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SHEAR BEHAVIOR OF HIGH STRENGTH CONCRETE BEAMS REINFORCED WITH GFRP BARS AND STRENGTHENED BY CFRP SHEETS

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Abstract: This paper presents an experimental investigation on shear behavior of Glass Fiber Reinforced Polymer (GFRP) reinforced high strength concrete beams externally strengthened in shear using Carbon Fiber Reinforced Polymer (CFRP) with various configurations: full side sheets, U-strips, vertical side strips and diagonal side strips; and three steel fiber ratios (0%, 0.5% and 1%). Results show that using GFRP bars as tension reinforcement instead of traditional steel bars slightly increases ultimate load but shows lower stiffness. Although internal steel stirrups are still the most effective way to enhance shear capacity of concrete beams, externally bonded CFRP U-strips can also be an effective alternative for durability and/or architectural considerations with about 85% strength efficiency and comparable load-deflection behavior. A combination of U-strips and sufficient amount of steel fiber is shown to perform better than steel stirrups in terms of increasing carrying capacity and decreasing deflections of GFRP reinforced concrete beams.

Keywords: *GFRP bars, CFRP Strengthening, Shear Behavior, High-Strength concrete.*

سلوك القص للعتبات الخرسانية عالية المقاومة المسلحة بقضبان GFRP و المقواة باستخدام صفائح CFRP

الخلاصة: يقدم هذا البحث دراسة عملية على سلوك القص للعتبات الخرسانية عالية المقاومة المسلحة بقضبان الياف الزجاج البوليمرية (GFRP) و المقواة باستخدام الياف الكاربون البوليمرية (CFRP)بانماط متعددة : الصفائح الجانبية الكاملة، الشرائح بشكل U، الشرائح الجانبية الشاقولية و الشرائح الجانبية القطرية و باستخدام الياف الفولاذ بثلاث نسب (0%، 0.5% و 1%). اظهرت النتائج ان استخدام قضبان (GFRP) كتسليح شد بدلا عن قضبان الفولاذ التقليدية زاد الحمل الاقصى بمقدار بسيط الا انه اظهر جساءة اقل. على الرغم من ان ركابات الفولاذ الداخلية لا زالت هي الطريقة الاكثر فاعلية في تحسين مقاومة القص للعتبات الخرسانية، فان شرائح CFRP المربوطة خارجيا بشكل حرف U يمكن ان تكون بديلا فعالا لاعتبارات الديمومة و المعمارية بكفاءة مقاومة حوالي 85% و سلوك حمل-هطول مقارب. لقد ظهر ان استخدام شرائح CFRP المربوطة خارجيا بشكل حرف U مع كمية كافية من الياف الفولاذ يؤدي افضل من الركابات الفولاذية من حيث زيادة قابلية التحمل و تقليل الهطول للعتبات الخرسانية المسلحة بقضبان (GFRP).

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1. Introduction

Fiber Reinforced Polymer (FRP) is a composite material consisting of carbon (CFRP), aramid (AFRP) and glass (GFRP) fibers embedded in a polymeric matrix to form various types of products such as bars, structural sections, plates and sheets [1,2,3].

The use of non-metallic FRP bars as an alternative to steel reinforcement bars in concrete structures has become accepted in construction industry mainly due to its excellent electrochemical corrosion resistance and its high mechanical performance [4, 5].

GFRP bars (which is the least expensive among other types of FRP) possess numerous well-defined properties such as high strength-to-weight ratios (10 to 15 times than steel), high tensile strength, excellent fatigue behavior, impact resistance, non-magnetization, non-conductivity while their thermal expansion is close to that of concrete [1,3,4,6,7]. However, the modulus of elasticity of GFRP bars (40-55 GPa) is lower than that of steel bars which lead to larger deflections and crack widths than steel reinforced concrete (RC) members [3,6,8,9,10]. Also, GFRP bars do not yield and behave elastically until sudden brittle rupture so it is recommended to avoid under reinforced design of GFRP reinforced concrete members [6, 7, 10, 11].

The use of externally bonded CFRP reinforcement to strengthen RC structures is becoming the most popular retrofit technique among the other alternatives because of their high strength and corrosion resistance as well as their light weight and formability which make them easy to handle and to apply on any flat, curved or geometrically irregular surfaces [2, 12, 13, 14]. These advantages make the use of FRP for structural strengthening more cost-effective and less effort and time requirements than the traditional techniques [5].

In general, FRP strengthening systems can be used to enhance the ductility as well as the flexural and shear capacity of all structural members (columns, beams, slabs, walls). Relatively less experimental data on the use of FRP systems for shear strengthening is available than for flexural or axial members [2, 12, 14, 15].

Three typical schemes of FRP sheets are commonly used for shear strengthening: complete wrapping (may not be possible for beams due to geometrical restrictions), U-wrap (on three sides) and side bonding (two separate sheets on opposite sides of the beam) [14, 15, 16]. The bond behavior at interface between concrete substrate and FRP sheet controls the performance of shear strengthening. Recent studies reported that debonding is the dominant mode of failure for beams strengthened with FRP and bonded on the sides only. FRP debonding almost never takes place in beams strengthened with complete wrap or U-wrap with anchorage systems where failure is governed by rupture of the FRP sheet [14, 15].

