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Influence of Soffit Bonded CFRP Strips on Shear Capacity and Failure Type of RC Beams without Stirrups

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Abstract

Presented herein is an experimental investigation on the efficacy of soffit-bonded longitudinal CFRP strips in upgrading the load-carrying capacities of RC beams without steel stirrups, a necessary disposal when the wrapped or the side transverse CFRP strips bonding is impossible due to the inaccessibility of the beam sides. The program deals with testing eight RC beams destitute of web reinforcement and strengthened by various CFRP strips combinations of soffit-bonded strips frequently accompanied by longitudinal top-bonded ones, in addition to three unstrengthened beams one of which is provided by the minimum amount of steel stirrups. The purpose is to evaluate their prime performances (shear resistance and concrete fracture mechanism with CFRP failure modes) and complementary properties (stiffness, ductility and energy absorbability). Effects of the fiber orientation in the CFRP strips and the shear span-to-depth ratio are specially attended. Test results demonstrate the profitable role of the flat soffit-bonded CFRP strips in delaying shear failure, admitting additional deflection and elevating the energy absorbability by 22 %. They also manifest the effective role of the longitudinal full-length top CFRP strips in contributing the resistance to shear failure announced by its transverse rupture. The advantageous effect of the two narrow side “crooks” along the soffit-bonded CFRP strips appears in the substantial increase in the energy absorbability and ultimate resistance attributed to magnifications in the concrete fracture pattern and CFRP debonding.

Keywords: CFRP; Shear; Strengthening; Reinforced concrete; Soffit-bonded.

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1. Introduction

Strengthening of RC beams using carbon fiber reinforced polymer (CFRP) has gained wide acceptance over the last two decades due to its high strength to weight ratio, high stiffness, light weight, flexibility, ease of installation, and resistance to corrosion as compared to other materials. CFRP composite strips are widely used to externally strengthen RC beams in flexure and shear. The technique of externally strengthening RC beams in shear by binding transverse (vertical or inclined) CFRP strips to the beam's two sides (or wrapping them) via epoxy adhesives showed a considerable enhancement in the load-carrying capacity and stiffness of the strengthened specimens. The recent twenty years testified extensive experimental research studies on strengthened RC beams in shear [1,2,3,4,5,6,7,8,9,10], the results showed an increases in the shear capacities of the strengthened beam specimens with CFRP laminates up to 58 % over the control unstrengthened specimens. The onset of the third millennium attended the first development of a layered nonlinear FE model in an attempt to foretell the response of up-to-failure loaded RC beams strengthened by external CFRP strips [11], followed by several attempts in the same respects [12,13,14,15,16,17] till 2015 [18].

2. Significance and Objectives

Strengthening the shear deficient RC beams by longitudinal soffit bonded CFRP strips to elevate their aptitude to withstand service lateral loads becomes profoundly necessary when their sides are not accessible to efficiently attach neither the traditional transversely aligned CFRP strips at webs nor the wrapped ones (popular in multi-girder bridge decks). Hence, the gross objective of this research is to investigate the efficacy of such CFRP strengthening to provide that capability. In specific, the discrete objectives are:

1. Examining the validity of this system of strengthening by externally bonded longitudinal soffit-bonded CFRP strips with or without top bonded ones in upgrading -as a prime importance- the shear resistance of RC beam destitute of steel stirrups, then the failure mode, and elevating the energy absorbability.
2. Addressing the most efficient patterns of external strengthening by longitudinal bottom CFRP strips by investigating performances (in the respects specified in the former item) of some suggested combinations of soffit and top longitudinal strips.
3. Investigating the role of reducing the shear span-to-depth ratio in increasing the shear resistance of such strengthened RC beams.

3. Experimental Program

3.1. Scheme

The experimental program was founded on studying the effects of three parameters on the performance of shear deficient RC beam strengthened by soffit bonded CFRP strips loaded upto failure by four-point-load system. Those parameters are: the shear span-to-effective depth ratio a/d, shapes of the attached CFRP strips, and their amounts and distributions.

3.2. Description of test specimens

Eleven reinforced concrete beams were loaded and tested up to failure by four-point-load system. All beams cross-sections were of 150 mm breadth and 200 mm depth, the overall length was 1500 mm with clear span 1300 mm. All beams without web reinforcement except one beam with minimum web reinforcement according to the ACI 318M-14 [19]. They are all longitudinally reinforced with three deformed bars of 12 mm diameter at bottom and two deformed bars of 4 mm diameter at top. All test beams were devoid of transverse steel reinforcement except one beam with minimum steel web reinforcement formed from 4 mm diameter deformed bars provided at a spacing of 85 mm on center. All beams were tested with (a/d) ratio equal to either 2.5 or 3. The specimens were divided into two groups A and B. Group A with (a/d) equal to 3 and group B with (a/d) equal to 2.5. Group A involves six beams strengthened by CFRP, and two reference beams. These reference beams have not beam strengthened by CFRP strips. Figure 1 shows details of Group A. Group B involves two beams strengthened by CFRP, and one reference beams (not strengthened by CFRP). Figure 2 shows details of Group B.

