Experimental Investigation of the Flexural Behaviour of Concrete Beams Reinforced with Hybrid Bars (GFRP Bars with Steel Wires)

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Abstract— Steel material is the most commonly used material to be used with concrete due to its well -performance. Nevertheless, environmental boundary conditions can lead to severe damage to steel bars due to the common corrosion effects. Aside from that, steel production alerts the environment in many different ways. All these reasons promote engineers to define a new eco-friendly alternative for steel to be used in reinforced concrete structures. Thus, the use of fibre reinforced polymer (FRP) as an alternative to the steel reinforcement became common research concern. One of the major challenges of the use of FRP is the low modulus of elasticity which might lead to a significant reduction in stiffness consequently, exceedance to deformation limit states. In this context, this paper provides solutions to overcome the previous problems by using a hybrid bar. Hybridization of the bars was conducted using glass fibres and unsaturated polyester resins incorporated with steel wires. This research presents an experimental study to investigate the flexural behaviour of concrete beams which reinforced with hybrid bars reinforcement under static loading. A set of eight reinforced concrete beams were monotonically tested under four point bending. Crack pattern and mode of failure, cracking and ultimate load, mid span-deflection, strain in main reinforcement and the ductility index were studied. Two main parameters were analysed; ratio of GFRP area to the concrete cross-section area and hybridization ratio of GFRP.

Keywords— Hybrid Bar, Crack Pattern, Mode of Failure, Mid Span-deflection, GFRP, ultimate load, cracking load.

1. INTRODUCTION

One of the main reasons for shortening the service life of reinforced concrete structures (RC) is the corrosion of reinforcement bar (reinforcing steel). As shown in Fig, 1 in [1], Corrosion of steel bars is a physical problem. The main challenge for engineers is to provide the building materials sustainable, eco-friendly and economical. Finding new building materials that can provides these requirements is a must. Fibre-reinforced polymers (FRP) have been widely used as reinforcing materials in the last decades [2]. At the beginning, FRP material was expensive and it was limited to specialized markets. In the past three decades FRP materials have been used as an alternative material to steel which used as reinforcing bars for concrete structures, [3]. FRP composites have advantages more than steel such as noncorrosive, lightweight and have high tensile strength, all of these reasons make the use of FRP as an affordable alternative to steel reinforcement. Furthermore, since they are non-conductive, they are suitable in medical applications that are highly sensitive to electromagnetic fields including magnetic resonance imaging (MRI) facilities. The most commonly used FRP types in infrastructure are carbon fibre reinforced polymer (CFRP), Aramid fibre reinforced polymer (AFRP), glass fibre reinforced polymer (GFRP) and basalt fibre reinforced polymer (BFRP), [3].

Fig. 1–Corrosion of steel bars.

FRP materials can be manufactured as sheets, plates and wraps for strengthening applications of existing structures, or as bars, and tendons for reinforcement of concrete in new construction, or as a structural element itself. The disadvantage of using FRP bars is the low modulus of elasticity which led to increase in deformations, while using steel bars led to give a high ductility, [4]. Hybrid bars are the new types of reinforcement which used as a good alternative to steel to reinforce a concrete structure and to improve disadvantages of FRP bars such as cost and elastic modulus as shown in Fig. 2, [1, 5-8].

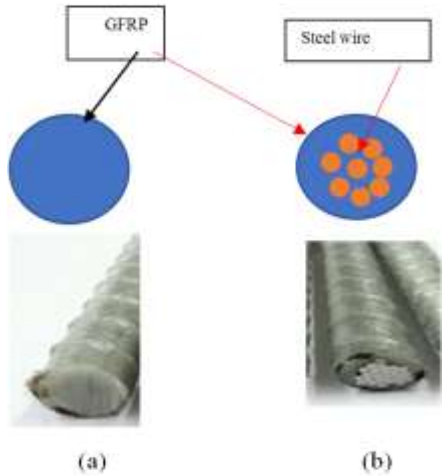

Fig. 2–Cross section types of "FRP Bar"; Type (a) (GFRP bar); Type (b) (GFRP with steel wires).

For the completeness, the advantages and disadvantages of using FRP and hybrid bars reinforcement are given in Table1.

TABLE 1- COMPARISON BETWEEN THE USE OF FRP AND USE OF HYBRID BARS IN REINFORCED CONCRETE STRUCTURES.

