shaped. The complete manufacturing process of these stirrups was quite easy and didn't require a seriesof separate processes needed for the production of specific FRP rod stirrups. All these stirrups including steel stirrups were used as internal shear reinforcement of eight concrete beams. Test results indicated that Steel-CFRP stirrups are comparable with steel bar stirrups, so they could be used as shear reinforcement in lieu of steel bars and the efficiency factor for beams reinforced with steel-CFRP was higher than the beam reinforced with steel bar stirrups.

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