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# Steel–CFRP composite and their shear response as vertical stirrup in beams

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**Abstract.** An experimental study was conducted for the effectiveness of steel-CFRP composite (CFRP laminates sandwiched between two steel strips) as stirrups in concrete beam to carry shearing force and comparison was made with conventional steel bar stirrups. A total numbers of 8 concrete beams were tested under four point loads. Each beam measured 1,600 mm long, 160 mm width and 240 mm depth. The beams were composed of same grade of concrete, with same amount of flexural steel but different shear reinforcements. The main variables include, type of stirrups (shape of stirrups and number of CFRP layers used in each stirrup) and number of stirrups used in shear spans. After getting on an excellent closeness between the values of ultimate shear resistance and ultimate tensile load of steel-CFRP stirrups, it could be concluded that the steel-CFRP stirrups represent the effective solution of premature failure of FRP stirrups at the bends.

**Keywords:** steel-CFRP composite; stirrups; concrete beams; shear span; good approach

## 1. Introduction

Fiber Reinforced Polymer (FRP) has become a practical alternative construction material in various structural aspects. It can be used externally to improve the flexural and shear capacities of beams Bousselham and Chaallal (2008), Pellegrino and Modena (2008). Also, it can be used internally as reinforcement bars (rebars) replacing conventional steel reinforcement in reinforced concrete (RC) structures, Lau and Pam (2010). The use of FRP reinforcement for shear has not yet been fully explored. Because FRP and steel bars have different properties, including the modulus of elasticity, transverse strength, and the surface and bonding characteristics, the shear behaviour of concrete beams reinforced with FRP stirrups may differ from those of beams reinforced with conventional steel stirrups. In addition, bends of FRP bars at their ends to develop sufficient anchorage was found to reduce the ultimate capacity of the FRP stirrups, El-Sayed *et al*. (2007). The problem of reducing the capacity of FRP as a result to bend it, when using as stirrup,

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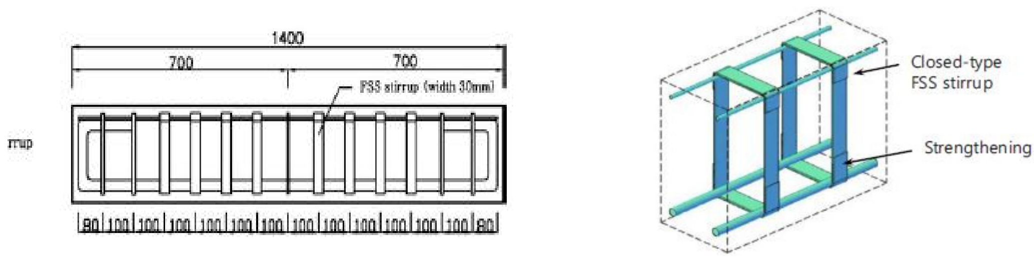
represents a big challenge. Lee *et al*. (2010) mentioned that the conventional FRP rod stirrups have the following shortcomings: they are not flexible enough to bend to form a stirrup as required in the construction field due to several inherent material disadvantages of FRPs such as non-plastic behaviour and very low shear or transverse strength, a separate manufacturing process is needed for fabricating different sizes and shapes of FRP stirrups, and premature failure at a bent portion of FRP stirrups due to a stress concentration requires the use of FRP stirrups with excessive sectional area, leading to a partial loss of competitiveness in cost.

This statement came coinciding to the confirmation of many codes and researches that FRP stirrups, and according to various test results, 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, ACI 440.1R-06 ( 2006), ACI 440.4R-04 (2004), El-Sayed *et al*. (2007), CAN/CSA-S06-06 (2006). To solve the inherent problem of bend FRP when used as stirrups, Lee *et al*. (2010) strengthened the bend points of fibre sheet strip stirrups by bonding additional overlaps of fibre sheet strip stirrups (FSS) at bend portion. Five auxiliary steel stirrups of diameter 6 mm two at the vicinity of each support and one at mid span were used to support the flexural reinforcement cages before applying the FSS stirrups, Fig. 1. The results indicated that the premature failure at bent portion of FSS stirrups could be relieved to some degree by using this technique.

The use of FSS as stirrups and its subsequent strengthening against premature failure doesn't seem to be a fool proof technique for the following reasons.

(1) The process of wrapping FSS around the reinforcement cage and in situ strengthening of the bend portions is very difficult affair almost impractical. It is also a time consuming process.
(2) During casting of concrete, the stirrups would be susceptible to damage which can initiate the failure even at lower load.