The contribution of externally bonded FRP sheets to shear capacity of RC beams depends on several parameters including the compressive strength of the concrete, the quality of the epoxy resin, the stiffness of the sheet, the wrapping configuration and the angle of fiber orientation [2]. However, it was observed that the shear strength of RC beams can be increased by 60-120% using externally bonded FRP sheets [5, 13]. U-wrap scheme provided the most effective strengthening for RC beams with about 119% increase in shear strength, while CFRP complete wrapping (if applicable) was more efficient in shear as well as flexural strengthening [5,17]. Using 45° fiber orientation led to greater strengthening effect and better control on the shear crack propagation [13]. Shear resistance of externally strengthened members with high internal shear reinforcement (stirrups) is less enhanced than the ones with low (or no) stirrups [14].

The objective of this research is to investigate the shear behavior of high strength concrete beams reinforced longitudinally with GFRP bars and externally strengthened in shear with bonded CFRP sheets/strips. Steel stirrups were not used in strengthened beams in order to fully exploit the benefits of using GFRP bars especially their light weight and corrosion resistance (GFRP stirrups are not easily fabricated since GFRP bars cannot be bent in the field), besides; elimination of stirrups provides greater architectural freedom, allowing nearly limitless structural member shapes. Instead, externally bonded light weight, non-corrosive CFRP sheets/strips were used as shear reinforcements. Effect of steel fibers on shear behavior was also investigated.

2. Experimental Program

Ten reinforced high strength concrete beams were cast and tested up to failure under shear in this work. Eight of them were longitudinally reinforced with deformed GFRP bars and two with traditional deformed steel bars. GFRP reinforced beams were externally strengthened in shear using CFRP with various configurations. Details of the main stages of the experimental program are given in the following.

2.1 Materials

Ordinary Portland Cement (ASTM Type I),naturalsandof4.75mm maximum size and crushed gravel with maximum size of 10mm were used for concrete mixtures. In addition, high strength concrete mixtures contained modified polycarboxylate based high range water reducing admixture (super plasticizer) (density = 1.09 kg/l at 20°C) and hooked end steel fibers with aspect ratio of 80 (length = 30mm and diameter = 0.375mm) and yield stress of 1130 MPa.

Deformed steel bars of nominal diameter of 8mm for closed stirrups (in two beams) and 12 mm for main reinforcement were used in steel reinforced beams, while 12 mm GFRP bars "Fig.1" were used in other beams. Table (1) gives the tensile test results conducted on samples of the used steel bars, while GFRP tensile properties are taken as reported by the manufacturer.

2.2 Mix Proportions

Based on several trial mixes, three high strength concrete(HSC) mixes that differ from each other only in volumetric steel fibers ratio (V_f) were adopted in this work as shown in Table (2).

Figure1.Samples of the used GFRP bars

Table 1.Tensile properties of steel and GFRP bars

Bar type	Steel		GFRP
Nominal diameter (mm)	8	12	12
Yield stress (MPa)	428	532	---
Ultimate strength (MPa)	537	715	1200
Modulus of elasticity (MPa)	200000		55000

Table2. Mix Proportions and properties of concrete

Mix	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	w/c	Super-plasticizer kg/m^3	Steel fiber* %	Steel fiber kg/m^3	Compressive strength MPa	Modulus of rupture MPa
HSC0	550	460	1058	0.35	8.5	0	0	66.5	5.9
HSC0.5	550	460	1058	0.35	8.5	0.5	39	70.8	7.5
HSC1	550	460	1058	0.35	8.5	1	78	73.1	8.3

*Percent of mix volume.

Three cubes of 150mm size and three prisms of 100x100x500 mm were cast with each mix to determine the compressive strength and modulus of rupture of concrete, respectively (Table (2)). Twenty four hours after casting, specimens were demolded and cured in water at room temperature for 28 days before testing.

2.3 Details of the Tested Beams

The specimen details are summarized in Table (3), where (R) and (G) refer to steel and GFRP bars, respectively, for longitudinal reinforcement and the numbers 0, 0.5 and 1 refer to steel fibers content as a percentage of concrete volume. The letter at the end of the beam designation refers to shear strengthening configuration as follows, N: no shear strengthening is provided, S: internal shear reinforcement (Φ8@75mm stirrups), U: external CFRP U-strips (50mm width and clear spacing on three sides), V: external CFRP side vertical strips (50mm width and clear spacing on two sides), D: external CFRP side diagonal strips (50mm width and clear spacing on two sides) and F: external CFRP side full sheets (full shear spans on two sides). Details are shown in "Fig.2".

All ten beams were identical in nominal dimensions with rectangular cross section of 150mm x 200mm, total length of 2000mm and reinforced longitudinally with 3 bars of 12mm diameter (two beams with steel bars and eight with GFRP bars). The reference beam (R-0-N) was neither reinforced with stirrups nor strengthened by CFRP sheets. Steel stirrups (Φ8@75mm) were used in two beams (R-0-S and G-0-S) while the other seven beams were externally strengthened with CFRP sheets within shear spans in various configurations (Table (3) and "Fig.2").

Table3. Details of the tested beams

Beam designation	Main reinforcement type	Steel fiber ratio (V_f) %	Shear strengthening configuration*
R-0-N	Steel	0	None
R-0-S	Steel	0	Stirrups
G-0-S	GFRP	0	Stirrups
G-0-F	GFRP	0	Side Full Sheets
G-0-U	GFRP	0	U-strips
G-0-D	GFRP	0	Side Diagonal Strips
G-0.5-U	GFRP	0.5	U-strips
G-0.5-V	GFRP	0.5	Side Vertical Strips
G-1-U	GFRP	1	U-strips
G-1-D	GFRP	1	Side Diagonal Strips

*See "Fig.2"

2.4 CFRP Strengthening Procedure

Before testing, beams were prepared for strengthening. First, the beam surfaces were smoothed (if rough or uneven) by grinding machine and cleaned by compressed air to obtain a sound, dry and contaminant free substrate.

