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Behaviour of Concrete Beams Reinforced with Hybrid Fiber Reinforced Bars

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Abstract

Due to the linear elastic behaviour of FRP bars, the flexural behaviour of FRP reinforced beams exhibits no ductility as occurs in the steel reinforced structures. In this paper, study of the enhancement of the behaviour of concrete beams reinforced with FRP bars was carried out by testing nine beams reinforced with locally produced hybrid fiber reinforced polymer (HFRP) bars. The used hybrid fibers were aramid–glass and carbon–glass. Some of test specimens were reinforced by FRP bars provided with anchorages along the bar length. Crack patterns, cracking and ultimate loads, and deformation were observed and recorded for all tested beams. The effect of using the hybrid fiber reinforced bars and the bar anchorage system were judged by comparing the behaviour of the tested beams by two reference specimens, one reinforced by GFRP bars and the other one reinforced by traditional steel bars. The comparison revealed that HFRP bars provided with the used bars anchorage played a significant role in enhancing the behaviour of concrete beams reinforced with FRP bars.

Keywords

Semi-ductility, hybrid fiber reinforced polymers bars, RC beams, anchored bars, GFRP, HFRP

1. Introduction and Background

Fiber reinforced polymers (FRP) have been identified as an attractive candidate material for civil infrastructure applications because of its light weight, high strength, non-corrosive and non-magnetic characteristics [1]. In spite of these attractive features, the adaptation of FRP to civil infrastructure applications has been implemented slowly, especially as concrete reinforcements. This can be attributed to the lack of ductility of FRP which have linear elastic tensile stress–strain behaviour up to ultimate load and they fail in a brittle manner. The most widely used FRP con-

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crete reinforcement bars are the glass FRP bars. Thus, the response of these FRP bars in reinforced concrete beams and slabs exhibit little ductility.

There is a need for a FRP rebar system which has a steel-like stress–strain curve. A great deal of effort has been made to improve and define the ductility of beams reinforced with FRP rebars. In addition to the lack in ductility of GFRP bars there is a weakness in its bond to concrete. Therefore, in this paper, an experimental program involving the testing of nine beams was performed to investigate the behaviour of beams reinforced with locally produced hybrid fiber reinforced polymer (HFRP) rebars and to compare them with a conventional beam reinforced with steel bars and beam reinforced with GFRP bars. The paper also includes a study of the effect of the number of anchorages along the length of the FRP rebars on the behaviour of tested specimens. The study addresses the effect of using hybrid fiber reinforced polymer rebars in improving the behaviour and the ductility characteristics of RC beams reinforced with fiber reinforced polymer bars.

2. Research Program

2.1. Test Program

The research program consisted of nine reinforced concrete beams having different types of reinforcements. Test beams in this program were divided into two groups. The first group consisted of four beams reinforced with GFRP rebars with different anchorage systems. The anchorage system was chosen as follows:

- no anchorage, i.e., plain bar, control specimen;
- bars with anchor at each end;
- bars with three anchors, one at each end and one in the middle of the bar;
- bars with five anchors, one at each end and three anchors regularly distributed along the bar length.

The second group consisted of beams reinforced with hybrid FRP rebars with two anchors at each end; two beams reinforced using HFRP rebars manufactured with aramid and glass fibers with volume fractions V_A/V_G, 9/52.6 and 17/44.5, respectively, and two beams reinforced using HFRP rebars manufactured with carbon and glass fibers with volume fraction V_C/V_G, 10.6/50.4 and 19/42.6, respectively. The hybrid FRP rebars were fabricated using the mechanical pultrusion system. A steel reinforced beam was tested as reference beam. A summary of details of the beams is shown in Table 1.

2.2. Materials

The beams tested in this experimental program were cast using concrete of normal strength of 25 MPa characteristic strength, made of local materials, ordinary Portland cement (OPC). Fine and coarse aggregates were composed of siliceous sand

and good dolomite clean from impurities and well graded complying with the specifications of the Egyptian Code of Practice for Designing and Executing Concrete Structures, ECP 203-2007 [2]. Normal mild steel 24/36 was used for stirrups and high grade steel 36/52 was used for longitudinal bars. Manufacturing and testing of test beams were carried out in the Materials Laboratory in the Housing and Building National Research Center, Cairo, Egypt. Table 2 presents the properties of the used FRP rebars [3].

Table 1.
Summary of beams details

Beams groups	Beam code	Reinforcement and anchorage	V_f of used rebars	b (mm)	d (mm)	A_f (mm^2)
Reference	A	Steel	–	150	300	157
Group one	B*	GFRP without anchorage	61% glass	150	300	114
	C	GFRP with two anchorages	61% glass	150	300	114
	D	GFRP with three anchorages	61% glass	150	300	114
	E	GFRP with five anchorages	61% glass	150	300	114
Group two	F	HGAF1 with two anchorages	52.6% glass and 9% aramid	150	300	114
	G	HGAF2 with two anchorages	44.5% glass and 17% aramid	150	300	114
	H	HGCF2 with two anchorages	50.4% glass and 10.6% carbon	150	300	114
	I	HGCF3 with two anchorages	42.6% glass and 19% carbon	150	300	114

* A control specimen for specimens reinforced with FRP rebars.