Hence, it could be concluded that this technique doesn't rule out the possibility of premature failure of FSS stirrups and therefore, needs radical changes. To avoid all these inherent defects to use FSS technique, steel-CFRP composite stirrups were developed in this present study. Using woven carbon fibre fabric instead of fibre sheet as a main reinforcement and applying the wet layup system to paste this fibre on steel strips, which was like a mould, provides the perfect solution. The new steel-CFRP stirrups would be strong enough to support all reinforcement cage, protected from damage, and resist the applied load without any reduction in its capacity. Though,




(a) (b)

Fig. 1 FSS technique

the present research presents the solution of premature failure of FRP stirrups at the bends, yet one undesirable phenomenon of corrosion would emerge. This new challenge could be solved by coating steel strips with thin layer of the same epoxy used to paste CFRP laminate however further study needs to be conducted to recognize the range of its effect on the ultimate capacity of steel-CFRP stirrups. In this study, the effectiveness of steel-CFRP stirrups in resisting shear was evaluated by comparing experimental results of reinforced concrete beams without stirrups, with steel stirrups and with different types of steel-CFRP stirrups. The results indicated that steel-CFRP stirrups reach to their ultimate tensile strength without any reduction of its capacity resulting from the process of framing.

## 2. Objective of study

Premature failure of the FRP stirrups at the bends due to stress concentration is attributed to lack of ductility of the stirrup. To prevent from developing stress concentration at the bends, configuration of CFRP fabric is most suitable and wet layup system on the steel strip provides the perfect solution to the required shape of the stirrup. Too, applying the impregnated fibre to the reinforced cage in construction field could not be practically viable.

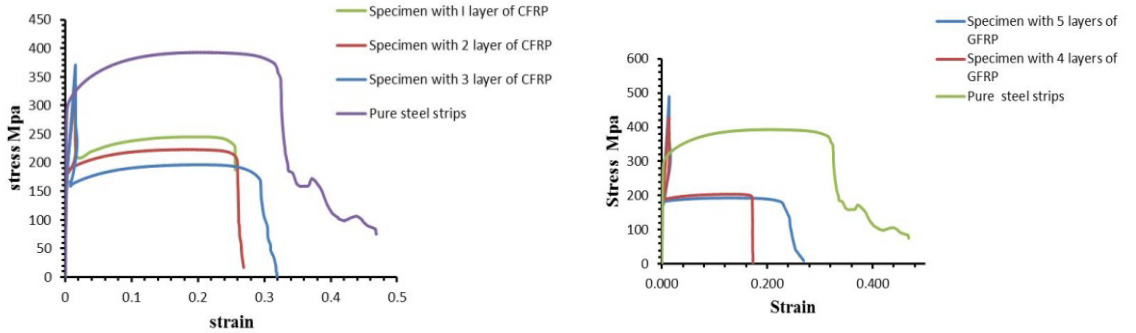
In order to fabricate stirrups with sufficient stiffness and without stress concentration therefore, pasting of impregnated FRP fabric on steel strips could give remarkable results. From what mentioned above, the objective of this experimental work is to study the behaviour of steel-CFRP composite stirrups in beams.

## 3. Mechanical properties of Steel-CFRP (SCFRP) specimens

Uriayer and Mehtab (2013) have studied the behavior of Steel-CFRP (SCFRP) composite specimens under uni-axial tension. Fifteen composite specimens have been fabricated and tested. Woven carbon fibre fabric (Sika Wrap®-300C) and 2-part epoxy impregnation resin (Sikadur®-330) were used to make the steel-CFRP composite specimens. Single layered to five layered, three of each type, total fifteen composite specimens were prepared. These fifteen specimens of steel-CFRP composite and three standard specimens of pure steel were tested under uniaxial tension test. Test results showed that the stress-strain curve of the composite specimen was bilinear prior to the fracture of CFRP laminate. Fig. 2 shows the stress-strain curves of the uniaxial tensile test on specimens. In study of Uriayer and Mehtab (2013), the ultimate load for steel-carbon fiber reinforced polymer (SCFRP) composite specimens was found using the model proposed by Wu *et al*. (2010) and nonlinear FE analysis. The ultimate loads obtained from FE analysis are found to be in good agreement with experimental ones, but there was a big gap between experimental and theoretical results. So is the case in Wu *et al*. (2010). To give a good estimate of ultimate load of steel-CFRP (SCFRP) composite specimens, Uriayer and Mehtab (2013) modified Gang's model to be as follows

$$p_{ult.} = f_y A_s + e^{(0.2391i)} \varepsilon E_f A_{f,1} \tag{1}$$

Where $p_{ult}$ represents the ultimate tensile load of CFRP layers, $i$ is the number of used layers. $A_s$ and $f_y$, are cross section area and yield stress of steel strip respectively. $\varepsilon$ and $E_f$, are ultimate strain




(a) Stress-strain curves of specimens with 1,2,3 layers of CFRP and pure steel strips

(b) Stress-strain curves of specimens with 4,5 layers of CFRP and pure steel strips

Fig. 2 Stress-strain curves of steel-CFRP specimens and steel strips

and elastic modulus of fibre respectively. $A_{f,1}$, is cross section area of one layer of fibre.