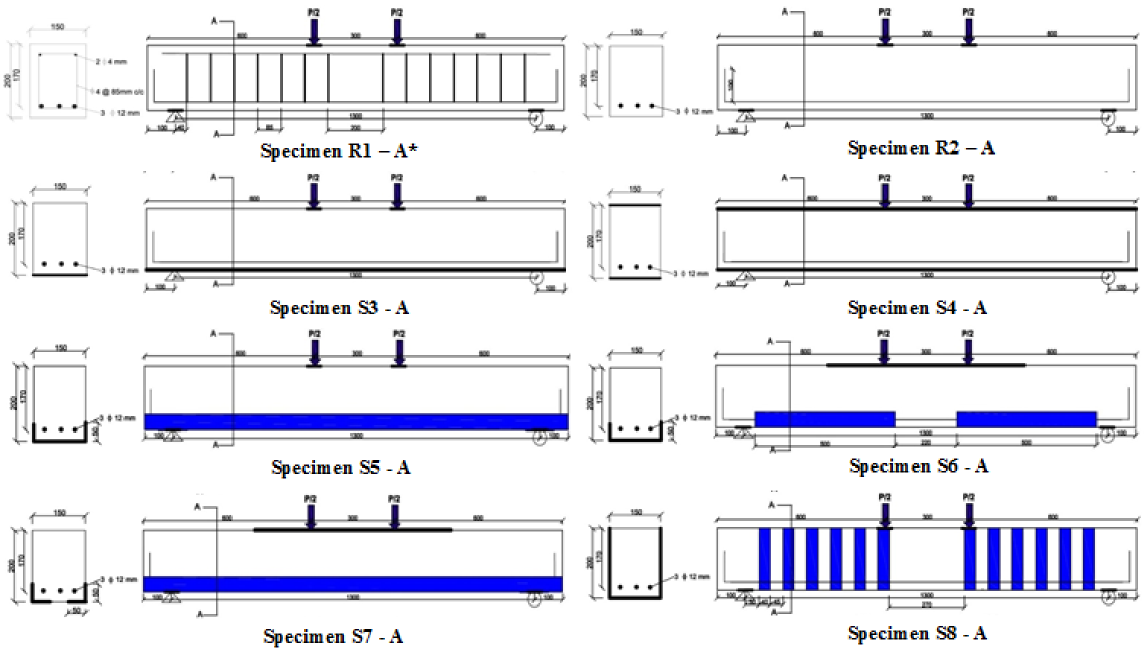


Figure 1: Group A, control and strengthened specimens details.

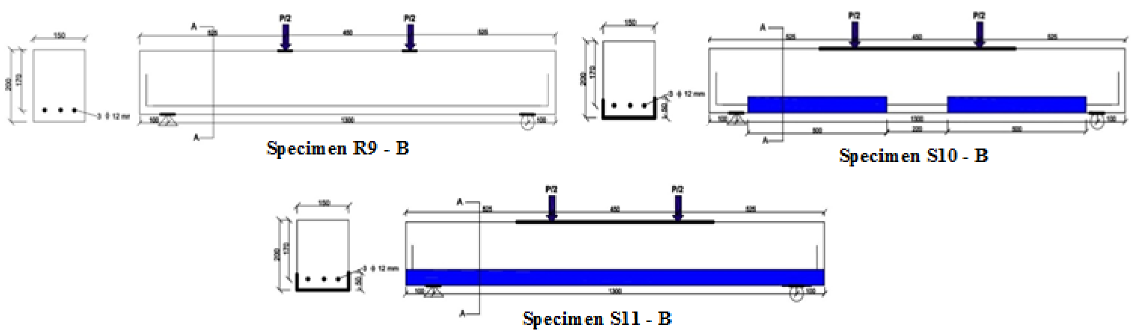


Figure 2: Group B, control and strengthened specimens details.