The Advantages of FRP ACI (2015) [9].	The Disadvantages FRP ACI (2015) [9].	Advantage Hybrid Bars
High tensile strength. Corrosion-resistant Nonmagnetic. High fatigue endurance (varies with type of reinforcing fibre). Lightweight (about 1/5 the weight of steel). Low thermal and electric conductivity (for glass and aramid fibres). Adequate damping property.	brittle mode failure mechanism. Low modulus of elasticity. Premature exceedance of deformation limit state. High coefficient of thermal expansion perpendicular to the fibres, relative to concrete. Inadequate thermal performance High material costs.	Low cost. The fibres dose not corrode. High modulus of elasticity. Light weight. Nonconductive. Nonmagnetic. High strength. Ductile failure.

2. RESEARCH OBJECTIVES

This experimental study aims to investigate the flexural behaviour of concrete beams reinforced with GFRP bars only or hybrid bars in terms of cracking pattern and modes of failure, cracking and ultimate load, mid span deflection and GFRP bars and hybrid-bars tensile strain. In order to achieve research objectives, the following sub-objectives are identified.

1. EXPERIMENTAL WORK MATERIALS

The possibility of using hybrid bars in concrete beams. The flexural behaviour of concrete beams reinforced with GFRP bars only or steel bars only. To investigate through experimental tests, the deflection behaviour of concrete beams reinforced with GFRP bars only, steel bars only or hybrid wire reinforcement, as well as the behaviour of deflection-related parameters. These involve bars strains, crack width and spacing. To test the FRP RC beams used in the study until failure to examine failure modes and the flexural behaviour. Investigate the flexural performance of hybrid bars reinforced of concrete beams experimentally. We tested beams with different reinforcement ratios of GFRP to steel wires in one. In order to achieve these objectives, two main groups (A) and (B) were classified, the main parameter in group (A) was the ratios of the area of GFRP bars (A_f) to the area of concrete cross section (A_c). In group (B) the main parameter was the ratios of the area of GFRP steel bars (A_w) to area total area of hybrid bars (A_f+A_w).

At first, tests were conducted according to Egyptian code (ECP208-2005) [10], to determine the mechanical properties of the hybrid bars, the results from these tests have been shown in Table 2. An experimental program was conducted to investigate the behaviour of RC beams reinforced with hybrid bars as a main reinforcement to enhance the flexural behaviour of concrete beams under static loads. Eight reinforced concrete beams of 35 MPa concrete compressive strength were prepared. These beams have a rectangular cross-section of 150 mm width and 250 mm height and are tested under four-point loading bending test over a simple span of 2000 mm. In order to have flexural behaviour, the shear-span to depth ratio is set to be equal 3.2. All tested beams were reinforced with two top reinforcement bars of 8 mm diameter. All beams were provided with shear reinforcement of 8 mm plain bars at a spacing of 200 mm. Table 3 provide full details of the tested beams also Fig. 3, provide details of the reinforcement arrangement for the considered beams. The induced strains in glass FRP, hybrid bars and steel bars at mid - span were measured by means of electrical strain gauges. These strain gauges had a 350 Ohms resistance, 2.04 gauges factor and a length of 15 mm. The strain gauges were attached to the bottom surface of main reinforcement at mid span, as shown in Fig. 4.

TABLE 2- PROPERTIES OF TESTED BARS.

Specimen Type	Actual bar diameter. (mm)	Yield Tensile strength or proof strength (MPa)	Ultimate Tensile strength (MPa)	Elastic Modulus (GPa)	Modules of Toughness (MPa)
Steel	7.9	248	355	200	8.93
	9.9	368	525	200	11.89
GFRP	8	------	1048	44	12.58
Hybrid 50%Steel	8.2	610	923	82.5	21.88
Hybrid 50%Steel	16.1	501.16	1180	110	19.89
Hybrid 65%Steel	12.7	708	1200	135	10.7
Hybrid 75%Steel	15.8	615.11	1030	130	25.1
Hybrid 35%Steel	12.7	----	957.13	60	10.1
Hybrid 25%Steel	16.3	------	920	52	14.82

TABLE 3- THE DETAILS OF THE TESTED BEAMS.