## 4. Experimental program

The experimental work was accomplished in two phases.

### *4.1 Phase (1): Fabricating steel-CFRP composite stirrups*

Three materials were used to manufacture the steel-CFRP composite stirrups. They are as follows:

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

Table 1 shows the properties of CFRP (SikaWrap®-300C) and Adhesive (Sikadur®-330) as reported by manufacturer but properties of steel strips have been found experimentally. It is worth mentioning that the materials reported above are the same material used in study of Faris and Mehtab (2013). Two types of stirrups were prepared.

*U-shaped*:
Two steel strips were cut and bent to the required shape of a stirrup. One by one, CFRP layers were pasted on outer face of one of the two. By using parallel clamps, the second steel strip was glued tightly to the first one. Two types of *U*-shaped stirrups were prepared, one with two layers of CFRP and the second with five layers of CFRP, Fig. 3(a).

*D-shaped*:
The same procedure was used to prepare two parts of identical *C*-shaped of steel-CFRP composite. Two layers of CFRP were sandwiched between the strips of *C*-shaped. The two *C*-shaped were assembled by overlapping the top and bottom flanges to get one *D*-shaped stirrup.

Table 1 Properties of material

| Material | SikaWrap®-300C(CFRP) | Sikadur®-330(Epoxy) | 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 |

(a)

(b)

Fig. 3 Steel-CFRP composite stirrups

Steel wire was used to tie the overlapped flanges tightly, Fig. 3(b). All these stirrups including steel stirrups were used as shear reinforcement to reinforce the shear spans of the seven beams cast and tested in this study. The structural behaviour of these seven beams with different shear reinforcements and one beam without shear reinforcement was investigated in this phase.

#### *4.1.1 Preparation of Steel-CFRP Reinforcement*

To fabricate the steel-CFRP stirrups, the same procedure reported in study of Uriayer and Alam (2013) had been followed with nuances representing with the size and shape of steel strips. The steps followed in fabrication of steel-CFRP stirrups were as follows:

(1) Steel strips with width of 10 mm had been cut from a full size mild steel plate. Huge cutting machine was used to cut the plate in a machine shop outside the laboratory of concrete. The total length of these strips was 650 mm.
(2) To remove all scaling, rust, paint, and primer from the steel strips, grinder was used.
(3) To the desired dimensions, Specified SikaWrap®-300C fabric had been cut.
(4) Resin and hardener (Sikadur®-330) were correctly proportioned by a sensitive balance and thoroughly mixed together by a drill.
(5) The Sikadur®-330 was applied to the prepared substrate by a brush.
(6) The SikaWrap®-300C fabric was placed in the required direction onto the Sikadur®-330.
(7) The excess epoxy and air were removed applying mild pressure to a plastic roller moving in the direction of the fibre.
(8) The final stage of preparing the specimen was to put the second steel strip on the epoxy coated fabric. Parallel clamps were tightened to hold the sandwiching CFRP and steel specimens together to ensure removal of any air that might be entrapped between CFRP laminate and the second strip. Fig. 4 illustrates the role of parallel clamps to prepare the longitudinal reinforcement.

Fig. 4 Parallel clams

### *4.2 Phase* (2): *Casting and testing of the beams*

#### *4.2.1 Phase* (2): *Casting and testing of the beams*

The average 28 day compressive strength from three cylindrical specimens of 150 mm diameter and 300 mm height was 26 MPa while it reached to 31 MPa on the first day of testing the beams. Five deformed steel bars were used as longitudinal reinforcement on tension face in two layers, three bars of diameter 16 mm in lower layer and two bars of diameter 10 mm in upper layer. Flexure tension steel ratio was 0.025 with effective depth of 184 mm. The beam was designed to ensure that the shear failure of beams would occur prior to flexure failure.

#### *4.2.2 Shear response of steel CFRP composite stirrup in RCC beams*

##### *4.2.2.1 Reinforced concrete beams*

A total of 8 concrete beams were cast. Table 2 shows the full details of stirrups used in the beams. The beams have been designated using English alphabets and Arabic numerals. The first character in the designation of a beam refers to the type of stirrup material (*N*: no stirrups, *S*: steel stirrups and *C*: composite stirrups), the following subscript numeral to either the width of composite stirrup or the diameter of steel bar stirrup, the next character to the shape of stirrup U or *D* as illustrated in Fig. 3, the last but one digit for the number of CFRP layers used and the last digit for the number of stirrups used in each side of shear spans. All beams have cross-sectional dimensions 160 mm × 240 mm and length of 1,600 mm. Three deformed steel bar, two with diameter of 16 mm and one with diameter of 12 mm were used as top compression bars. Three different types of steel-CFRP stirrups were considered, two types of *U*-shaped stirrups and one type of *D*-Shaped stirrup, Fig. 5.

