SHEAR STRENGTHENING OF REINFORCED CONCRETE BEAMS USING CFRP LAMINATES

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ABSTRACT

Carbon Fiber-reinforced polymers (CFRP) are becoming more widely used for strengthening reinforced concrete (RC) beams. This research investigates the effectiveness of strengthening shear-deficient RC beams with CFRP laminates. Eight beams, including four beams strengthened in shear with bonded CFRP laminate, were tested under three-point static loading using a 100 kips capacity displacement-controlled hydraulic actuator ram controlled with an electric pump. The RC beams had dimensions of (5” x 9.75” x 60”) and were reinforced with 3#5 longitudinal bars and had different spacing of steel stirrups. Instrumentations of LVDT’s mounted for deflection measurements, were connected to a data acquisition system to automatically record the data of the load and displacements. The results indicated that the strengthened beams with U-wrapped CFRP showed an increased shear capacity and eliminated the brittle shear failure.

Keywords: Concrete, Beam, Shear, CFRP, Strengthening

INTRODUCTION AND REVIEW OF CURRENT RESEARCH WORK

The shear strength of concrete beams and columns can be increased by wrapping or partially wrapping the members with FRP systems[1,2,3,4]. Orienting the fibers transverse to the axis of the member or perpendicular to potential shear cracks is effective in providing additional shear strength[5]. The use of such externally bonded CFRP laminates to strengthen concrete beams has become a good technique due to their light weight, high strength, non-corrosive nature, formability, and. ease of installation. Although several studies have been conducted to investigate the behavior of beams strengthened in flexure with externally bonded FRP, there is not much literature on FRP shear strengthening and there is a variety of its configurations. Flexure strengthening increases the moment capacity beams in flexure; yet, their shear capacity may be exceeded. Increasing the shear strength can also result in flexural failures, which are relatively more ductile in nature as compared to shear failures[6].

The shear behavior of concrete members reinforced longitudinally with FRP bars has not yet been fully explored. Due to the difference in mechanical properties between FRP and steel reinforcement, particularly the modulus of elasticity, the shear strength of concrete members reinforced longitudinally with FRP bars may differ from that of members reinforced with steel. Several studies investigated the shear strength of FRP beam[7,8,9,10].

The applied shear stresses in a cracked reinforced concrete member without transverse reinforcement are resisted by various shear mechanisms. Joint ACI-ASCE[11] Committee 445, Shear and Torsion, identified the following five mechanisms of shear transfer: 1) shear stresses in uncracked concrete; 2) interlocking action of aggregate; 3) dowel action of the longitudinal reinforcing bars; 4) arch action; and 5) residual tensile stresses transmitted directly across the cracks. Aggregate interlock results from the resistance to relative slip between two rough interlocking surfaces of the crack, much like frictional resistance. As long as the crack is not too wide, this action can be significant. Dowel forces generated by longitudinal bars crossing the crack partially resist shearing displacements along the crack. Arching action occurs in deep members or in members in which the shear span-to-depth ratio (a/d) is less than 2.5. This is not a shear transfer mechanism in the sense that it does not transmit a tangential force to a nearby parallel plane, but permits the transfer of a vertical concentrated force to a reaction, thereby reducing the contribution of the other types of shear transfer. The basic explanation of residual tensile stresses is that when concrete first cracks, a clean break does not occur. Small pieces of concrete bridge the crack and continue to transmit tensile force up to crack widths in the range of 0.05 to 0.15 mm. Due to the relatively low modulus of elasticity of FRP composite material, concrete members reinforced with FRP bars will develop wider and deeper cracks than members reinforced with steel. Deeper cracks decrease the contribution to shear strength from the uncracked concrete due to the lower depth of concrete in compression. Wider cracks in turn decrease the contributions from aggregate interlock and residual tensile stresses. Additionally, due to the relatively small transverse strength of FRP bars and relatively wider cracks, the contribution of dowel action can be very small compared to that of steel. Finally, the overall shear capacity of concrete members reinforced with FRP bars as flexural reinforcement is lower than that of concrete members reinforced with steel bars. Other studies investigated the effectiveness of strengthening RC beams with CFRP laminates.

Substantial experimental and theoretical research has been conducted over the last decade into the effectiveness of using FRP sheets/strips to strengthen or retrofit RC members and the behavior of the strengthened structural elements[12,13,6,14,15,16]. Bonding FRPs to the members' surface has a common problem of debonding and hence could not fully utilize the full tensile strength of the FRP[17]. Externally bonding carbon fiber reinforced polymer (CFRP) laminates to reinforced concrete girders is becoming a more established technique for both strengthening and stiffening reinforced concrete (RC) bridge girders.

Most of the shear design provisions currently in effect for concrete structures reinforced with FRP bars are based on the design formulas of members reinforced with conventional steel considering some modifications to account for the substantial differences between FRP and steel reinforcement. These provisions are based on the traditional modified 45-degree truss model. This model identifies the shear strength of a reinforced concrete flexural member as the sum of the shear capacity of the concrete component Vc and the shear reinforcement component Vs. This section reviews the concrete shear strength component Vc,f of members longitudinally reinforced with FRP bars as recommended by many references[6, 18, 19].