Table 2.
Experimental test results [3]

Specimen code		Average ultimate strength (kg/cm^2)	Average modulus of elasticity (GP) – kg/cm^2	Average ultimate strain (%)
GF		12 142	(41.43) – 414 300	3.03
HGAF	1	11 190	(44.29) – 442 900	2.87
	2	11 331	(45.65) – 456 500	2.76
	3	11 666	(50.07) – 500 700	2.67
HGCF	1	10 803	(50.47) – 504 700	2.47
	2	11 331	(55.74) – 557 400	2.85
	3	10 309	(65.35) – 653 500	2.81

2.3. Concrete Dimensions and Reinforcements

All beams had a rectangular cross-section 150 mm wide, 300 mm high and are 2050 mm long. The clear span of tested beams was fixed at 1900 mm. The longitudinal top reinforcements of the beams are two 6 mm diameter mild steel bars. The shear reinforcement (stirrups) are seven 8 mm/m′ diameter normal mild steel for each beam. The number of bottom reinforcement bars was kept constant for all beams (2 bars). The FRP rebars used had a constant diameter of 8.5 mm. Figure 1 shows the concrete dimensions and the reinforcement of tested beams. The diameter of the FRP bars was chosen on the basis of the load carrying capacity of the steel bars of the control beam.

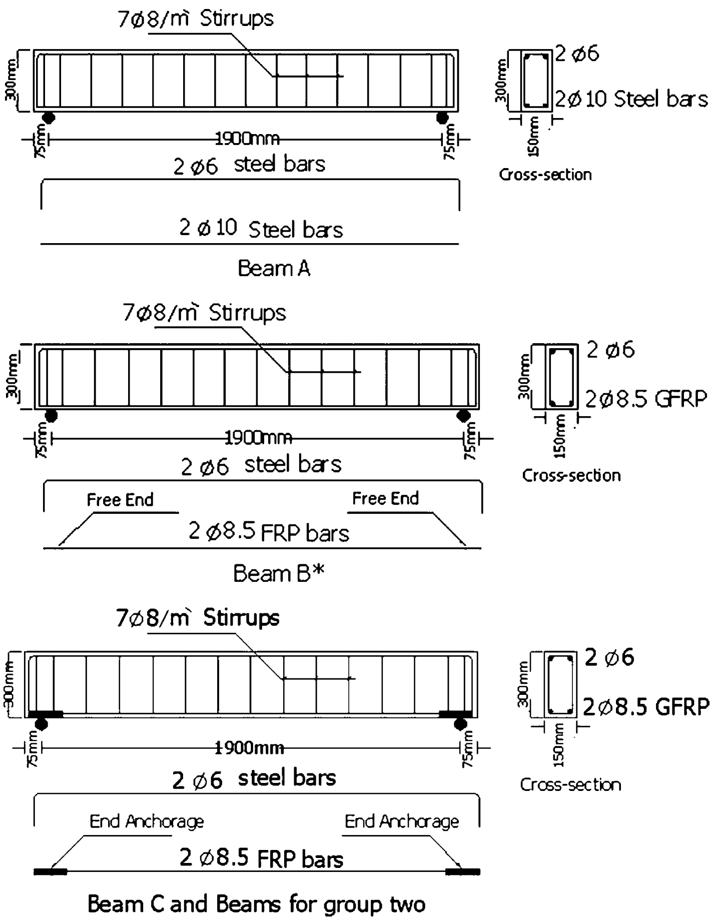


Figure 1. Concrete dimensions and reinforcements of beams. (*A control specimen for specimens reinforced with FRP rebars.)

2.4. Anchorage System

The anchorage system [4, 5] was used in the FRP reinforced concrete beams to develop higher bond strength between rebars and concrete and to prevent longitudinal splitting of the concrete at the ends of the FRP reinforced beams (and subsequent pullout of the reinforcing bars). The anchorage system was composed of a steel tube of 28 mm, and 20 mm external and internal diameters, respectively, and length 150 mm. This gave a free length (the length of the test specimen between the two anchors) of 1700 mm. The steel tubes were filled with a high performance resin grout to assure a good bond between the rebar and the steel tube. Figure 2 shows schematic details of the anchorage system. Figure 3 shows the details of FRP rebar with anchors. Figure 4 shows the details of beam reinforcements.

2.5. Test Setup and Instrumentation

Test specimens were cured for a complete 28 days in the laboratory before they were moved to the testing frame. The beams were tested under static load using a two-point loading setup. Loading set-up and specimen instrumentation are shown in Fig. 5. The load was applied using a 50 ton hydraulic jack. A 50 ton load cell was used for measuring the load. A vertical LVDT was used to measure the vertical deflection at beam mid-span. Two horizontal LVDTs were installed at the top and bottom at the sides of the beam for measuring the compression and tension defor-