3.3. Material properties

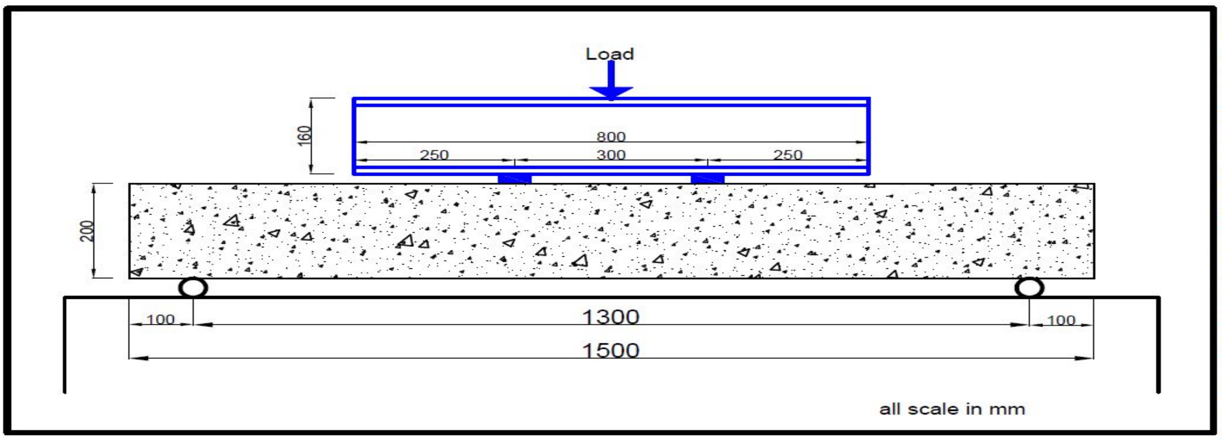
The eleven beam specimens, being cast in the same concrete mix production batch with their disciple control specimens (including standard 150 x 300 mm cylinders for compressive strength), had an average 28-day concrete compressive strength of 37 MPa. The used 12 mm diameter steel rebars had average values of elastic modulus, yield stress, tensile strength, and elongation percentage at failure of 199.9 GPa, 610 MPa, 706 MPa and 8.75 %, respectively which were extracted from a standard tensile test of a 10 mm/min rate. Marks and mechanical properties of the used 0.131 mm thick CFRP strips and their epoxy adhesive are given in Table 1. The strips were attached to concrete surfaces by Sikadur-330 epoxy. Consisting of two liquid components with a mixing ratio of 1:4. The advantage of using epoxy is that no primer is needed, easy to mix, and it is suitable for dried concrete surfaces.

Table 1: Mechanical properties.

Material	Design thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Elongation at failure (%)
SikaWrap_230 C	0.131	234	4300	1.8
Sikadur_330	---	4.5	30	0.9

3.4. Test setup

All beams had a total span length of 1500 mm. They were tested under four-point bending using Universal Testing Machine (UTM) as shown in Figure 3a and b. Plates were used as supports at both ends. The load was applied to the beam using a hydraulic actuator with a capacity of 1000 kN at a rate of 2 mm/min. Beam deflection was measured at mid span using LVDT. Load–deflections were continuously recorded during the test. Crack formations were also marked on the beams throughout the test.



(a)

(b)

Figure 3: Test setup: (a) schematic diagram, (b) photograph.

4. Presentation and Discussion of Results

4.1. Fundamental effects of CFRP strips configuration and amounts

Note: Responses of the CFRP strengthened test beams are discussed and assessed herein in comparison with their reference unstrengthend beams.

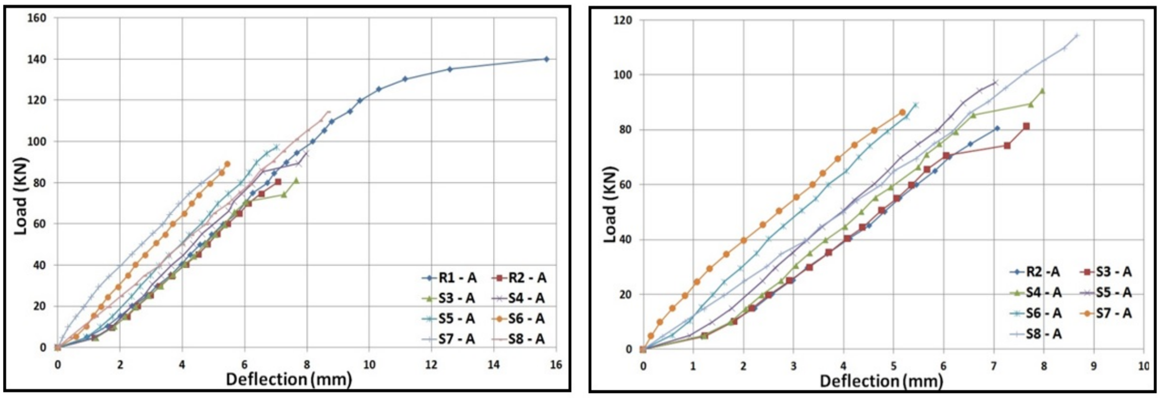
i) Directly measured responses for Group A beams (w.r.t. Figs. 1 and 4)

Beam S3-A revealed slight increase in the ultimate load at failure accompanied with significant increase in the deflection value which may be reasonably attributed to the profitable role of the CFRP strips in delaying the shear failure while the applied load was being monotonously increased. Moreover, beam S4-A exhibited a qualitatively close behavior to the former one with considerably significant increase in the value of the failure load, thus indicating the role of the top CFRP strip, as a participant, in withstanding the shear failure due to the applied load. Furthermore, it has provided the beam by significant plasticity.

Beam S5-A (provided by a longitudinal bottom-bonded full-length “crooked” CFRP strip bonded to and enclasping the beam soffit to a slight height not exceeding 50 mm at each side as shown in Figure 1) gained significant increase in the failure load value (even slightly larger than that of beam S4-A) and favorite delays in the first-crack appearances for both flexure and shear (i.e. increases in their associated applied load values). This phenomenon refers to the role of that CFRP strengthening pattern in arresting the initiation -then the propagation- of the two types of cracks.