Since only two compression bars could be held by *U*-shaped stirrups as illustrated in Fig. 4, therefore, four auxiliary steel hoop stirrups of diameter 10 mm were used to support the third compression steel bar. Middle third of the beam was provided with two auxiliary stirrups, one at each middle third point in zone of zero shear force and each support was provided with one stirrup. The eight tested beams in this phase consisted of three types i.e., Type-1, Type-2 and Type-3.

- Type-1: only one beam without any stirrup in the shear spans.
- Type-2: four beams namely $S_8$-1 / $C_{10}$-$U$-2-1 / $C_{16}$-$D$-2-1/ $C_{10}$-$U$-5-1. Each of the four beams

was provided with only one stirrup in each shear span.

- Type-3: three beams $C_{10}$-*U*-2-2 / $C_{16}$-D-2-2 / $C_{10}$-*U*-5-2 each with two steel-CFRP stirrups in each shear span.

Table 2 Details of stirrups used to reinforce beams

| Designation of beams | Type of stirrups | Number of layers of CFRP | Width or diameter of stirrups (mm) | Area of steel used ($mm^2$) | Surface area of stirrups ($mm^2$) | Spacing of stirrups in beams (mm) |
|---|---|---|---|---|---|---|
| $S_8$-1 | Steel bar | | 8 | 50 | 25 | 250 |
| $C_{10}$-*U*-2-1 | Steel-CFRP | 2 | 10 | 30 | 30 | 250 |
| $C_{16}$-*D*-2-1 | Steel-CFRP | 2 | 16 | 48 | 42 | 250 |
| $C_{10}$-*U*-5-1 | Steel-CFRP | 5 | 10 | 30 | 32 | 250 |
| $C_{10}$-*U*-2-2 | Steel-CFRP | 2 | 10 | 30 | 30 | 166.6 |
| $C_{16}$-*D*-2-2 | Steel-CFRP | 2 | 16 | 48 | 42 | 166.6 |
| $C_{10}$-*U*-5-2 | Steel-CFRP | 5 | 10 | 30 | 32 | 166.6 |

(a)


(b)

Fig. 5 Tension and compression reinforcement

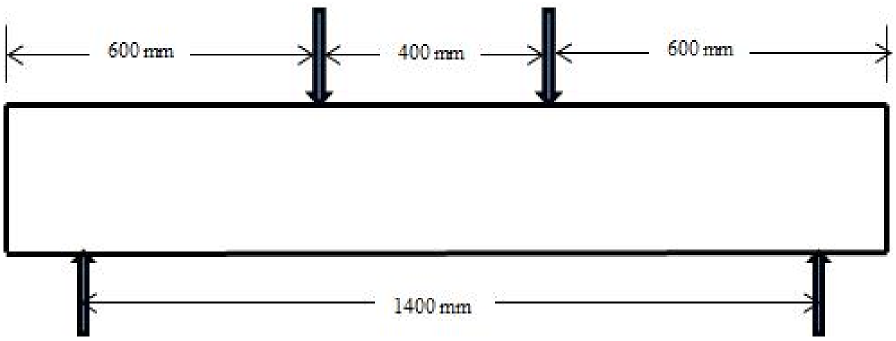



Fig. 6 Four -point loading system

#### *4.2.2.2 Loading and measurements*

Fig. 6 shows the loading arrangement for four-point loading system with centre to centre span of 1,400 mm. All beam specimens were loaded in the beam testing machine of capacity of 500 kN under quasi-static loading at displacement control rate of 2 mm per minute. Vertical deflections at the mid span were measured by linear variable differential transducer in built with the machine.

#### *4.2.2.3 Load deflection curves and behaviour of beams*

Fig. 7 shows load deflections curves of all beams tested in this study. For all beams, flexural cracks appeared first in zero shear zone, followed by web-shear cracks in the shear span. Subsequently, some of the web-shear cracks started propagating and met each other constituting diagonal crack which further widened and grew to a major diagonal crack, leading to abrupt shear failure of the beam. The abrupt failure was accompanied with a loud sound (tick) and sudden widening of the major diagonal crack. The two symptoms clearly refer to ultimate shear failure of the beams reinforced with shear stirrup(s) of steel CFRP composite due to rupture of the CFRP laminate. However, no rupture of steel bar stirrup in the beam reinforced with traditional steel stirrups occurred and the loud sound noticed was due to bond failure between stirrup bar and surrounding concrete. This is because of:

(1) less surface area of the stirrup bar
(2) Insufficient anchorage length of the stirrup bar
(3) High yield strength of the stirrup bar

It is worth mentioning that after the rupture of CFRP laminates of steel- CFRP composite stirrup, only steel component of the stirrup(s) carried the shearing load. This resistance lasted for a long time, during which the cover of concrete spelled off and leg of stirrup(s) was completely exposed. During this resistance of stirrup’s steel, deflection continued and this steel strain reached to the necking phenomenon and ultimately ruptured. The route of diagonal cracks for all beams could be seen to have started from one reaction and terminated at point load located on the same side of reaction after crossing the stirrup(s).