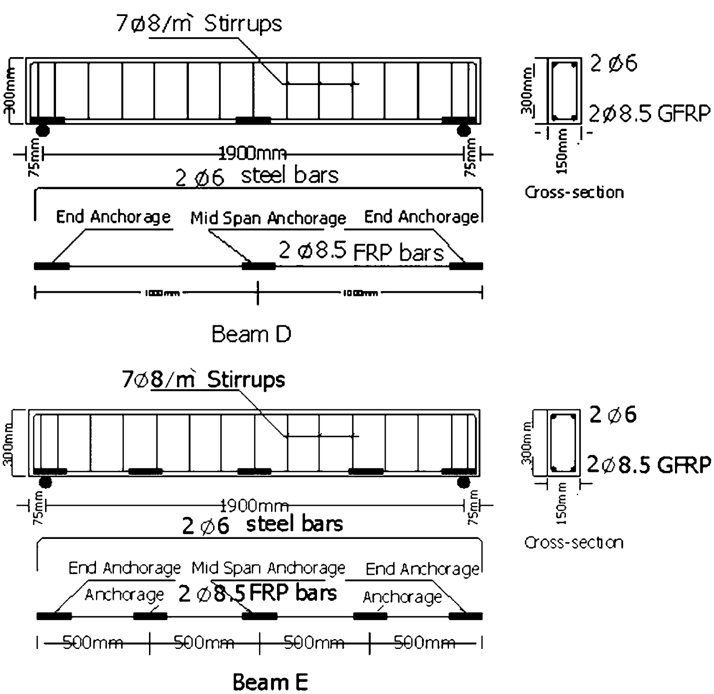


Figure 1. (Continued.)

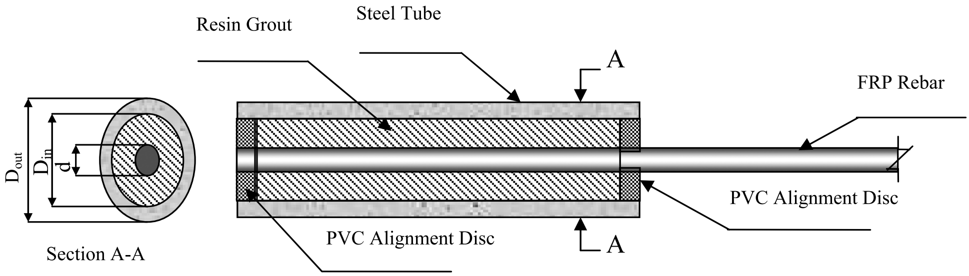


Figure 2. Schematic details of the anchorage system.

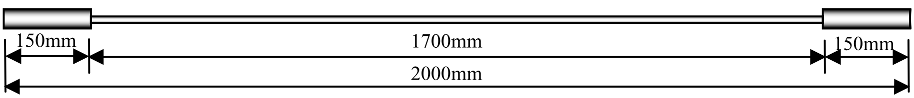
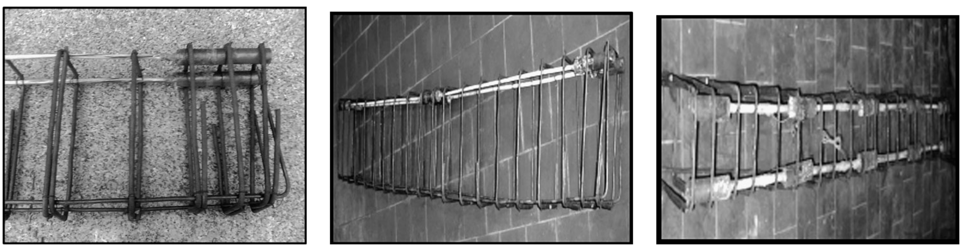


Figure 3. Schematic details of a specimen rebar.



(a) (b) (c)

Figure 4. Details of beams reinforcements. Bars with anchors: (a) two, (b) three and (c) five.

mations and for accurate estimation of the initiation of cracks (Figs 5 and 6(c)). Strain gages were used to measure the strains in compressed and tensile reinforcements of the beam. The load and location of the first crack were recorded and the propagation of crack was traced until failure.

3. Test Results

3.1. Crack Patterns and Modes of Failure

3.1.1. Control Beam and Group One

Control beam A showed a typical flexural-ductile failure (Fig. 6(a)). Beams B and C showed a flexural failure mode with two cracks directly under the load application points (Fig. 6(b)). Beams D and E (Fig. 6(c)) also showed a flexural failure mode with one main crack directly under one of the load application points and some other small cracks propagated along the length between the two-points-load. The failure mode for beams D and E demonstrated a significant increase in bonding between FRP bars and concrete. This was clearly seen with the increase of crack

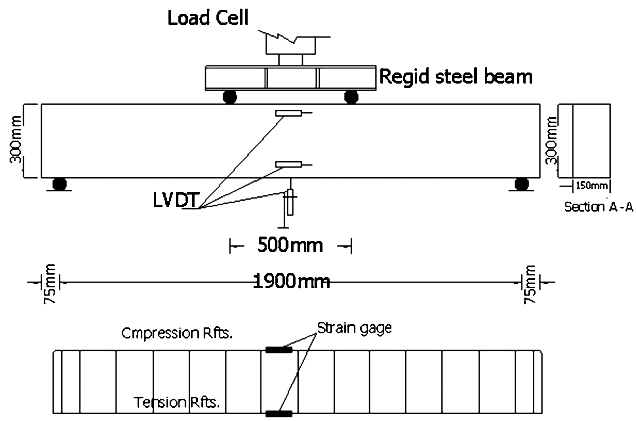


Figure 5. The loading set-up.