A two part epoxy based resin (Sikadur – 330) was then brushed onto concrete surfaces within the pre-marked portions in shear spans, then, a CFRP sheet (FOSROC- Nitowrap FRC 230, "Fig.3") with 0.131mm thickness and 35500 kg/cm2 tensile strength was carefully applied on the beam surface until the resin was squeezed out between and through the fibres strands and distributed evenly over the entire sheet surface. After applying, the sheet was again coated with a layer of the epoxy resin to ensure that the sheet was fully soaked with resin.

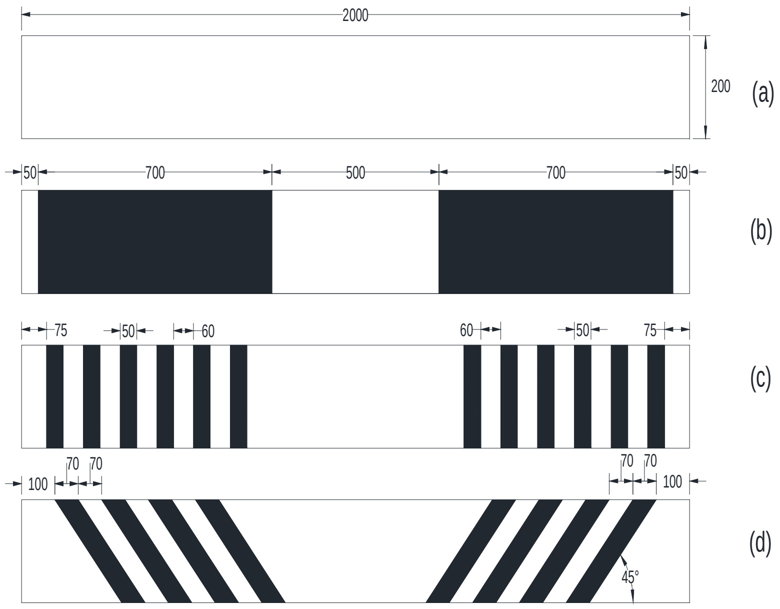


figure2. Shear strengthening configuration (All dimensions in mm).

(a): without strengthening,
(b): full side sheet, (c): U- or vertical
side strips, (d): diagonal side
strips

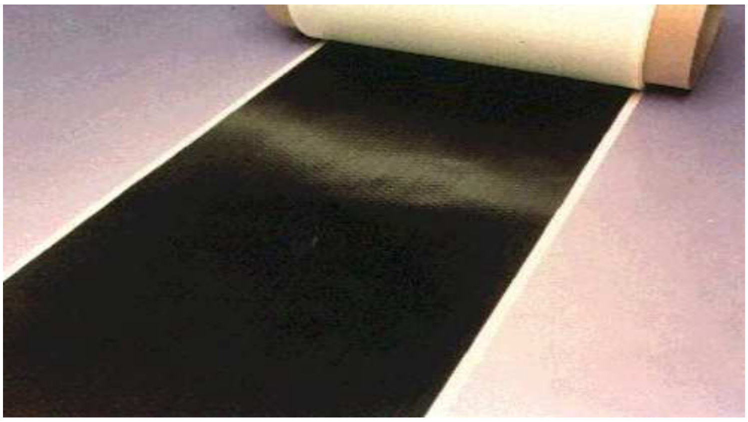


Figure 3. Sample of CFRP Sheet

2.5 Measurements and Testing Procedure

During the test of each beam, mid span deflection has been measured by means of dial gauge placed at tension (bottom) face of the tested beam "Fig.4". Dial gauge readings were recorded for each load increment to obtain complete load-deflection behaviour. The beams were tested under static loads, loaded gradually in successive increments of 5 – 10 kN, up to failure.

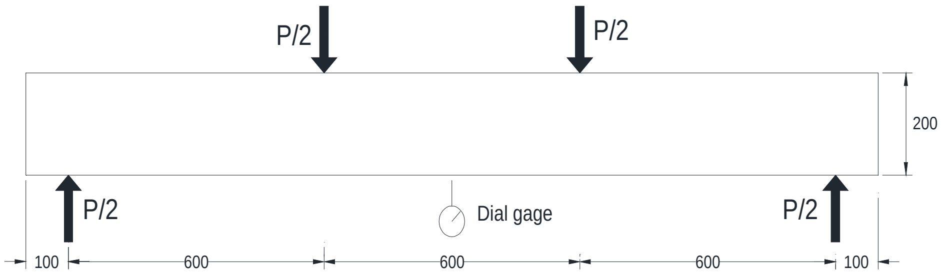


Figure4.Test Set-up (All dimensions in mm).

General behaviour of the tested beams was monitored especially near failure where steel start in yielding, GFRP in rupturing, concrete in crushing, and CFRP in rupturing or debonding which may take place as well. Also cracks propagation in the beam was observed during the test and crack patterns were marked. "Fig.5" shows one of the beams under test.

Figure5.Beam under testing

3. Tests Results

Table (4) summarizes the results of the tests conducted on ten simply supported reinforced high-strength concrete beams in this research. Effect, of the types of reinforcing bars, various strengthening configurations and steel fiber content, on shear strength, load-deflection behavior, cracking and modes of failure of the tested beams are discussed in detail through the following sections.