The shear strength of slender reinforced concrete beams ($a/d > 2.5$) is affected by various design parameters. Shear failure of RC beams without web reinforcement is caused by diagonal tension cracking that develops perpendicular to the principal tensile stress axis. The shear strength of a concrete beam is affected by the compressive strength of the concrete. The shear strengths of slender beams may vary with the amount of longitudinal reinforcement and the concrete compressive strength. ACI 318[20] proposed an improved shear strength equation for reinforced concrete beams based on the concrete compressive strength and the amount of longitudinal reinforcement.

Kani performed experimental studies to investigate the effect of shear span to depth ratio (a/d) on the shear strengths of beams and indicated that the shear strength increases as a/d decreases. In beams with a low a/d, the applied force is transmitted directly to the supports by arch action (compressive struts) of the concrete. If the a/d is greater than 2.5, however, flexural action is dominant and the shear strength of the beam is not significantly affected by the a/d ratio. Kani also found experimentally that although the shapes, material properties, and reinforcement ratios of the beams were kept uniform, the shear strengths of concrete beams decrease as the size of the beams increase[21, 22]. Bažant theoretically proved that the size effect must be addressed in the evaluation of shear strengths of concrete, to satisfy the condition of energy balance[23]. According to the existing test results previously mentioned, the primary parameters that affect the shear strengths of concrete beams are the compressive and the tensile strengths of concrete, the ratio of flexural reinforcement, the a/d, and the size of the beam.

RESEARCH SIGNIFICANCE

This study provides data on the shear behavior of reinforced concrete beams strengthened with CFRP that complements previous studies using small and full-scale beams. The contribution of CFRP reinforcement to the shear capacity depends on several parameters that might include the CFRP sheet stiffness, the quality of the resin, the concrete compressive strength, the number of plies of CFRP sheet, the wrapping scheme, and the fiber orientation angle. It is rather very difficult to quantify the CFRP contribution due to the big number of variables and the lack of adequate experimental results. The nominal shear strength of a concrete member strengthened with an FRP system should exceed the required shear strength as shown in Eq. (1).

$$\Phi V_n \geq \Phi\ V_u \tag{1}$$

The nominal shear strength of FRP-strengthened concrete beam can be determined by adding the contribution of the CFRP reinforcing to the contributions from the reinforcing steel (stirrups, ties, or spirals) and the concrete as shown in Eq. (2). An additional reduction factor ψ_f is applied to the contribution of the FRP system.

$$\Phi V_n = \Phi\ (V_c + V_s + \psi_f V_f) \tag{2}$$

The shear contribution of the FRP shear reinforcement is then given in Eq. 3 as

$$V_f = A_{fv}\, f_{fe}\, (\sin\alpha + \cos\alpha)\ d_f\ /\ s_f \tag{3}$$

where

$$Af_v = 2nt_f w_f \tag{4}$$

The tensile stress in the FRP shear reinforcement at ultimate is directly proportional to the level of strain that can be developed in the FRP shear reinforcement at ultimate.

$$f_{fe} = \varepsilon f_e E_f \tag{5}$$

The total shear reinforcement should be taken as the sum of the contribution of the FRP shear reinforcement and the steel shear reinforcement. The total shear reinforcement should be limited based on the criteria given for steel alone in ACI 318-99 Section 11.5.6.9. This limit is stated in Eq. (6).

$$V_s + V_f \ \leq 8 b_w d\ (f'c)^{1/2} \tag{6}$$

The additional reduction factor ψ_f be applied to the shear contribution of the FRP reinforcement. For bond-critical shear reinforcement, an additional reduction factor of 0.85 is recommended. This research investigates the effectiveness of strengthening shear-deficient RC beams with U-wrapped CFRP laminates.

DESCRIPTION OF THE EXPERIMENTAL PROGRAM

An investigation of the effectiveness of using u-shaped CFRP laminates in shear strengthening of RC beams has been conducted. This experimental testing provides more data on the effect of CFRP in shear strengthening. This study evaluates the shear strength of CFRP strengthened concrete beams with shear-span-to-depth ratio, $a/d > 2.5$ with and without stirrups.

SPECIMENS' DETAILS

The concrete ultimate compressive strength for the tested beams was 8000 psi. The beams' dimensions were 5 inches wide, 9.75 inches deep and 5.0 feet long. The span length was 4.5 feet. Eight RC beams were tested including four control beams and four strengthened beams with

CFRP laminate. The longitudinal main reinforcement was 3 #5 bars at the tension side for flexure (reinforcement ratio of 2.1%) and # 2 stirrups for shear at variable spacing.