(a) (b) (c)

Figure 6. The typical crack pattern for tested beams. (a) Control beam. (b) Beams with two and three anchors. (c) Beam with five anchors.

Table 3.
Cracking and ultimate loads for group one beams

Beam code	P_u (ton)	P_{cr} (ton)	P_{cr}/P_u (%)	P_y (ton)	Enhancement in ultimate load (%)
A	8.50	3.30	39	4	Reference specimen
B	3.75	1.00	26	–	Control specimen
C	4.26	1.20	28	–	13.60
D	5.25	1.60	30	–	40.0
E	6.20	2.20	35	–	65.33

intensity in this beam compared to beams B and C. Table 3 shows the cracking and the ultimate loads for control and group one beams.

3.1.2. Group Two

All beams showed a flexure failure mode with two cracks similar to the mode of failure for beam C (Fig. 6(b)). This is logical as all beams in Group Two are rein-

Table 4.
Cracking and ultimate loads for group two beams

Beam code	P_u (ton)	P_{cr} (ton)	P_{cr}/P_u (%)	P_y (ton)	Enhancement in ultimate load (%)
A	8.50	3.30	39	4	Reference specimen
B	3.75	1.00	26	–	Control specimen
F	4.85	1.50	31	5.53	29
G	5.12	1.68	34	5.79	37
H	4.25	1.25	29	4.26	13
I	4.90	1.80	34	4.91	31

forced with HFRP bars with end anchorage only, the same as the rebars in beam C. Table 4 shows the cracking and the ultimate load for Group Two beams.

3.2. Load–Vertical Deflection Relationships

3.2.1. Effect of Anchorage System on Mid-Span Deflection

The beam reinforced with high tensile steel bars showed a typical load–vertical deflection relationship of steel reinforced concrete beams (Fig. 7(a)). The beams reinforced with FRP rebars showed a different load–vertical deflection relationship than the steel reinforced beam. The relationships consisted generally of a bilinear curve: stiff up to the cracking load, and then softening at cracking of concrete but becoming linear up to failure (Fig. 7(b)–(e)). Table 5 shows the ultimate and cracking load and their corresponding deflections.

With reference to Table 5 and Fig. 7(a)–(e), it is generally noticed that increasing the number of anchorages increases the cracking deflection of tested beams. It is also shown that the deflections at failure increase significantly with increase in the number of anchors along the bar length. This is almost related to the effect of anchorage system used in tested specimens in increasing the bond strength between concrete and the reinforcing bars along the total length of the bars. Also the presence of two end anchorages enhances the beam ductility with respect to the specimen without anchorage (the control specimen, beam B) (Fig. 7(b) and 7(c)). For the specimen with three anchors, Fig. 7(d), the load–deflection relationship is clear bilinear with clear plateau showing a ductile behaviour of the beam. For specimen with five anchors (Fig. 7(e)), the load–deflection relationship shows that the behaviour of this beam is similar to that of the reference steel reinforced beam but with lower deflection values. Generally, it is clear from Fig. 7(a)–(e) that using anchored GFRP bars in reinforcing concrete beams in the way shown in this paper improves their load–deflection behaviour. Also increasing the number of anchors along the bar length enhances the behaviour of the beams and helps in approaching the typical behaviour of reference steel reinforced beams.