Group	Beam NO	BOTTOM REINF.	$(A_f/A_c)\%$	$A_f / (A_f + A_w)$	System of tension reinforcement
A	S1	3 Ø 10 S	0	------	Steel
	G1	2 Ø 8 G	0.698		GFRP
B	w1	2Ø8 (S+G) 50% (steel)	------	0.5	Hybrid bars
	W2	2Ø12 (S+G) 65%(steel)		0.65	
	W3	2Ø16 (S+G) 75%(steel)		0.75	
	W4	2Ø16 (S+G) 50% (steel)		0.5	
	W5	2Ø12 (S+G) 35% (steel)		0.35	
	W6	2Ø16 (S+G) 25% (steel)		0.25	

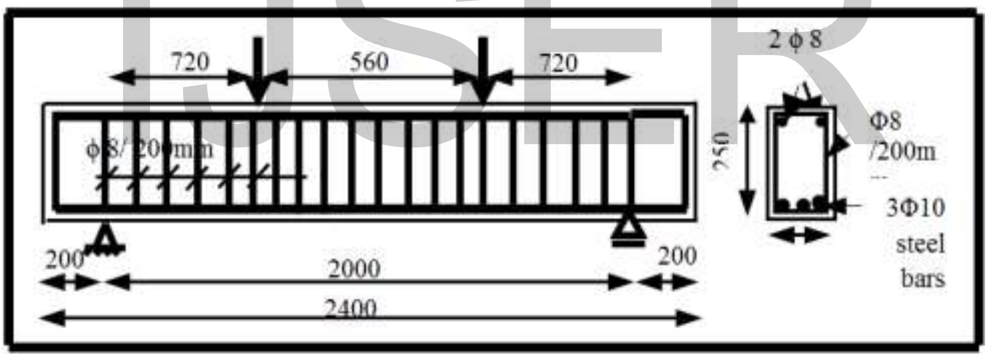

Fig. 3–Tested beams description S1.

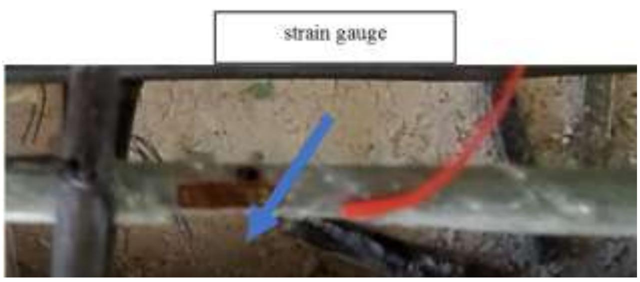

Fig. 4–Strain gauge installation.

2. Testing Machine, Setup and Procedure

(EMS 60-Ton PU) testing machine, shown in Fig. 5, was used in testing the beams. The used machine has three ranges of loading (15, 30 and 60) Tons. The first and the second ranges were used, depending on the predicted ultimate load of the tested beams. The used supports were steel bearing plates with dimensions of (20x10x1.25) cm. One of these supports was roller support while the other was hinged support. I-beam was used to make load concentrated in two point instead of one point. The setup of the test specimens is shown in in Fig 5 a.

All beams were tested after 28 days. Firstly, the beams were placed on the test machine by a crane. The LVDTs and crack width measurement device (Fig 5 b and c, respectively) were connected to the data recording system which shown in Fig. 6. All instrumentations were checked and zeroed prior to the start of testing. A static load was applied in increments of 0.4 ton until first cracking, then the remaining load was applied continuously until failure occurred.

Fig. 5 (a). Set up of tested beams.

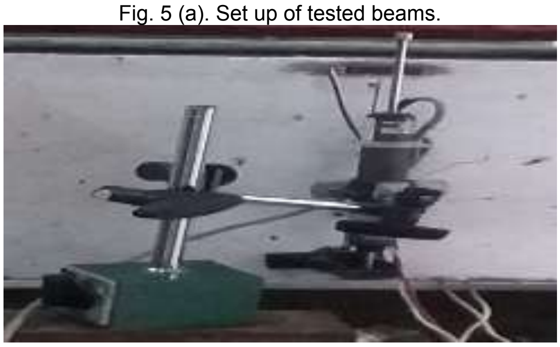

Fig. 5 (b). LVDT.

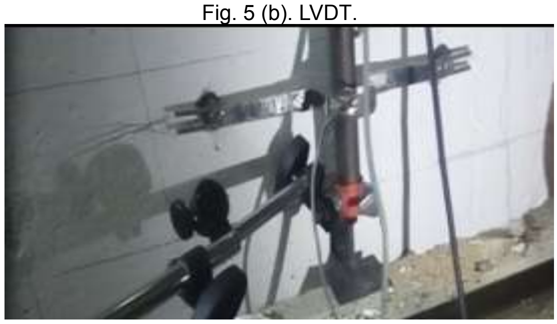

Fig. 5 (C). Crack width measurement device.
Fig. 5–Experimental tools

Fig. 6–Data loggers system.