Beams S1 and S5 had no stirrups as shown in Tables 1 &2. The #2 shear stirrups were spaced uniformly at 2.2", 6" and 8" for beams' pairs (S2 & S6), (S3 & S7), and (S4 & S8), respectively. CFRP U-wrapped laminates were bonded to the sides and bottom of RC beams to increase their shear strength capacity. Six u-shaped CFRP strips of 6 inches wide, each having two layers, were applied to the sides and bottom of the four strengthened beams S5, S6, S7, and S8. Comparisons were made between control and strengthened beams in each of the following pairs (S1 & S5), (S2 & S6), (S3 & S7), and (S4 & S8).

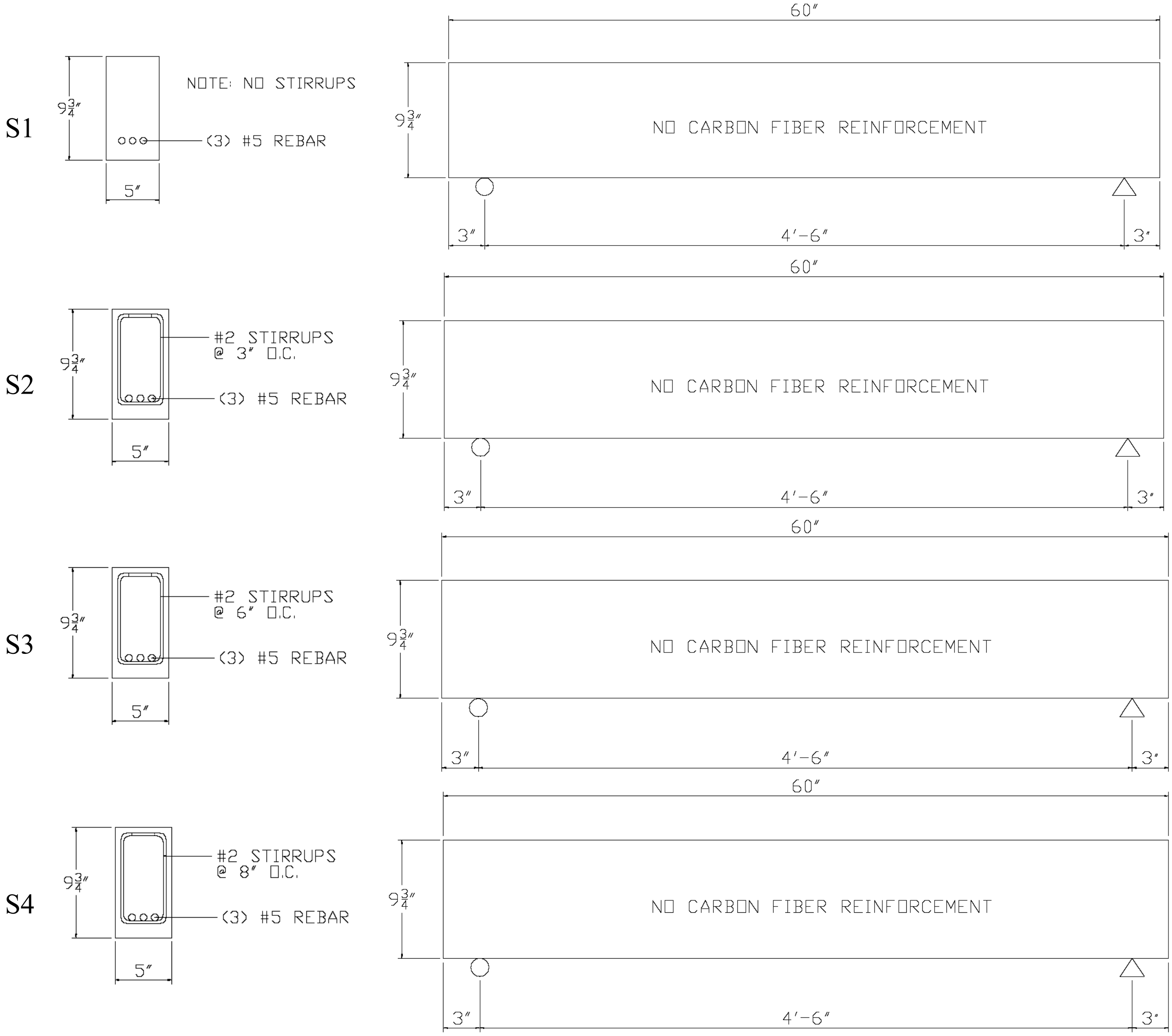
CFRP laminates were substrate elements stitched with carbon fabric tape. The characteristics of light weight, high strength, and corrosion resistance of CFRP made them ideally suited for quick and effective structural repairs. This material has adhesion strength to concrete of 500 psi per ASTM D 4541, and the following mechanical properties: Dry fabric weight = 13 ounces per square yard, tensile strength = 123,000 psi, tensile modulus = 11,400,000 psi, compressive strength = 20,000 psi, and interlaminar shear strength = 2,800 psi.