From Fig. 7(i)-(j), it could be seen 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. Immediately, after reaching to the peak load, curves dipped abruptly for all beams reinforced with steel-CFRP stirrups due to the rupture of CFRP laminates, while for beam reinforced with steel stirrups the load descended gradually. Maximum deflection, accompanied to the peak load, ranged between 9.54 mm for beam $S_8$-1 to 11.54 mm for beam $C_{16}$-$D$-2-1 within the group of Type-2 while the maximum deflection was 13.16 mm for beam $C_{10}$-$U$-5-2 within the group of Type-3, Fig. 7.

## 5. Failure mode of beams

Structure behavior of each beam tested under four- static load is given below:

*$S_8$-1:*

$S_8$-1 is a beam reinforced with one steel stirrup of 8 mm diameter in each side of shear span of the beam. At load of 100 kN, a flexural crack in maximum flexure zone followed by initial web-shear crack in a shear zone appeared. With increasing the load, a few more diagonal cracks

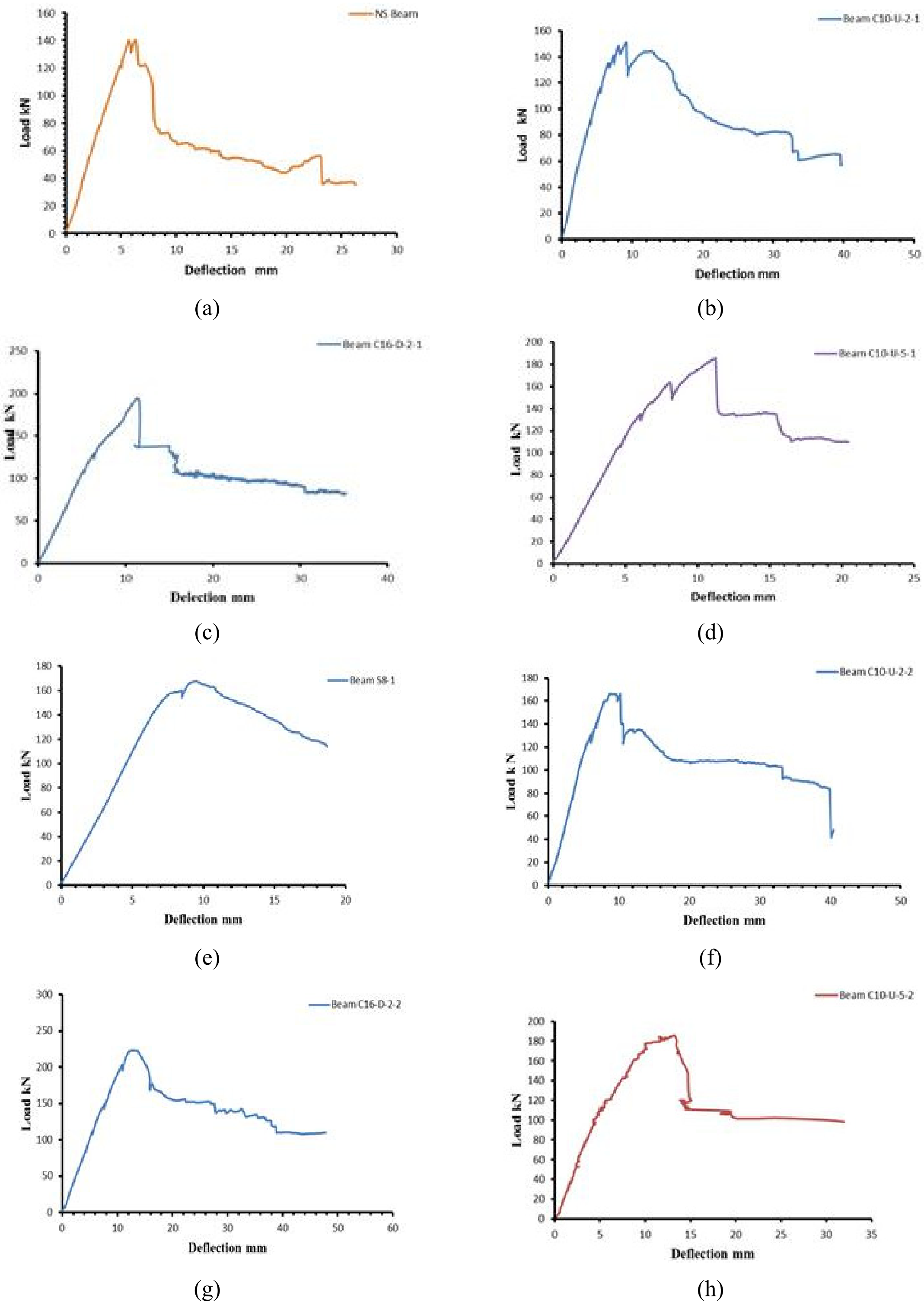
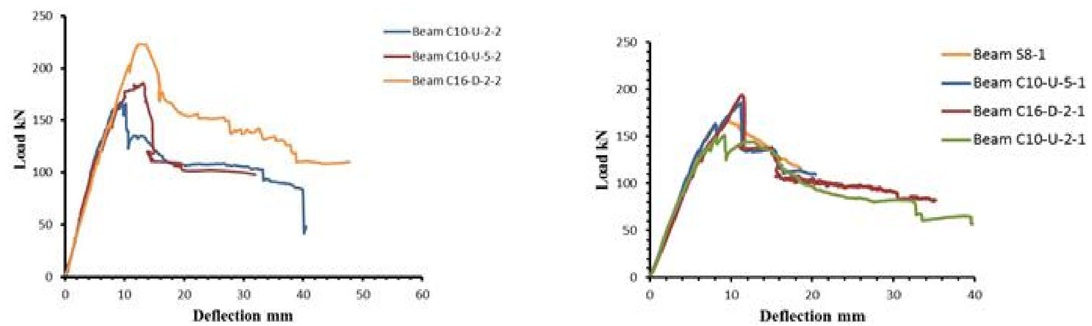