3. TEST RESULTS AND DISCUSSION

W. R. T Crack patterns and mode of failure.

Cracks propagation for the different tested beams were observed visually and with a magnifying glass. For all beams, it was noticed that the cracks in both sides of studied beams were approximately similar. The cracks initiated at the bottom side in the flexural moment zone at low load level. The observed first crack was extending up to a point higher than half of the beam depth. As the load increased, the cracks widened and propagated upward. Later, new cracks were developed along the bottom of the beam and these cracks propagated towards the point of load application. The pattern of cracks was observed at different load levels. Furthermore, modes of failure were recorded for all tested beams as follows:

For Group A (A0 and G1)

For beams of G1 with GFRP bars, the number of cracks at failure was noticed to be fewer than that in reference beam A0 which having steel bars only. The cracks height and width in beams of G1 was more than the reference beam A0. This is due to the low modulus of elasticity of GFRP bars than steel bars, see Fig. 7 and 8.

For Group B (W1, W2, W3, W4, W5 and W6)

It is observed that the number of cracks in hybrid beams W3 and W2 is more than that in the beams W4, W6 and W5. This mainly due to the ratio of A_f / (A_f +A_w) in W3 and W2 is less than that in beams W4, W6 and W 5. Also, for this reason the number of cracks in beam W1 are more than that in beam G1. Also, the crack widths in beams W3 and W2 were less than that in beam W4, W6 and W5. The modes of failure in beams W4, W5 and W6 were flexural failure while in beam W1 was flexural with rupture in hybrid bar. Flexural with bond failure occurred in W2 and W3. This change in mode of failure is due to the under reinforcement of beam W1 and higher ratio of wires and less strain in steel in beams W3 and W2 as shown from Fig. 9 to 14.

Fig. 7–Pattern of cracks of beam (A0).

Fig. 8–Pattern of cracks of beam (G1).

Fig. 9–Pattern of cracks of beam (W1).

Fig. 10–Pattern of cracks of beam (W2).

Fig. 11–Pattern of cracks of beam (W3).

Fig. 12–Pattern of cracks of beam (W4).

Fig. 13–Pattern of cracks of beam (W5).

Fig. 14–Pattern of cracks of beam (W6).

W. R. T Cracking and ultimate loads

The cracking load for the concrete beam (A0) provided with steel bars only are higher than that of beam group (A) reinforced with GFRP bars only. Group (B) is almost similar to group (A) in cracking load. The increasing in cracking and ultimate load is different from group to another as follows: -

For Group A (A0 and G1)

As shown in Fig. 15, the ultimate failure load for beams reinforced with steel reinforcement is larger than that of GFRP beams. The obtained result agrees with the previous result reported by [11]. This may be attributed to the low modulus of elasticity for GFRP bars. Due to the low modulus of elasticity of GFRP bars, the crack initiation load was found to be early in beams with GFRP reinforcement when compared to beams with conventional steel reinforcement. The obtained result confirms with the previous result reported by [12].

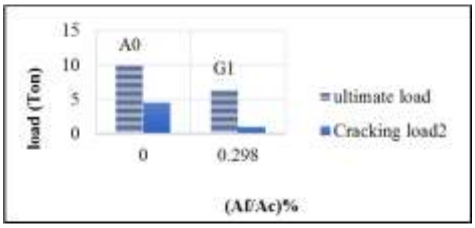

Fig. 15–Group A, effect of A_f / (A_c) ratio on ultimate load and cracking load for group A.

For Group B (W1, W2, W3, W4, W5 and W6)

Fig. 16 shows the effect of A_f / (A_f +A_w) ratio in hybrid bars on cracking and ultimate load for the tested beams. It is obvious from these figures that, when the A_f / (A_f +A_w) ratio increases the ultimate load decrease such as W2 and W5. However, the cracking load has not been affected due to change A_f / (A_f +A_w) ratio.