Beam S6-A revealed significant rise in the stiffness and the early load-bearing ability accompanied by small deflection. But a sudden failure has taken place. A change in the bottom longitudinal CFRP strip pattern wasintroduced in beam S7-A with keeping the top style of CFRP strip unchanged. The bottom CFRP strengthening style has consisted of two longitudinal strips bonded to the two corners along the whole span. The behavior was close to that of the former beam with achieving higher stiffness.

Beam S8-A (provided by a high amount of the traditional CFRP strengthening pattern recommended by the ACI-440 committee [20] for shear resistance) exhibited significantly higher load carrying capacity, but still governed by shear failure (diagonal shear cracks running in the shear span and extending over beam depth till the top face). That result confirms the insight into the external CFRP-strip strengthening implying that no configuration or pattern of that strengthening is capable of turning the unfavorite brittle shear failure of shear under-reinforced concrete beams into the ductile bending one, but merely elevating its load-carrying capacity.



(a) with R1-A **(b) without R1-A**

Figure 4: Load versus midspan deflection of specimens in Group A.

ii) Directly measured responses for Group B beams (w.r.t. Figs. 2 and 5)

The CFRP-strip strengthening of beam S10-B was identical to that of beam S6-A in Group A except that its soffit CFRP strip only was bond such that its fibers was oriented by 90 degrees to that bonded at soffit of beam S6-A. The latter fiber orientation revealed higher load resistance and larger deflection. It exhibited smaller deflection than the references beam R9-B; furthermore, its stiffness was increased by the strengthening technique. Meanwhile, beam S11-B (strengthened at its bottom by a full span length “crooked” CFRP strip and a one-third span length strip at its top face) revealed valuable increases in stiffness, load resistance, and deflection extent till failure when compared with the other seven CFRP strengthened beams shown in Figure 6.

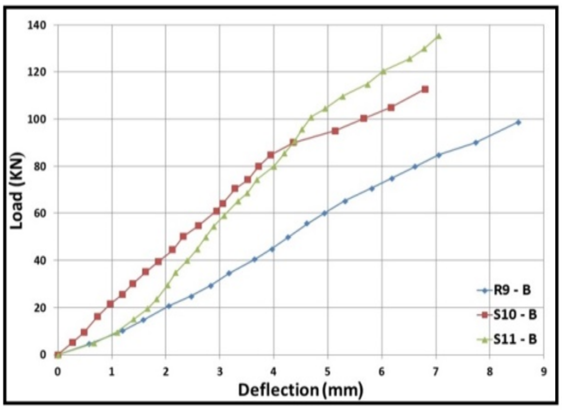


Figure 5: Load versus midspan deflection of specimens in Group B

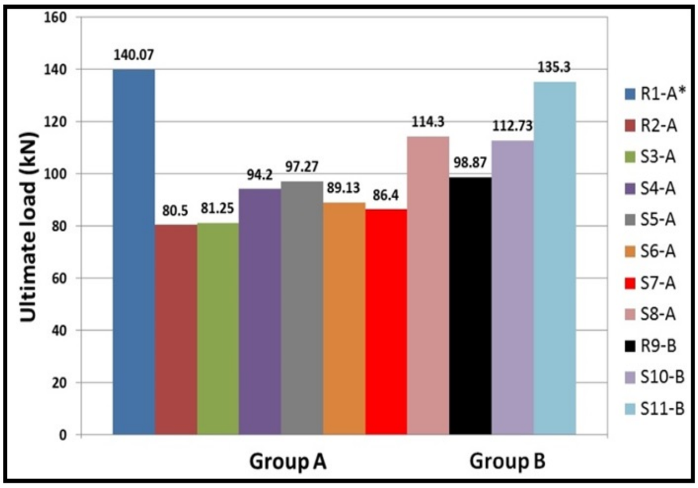


Figure 6: Bar representation of the ultimate loads for all beam specimens.

iii) Failure modes of Group A beams (w.r.t. Figure 7 and Figure 8a to h)

A typical flexural fracture pattern due to yielding of bottom tension reinforcement is observed on beam R1-A* (provided by the minimum steel stirrups) at failure, while a perfect transversely oriented line of rupture in the top CFRP-strip adjacent to the end of failure shear crack accompanied the inclined shear mechanism (previously encompassing beams R2-A and S3-A) was observed on beam S4-A after fracture.

The soffit bonded “crooked” CFRP-strips enclasping the beam bottom beams S5-A, S6-A, S7-A, S10-A and S11-B revealed a modified shear fracture at failure announced by the reduced inclination path of the failure shear crack at the level of crook edge, which refers to a favorite delaying shear failure. For beam S5-A, an internal local debonding in that CFRP-strip at mid-height of each of the two sides “crooks” of the soffit bonded CFRP-strip; adjacent to the lower end of each of the two shear cracks (i.e. four locations of CFRP-strip debond) took place.

