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Experimental and Analytical Investigation of FRP Reinforced Concrete Beams in Flexure

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Abstract: Rebars fabricated from Fiber-Reinforced Polymers (FRP) are innovative materials utilized as an alternative to traditional steel reinforcement rebars in reinforced concrete structures to overcome corrosion problems especially in harsh and aggressive environments. FRP rebars manufactured from glass or basalt fibers embedded in a polymer matrix have high tensile strength, stiffness and enhanced durability. Also, FRP rebars have moderate costs. This research investigates experimentally the flexural performance of FRP-reinforced concrete beams. In the experimental program, two concrete beams reinforced by glass and basalt FRP bars were tested under a four-point flexural test until failure. Both the failure load, the failure mechanism and the mid-span deflection of the tested beams are presented and discussed. The experimental investigation showed that the major failure mode of the tested beams reinforced by FRP bars is crushing of concrete at the top substrate. Additionally, theoretical analysis of the ultimate flexural capacity and the failure loads were computed using American design guidelines and were found to be in good agreement with the experimental results.

Keywords: Concrete beams; FRP reinforcement; flexure capacity; experimental investigation.

1. INTRODUCTION

Using fiber-reinforced polymer (FRP) rebars as reinforcement instead of conventional steel reinforcement in concrete structures is currently increasing to overcome the major problem of traditional steel reinforcement which is corrosion. This is especially important in concrete structures exposed to harsh environmental exposure to preserve structural durability [1]. Bars fabricated from fiber-reinforced polymers (FRP) are preferred in such cases due to their high tensile strength, stiffness, corrosion and chemical resistance [2, 3]. However, the tensile behavior of FRP rebars is characterized by a linear elastic stress-strain relationship up to failure, which causes concrete beams reinforced with FRP bars to exhibit brittle failure without warning [4-6]. Most design codes such as the American design guidelines are recommending to design the maximum moment section of concrete beams reinforced by FRP rebar to be over-reinforced since the nonlinear behavior of concrete in a compression zone can sustain a limited degree of deformability which may lead to a less catastrophic failure [7]. Experimental tests studied the flexural performance of concrete beams reinforced by GFRP rebars and showed high load carrying capacity compared, however a brittle failure was adopted due to the nature of the GFRP tensile stress-strain curve which is linear relationship up to failure [8-10]. The ultimate load carrying-capacity of concrete beams increases with using FRP rebars compared to the same beams reinforced by traditional steel reinforcement which is mainly due to the high tensile strength of FRP rebar compared to the yield strength of steel reinforcement. Several types of research investigated experimentally the flexural performance of hybrid concrete beams reinforced by GFRP rebars and steel rebars at different levels [11-14]. The authors reported that the concrete crushing failure mode was the major failure mode of the over-reinforced hybrid concrete beams, moreover, the hybrid-reinforced concrete beams showed a higher flexure capacity than the conventional steel or GFRP reinforced concrete beams. Since basalt fiber-reinforced polymer (BFRP) rebars are considered new materials, limited studies investigated the flexural behavior of concrete beams BFRP rebars [15-17] or hybrid steel-BFRP reinforcement [18, 19]. Furthermore, BFRP rebars are not included in design guidelines. The paper aims to study and provide an experimental/analytical investigation of the flexural performance of concrete beams reinforced by different FRP rebars. An experimental program is conducted where two concrete beams reinforced by different FRP rebar types (GFRP and BFRP) were tested under a four-point flexural test. Failure loads, failure modes and mid-span deflections of the tested beams are presented and investigated. The ultimate loads of the tested beams are also evaluated analytically using the American design guidelines and were found to agree with the values measured experimentally.

2. EXPERIMENTAL PROGRAM

An experimental program was conducted to investigate the flexural performance of concrete beams reinforced by GFRP or BFRP rebars under a four-point bending test. Two concrete beams with cross-section of 120x240 mm were cast. One of those beams had the bottom reinforcement of two GFRP rebars, and the other beam was reinforced by two BFRP bottom rebars, as listed in Table 1. The experimental work has been conducted in the Concrete Laboratory at the Housing and Building Research Centre (HBRC), Cairo, Egypt.