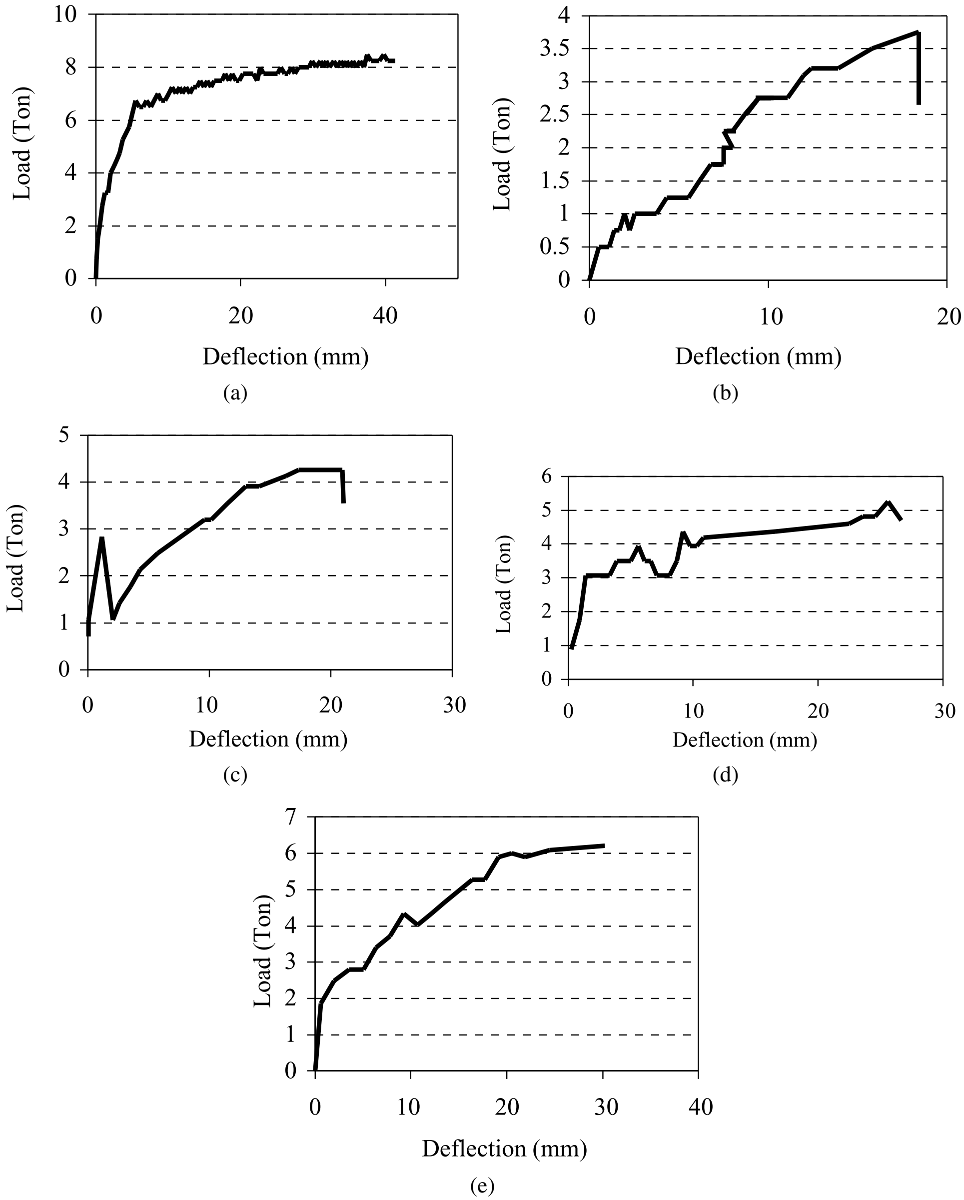


Figure 7. Load–deflection relationship for (a) beam A, (b) beam B, (c) beam C, (d) beam D and (e) beam E.

3.2.2. Effect of FRP Bars Type on Mid-Span Deflection

The mid-span deflection for beams F, G, H and I is shown in Fig. 8(a)–(d). With reference to Fig. 8(a) and 8(b) and Table 5, it is noticed that the load–deflection relationships for beams F, and G are almost the same. Also beams F and G showed the same cracking deflection (Table 5). Their deflections at the ultimate load are

Table 5.
Cracking and ultimate load and the corresponding deflections

Beam code	P_u (ton)	Deflection at P_u (mm)	P_{cr} (ton)	Deflection at P_{cr} (mm)
A	8.50	41.40	3.30	1.25
B	3.75	18.41	1.00	1.96
C	4.26	20.96	1.20	1.00
D	5.25	25.60	1.60	1.20
E	6.20	30.20	2.20	1.50
F	4.85	24.00	1.50	2.00
G	5.12	25.80	1.68	2.00
H	4.25	12.00	1.25	1.60
I	4.90	32.10	1.80	1.10

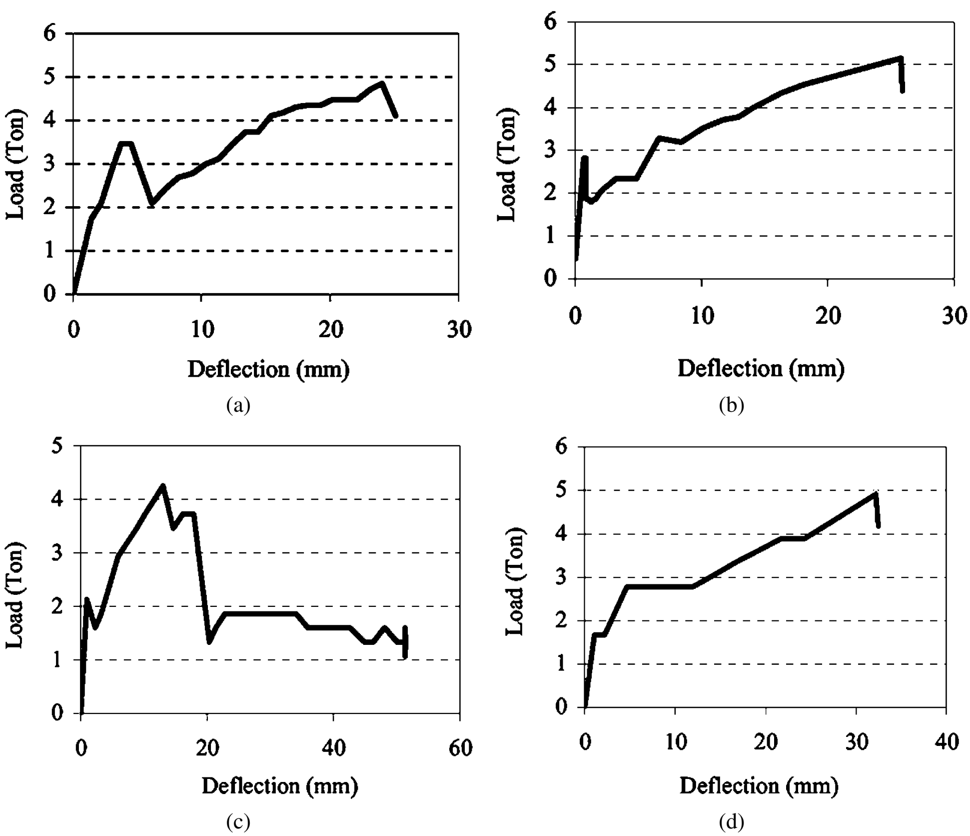


Figure 8. Load–deflection relationship for (a) beam F, (b) beam G, (c) beam H and (d) beam I.