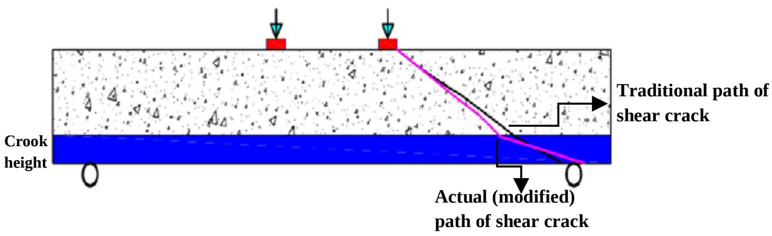


Figure 7: Schematic profile of a typical RC beam with a soffit bonded "crooked" CFRP strip showing the positive effect of the "crook" in reducing the inclination of the diagonal shear crack.

A modified path of shear crack at failure within the “crook” level of the soffit-bonded “crook” CFRP-strip enclasping the bottom of beam S6-A of the same trend occurred in the final step of loading that beam, with suffering significant additional decrease in the inclination of the path of shear crack within the “crook” height.

That additional reduced inclination of the shear crack path is favorite in increasing the shear fracture surface thus delaying the shear failure instant and raising the shear failure resistance. Moreover, the interior end of each of the two soffit-bonded "crook" CFRP strips (extending along the two shear spans) sustained a preferable rupture at failure. Finally, the bottom fracturing, debonding and rupture was accompanied by rupture of the top CFRP strip (similar to that of beam S4-A), thus extra raising its load resistance and other aspects of performance. Obviously, the fracture appearance at the level range of the bottom "crooked" CFRP strip for beam S7-A is similar to that of beam S6-A with the exception of the rupture location of that bottom CFRP strip since it was extending along the full length of the latter beam. However, no rupture emerged in the top CFRP strip where its response at failure was restricted to local debonding.

As easily noticed concerning fracture features of beam S8-A traditional CFRP-strip strengthening for shear as recommended by ACI-440 committee: that utilization of that traditional configuration of external CFRP-strip strengthening for shear is incapable of altering the undesired mode of sudden shear failure to the favorite mode of cautionary bending failure (due to yield of tensile steel), but merely elevating the shear failure resistance. The transverse CFRP shear strips bonded across the two sides of the web (along the two shear spans of beam S8-A) suffered debonding at locations where the failure shear crack crosses them, with preservation of the spanwise symmetry.

Figure 8: Typical failure modes for specimens Group A.

iv) Failure modes of Group B beams (w.r.t. Figure 9a to c)

The fracture pattern at failure of S10-B beam is of the same features at those for beam S6-A (within Group A which is apparently of the same CFRP-strip configuration of the current beam bottom “crooked” strip by 90°), but of higher degree of debond of that strip due to its described fiber orientation. In precise, that 90° fiber orientation of the bottom “crooked” CFRP strip has rendered the vertical direction of the “crook” to be “the stronger”, thus rupture of that CFRP strip has not occurred but accompanied by debond of more intensity

The features of the fracture pattern of failure for beam S11-B resemble -in appearance- those of beam S7-A (of almost the same configuration of the CFRP strips for the current beam). The single exception is that the decrease of the shear span-to-depth ratio a/d in the case of beam S11-B raised its load resistance and the efficacy of its CFRP-strips, thus leading to more advanced debond and unprecedented rupture of much higher intensity in the soffit bonded “crooked” CFRP strip at the support.

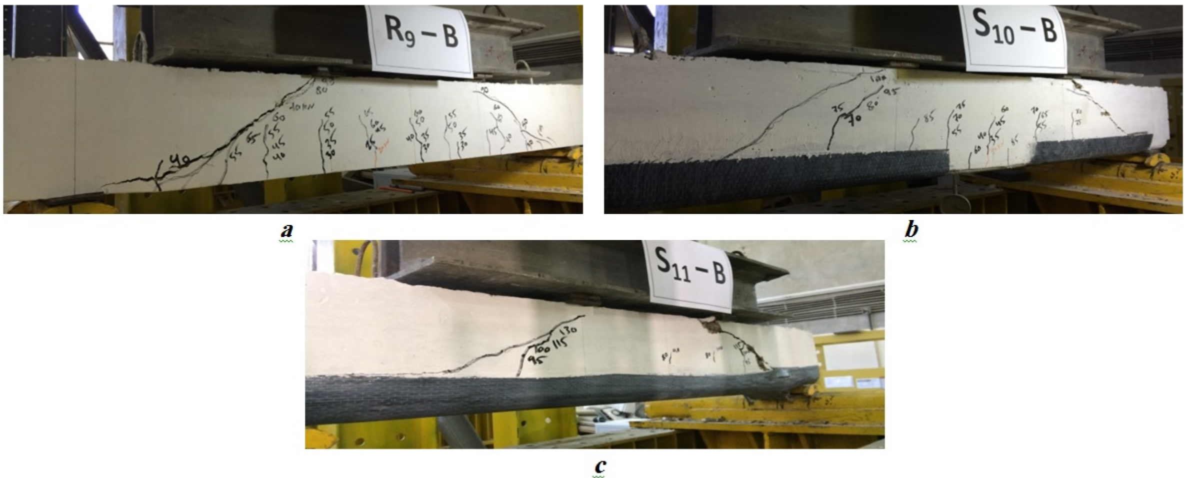


Figure 9: Typical failure modes for specimens Group B.