TABLE 1. Experimental program

Beam No.	Cross-Section Dimensions (mm)	FRP Bottom Reinforcement	FRP Rebar Type	ρ_f%	Steel Top Reinforcement	Steel Shear Stirrups
B1	120 x 240	2T10	GFRP[a]	0.64	2Ø8	Ø8-100
B2	120x240	2T8	BFRP[b]	0.41	2Ø8	Ø8-100

[a]*GFRP: Glass fiber reinforced polymer rebar.*
[b]*BFRP: Basalt fiber reinforced polymer rebar.*

TABLE 2. Mix constituents per 1 $m^3$of concrete.

Cement (kg)	Sand (kg)	Coarse aggregate (kg)	Water (L)	HRWR[a] (L)
450	690	1120	190	10

[a]*HRWR: High-range water reducer (Sikament ®-R4PN).*

2.1. Materials

The concrete mix was designed with a target concrete cube compressive strength of 40 MPa. The constituent materials of the used concrete mix are: Portland cement conforming with the Egyptian standard specification ES 4756-1[20], washed-crushed limestone coarse aggregate of nominal maximum size of 20 mm, clean natural siliceous sand conforms with the Egyptian specification ES 1109 [21], drinkable clean water in addition to a high range water reducer and slump retaining concrete admixture (Sikament®-R4PN) to improve the concrete mix workability and compressive strength at early stages. Concrete mix proportions are listed in Table 2. The tensile strength and maximum tensile strain for GFRP are 950 MPa and 0.02 mm/mm, respectively, while for BFRP rebar the tensile strength is 1100 MPa and the maximum tensile strain is 0.022 mm/mm. Stirrups and two longitudinal top reinforcements were 8 mm diameter mild steel bars with yield stress 240 MPa and ultimate strength 520 MPa conforming to the Egyptian Specification ES: 262-2 [22].

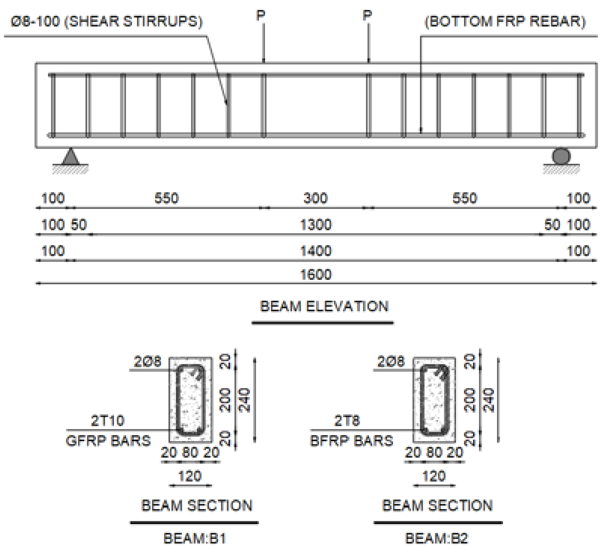

Fig. 1. Beam dimensions and reinforcement details (dimensions in mm).

2.2. Specimens' preparation

Two concrete beams reinforced with different FRP bars. One beam is reinforced by two GFRP rebars of 10 mm diameter, and the other beam is reinforced by two BFRP rebar with a diameter of 8 mm was designed according to ACI 440.1R design guidelines [7]. Both beams had the same rectangular cross section of 120mm width and 240mm depth and had top longitudinal reinforcement of two 8 mm diameter steel rebars. Shear stirrups used were 8 mm diameter mild steel, spaced at 100 mm over the beam shear span, as shown in Fig. 1. Wooden moulds and reinforcement cages were prepared and the concrete constituents were mixed using a mechanical mixer and all concrete beams specimens cast and allowed to set for 24 hours inside the formwork, then the beams were left and placed in the curing water tank for 28 days before testing.

2.3 Material tests

Three standard cubes (150x150x150) mm were cast from the same concrete mix, cured under the same conditions and tested after 28 days in compression; the average concrete cube compressive strength was 41 MPa. Concrete cubes and testing machine is shown in Fig.2.

Three BFRP bars and three GFRP bars samples were tested in tension according to the ASTM D7205 standard [23] using the universal testing machine of 1000 kN capacity, as shown in Figs. 3 and 4. To avoid bar slippage or local failure of the bar in the anchorage zone, a steel pipe 250 mm long with an outer diameter of 55 mm was used at each end of the tested FRP-rebar adhered using epoxy resin and hardener. The average tensile strength of the GFRP-rebar was 950 MPa with a corresponding ultimate tensile strain was 0.02 mm/mm, while the BFRP-rebar had 1100 MPa as an average tensile strength with an ultimate tensile strain of 0.022 mm/mm.