Table (4): Tests results of the tested beams

Beam	Main reinforcement type	V_f %	Shear strengthening configuration*	Concrete comp. strength, MPa	Ult. load, kN	Max. deflection mm	Mode of failure	Max. crack width, mm
R-0-N	Steel	0	None	66.5	58	6.5	Shear	< 0.5
R-0-S	Steel	0	Stirrups	66.5	145	15.5	Flexure	0.75
G-0-S	GFRP	0	Stirrups	66.5	156	20.6	Flexure	0.6
G-0-F	GFRP	0	Side Full Sheets	66.5	88	21.4	Flexure	1
G-0-U	GFRP	0	U-strips	66.5	133	19.7	Shear	< 0.5
G-0-D	GFRP	0	Side Diagonal Strips	66.5	78	16.9	Flexure	0.72
G-0.5-U	GFRP	0.5	U-strips	70.8	174	23.2	Flexure-shear	0.55
G-0.5-V	GFRP	0.5	Side Vertical Strips	70.8	103	17.2	Flexure	0.7
G-1-U	GFRP	1	U-strips	73.1	193	21.2	Shear	0.5
G-1-D	GFRP	1	Side Diagonal Strips	73.1	102	21.1	Flexure	0.6

*See "Fig.2"

3.1 Ultimate loads

The reference beam R-0-N is a steel reinforced high-strength concrete beam without shear reinforcement (stirrups) and steel fibers. As pre-designed, it failed in shear at 58 kN ultimate load (P_u). Using ϕ8@75mm closed stirrups (beam R-0-S) raised P_u to 145 kN (150% increase) and changed failure mode to flexure which is also an expected result (Table (4)).

GFRP bars were used in all other eight beams instead of traditional steel bars as flexural reinforcement to evaluate their shear strength using various shear strengthening configurations. Using ϕ8@75mm closed stirrups (beam G-0-S) led to slightly higher P_u of 156 kN than the corresponding steel reinforced beam R-0-S (7.6% increase) as a result of the higher tensile strength of GFRP bars (both beams failed in flexure).

For the same steel fiber content (0%), three strengthening configurations of externally bonded CFRP sheets/strips were used in the beams G-0-F, G-0-U and G-0-D which are : full side sheets (700x200mm sheet for each side of each shear span), U-strips (six 50x200mm continuous strips on three sides of each shear span) and diagonal side strips (four 45˚oriented 50x280mm strips for each side of each shear span), respectively (“Fig. (2)). As a percentage of P_u of beam G-0-S (with stirrups), the ultimate loads of the beams G-0-F, G-0-U and G-0-D were 56.4% (88 kN), 85.3% (133 kN) and 50% (78 kN), respectively (Table (4) and "Fig.6").

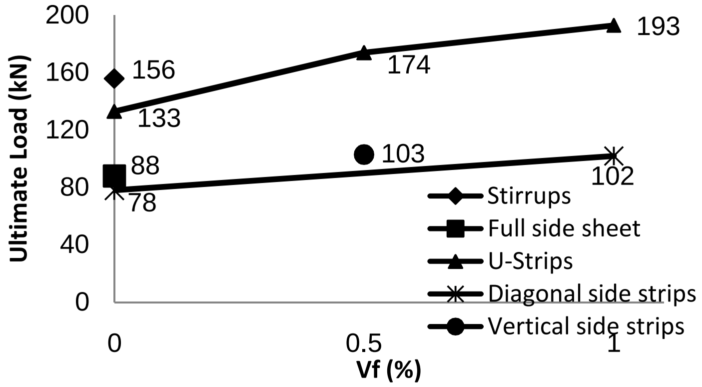


Figure (6): Effect of strengthening configurations and steel fiber content on ultimate loads.

The above results show that internal steel stirrups still the most effective way to enhance shear capacity of concrete beams (especially for non-fibrous concrete), but if it is desired to eliminate steel stirrups for durability (corrosion concerns) and/or architectural (geometric restrictions) considerations, U-strips strengthening configuration is clearly better than full sheets and diagonal strips. This may be attributed to the confining effect of U-strips which are continuous on three sides of the beam section (two laterals and bottom) so they contribute to enhance both shear and flexural capacities of the beam.

U-strips and vertical side strips (six 50x200mm on each side of each shear span) were used to strengthen the beams G-0.5-U and G-0.5-V, respectively, with steel fiber ratio of 0.5%, while the beams G-1-U and G-1-D with 1% steel fiber content were strengthened by U- and diagonal strips, respectively. The ultimate load of beam G-0.5-V is 103 kN which is 59.2% of that of beam G-0.5-U (174 kN), while the ultimate load of beam G-1-D is 102 kN which is 53% of that of beam G-1-U (193 kN) (Table (4) and "Fig.6"). This again shows the effectiveness of U-strips configuration in enhancing shear capacity of concrete beams.

It can also be concluded from the above results that a comparable results are obtained among the other configurations with the following order of preference: full side sheets (66.2% of U-strips), vertical side strips (59.2%) and diagonal side strips (52.8-58.6%). This reveals (within the limits of this work) that the total path length of CFRP the diagonal shear crack should cross to cause failure is more important than the orientation of fibers within CFRP sheet.

Table (4) and "Fig.6" also show that using steel fiber up to 1% volumetric ratio in GFRP reinforced concrete beams increases ultimate loads from 133 kN to 193 kN (45.1% increase) in U-strips strengthened beams and from 78 kN to 102 kN (30.7% increase) in diagonal strips strengthened beams. A combination of externally bonded CFRP U-strips and sufficient amount of steel fiber (beams G-0.5-U and G-1-U) is shown to perform better than steel stirrups (beam G-0-S) in terms of increasing carrying capacity of GFRP reinforced concrete beams; an increase of 11.5% (beam G-0.5-U) and 23.7% (beam G-1-U) is obtained by using this combination.