Fig. 7 Load-deflection curves of beams reinforced with steel-CFRP stirrups




(i) (j)

Fig. 7 Continued


Fig. 8 Failure mode of beam $S_8$-1

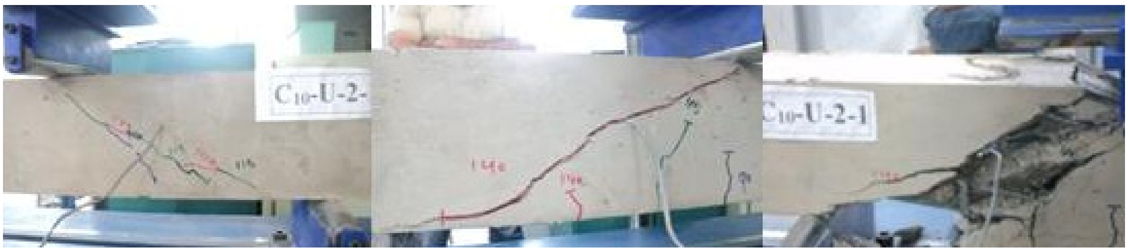



Fig. 9 Failure mode of beam $C_{10}$-$U$-2-1

were formed and one of these cracks eventually grew to a dominant diagonal crack from the support to the loading point and led the beam to the shear failure at maximum load of 168 kN, Fig. 8.

*$C_{10}$-U-2-1*:

$C_{10}$-$U$-2-1 is a beam reinforced with one $U$-shaped stirrup of steel-CFRP composite in each shear span. Each stirrup is with two layers of CFRP and width of 10 mm. At loading of 90 kN, flexural cracks followed by one initial web-shear crack appeared. During the loading, new cracks developed and they joined together to constitute a diagonal crack. Reaching the load of 140 kN, a sudden diagonal crack appeared in the other shear span of the beam while the crack that initially opened didn't propagate. Ultimately failure occurred due to rupture of CFRP laminate at


Fig. 10 Failure mode of beam $C_{10}$-U-5-1

Fig. 11 Failure of beam $C_{16}$-*D*-2-1

151.18 kN, Fig. 9.

$C_{10}$-*U*-5-1:

$C_{10}$-*U*-5-1 is a beam reinforced with one U-shaped stirrup of steel-CFRP composite in each shear span. Each stirrup is with five layers of CFRP and width of 10 mm. An initial web-shear crack appeared at loading 104 kN. After appearing one flexural crack in zero shear zone. Load kept on increasing during which another sudden diagonal crack occurred in the other shear span of beam. Ultimate collapse load due to shear failure was 185.6 kN. The deflection of beam and the strain of stirrups' steel increased continuingly until the fracture of steel strips of the stirrups occurred. Fig. 10 shows the failure mode of beam.

$C_{16}$-*D*-2-1:

$C_{16}$-*D*-2-1 is a beam reinforced with one D-shaped stirrup of steel-CFRP composite in each shear span. Each stirrup is with two layers of CFRP and width of 16 mm. At 108 kN, a single initial web-shear crack appeared. At loading 130 kN, a few additional flexural cracks in maximum flexure zone appeared and the web-shear crack widened and propagated up and down to constitute the major diagonal crack that caused the failure of the beam at 192 kN, Fig. 11.