close. This indicates that varying the ratio of aramid to glass fiber in the reinforcing rebars, in the range considered in this paper, has no effect on the load–deflection behaviour of the tested beams. Comparing between the load–deflection relationships for beams H and I (Fig. 8(c) and 8(d)), it is clear that increasing the ratio of carbon to glass fibers in the reinforcing bars, increases the beam deflection at the ultimate load, while the deformation at cracking of beams decreases with increase in the carbon to glass ratio. This is related to the effect of the behaviour of the hybrid carbon–glass fiber rebars [3], as for this type of bars increasing the carbon ratio increases the Young's modulus of the bars until yielding, then significantly decreases. The effect of the bar behaviour on the load–deformation relationship of tested beams, H and I is explained in Fig. 8(c) and 8(d), as the flexural stiffness of the beam with the lower carbon percentage, H, is the lower until cracking load then it increases compared to that for beam I with the higher carbon percentage. It is also noticed that beam (H) showed better post-peak behaviour than beam (I). This is indicated by the gradual decrease in loading for beam (H), while the deformation increases after reaching the peak value of the load (Fig. 8(c)). For beam I, the load decreases suddenly after reaching the peak value of the load (Fig. 8(d)).

3.3. Load–Strain Relationship

The relationships between load and strain in the tensile reinforcements are drawn in Figs 9 and 10. A typical load–strain relationship was shown for the tensile steel of the reference beam (Fig. 9(a)). The beams reinforced with FRP bars showed different load–strain relationships those consisted generally of a bilinear curve stiff up to the cracking load, and then softens when concrete cracks but becomes also linear up to failure.

3.3.1. Effect of Anchorage System on Load–Strain Relationships

By studying the load–strain relationships for beams A, B, C, D and E shown in Fig. 9(a)–(e), it is clear that the relatively large strains and the relatively low ultimate load shown for beam B indicates an obvious slippage between the rebars and concrete (Fig. 9(b)). The bars behave linearly up to concrete first crack, then debonding at the concrete–bar interface was initiated along the bar length up to failure. With reference to Fig. 9(c) it is clear that the two anchors at the bar ends of beam C enhanced the bond strength between the FRP bars and concrete as the first crack of concrete initiated at relatively low strain and widened up clearly in a short time, then the two anchors at the bar ends worked as end blockage and thus the FRP bars showed almost linear behaviour until failure. Using FRP bars with three anchors improves the ductility of the FRP bars those showed behaviour similar to some extent to that of ductile steel bars, as bar showed a clear yielding (Fig. 9(d)).

For beams reinforced with FRP bars with five anchors, the load–strain relationship is bilinear with clear plateau. This results in remarkable enhancement in the beam ductility. Also this improved the failure mechanism of the beam that was shown to be similar to some extent to the failure mechanism of similar steel reinforced beams (Fig. 6(c)).