3.2 Load-deflection behaviour

Load-deflection behavior of the tested beams is illustrated in "Figs.7 to 13". "Fig. 7" shows that adding steel stirrups to steel reinforced beams increases ultimate load (as discussed earlier), stiffens load-deflection response (lower deflections) and leads to a more ductile flexural failure (beam R-0-S) rather than sudden shear failure (beam R-0-N). Using GFRP bars as tension reinforcement (beam G-0-S) instead of traditional steel bars (beam R-0-S) slightly increases ultimate load (see section 3.1) but shows lower stiffness (higher deflections) as shown in "Fig.8" because of the lower modulus of elasticity of GFRP bars as compared to steel bars (Table1). This should be taken into account when serviceability considerations are of major importance.

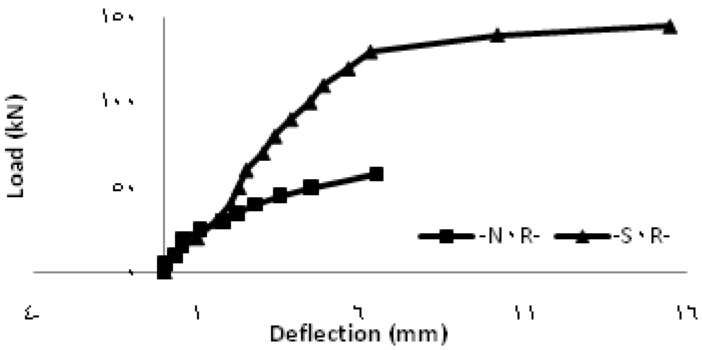


Figure (7): Load-deflection curves of steel reinforced beams.

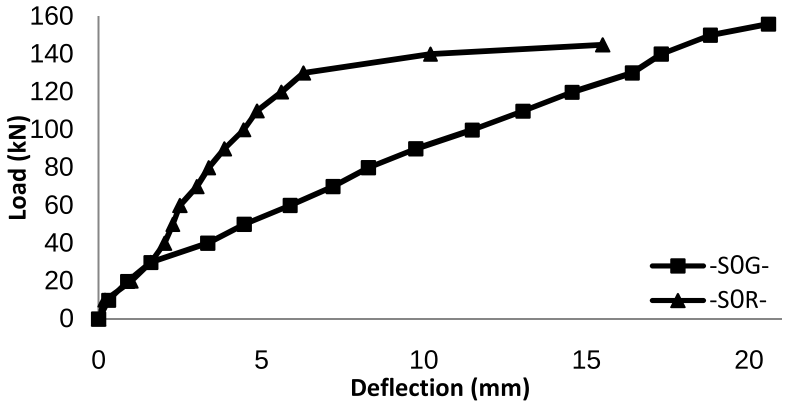


Figure (8): Load-deflection curves of beams with stirrups.

"Figs.9 to 11" shows load-deflection curves of GFRP reinforced beams with different steel fiber ratios and various shear strengthening configurations. As in ultimate loads, U-strips perform better than the other CFRP strengthening configurations with comparable stiff behavior (relatively low deflections) to GFRP beam with stirrups (beam G-0-S) as shown in "Fig.9". Approximately similar load-deflection behaviors are observed among beams with strengthening configurations other than U-strips.

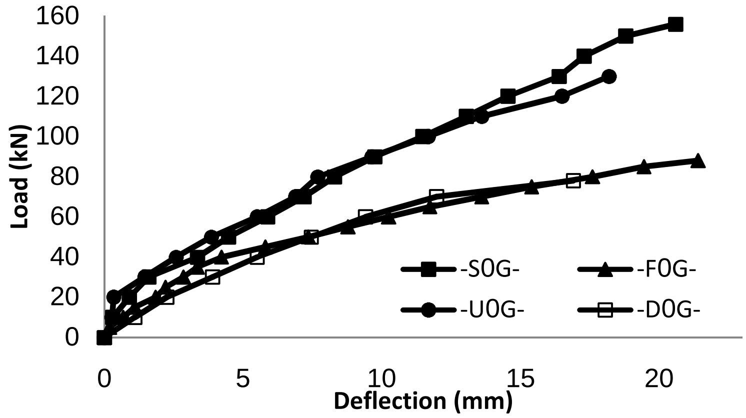


Figure (9): Load-deflection curves of GFRP reinforced beams with 0% steel fiber.

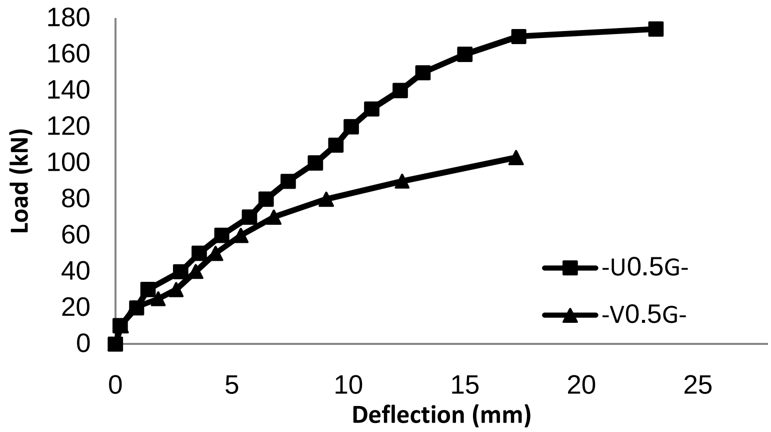


Figure (10): Load-deflection curves of GFRP reinforced beams with 0.5% steel fiber.