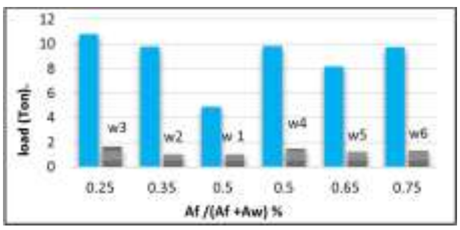

Fig. 16–Effect of A_f/ (A_f +A_w) ratio on Cracking and ultimate load for beams group B.

W. R. T Mid-Span Deflection

The relation between the applied load and the measured mid-span deflection is illustrated from Figures 17 to 20, for different tested beams. Generally, through these figures, it is obvious that the initial part of the curves was linear for all beams. At the end of the linear phase, the beams began to crack. Also, in these figures, it can be seen that the deflection at failure in groups B was slightly larger than that in beam A0 (control) and smaller than for beams of group A.

For Group A (A0 and G1)

The increase in deflection after first cracking up to (50%) of the ultimate load for beam G1 (2G) which was reinforced with GFRP bars only was 400% more than that for beam A0 which was reinforced with steel bars only as shown in Figure 17. The obtained results showed a similar trend as was observed in a previous work by [13].

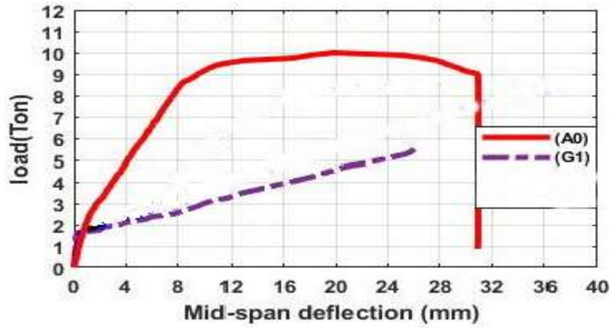

Fig. 17–Load mid-span deflection curves for group A.

For group B (W1, W2, W3, W4, W5 and W6)

Fig. 18 and 19 present the load- mid span deflection for beams W (2, 3, 4, 5, 6), It is observed that by increasing the ratio of the A_f / (A_f + A_w) ratio, this increased the deflection in the beam's hybrid bars because of the low modules of elasticity of the fibre compared to the steel wires, such as beams W3 with W4 and W6 and the beam W5 with W2.

At any level of loading, the deflection of the GFRP beams is higher than that of the hybrid beams, because the modulus of elasticity of the hybrid bars is higher than that of the GFRP bars such as G1 and W1 see Fig. 20.

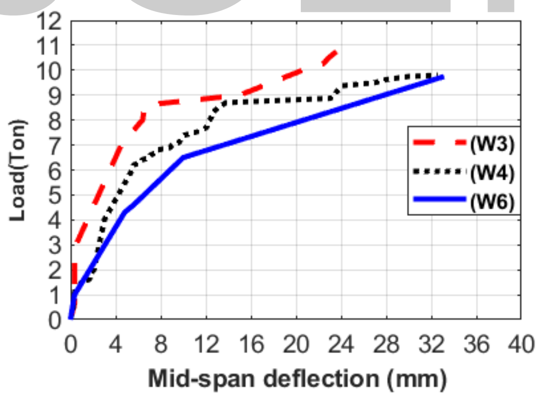

Fig. 18–Load mid-span deflection curves for hybrid beams (W3, W4 and W6).

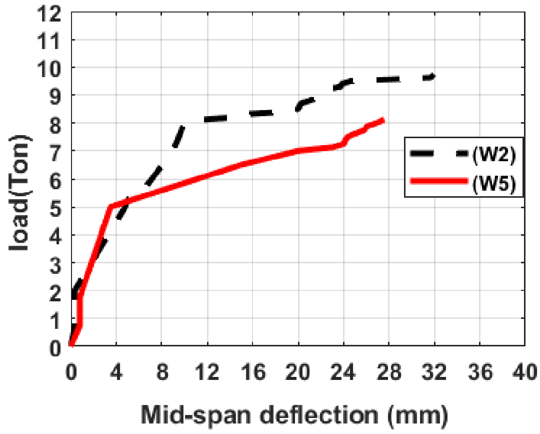

Fig. 19–Load mid-span deflection curves for beams W2 and W5.