v) Flexural toughness (w.r.t Table 2)

The basic concept of toughness deals with the amount of energy per volume that a material can absorb before rupture. In beams strengthened by external CFRP-strips for shear, the efficient pattern of shear strengthening is that giving rise to substantial elevation in that energy absorption ability in which the CFRP-strips participate a valuable fraction.

Toughness is represented by the “modulus of toughness (MOT)” which is equal to the area under the load-deflection curve. On that basis values of that modulus have been calculated for the eleven test beams and presented in Table 2. In the following paragraphs the toughness properties of the test beam are assessed for each group individually.

Table 2: Shear and Flexural parameters for the eleven test beams determined by interpretation of their measured responses drawn from the experimental loading and the graphical representations of their load-deflection relations.

Specimens	$P_{cr.F}^{(1)}$ (kN)	$P_{cr.V}^{(2)}$ (kN)	$P_u^{(3)}$ (kN)	$\%\Delta P_{cr.V}^{(4)}$	$\%\Delta P_u^{(4)}$	$\delta_{cr.V}^{(2)}$ (mm)	$\delta_u^{(3)}$ (mm)	$MOT^{(5)}$ (kN.mm)	$\%\Delta MOT^{(6)}$
R1 – A*	25	75	140.1	15.4	74	6.2	15.7	1331.1	455.3
R2 – A	25	65	80.5	----	----	5.8	7.1	239.7	----
S3 – A	45	65	81.2	0	0.9	5.6	7.6	291.6	21.6
S4 – A	45	75	94.2	15.4	17	5.8	7.9	358.8	49.7
S5 – A	65	85	97.3	30.8	20.8	6.1	7	312.4	30.3
S6 – A	30	70	89.1	7.7	10.7	4.4	5.4	233	-2.8
S7 – A	50	75	86.4	15.4	7.3	4.3	5.2	247.3	3.2
S8 – A	25	80	114.3	23.1	41.9	6.4	8.6	483.2	101.5
R9 – B	20	65	98.9	----	----	5.3	8.5	420.8	----
S10 – B	30	70	112.7	7.7	14	3.9	6.8	442.7	5.2
S11 - B	75	100	135.3	53.8	36.8	4.5	7	471.4	12

(1) Applied load at instant of the first flexural crack appearance at bottom beam.
(2) Applied load and midspan deflection at instant of appearance of the first shear (i.e. diagonal tension) crack.
(3) Applied load and midspans deflection at ultimate stage.
(4) Percentage differences of the shear cracking loads and the corresponding ultimate loads relative to the corresponding values for the reference beam for each group.
(5) Modulus of toughness; which is equal to the area under the load versus midspan deflection curve for each of the eleven beams.
(6) Percentage difference of the modulus of toughness of the specified beam relative to the relevant reference beam.

vi) Relative modulus of toughness ($MOT_{rel.}$) for Group A beams (w.r.t. Figure 10)

Based on the numerical values of the MOT given in Table 2, the percentage of relative values of that parameter (in proportion to its absolute value for the reference beam of this group, beam R2-A) for each of the other seven beams of the group are presented diagrammatically. Where the beam of traditional CFRP-strip strengthening recommended by ACI-440 committee revealed the highest relative toughness value attaining 202 % of the absolute MOT value of the reference beam R2-A. Subsequent to it and not far below, beam S4-A became to verify the efficient role of the CFRP-strip bonded longitudinally along the entire length of the top face of the beam.

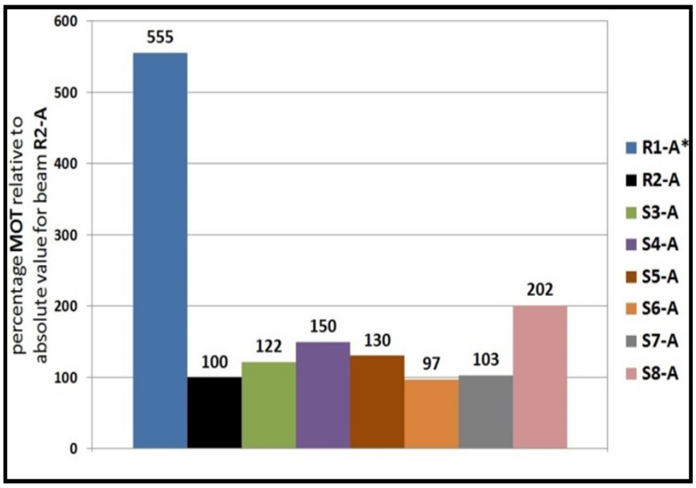


Figure 10: Bar representation of the relative MOT of the test CFRP-strengthened test beams of Group A beams relative to the absolute value for R2-A.

vii) Relative modulus of toughness ($MOT_{rel.}$) for Group B beams (w.r.t. Figure 11)

Beam S11-B which was the superior of the group in regard to stiffness, resistance, and deflection extents exhibited the highest relative toughness value reaching 137 %.