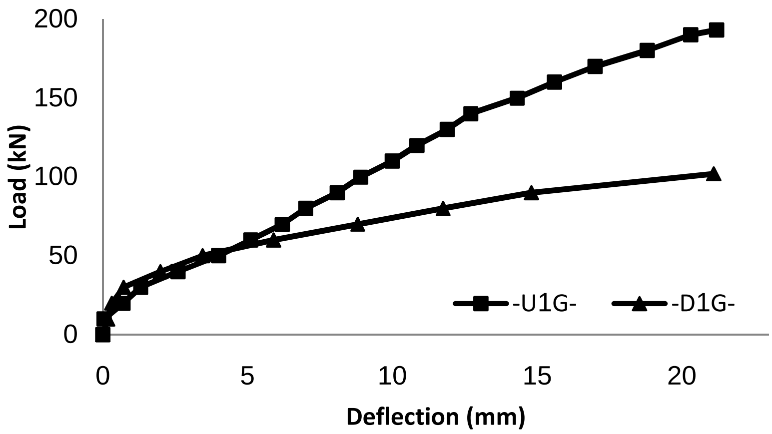


Figure (11): Load-deflection curves of GFRP reinforced beams with 1% steel fiber.

Effects of steel fibers on load-deflection behavior of GFRP reinforced beams are shown in "Figs.12 and 13". Increasing steel fiber ratio from 0% to 1% provides more ductile and stiffness response. As mentioned before, "Fig.12" shows that using steel fiber in addition to U-strips gives not only higher strength but also stiffer load-deflection behavior (lower deflections).

Maximum deflections (deflections at failure) of GFRP reinforced beams ranged from about 17mm to 23mm which are, in general; higher than those of steel reinforced beams as listed in Table (4). However, no clear effect can be observed on maximum deflections when strengthening configurations and/or steel fiber content are changed.

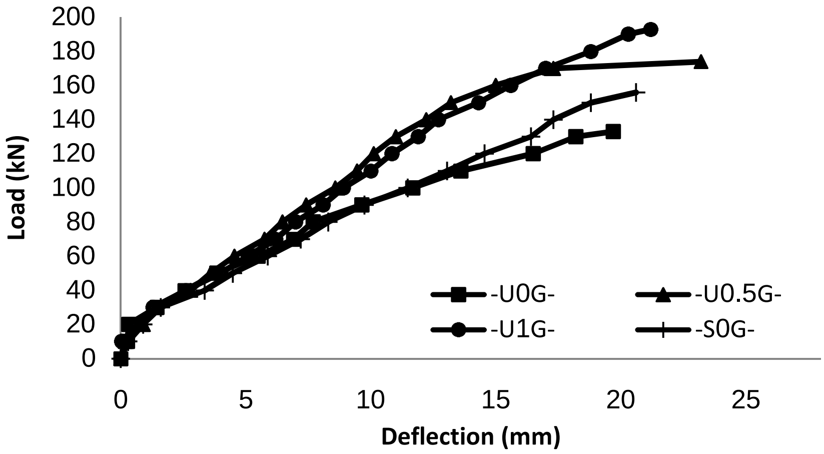


Figure (12): Load-deflection curves of GFRP reinforced beams strengthened by U-strips.

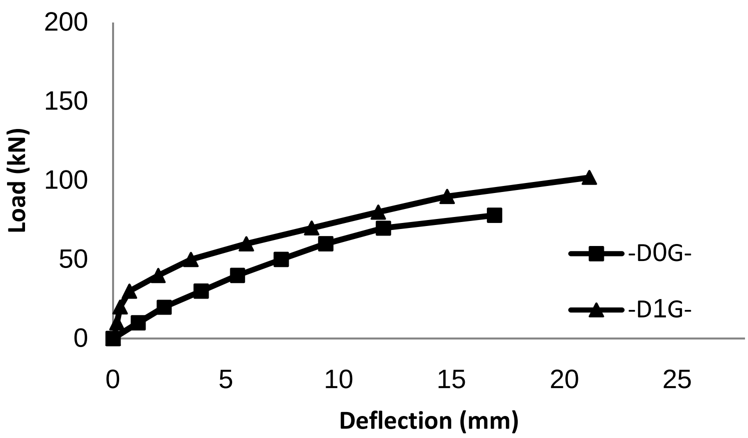


Figure (13): Load-deflection curves of GFRP reinforced beams strengthened by diagonal side strips.

3.3 Cracking and modes of failure

Cracking patterns of the tested beams are presented in "Fig.14".Seven beams failed in flexure (Table (4)), where at early stage of loading, several cracks appeared in the tension face at the constant maximum moment region (middle portion of the beam between the two point loads).

With further loading, these cracks extended upwards and became wider as well to other cracks started at each of the adjacent shear spans. Before the complete formation of the diagonal crack, one (or more) of the middle region cracks propagated and widened faster than the others passing through the compression zone, then longitudinal steel bars yielded (as in beam R-0-S) or compression concrete crushed as a result of that the strain in the compression face exceeds the ultimate strain of concrete (as in beam G-0-S) and consequently the beam failed.