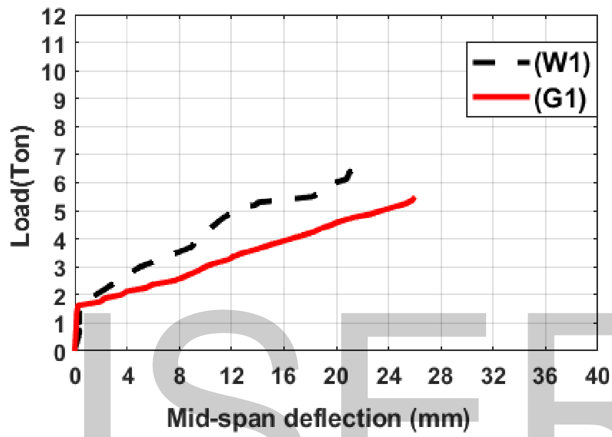

Fig. 20–Load mid-span deflection curves for beams W1 and G1.

W. R. T Ductility and Toughness.

Ductility of reinforced concrete beams can be measured based on measuring of the mid-span deflection at cracking and at failure. Also, the toughness can be measured based on measuring of the energy absorption capacity as represented by the area under the load-deflection curve.

The displacement ductility index $[\mu_D]$ considered here was measured as the ratio between maximum deflection $[\Delta_{max}]$ and the deflection corresponding to cracking load $[\Delta_{cr}]$. Total energy absorption capacities (E_{abs}) were determined by calculating the area under the load-deflection graph for the RC beams under static loading.

Toughness of reinforced concrete beams can be measured based on total energy absorption capacity.

The effect of A_f / $(A_f + A_w)$ ratio (hybrid bar) on the displacement ductility index for these reinforced beams is illustrated in Fig. 21. It is noted from these Figure that, as the A_f / $(A_f + A_w)$ ratio increased for beams having the same total area of reinforcement, the ductility index decreased such as W3 and W 4.

Fig. 21, showed that the ductility index increased with increasing in the ratio of tensile reinforcement for group (A). Also, shows that the ductility of group B is better than the group A.

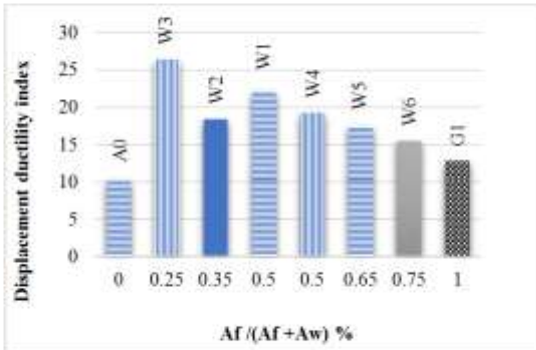

Fig. 21–Effect of (Δ_{max} / Δ_{crack}) ratio on ductility for beams.

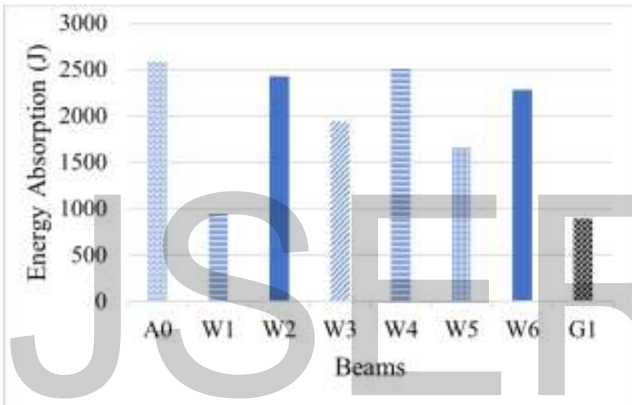

Fig. 22–Energy absorption capacity for beams.

W. R. T Induced strain

The tensile strain in the main longitudinal reinforcement (steel, glass FRP bars and hybrid bars) was measured at mid span for different beams tested under static load condition. The measured values were plotted against the applied load from zero loading up to failure as shown in Fig. 23 and 25.

For Group A (A0 and G1)

Fig. 23, it is obvious that, for glass FRP reinforced concrete beam G1, the increase in strain after first crack is more than that in beam A0 which was reinforced with steel bars only. This means that the deformation of GFRP concrete beams increases quickly after the first crack. It is clear from this figure that, after cracking stage and at any load level, beam G1 recorded a greater strain in GFRP bars. This is due to the lower modulus of elasticity of GFRP. with the increasing in the applied load the load strain relationship increased linear up to failure.