Fig. 2. Concrete cube compressive strength test.

Fig. 3. Tensile testing of GFRP bars.

Fig. 4. Tensile testing of BFRP bars

2.4 Flexural testing of beams

Concrete beam specimens were subjected to a four-point flexural test up to failure through a universal testing machine of 1000 kN capacity. The beams were simply supported along with an effective span of 1400 mm. Under flexural tests, the beams were loaded through a hydraulic actuator and steel spreader beam to distribute the load into two equal loads spaced at 300 mm and 550 mm from beam supports, to ensure flexural failure of beams. The load was increased at a uniform rate until beam failure. Mid-span deflection of the tested beams was captured by using a dial gauge of least count 0.01mm at the center of the specimen. Three Linear Variable Differential Transformers (LVDTs) were used to measure deflection, one at the center of the beam and two under the applied loading. The data acquisition system was connected to record the applied load along with the corresponding mid-span deflection. Figure 5, shows the test set-up of the beam

Fig. 5. Test setup for four-point bending test of beams.

1. EXPERIMENTAL RESULTS AND DISCUSSION

During the flexural test, the beams reinforced with GFRP or BFRP rebar started to crack in the beam mid-span and with increasing the flexural loading level. The cracks increased in width and depth and spread towards the beam supports until failure; concrete crushing in compression at the top of beam substrate was the major failure mechanism. Figure 6 shows the cracking patterns of the GFRP beam and BFRP beams. The load-deflection curve of both beams shown in Fig. 7 shows that the ultimate failure load of the GFRP beam and BFRP beam were 85.26 kN and 72.30 kN, respectively. This is mainly due to the higher FRP reinforcement ratio of GFRP rebar than the BFRP rebar. Similar beam behavior was reported in the literature by Urbanski et al. [2] for (BFRP reinforced concrete beams) and by El-Nemr et al. [8] for (GFRP reinforced concrete beams). Table 3 lists the ultimate load of both concrete beams at failure with the corresponding mid-span deflection, where the beam reinforced by the GFRP rebar exhibited 28.50 mm mid-span deflection compared to the 25.80 mm mid-span deflection obtained from the beam with the BFRP rebar.

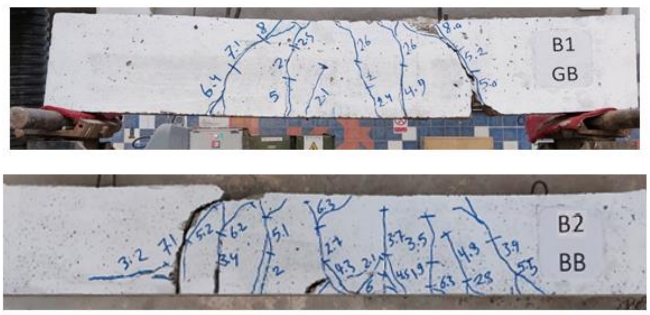

Fig. 6. Cracking pattern of beams.

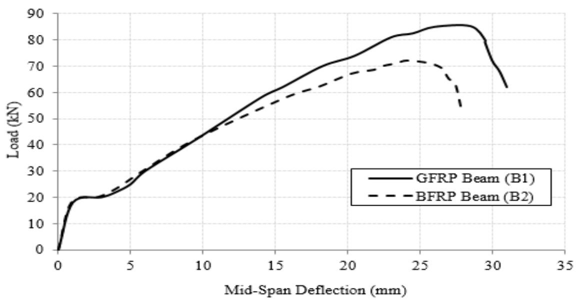

Fig. 7. Load-deflection curves of tested beams

2. ANALYTICAL INVESTIGATION

The analytical approach is one of the powerful techniques to evaluate the carrying capacity and deflections using available design guidelines to trace and verify the experimentally measured results for the beams. American guidelines ACI 440.1R [7] are utilized to compute the nominal flexural capacity of the beams.