TEST PROCEDURE AND INSTRUMENTATION

The beam specimens were tested in a three-point flexural configuration as shown in Figures 1, 2. Instrumentations of LVDTs mounted to measure deflections were connected to a data acquisition system to automatically record the data of load and displacements. Also the load cell in the actuator recorded the deflection and load data. The performance of the beams was evaluated by conducting static loading. Visual inspection was done to determine crack location & propagation and possible delamination or debonding between the CFRP membranes and concrete surface. Figures 1, 2 show the tested beams. The beams were tested using the Shorewestern load cell actuator in three-point bending over simply supported clear span of 54 inches (4.5 feet). The displacement controlled load application was applied. The load and displacement data were correlated with the LVDT's deflection readings and were electronically recorded during the test using a data acquisition system monitored by a computer. The cracks initiation and propagation were marked on the sides of the beams and recorded during testing.

Fig. 1 Testing of control beams (a) S1, (b) S2, (c) S3, and (d) S4

Table 1 Details of control beams

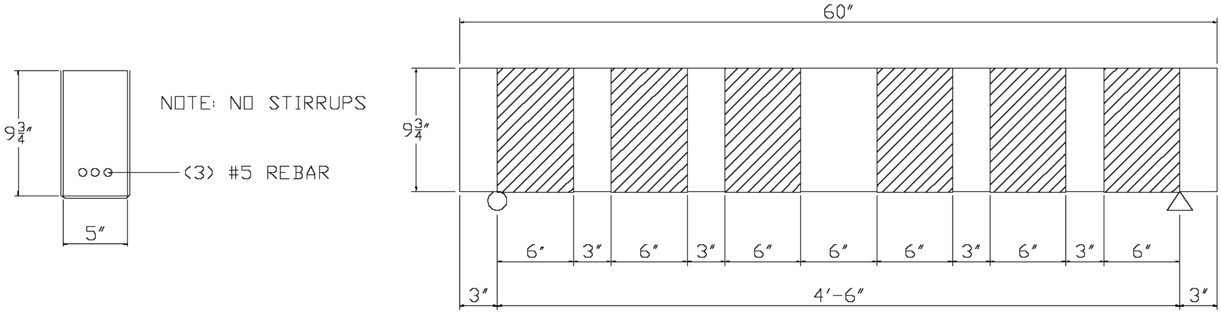


(a) (b) (c) (d)

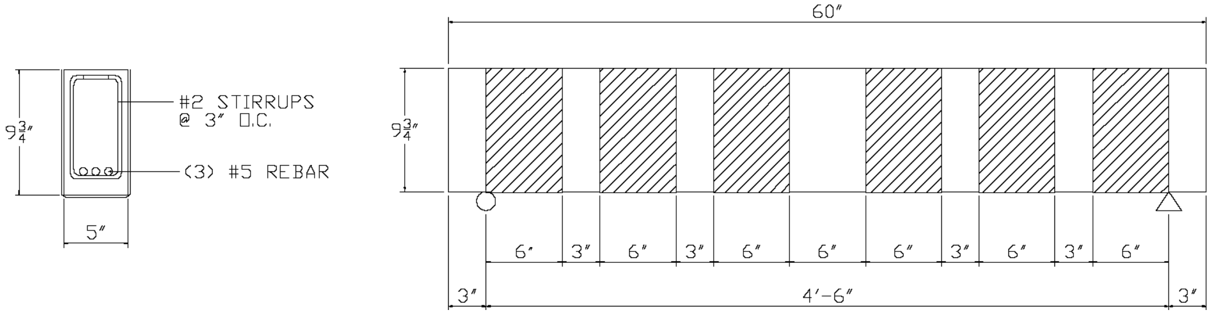
Fig. 2 Testing of shear strengthened beams (a) S5, (b) S6, (c) S7, and (d) S8