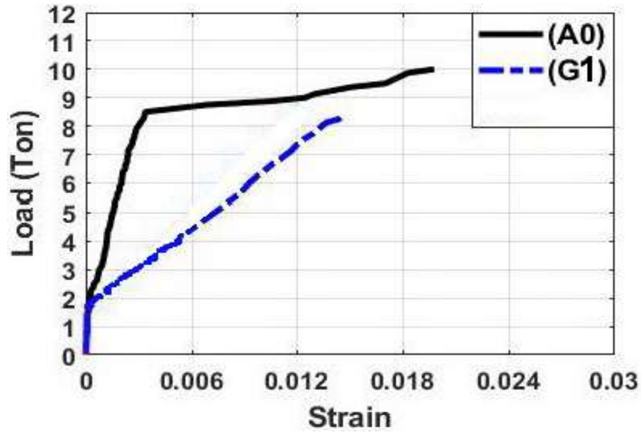

Fig. 23–Strain in GFRP and Steel in beams group (A).

For Group B (W1, W2, W3, W4, W5 and W6)

The load strain curve for hybrid bars in beams W3, W4 and W6 are shown in Fig. 24 and W5 with W2 are shown in Fig. 25. It is observed that the load strain curves were linear until cracking. After that the trend of the curves are semi linear up to failure. This is due to the combination effect of steel wires and glass fibres. At any load level, the increasing in A_f / $(A_f + A_w)$ ratio in bar led to increasing in strain value. For example, beam with 75% glass with 25% steel wires, the values of measured strain were larger than the strain in hybrid bars with 65% glass and 35% steel wires. This due to the low modules of elasticity of the fibre compared to the steel. The hybrid bar carries higher ultimate loads and small strain compared to GFRP beams.

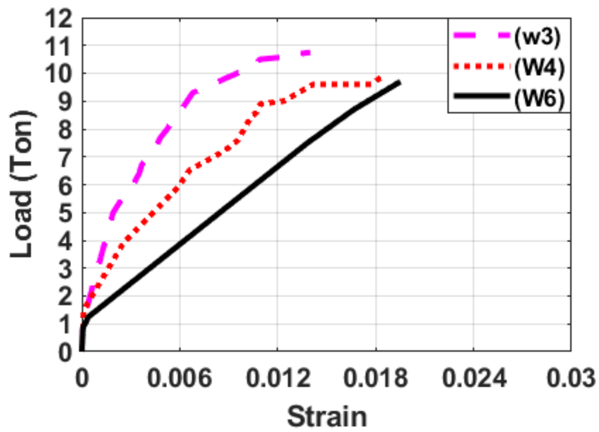

Fig. 24–Strain in hybrid bars in beams group (B) with the same amount of reinforcement beams w3, w4, and w6.

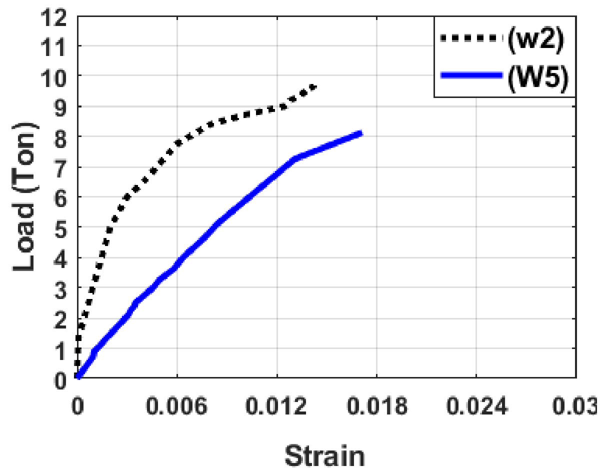

Fig. 25–Load main reinforcement-strain curves for beams W2 and W5 with the same amount of reinforcement.

W. R. T crack spacing

The averages spacing of the cracks in the constant flexure zone is shown in Fig. 26, for all the elements. In all the cases, cracks did form beneath or very close to the two loading blocks. Therefore, the spacing is averaged by dividing the length of the constant flexure zone by the number of cracks in that zone less one. The distance between the cracks in the beams reinforced with GFRP bars only are greater than that found in the beams reinforced with hybrids bars due to the poor bond between GFRP and concrete.

Figure 26, shows that the average crack spacing in group A and B about 1.78 and 0.59 times to the minimum crack spacing in beam A0 and maximum crack spacing in beam G1 respectively.