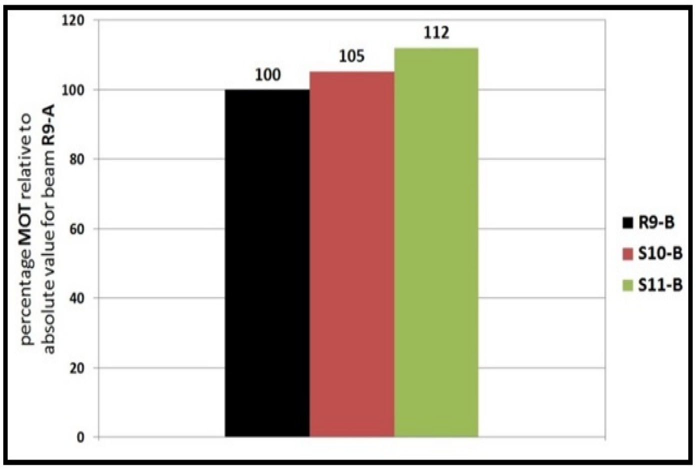


Figure 11: Bar representation of the relative MOT of the test CFRP-strengthened test beams of Group B beams relative to the absolute value for R9-A.

4.2 Influence of the Shear Span-to-Depth Ratio on Performances of the CFRP-Strengthened Beams

With reference to Table 3 it is observed that the influence of that parameter is considered in two respects, the first respect concerns the ultimate load; P_u, while the second one is associated with the modulus of toughness; MOT. Each respect of response is presented and discussed in a separate article.

Table 3: Variation percentages in shear and flexural parameters due to varying values of shear span-to-depth ratios (from 3.0 to 2.5) for three cases of CFRP strengthening.

	a/d	P_u	$\%\Delta P_u$	AFS	%ΔAFS	SD	%ΔSD	MOT	%ΔMOT
R2-A	3	80.50	----	12.12	----	1.15	----	239.72	----
R9-B	2.5	98.87	----	11.59	----	1.61	----	420.80	----
S6-A	3	89.13	10.72	16.41	35.39	1.23	6.96	233.04	-2.79
S10-B	2.5	112.73	14.02	16.57	42.97	1.71	6.21	442.72	5.21
S7-A	3	86.40	7.33	16.70	37.78	1.21	5.22	247.29	3.16
S11-B	2.5	135.30	36.85	19.22	65.83	1.55	-3.73	471.37	12.02

Note: All parameters notation are as defined in Table 2

viii) Variation of the load-carrying capacity with shear span-to-depth ratio (w.r.t. Figure 12)

It is observed that reducing a/d from 3 in beam S6-A to 2.5 in beam S10-B, (i.e. by 16.7 % reduction in a/d value) realized an increase in the load carrying capacity (i.e. ultimate load; P_u) reaching 30.78 %. On the other hand, when the a/d ratio for beam S7-A was reduced from 3 to 2.5 (to attain beam S11-B) the increase in the ultimate load P_u became as huge as 402.73 %.

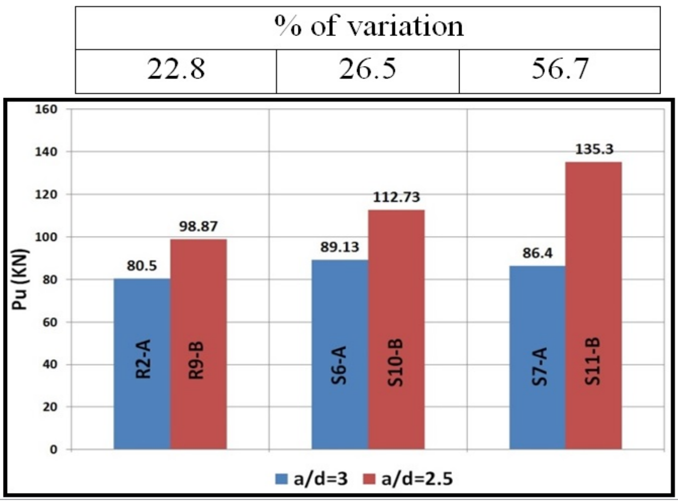


Figure 12: Variation of the ultimate load values with the value of span-to-depth ratio (from 3.0 to 2.5) for three conditions of CFRP strengthening patterns.

ix) Variation of modulus of toughness MOT with shear span-to-depth ratio (w.r.t. Figure 13)

Test results of Group A (of the larger value of a/d ratio which is equal to 3) show that the CFRP-strip strengthening patterns of beam S6-A and S7-A (consisting of partial top and bottom CFRP layers) did not achieve an increase in the MOT value. On the contrary, test results of Group B (of the smaller value of a/d ratio being 2.5) revealed that the CFRP-strip strengthening pattern that is almost similar to that of the beam S7-A (which is represented by that of the beam S11-B consisting of top and bottom CFRP-strips) accomplished an increase in the MOT value reading 12.02 %.