Table 2 Details of CFRP strengthened beams

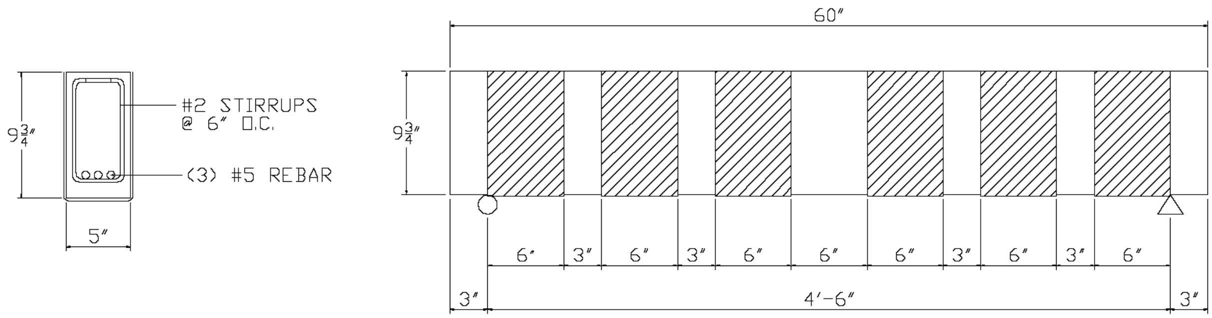
S5



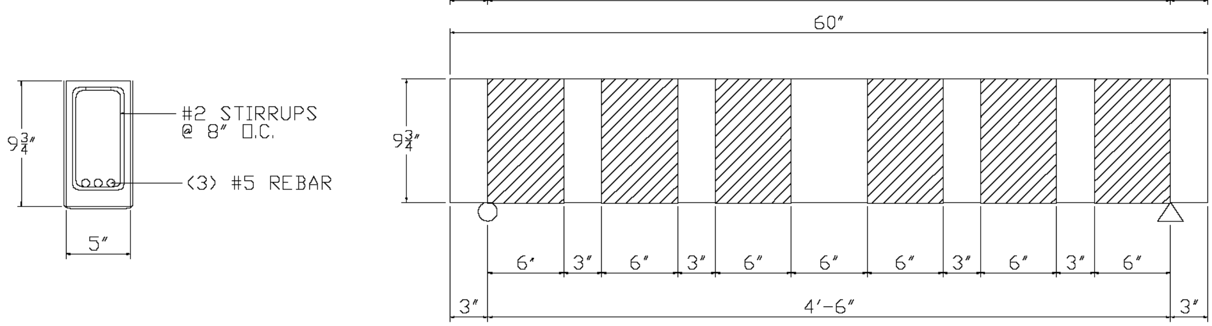
S6



S7



S8



RESULTS OF BEAMS TESTING

Table 3 shows the test results of the control and strengthened beams, including the maximum loads and deflections associated with maximum loads. There was a 92% increase in the maximum load for CFRP strengthened beam S5 than that for control beam S1 (Fig. 3). It is worth noting that at deflection of 5.91 mm associated with maximum load for control beam S1, a 39.6% load increase was recorded for strengthened beam S5.

For beam S1, a sudden shear cracking occurred at 58.41 kN and the load dropped sharply close to 5 kN. The crack strated from the support loaction all the way up and inclined toward the applied load. Cracks kept opening up excessively and deflection increased. However, for strengthened beam S5, at 95 kN shear cracking started and the load increased to 112.2 kN with rupture of the second CFRP U-shaped strip after 112.2 kN, then debonding of the same U-Shape from the other face of the beam.

There was also a relatively small increase of 15.85% in the maximum load sustained by strengthened beam S6 than that of control beam S2 (Fig. 4). Also, there was a relatively slight increase of the load of S6 compared to that of S2 at the deflection of 14.97mm associated with the maximum load of beam S2. That might be because the heavy steel stirrups content of #2 spaced at 2.2" resulted in a little effect for extra CFRP U-shaped stirrups. For control beam S2, at 79 kN, fine flexural and shear cracking initiated. The load increased to 90 kN.with more shear crackes / diagonal tension cracks developing. Then the load increased to 146 kN with cracks opening and deflection increased. However, for strengthened beam S6, at 115 kN flexural carcking started at center. Load increases to 169.29 kN and concrete at top experienced compression crushing while load dropped from 169.29 kN to 120 kN. Then load kept dropping. The mode of failure was crushing of concrete. The flexural cracking was still very narrow. No sign of CFRP debondoing. The load kept constant at 73 kN and concrete crushing kept progressing. The 5th CFRP U- shaped strip ruptured from the other side of the beam.

Strengthened beam S7 showed and increase of its maximum load than that for control beam S3 by 22.6% (Fig. 5). At the deflection of 9.44mm associated with the maximum load of beam S3, there was a load increase of 17% for the S7 compared to that of S3. For control beam S3, At 107 kN sudden shear cracking strated from the support to the point load. Several diagonal tension cracks developed and the load increased to 131.47 kN with shear / diagonal tension cracks opening. However, for beam S7, small flexural and shear carcking occurred at 145 kN. Load increased to 161.18 kN. Load droped as compression concrete started crushing at top. Then the load kept dropping while big flexutral cracking was formed. The mode of failure was crushing of concrete. The flexural cracking still somehow narrow. No sign of debondoing was noticed. The dropped load keeps constant at around 88 kN. Concrete crushing kept progressing and the 5th FRP-u Shaped ruptured from the other side of the beam. The load again kept holding at around 48 kN.

There was a significant increase of 72.9% in the maximum load for CFRP strengthened beam S8 (Fig. 6) than that for control beam S4. At the deflection of 5.84 mm associated with the maximum load of beam S4, there was a load increase of 8.4% for the S8 compared to that of S4. For control beam S4, sudden shear cracking started from the right support to the point load at 94.67 kN (maximum load). The load then dropped to 33 kN. Another diagonal tension crack developed as the load kept constant at 33 kN. Then load increased to 42 kN with shear / diagonal tension cracks opening more. For strengthened beam S8, small flexural and shear carcking started at 100 kN. Load increased to its max value of 163.07 kN. Sudden loud pop sound was heard and then several others followed. Then bigger shear cracking was noticed. Load was holding at 90kN. Shear cracking was the main mode of failure and then debonding Then crushing of concrete occurred. The load kept dropping. There were debondoing signs of the U-wrapped CFRP. The load kept constant at 68 kN and shear cracks kept progressing wider.