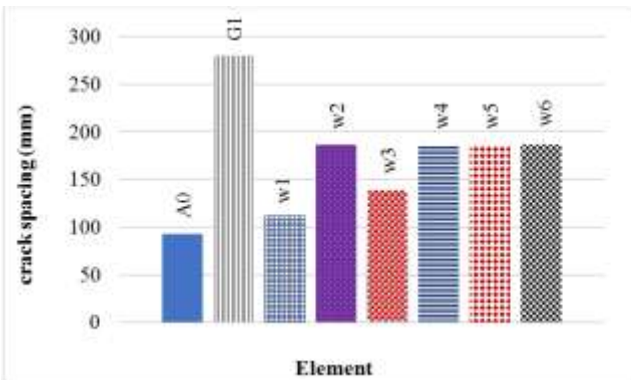

Fig. 26–Average spacing of the cracks in the constant flexure zone.

W. R. T crack width

Fig. 27 shows the load-crack width relationship. Increasing the steel reinforcement ratio reduced the crack widths. Since most FRP bars have a modulus of elasticity lower than that of steel, crack widths in FRP-reinforced members are expected to be larger than those in steel-reinforced or hybrid RC beams at any load. All specimens exhibited elastic characteristics before initial cracking of concrete. with increasing of the vertical loads, short and fine flexural cracks initiated at constant moment regions. *A s* the vertical loads continued increased, the existing fine vertical cracks extended longer and wider, and meanwhile a few new cracks could be observed at constant moment regions as well as bending shear regions. The steel-RC beams showed the smallest crack widths as they had very high reinforcement axial stiffness (E_s*A_s) compared to the FRP-RC beams. Moreover, at the yield load of steel-RC beams, the average cracks widths in GFRP-RC beams were about 2.4 times higher than that in steel-RC beams. These results were expected due to the higher modulus of elasticity of steel bars compared to GFRP bars. The cracks at any load was wider for the beams reinforced with GFRP only or hybrid bars compared to the control beam which reinforced with steel only.

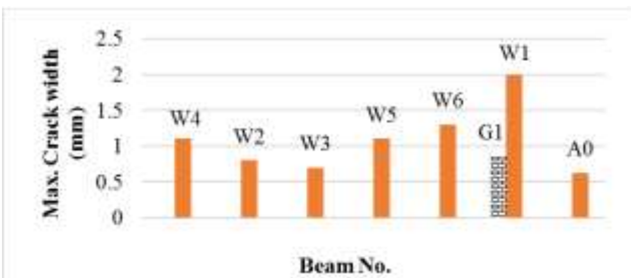

Fig. 27–Load vs. midspan crack width for beams having the same tensile force of the main reinforcement.

4. Conclusion

Based on the results of the experiments carried out on the beams reinforced longitudinally with hybrid bars and the predicted results, the main conclusions can be drawn.: -

1) If the ratio of A_f / (A_f +A_w) ≥ 50% in the hybrid reinforced beams, it is preferable to be designed as over reinforcement beams.
2) All beams of group B (reinforced with hybrid bars) had a flexural failure mechanism. This is due to the hybridization of fibers with steel wires and also due to the under-reinforcement design of such beams.
3) The cracks width in hybrid beams is mainly controlled by steel wires content. As the ratio of steel wires increased, the cracks width decreases.
4) At any load, the cracks width in hybrid beams are smaller than the cracks width in GFRP beams.
5) The increasing of the A_f / (A_f +A_w) ratio, led to a decrease of the number of cracks and an increase of the spacing between the cracks.
6) Using of the A_f / (A_f + A_w) ratio gives an acceptable parameter for measuring the improvement in the flexural behaviour in concrete beams with hybrid bars.
7) Decreasing the A_f / (A_f +A_w) ratio in hybrid bars reinforced beams increased the moment capacities.
8) Beams reinforced with GFRP bars only gives higher deflection compared with beams reinforced with hybrid bars. This is due to the lower modulus of elasticity of GFRP bars.
9) The increasing in steel wires in hybrid beams from zero to 75% led to a decreasing in mid span deflection gradually in beams of group B.
10) At the same load level, less deflections were observed for hybrid reinforced beams compared to the beam reinforced by GFRP bars only.

The ductility indices in hybrid beams is better than the GFRP beams. This due to the presence of glass fiber with steel wires in one bar.

Increasing in the ductility has been achieved by replacing part of the GFRP bars by steel wire in hybrid reinforced beams.

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