% of variation		
75.5	90	90.6

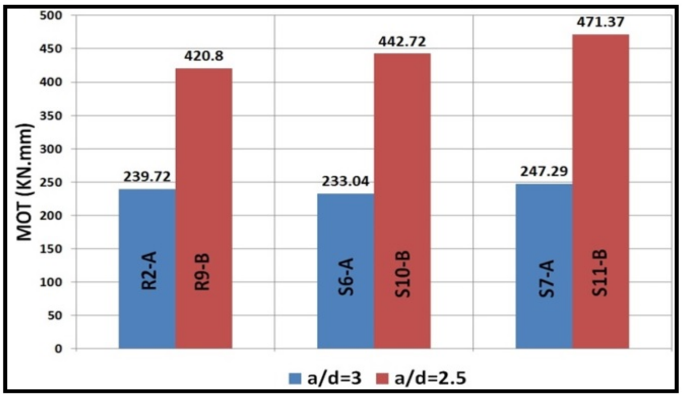


Figure 13: Variation of the MOT values with the value of span-to-depth ratio (from 3.0 to 2.5) for three conditions of CFRP strengthening patterns.

5. Conclusions

1. The flat "uncrooked" soffit bonded longitudinal CFRP strip delays shear failure, admits additional deflection, and elevates the modulus of toughness by 21.66 %.
2. Longitudinal full-length top CFRP strip stands as a vital participant in withstanding shear failure by increasing the ultimate load certainly due to diagonal tension cracking significantly accompanied by transverse rupture line in the top CFRP strip, and substantially increasing its energy absorbability upto failure by about 31 %.
3. The "crooked" soffit bonded longitudinal CFRP strip significantly increases load at initial shear cracking ultimate load, and energy absorbability by 31 %, 21 % and 30 %, respectively. Those substantial advantages are attributed to the modified failure shear fracture announced by the reduced inclination path of the failure shear crack within the "crook" level representing favorite delaying shear failure accompanied by internal local debonding on the CFRP-strip at that location.
4. In addition to its distinctive role in increasing shear stiffness, the top CFRP strip, along the interior one-third length (with the "crooked" soffit-bonded strip) it gains innegligible rise in ultimate load by an average of 9 % with preserving the advantages of the "crook" explained in the former item.
5. Providing beams by perfectly full-length top CFRP-strips (in addition to the primary soffit-bonded

ones) significantly elevates their performances represented by extremely raising their energy absorbability upto rupture and considerably increasing their ultimate load resistances by about 50 % and 17 %, in average, respectively.

6. The 16.7 % reduction in the shear span:depth ratio causes valuable increases in the load-carrying capacities and the energy absorbability's of the CFRP-longitudinal strip strengthened beams attaining 31 % and 13 % in average, respectively.
7. The 90° fiber orientation in the "crooked" soffit bonded CFRP-strips plays an important role in elevating the load resistance and deflection at failure, in precise, orienting the fiber direction in the "crooked" bottom CFRP strip enclasping the beam soffit by 90 degree such that it (fiber direction) is aligned transversely renders the vertical direction of the "crook" to be the stronger, keeping those CFRP strips unruptured but furtherly debonded.
8. It is found that the optimum pattern consists of "crooked" soffit-bonded and top intermediate one-third length CFRP-strips. That pattern gains substantial increases in values of the shear cracking load, ultimate load, energy absorbability attaining about 37 %, 54 % and 12 %, respectively, in addition to stiffness rise and deflection extent. It also exhibits more advanced debond and unprecedented rupture of much higher intensity in the soffit-bonded CFRP strips at the support.
9. Superior performance of steel-stirrups provided beams without CFRP-strips is represented by the substantial ascendancy in the ultimate load and deflection values which attain levels of 36 % and 58 %, respectively, over the corresponding average values for the CFRP-strengthened beams (keeping a/d ratio unchanged).
10. In spite of achieving significant predominance's in values of the ultimate load and deflection attaining levels of 22 % and 23 %, respectively, the traditional shear-strengthening CFRP-strip pattern (i.e. transverse side strips) is incapable of altering the undesired mode of sudden shear failure to the favorite mode of bending failure, but merely elevating the shear failure resistance.

6. Recommendation Statement

For optimum strengthening of shear deficient reinforce concrete beams by longitudinal soffit and top bonded external CFRP strips (to overcome the inaccessibly of beams sides) it is suggested to use full-length "crooked" soffit bonded ones accompanied by flat top ones.

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