2.1. Analytical procedure of GFRP beam

The ultimate load of the GFRP RC beam has been calculated based the on cross-section of 120x240 mm with 2Φ10 GFRP rebars. Equations (1) and (2) compute the balanced fiber reinforcement ratio (ρ_{fb}), and the adopted fiber reinforcement ratio (ρ_f).

$$\rho_{fb} = 0.85\beta_1 \frac{f_{c'}}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} = 0.00298 \quad (1)$$

$$\rho_f = \frac{A_f}{b.d} = 0.00632 \quad (2)$$

Since $\rho_f > \rho_{fb}$, then the tensile stress in the GFRP bar is given by Equation (3), the assumed concrete crushing strain ε_{cu} =0.003 and FRP stiffness E_f = 47500 MPa are used in calculating the ultimate tensile stress in FRP bar.

$$f_f = \left(\sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_{c'}}{\rho_f} E_f \varepsilon_{cu}} - 0.5\, E_f \varepsilon_{cu} \right) = 632\, MPa \le f_{fu} \quad (3)$$

Finally, the nominal moment capacity (M_n) of the concrete beam is given by Equation (4). Concrete compressive strength *fc'*=0.80*41=32.80 MPa is used to calculate M_n.

$$M_n = \rho_f f_f \left(1 - 0.59 \frac{\rho_f f_f}{f_{c'}}\right) b d^2 = 21\, kN.m \quad (4)$$

2.2. Analytical procedure of BFRP beam

A similar approach to that used in clause 4.1, has been used to calculate the ultimate analytical load of concrete beam reinforced by BFRP bars. The beam has a 120x240mm cross-section with 2Φ8 BFRP rebars. Equations (5) and (6) show the balanced reinforcement ratio (ρ_{fb}), and the adopted reinforcement ratio (ρ_f).

$$\rho_{fb} = 0.85\beta_1 \frac{f_{c\prime}}{f_{fu}} \frac{E_f \varepsilon_{cu}}{E_f \varepsilon_{cu} + f_{fu}} = 0.00237 \quad (5)$$

$$\rho_f = \frac{A_f}{b.d} = 0.00409 \quad (6)$$

Since $\rho_f > \rho_{fb}$, then the tensile stress in BFRP bar is given by Equation (7). The assumed concrete crushing strain ε_{cu} =0.003 and FRP stiffness E_f = 50000 MPa have been used in calculating the ultimate tensile stress in FRP bar.

$$f_f = \left(\sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_{c'}}{\rho_f} E_f \varepsilon_{cu}} - 0.5\, E_f \varepsilon_{cu} \right) = 821.48\, MPa \leq f_{fu} \quad (7)$$

Finally, the nominal moment capacity (M_n) of the concrete beam is given by Equation (8). Concrete compressive strength fc'=0.80*41=32.80 MPa is used to calculate M_n.

$$M_n = \rho_f f_f \left(1 - 0.59 \frac{\rho_f f_f}{f_{c'}}\right) bd^2 = 17.75\, kN.m \quad (8)$$

Table 3 lists the experimental ultimate load along and compares the results with the analytical ultimate load. The computed analytical ultimate load of the GFRP and BFRP beam is 1.16 and 1.12 times the measured experimental failure load, respectively.

Where:

ρ_{fb}: Balanced FRP reinforcement ratio.

ρ_f: Provided FRP reinforcement ratio.

β_1: Factor of 0.75 for concrete strength $f_{c'}$ of 41 Mpa

$f_{c'}$: Cylindrical Concrete compressive strength (Mpa).

f_{fu}: Ultimate tensile strength (950 Mpa for GFRP) and (1100 Mpa for BFRP).

E_f: Modulus of elasticity of FRP rebar (Mpa).

ε_{cu}: Ultimate strain in concrete.

A_f: Area of FRP rebar (mm^2).

b: Width of concrete beam (mm).

d: Distance from extreme compression fiber to centroid of FRP tension rebar (mm).

f_f: Stress in FRP reinforcement in tension (Mpa).

M_n: Nominal moment capacity of concrete beam (KN.m)

TABLE 3. Experimental and analytical results of the tested beams.

Beam No.	Experimental Results			$P_{u\text{-Analytical}}$ (kN)	$\frac{P_{u-Experimental}}{P_{u-Analytical}}$
	P_u (kN)	δ_u (mm)	Failure Mechanism		
B1	85.26	28.50	Compression Failure	76.36	1.16
B2	72.30	25.80	Compression Failure	64.54	1.12

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