$C_{16}$-*D*-2-2:

$C_{16}$-*D*-2-2 is a beam reinforced with two *D*-shaped stirrups of steel-CFRP composite in each shear span. Each stirrup is with two layers of CFRP and width of 16 mm. At 108 kN, An initial web-shear crack appeared. With the increasing load, a few shear cracks occurred and met with some others to constitute the main diagonal crack. It was expected that this main diagonal crack would be the causative one that lead to the failure, but during the loading, a few additional cracks appeared and met together to constitute the diagonal crack on the other shear span of the beam. Fracture of CFRP laminate of stirrups made the shear failure of the beam at 223 kN. After the shear failure the load started dropping with increasing deflection and strain of the stirrup, Fig. 12.

*$C_{10}$-U-2-2*:

$C_{10}$-*U*-2-2 is a beam reinforced with two U-shaped stirrups of steel-CFRP composite in each shear span. Each stirrup is with two layers of CFRP and width of 10 mm. At 75 kN, a few flexural cracks in the maximum flexure zone and initial web-shear crack occurred. With increasing load the number of shear cracks increased and main diagonal crack formed. At 166 kN, shear failure

Fig. 12 Failure mode of beam $C_{16}$-*D*-2-2


Fig. 13 Failure mode of beam $C_{10}$-*U*-2-2

Fig. 14 Failure mode of beam $C_{10}$-*U*-5-2

happened. The deflection of beam and the strain of stirrups' steel continued to increase with decreasing post peak load, Fig. 13.

*$C_{10}$-U-5-2*:

$C_{10}$-*U*-5-2 is a beam reinforced with two *U*-shaped stirrups of steel-CFRP composite in each shear span. Each stirrup is with five layers of CFRP and width of 10 mm. At 96 kN, some flexure cracks in the maximum flexure zone with initial crack at one support appeared. With increasing load, a few new shear cracks appeared in either shear span of the beam. At 195 kN, shear failure happened. The deflection of beam and the strain of stirrups' steel continued till the collapse of steel strips, Fig. 14.

## 6. Beams strength

It can be seen from Fig. 7(i)-(j), that all beams transversely reinforced with stirrups exhibited higher strengths than the *NS* beam. The strength values ranged between 1.08-1.59 times the strength of *NS*. The strength values for beams of Type-2, i.e., beams $C_{10}$-*U*-2-1, $C_{16}$-*D*-2-1, and $C_{10}$-*U*-5-1 respectively were 0.9, 1.14 and 1.10 times of strength value of $S_8$-1. While the strength values for beams $C_{10}$-*U*-2-2, $C_{16}$-*D*-2-2 and $C_{10}$-*U*-5-2 of Type-3 were respectively 1.02, 1.10 and 1.32 times of strength of $S_8$-1. It is worth mentioning that the cross sectional area of *U*-shaped stirrups used in reinforcing beams $C_{10}$-*U*-2-1 and $C_{10}$-*U*-2-2 was equal to the cross sectional area of steel stirrup of diameter 8 mm of $S_8$-1. The area of steel in each stirrup of composite used in the beam $C_{10}$-*U*-2-1 was 60% of steel of 8 mm diameter bar stirrup in the beam $S_8$-1. Though the yield stress of steel strip of composite stirrups was 300 MPa and the amount of steel was 40% less than the amount of steel of bar diameter 8 mm with yield stress 550 MPa, yet the strength of beam $C_{10}$-*U*-2-1 was only 10 % less than that of beam $S_8$-1.

## 7. Stirrups capacity and premature failure of FRP

### 7.1 Test of the vertical legs of steel-CFRP stirrups

To check whether the steel-CFRP stirrups have reached to their ultimate capacity, nine pieces representing the vertical leg of the three types of stirrups were cut from the original stirrups and tested in tension in a 500 kN capacity Zwick Roell universal testing machine with a loading rate of 2 mm/min., Fig. 15. Table 3 shows the test results for each sample and the average values.

To compare the results of ultimate shear resistance of stirrups and their respective ultimate tensile strength, two procedures were followed:

(1) Since the space between stirrups of beams Type-2 was larger than the effective depth of beam and the route of all diagonal cracks caused failure of beams crossed all these stirrups, double values (two legs) of ultimate tensile load of samples was compared with the ultimate resistance force of stirrups of beams $C_{10}$-*U*-2-1, $C_{10}$-*U*-5-1 and $C_{16}$-*D*-2-2.

(2) Since the spacing between stirrups was less than the effective depth of beam as they were for beams $C_{10}$-*U*-2-2, $C_{10}$-*U*-5-2 and $C_{16}$-*D*-2-2, ultimate tensile strength of stirrups was calculated from $A_s f_y d/s$.