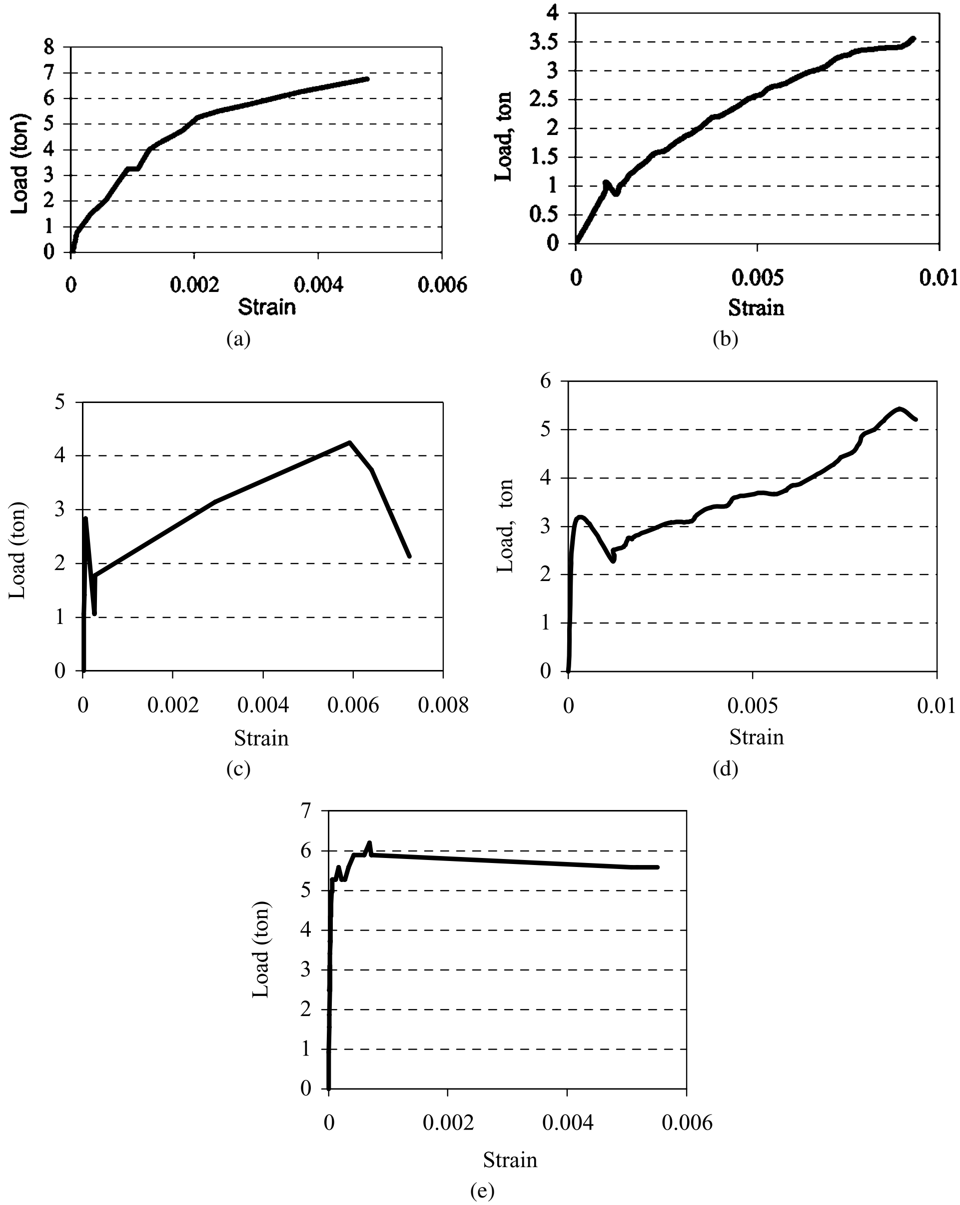


Figure 9. Load–strain relationship for (a) beam A, (b) beam B, (c) beam C, (d) beam D and (e) beam E.

3.3.2. Effect of FRP Bars Type on Reinforcement Strains

The load–strain relations of beams F, G, H and I are shown in Fig. 10(a)–(d). It can be noticed that changing the type of fibers used in manufacturing FRP rebars affects directly the measured tensile strains in the bars. With reference to Fig. 10(a) and 10(b), it is clear that increasing the aramid to glass ratio in the FRP bars decreases the tensile strain in the bars at cracking of concrete without significantly

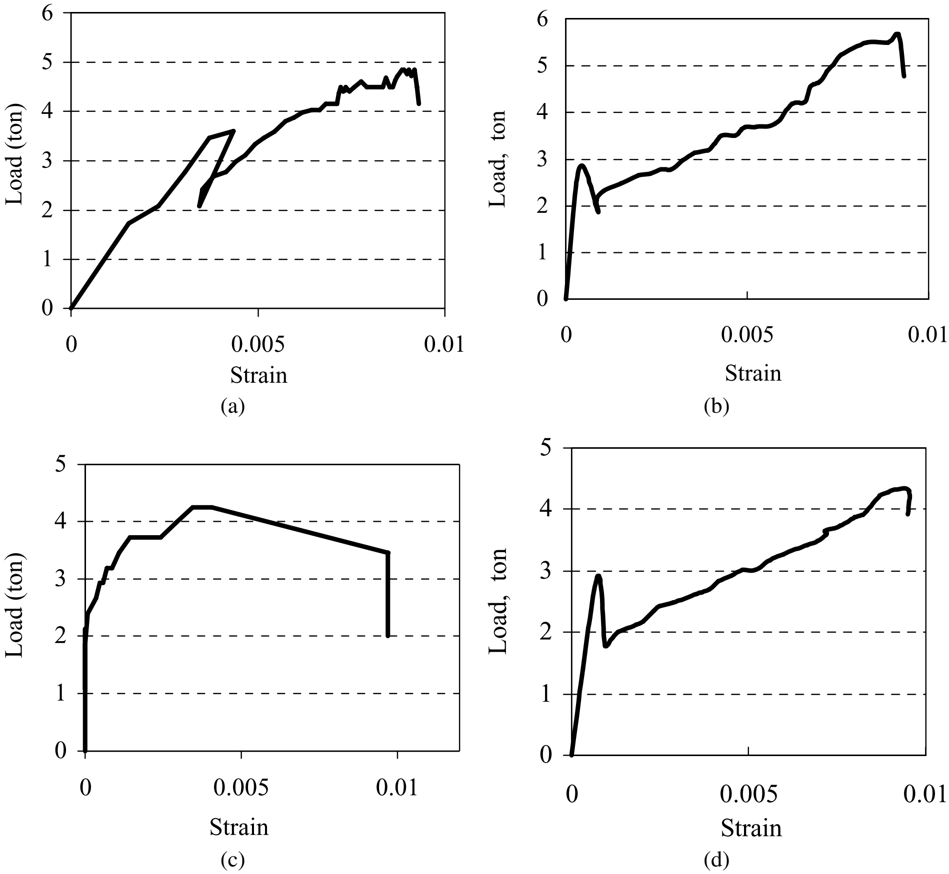


Figure 10. Load–strain relationship for (a) beam F, (b) beam G, (c) beam H and (d) beam I.