It should be noted that the shear stress, V/b_wd, at which an FRP-reinforced concrete beam without stirrups fails in shear, is not constant for all member depths. However; it was not intended by this paper to address all aspects associated with shear including the size effect and the applied moment.

Table 3 Summary of test results for the shear beams.

Beams	Maximum load kips (kN)	Deflection at maximum load inches (mm)
S1	13.13 (58.41)	0.23 (5.91)
S2	32.85 (146.1)	0.59 (14.97)
S3	29.56 (131.5)	0.37 (9.44)
S4	21.28 (94.67)	0.23 (5.84)
S5	25.22 (112.2)	0.40 (10.05)
S6	38.06 (169.3)	0.72 (18.33)
S7	36.24 (161.2)	0.59 (14.96)
S8	36.66 (163.1)	0.55 (13.96)

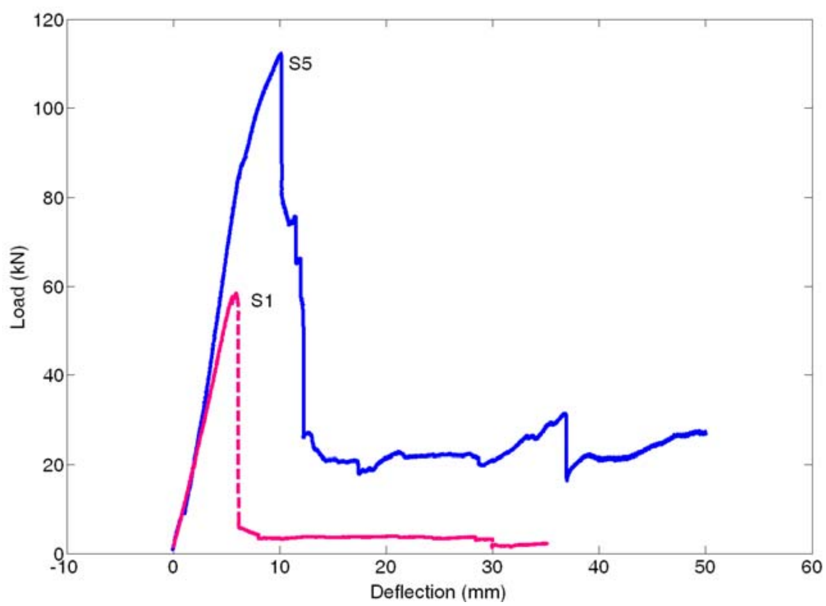


Fig. 3 Load-deflection curves for control beam S1 and CFRP strengthened beam S5

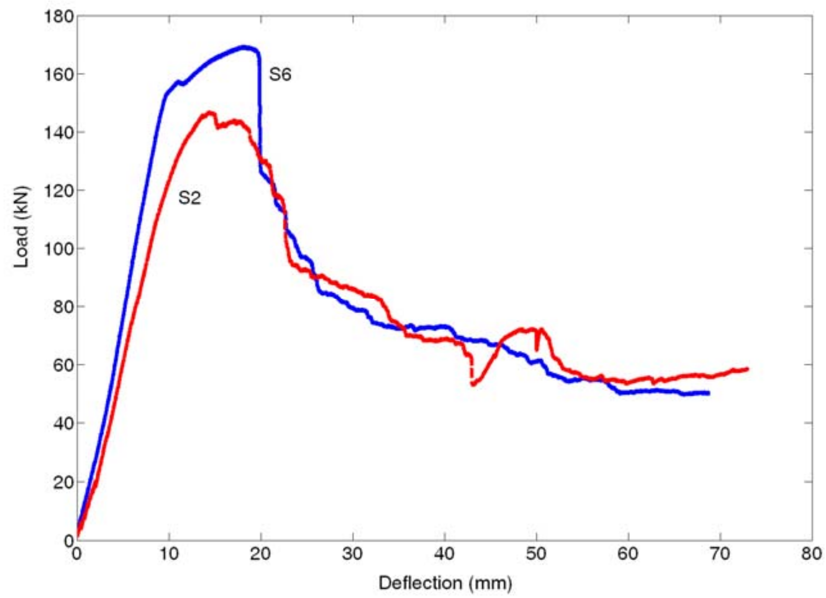


Fig. 4 Load-deflection curves for control beam S2 and CFRP strengthened beam S6

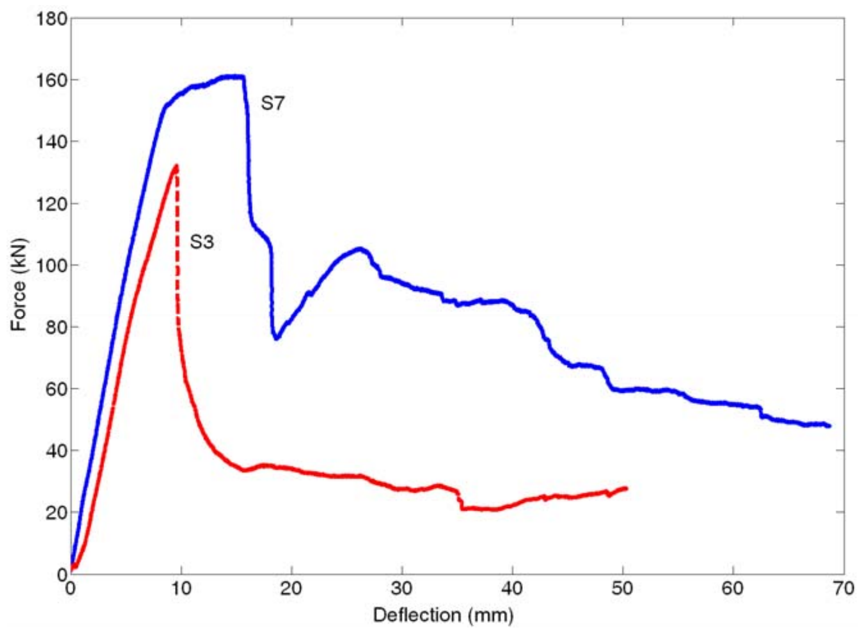


Fig. 5 Load-deflection curves for control beam S3 and CFRP strengthened beam S7

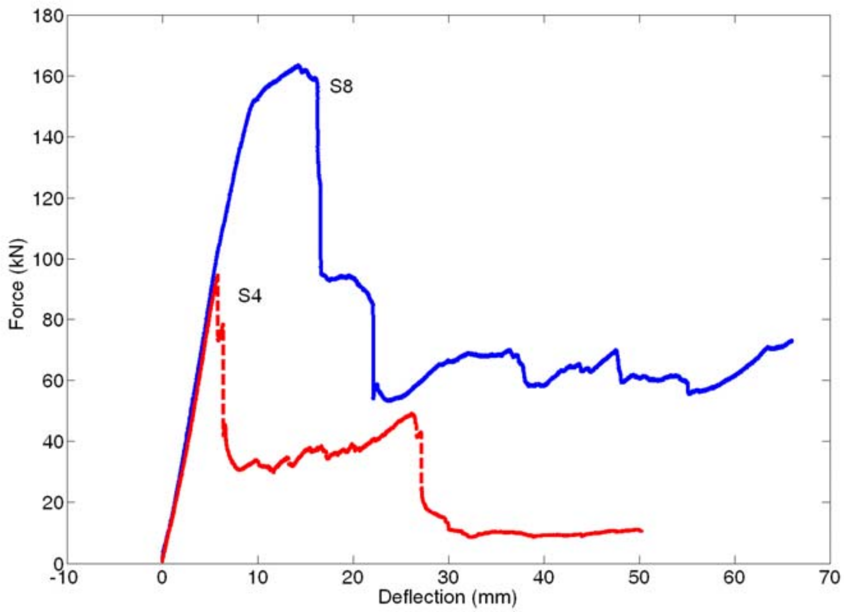


Fig. 6 Load-deflection curves for control beam S4 and CFRP strengthened beam S8

CONCLUSIONS

1. The use of U-wrapped CFRP composite laminates is an effective technique to enhance the shear capacity of RC beams.
2. The externally bonded U-wrapped CFRP strip laminates can increase the shear capacity of the beam significantly by 16% to 92% than that of the control beams, depending on the steel stirrups spacing in beams as investigated.
3. When beams having no shear steel reinforcement being strengthened with CFRP laminate strips, their maximum load capacity increases by 92% than that for control beam.
4. Strengthening beam having shear steel reinforcement spaced at d/4 slightly increased its maximum load by about 16% than that for control beam. Beams were also strengthened with CFRP laminate strips.
5. For strengthened beam with no shear steel reinforcement, the failure mode was rupturing of CFRP laminate indicating full utilization of the shear strengthening laminate.
6. Other mode of debonding failure was noticed in some beams. Therefore, anchoring the ends of the U-wrapped CFRP might eliminate such failure mechanism.

REFERENCES

1. Malvar, L.; Warren, G.; and Inaba, C., "Rehabilitation of Navy Pier Beams With Composite Sheets," *Second FRP International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Aug., Gent, Belgium, 1995, pp. 533-540.
2. Chajes, M.; Januska, T.; Mertz, D.; Thomson, T.; and Finch, W., "Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics," *ACI Structural Journal*, V. 92, No. 3, May-June 1995, pp. 295-303.