Fig. 15 Vertical legs of stirrups

Table 3 Ultimate tensile load of stirrups (Vertical legs)

| Sample | Ultimate tensile load of sample (vertical leg) (MPa) | Average of ultimate tensile load of three samples (MPa) |
|---|---|---|
| Vertical legs cut from *U*-shaped stirrup of two layer of CFRP | 12.87 | 14.51 |
| | 14.5 | |
| | 16.17 | |
| Vertical legs cut from *U*-shaped stirrup of five layers of CFRP | 18.12 | 18.59 |
| | 20.61 | |
| | 17.04 | |
| Vertical legs cut from *D*-shaped stirrup of two layers of CFRP | 24.12 | 21.37 |
| | 18.0 | |
| | 22 | |

Where, $A_s f_y$ represent the ultimate tensile load of sample which was calculated by Eq. (1) for steel-CFRP composite stirrups; $d$ represents the effective depth of beam, and $s$ is the spacing between stirrups.

### *7.2 The nearest approach to calculate shear resistance of stirrups*

The applied shear stresses in a cracked reinforced concrete member without shear reinforcement are resisted by various shear mechanisms such as shear stresses in un cracked concrete, interlocking action of the aggregate, dowel action of the longitudinal reinforcing bars, arch action, and residual tensile stresses transmitted directly across the cracks Lee *et al*. (2010), McGregor and Wight (2008). Following both latter researches, experimental shear resistance listed in column number (4) were calculated by subtracting the shear strength of the NS beam from the corresponding shear strength of the beams reinforced with steel-CFRP composite stirrup. El-Sayed *et al*. (2007) calculated the stirrup stress at failure by finding 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. Column number (5) gives experimental shear resistance of steel-CFRP composite stirrup following El-Sayed *et al*. (2007). Column number (6) gives values of ultimate tensile strength of stirrups' material from tension test. Table 4 shows the comparison

Table 4 Comparison between results of ultimate resistance and ultimate tensile load of stirrups

| Designation of beams | Beam shear capacity (kN) | Load causing initial shear crack (kN) | Exp. Shear resistance of stirrups (kN) | Exp. Shear resistance of stirrups (kN) | Ultimate load of steel-CFRP stirrups and yield load of steel stirrups (kN) |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| NS | 70 | 60 | - | - | - |
| $S_8$-1 | 84 | 50 | 14 | 34 | 55 |
| $C_{10}$-$U$-2-1 | 75.57 | 45 | 5.57 | 30.57 | 29.02 |
| $C_{16}$-$D$-2-1 | 96 | 54 | 26 | 42 | 42.74 |
| $C_{10}$-$U$-5-1 | 92.8 | 52 | 22.8 | 40.8 | 37.18 |
| $C_{10}$-$U$-2-2 | 83 | 37.5 | 13 | 45.5 | 32.39 |
| $C_{16}$-$D$-2-2 | 111.5 | 54 | 41.5 | 57.5 | 47.7 |
| $C_{10}$-$U$-5-2 | 97.5 | 48 | 27.5 | 49.5 | 41.5 |

between results of ultimate shear resistance and ultimate tensile strength of stirrups.

From Table 4 the values of shear resistance of steel-CFRP composite stirrup listed in column number (4) are consistently smaller than values listed in columns 5 and 6. It is clear that the presence of stirrup(s) weakens the shear resistance of concrete attributed to incompatibility of strains at the interface and thus developing web shear cracks at lower load than when there is no stirrup in the beam. Quite contrary, it could be seen that there is an excellent closeness between values listed in columns (5) and (6), the values of ultimate shear resistance and ultimate tensile load of stirrups respectively. Since All the values of ultimate shear resistance for all beams reinforced with steel-CFRP composite stirrups but beam $C_{16}$-$D$-2-1 (column 5) are larger than the values of ultimate tensile load of stirrups (column 6), one could be concluded that These results validate that all stirrups had reached to their ultimate tensile strength without reduction in their capacities.

## 8. Conclusions

The following conclusions were drawn from the experimental observations of beams reinforced with steel-CFRP composite stirrups:

(1) Using woven carbon fibre fabric instead of fibre sheet as a main reinforcement and applying the wet layup system to paste this fibre on steel strips, which was like a mould, provides the perfect solution without undergoing capacity reducing phenomenon of FRP while using as stirrups.
(2) Steel strips sandwiching the CFRP laminate called Steel-CFRP stirrups not only protect the CFRP but also provide ductility to this composite stirrup.
(3) Steel-CFRP stirrups are comparable with steel bar stirrups, so they could be used as shear reinforcement in lieu of steel bars.
(4) All beams transversely reinforced with stirrups exhibited higher strengths than the *NS* beam. The strength values ranged between 1.07-1.59 times of strength value of *NS*.

(5) Excellent closeness between the values of ultimate shear resistance and ultimate tensile load of stirrups refers to validate using steel-CFRP composite stirrups to resist shear forces.
(6) Since all the values of ultimate shear resistance for all beams reinforced with steel-CFRP composite stirrups but beam $C_{16}$-$D$-2-1 are larger than the values of ultimate tensile load of stirrups, one could be concluded that These results validate that all stirrups had reached to their ultimate tensile strength without reduction in their capacities.

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