affecting the cracking load. It is also noticed that the load strain behaviour of bars with higher aramid-to-glass ratio is similar to some extent to that of the steel reinforcing bars, while for FRP bars with lower aramid-to-glass ratio showed nonlinear behaviour after cracking and linear elastic behaviour before cracking load with remarkable lower modulus of elasticity compared to that for bars with higher aramid ratio. For beams with FRP bars manufactured with hybrid carbon–glass fiber, for beam H reinforced with bars having lower carbon-to-glass ratio, the load–strain in the bars showed ductile bilinear behaviour with clear yielding zone, while for beam I, the bar showed linear elastic behaviour until cracking, then the behaviour was nearly linear inelastic until failure. Thus using hybrid carbon–glass fiber bars with lower carbon fiber percentage improves the behavioural characteristics and failure mechanism than using hybrid bars with high carbon fiber percentage.

3.4. Ductility Index

Ductility describes the ability of a structural member to sustain large inelastic deformations before collapse without significant loss in resistance. FRPs have no ductility as is commonly associated with yielding of steel because they exhibit linear elastic behaviour until brittle failure. The lower strain at failure is of significant concern to design engineers. Ductility is measured beyond the yield point of reinforcement in a concrete structure to describe the behaviour of the structure. There are two concepts to define the ductility index [7].

3.4.1. Energy Consideration for Evaluation of Ductility

Although concrete by itself can be considered a rather brittle material, concrete structures are usually designed to behave in a ductile manner through proper reinforcements. Such ductility is primarily achieved because conventional steel reinforcements undergo inelastic deformation prior to failure allowing the full strain capacity of concrete to develop and hence consuming substantial amount of energy. Eventually, concrete members fail by the concrete due to excessive strain beyond their capacity. For a perfectly elasto-plastic behaviour, the ductility index can be calculated from equation (1):

$$\mu_{\mathrm{w}} = \frac{1}{2}\left(\frac{W_{\mathrm{total}}}{W_{\mathrm{elastic}}} + 1\right), \tag{1}$$

where W_{total} is the energy computed up to failure and W_{elastic} is the energy computed for the elastic portion of the load deflection.

3.4.2. Conventional Ductility Index

Several measures of ductility have been used in the past. They are generally expressed in the form of the ratio of deflection at ultimate to deflection at yield (equation (2)). In this definition two important reference points are needed; the yield point which helps define the denominator and the ultimate point which helps define the nominator:

$$\mu_{\Delta} = \frac{\Delta_{\mathrm{ultimate}}}{\Delta_{\mathrm{yield}}}, \tag{2}$$

where $\Delta_{\mathrm{ultimate}}$ is the ultimate deflection and Δ_{yield} is the yielding deflection.

A summary of the ductility indices for steel and the hybrid reinforced tested beams is given in Table 6. Table 6 shows that the steel reinforced beam exhibited

Table 6.
Ductility indexes for steel and hybrid reinforced tested beams

Beam code	μ_{w}	μ_{Δ}	Percentage of $\mu_{\mathrm{w\ (hybrid)}}/\mu_{\mathrm{w\ (control^*)}}$ (%)	Percentage of $\mu_{\Delta\ (\mathrm{hybrid})}/\mu_{\Delta\ (\mathrm{control^*})}$ (%)
A	9.66	8.67	100	100
F	6.64	7.00	68.7	80.7
G	6.80	7.25	70.4	83.6
H	7.72	8.21	79.9	94.7
I	8.33	8.52	86.2	98.3

* The control specimen here is the steel reinforced beam with code A.

high ductility indices, due to the large yielding plateau of steel. Beams reinforced with the hybrid FRP reinforced rebars demonstrated their effectiveness in providing semi-ductility to a concrete structure as indicated in Table 6.

4. Conclusions

In this paper the enhancement of concrete beams reinforced with FRP bars was studied by using rebars with anchorage along the length of the bars, and using FRP rebars manufactured with hybrid aramid–glass and carbon–glass fibers. Test results revealed that the use of bar anchorage as described in this paper provided good stress transfer between concrete and FRP rebars. It is also concluded that increasing the number of anchorage points along the length of the FRP rebars increases the ultimate load by about 14, 40 and 65% of the ultimate load of similar beams reinforced with pure glass FRP bars, for beams reinforced with FRP bars with two, three, and five anchorages, respectively. In addition, the anchorage system used enhances the load–deflection behaviour of tested beams and helps in approaching the typical ductile behaviour of the reference steel reinforced beam. On the other hand, it is concluded that, although using carbon–glass hybrid fiber bars in reinforcing beams in this paper enhanced their load–deflection behaviour, they gave relatively lower ultimate loads and ductility than those for beams reinforced with FRP bars manufactured with hybrid aramid–glass fibers. Beams reinforced with FRP bars manufactured with hybrid aramid–glass fiber of ratio 17–44.5% gives the maximum ultimate load that was estimated to be some 37% higher than that for beam reinforced with pure glass FRP rebars. It was also shown that beams reinforced with the hybrid FRP reinforced rebars demonstrated their effectiveness in providing semi-ductility to a concrete structure.

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