3. Norris, T.; Saadatmanesh, H.; and Ehsani, M., "Shear and Flexural Strengthening of R/C Beams with Carbon Fiber Sheets," *Journal of Structural Engineering*, V. 123, No. 7, 1997, pp. 903-911.
4. Kachlakev, D., and McCurry, D., "Testing of Full-Size Reinforced Concrete Beams Strengthened with FRP Composites: Experimental Results and Design Methods Verification," *Report* No. FHWA-OR-00-19, U.S. Department of Transportation Federal Highway Administration, 2000,.
5. Sato, Y.; Ueda, T.; Kakuta, Y.; and Tanaka, T., "Shear Reinforcing Effect of Carbon Fiber Sheet Attached to Side of Reinforced Concrete Beams," *Advanced Composite Materials in Bridges and Structures*, M. M. El-Badry, ed., pp. 621-627, 1996.
6. ACI 440 American Concrete Institute committee 440, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute committee 440, Farmington Hills, Michigan, 2002, 45 pages.
7. Alkhrdaji, T.; Wideman, M.; Belarbi, A.; and Nanni, A., "Shear Strength of GFRP RC Beams and Slabs," *Proceedings of the International Conference*, Composites in Construction-CCC 2001, Porto/Portugal, 2001, pp. 409-414.
8. Machida, A., "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials," Concrete Engineering Series 23, Japan Society of Civil Engineers, JSCE, Tokyo, Japan, 1997, 325 pp.
9. Razaqpur, A. G.; Isgor, O. B.; Cheung, M. S.; and Wiseman, A., "Background to Shear Design Provisions of the Proposed Canadian Standard for FRP Reinforced Concrete Structures," *Proceedings of the International Conference*, Composites in Construction-CCC 2001, Porto/Portugal, 2001, pp. 403-408..
10. Lubell, A.; Sherwood, T.; Bentz, E. C.; and Collins, M. P., "Safe Shear Design of Large, Wide Beams," *Concrete International*, V. 26, No. 1, Jan. 2004, pp. 66-78.
11. Joint ACI-ASCE Committee 445, "Recent Approaches to Shear Design of Structural Concrete," *Journal of Structural Engineering*, ASCE, V. 124, No. 12, 1998, pp. 1375-1417.
12. Grace, N.F., Sayed, G.A., Soliman, A. K., and Saleh, K. R., Strengthening Reinforced Concrete Beams Using Fiber Reinforced Polymer (FRP) Laminates. *ACI Structural Journal* Vol. 96, No. 5, 1999, pp 865-874.
13. Grace, N.F., Abdel-Sayed, G., and Rajheb, W.F., Strengthening of Concrete Beams Using Innovative Ductile Fiber-Reinforced Polymer Fabric. *ACI Structural Journal* Vol. 99, No. 5, 2002, pp. 692-700.
14. Tavakkolizdeh and Saadatmanesh, Repair of damaged steel-concrete composite girders using carbon fibre reinforced polymer sheets, ASCE Journal of Composite 2003, 7(4): 302 – 322
15. El-Hacha R. and Rizkalla S. H., Near-surface mounted fibre-reinforced polymer reinforcements for flexural strengthening of concrete structures, ACI structural journal, 101(5), 2004, pp. 717 – 721
16. Nanni, A.; Bakis, C. E.; Boothby, T. E.; Lee, Y. J. and Frigo, E. L... Tensile Reinforcement by FRP Sheets Applied to RC. 9C/1-8, ICE 97 International Composites Exposition, Jan., Nashville, Tenn., 1997, pp. 9C/1 to 8.
17. Lopez M.M. and Naaman A.E. Concrete cover failure or tooth type failure in RC beams strengthened with FRP laminates, Fibre-Reinforced polymer reinforcement for concrete structures (Proceeding of the sixth international symposium on FRP reinforcement for concrete structures (FRPRCS-6), (Tan K.H. editor), Vol 1, 2003, pp. 317 – 726
18. ISIS-M03-01, "Reinforcing Concrete Structures with Fiber Reinforced Polymers," The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures, ISIS Canada, University of Winnipeg, Manitoba, Canada, 2001, 81 pp.

19. CAN/CSA S806–02, "Design and Construction of Building Components with Fibre Reinforced Polymers," Canadian Standards Association, Rexdale, Ontario, Canada, 2002, 177 pp.
20. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (318R-02)," American Concrete Institute, Farmington Hills, Mich., 2002, pp. 184-186, 213-232, 337-342.
21. Kani, G. N. J., "The Riddle of Shear Failure and its Solution," ACI JOURNAL, *Proceedings* V. 61, No. 2, Feb. 1964, pp. 441-467.
22. Kani, G. N. J., "How Safe are Our Large Reinforced Concrete Beams," ACI JOURNAL, *Proceedings* V. 64, No. 3, Mar. 1967, pp. 128-141.
23. Bažant, Z. P., "Fracturing Truss Model: Size Effect in Shear Failure of Reinforced Concrete," *Journal of Engineering Mechanics*, ASCE, V. 123, No. 12, 1997, pp. 1276-1288.