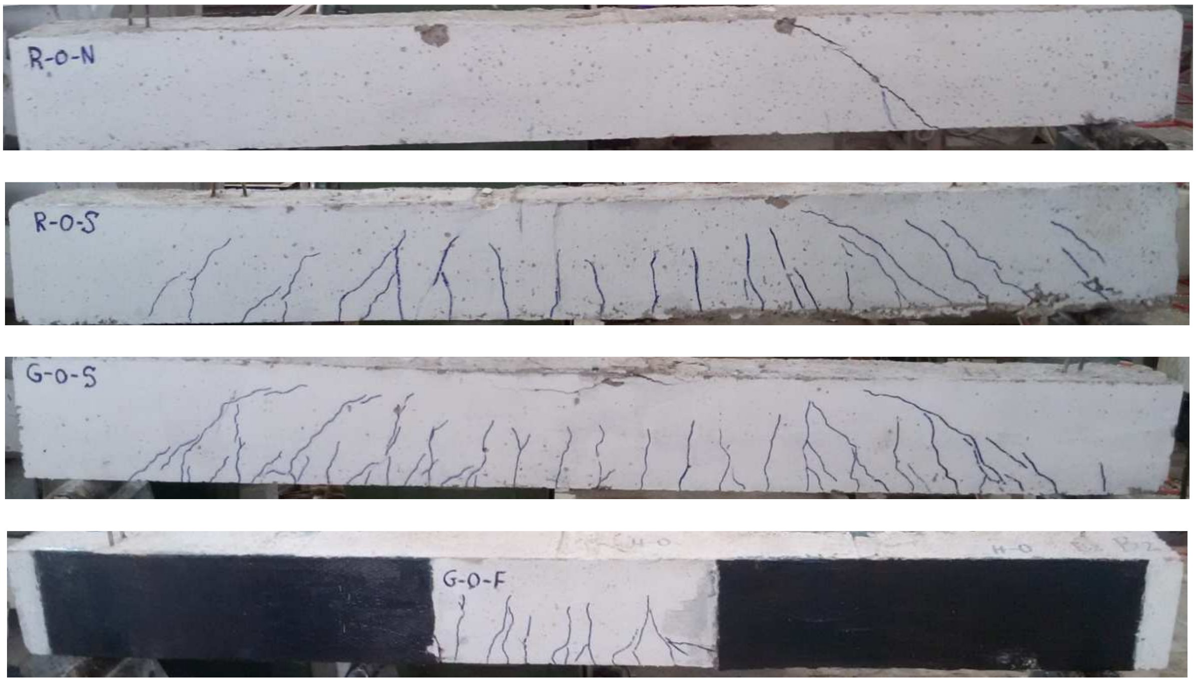
Three beams failed in shear (Table (4)) where the cracking behavior is generally similar to that mentioned above for beams failed in flexure but before flexural failure, a complete diagonal crack formed in the one of the shear spans followed by a sudden failure by a complete separation across the diagonal shear crack.
At failure, most of steel fibers in the cracks pull out of the cement matrix rather than snap in all tested beams.

Modes of failure of the tested beams are listed in Table (4) and shown in "Fig.14". As pre-designed, adding sufficient amount of stirrups to steel reinforced beams prevents sudden shear failure and changes the mode to ductile flexural failure (beam R-0-S) that characterized by yielding of tension steel.

Since GFRP bars do not yield, but rupture at their high ultimate strength (1200 MPa, Table (1)), GFRP reinforced beam with stirrups (G-0-S) failed in flexure by excessive deflections followed by crushing of concrete in the compression zone which is (unlike steel reinforced beams) preferred failure mode rather than without warning rupture of GFRP bars.

This mode of failure prevailed in other strengthened GFRP reinforced beams except U-strips beams where shear (or compound flexure-shear) failure took place. This may be attributed to the contribution of U-strips (continuous over three faces including tension face) in enhancing flexural as well as shear strength allowing the beam to carry higher loads (Table (4)).

In all strengthened beams, externally bonded CFRP sheets/strips neither debonded from concrete substrate nor ruptured at any stage of loading, instead; near failure of some beams failed by sudden diagonal shear crack, concrete shells around failure crack were spalled while still bonded to the CFRP strips as shown in "Fig.15".



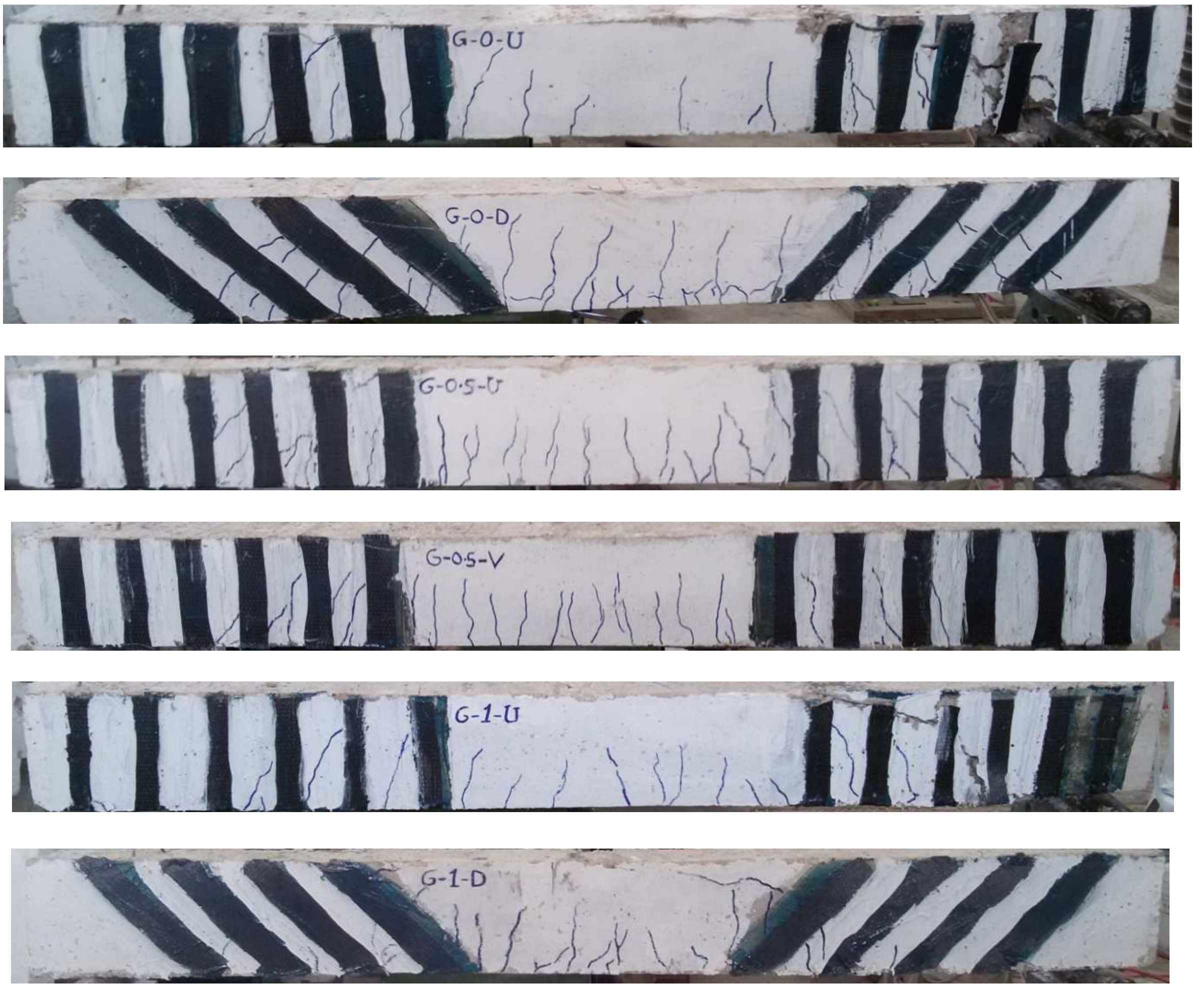


Figure (14): Cracking patterns of the tested beams.

Figure (15): Spalling of concrete while still bonded to the CFRP strips.

4. Conclusions

Ten reinforced high strength concrete beams were cast and tested up to failure under shear in this work. Eight of them were longitudinally reinforced with GFRP bars and two with traditional steel bars. GFRP reinforced beams were externally strengthened in shear using CFRP with various configurations: full side sheets (700x200mm sheet for each side of each shear span), U-strips (six 50x200mm continuous strips on three sides of each shear span), vertical side strips (six 50x200mm on each side of each shear span) and diagonal side strips (four 45° oriented 50x280mm strips for each side of each shear span) as shown in "Fig.2". Three steel fiber ratios were used (0%, 1% and 2%). Based on experimental results of the tests conducted on these beams, the following main conclusions can be drawn:

1. Using GFRP bars as tension reinforcement instead of traditional steel bars slightly increases ultimate load (7.6% increase) as a result of the higher tensile strength of GFRP bars but shows lower stiffness (higher deflections) because of the lower modulus of elasticity of GFRP bars as compared to steel bars. A balance should be made between strength and serviceability considerations when GFRP bars are to be used.
2. Although internal steel stirrups still the most effective way to enhance shear capacity of concrete beams (especially for non-fibrous concrete), externally bonded CFRP U-strips can be an effective alternative for durability (corrosion concerns) and/or architectural (geometric restrictions) considerations with about 85% strength efficiency and comparable load-deflection behavior.
3. A combination of externally bonded CFRP U-strips and sufficient amount of steel fiber is shown to perform better than steel stirrups in terms of increasing carrying capacity and decreasing deflections of GFRP reinforced concrete beams; an increase of 11.5% (for 0.5% steel fiber) and 23.7% (for 1% steel fiber) is obtained by using this combination.
4. Comparable results are obtained among the other strengthening configurations with the following order of preference: full side sheets (66.2% of U-strips), vertical side strips (59.2%) and diagonal side strips (52.8-58.6%).
5. Approximately similar load-deflection behaviors are observed among beams with strengthening configurations other than U-strips.
6. Using steel fibers up to 1% volumetric ratio in GFRP reinforced concrete beams stiffens load-deflection curves (lower deflections), provides more ductile response and increases ultimate loads by 45.1% in U-strips strengthened beams and 30.7% in diagonal strips strengthened beams.
7. Flexural failure by excessive deflections followed by crushing of concrete in the compression zone was the dominant failure mode in strengthened GFRP reinforced beams except U-strips beams where shear (or compound flexure-shear) failure took place. This may be attributed to the contribution of U-strips (continuous over three faces including tension face) in enhancing flexural as well as shear strength allowing the beam to carry higher loads.
8. In all strengthened beams, externally bonded CFRP sheets/strips neither debonded from concrete substrate nor ruptured at any stage of loading, instead; near failure of

some beams failed by sudden diagonal shear crack, concrete shells around failure crack were spalled while still bonded to the CFRP strips.

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