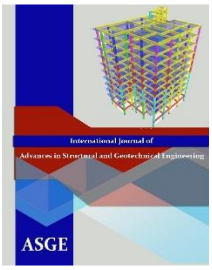

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Flexural behaviour of concrete beams reinforced with Basalt FRP bars

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ABSTRACT

The flexural properties of six 150 x 300 x2400 mm concrete beams reinforced with basalt FRP (BFRP) bars were investigated. The beams were divided into two groups , the first group consisted of four beams reinforced with only BFRP bars with reinforcement ratio (ρ_f) ranged from 3.59 to 8.95 times the balanced ratio (ρ_{fb}) according to ACI 440.1R-06 . The second group consisted of two hybrid beams reinforced with BFRP and steel bars with ρ_f 3.59 and 5.38 times ρ_{fb} in addition to one steel bar of diameter 10mm and yield strength 360 MPa . The beams were tested under four-point bending over a clear span of 2200 mm until failure. The test results of the first group indicated that when ρ_f increased by 150% , the ultimate deflection was reduced by 50% and ultimate load capacity was increased by 40% compared with the beam that had ($\rho_f = 3.59\ \rho_{fb}$) . The mode of failure of the first group beams is concrete crushing in the top compression fiber. The test results of the beams of the second group indicated that adding steel bar of diameter 10mm to the beam that had two BFRP bars (by steel to BFRP reinforcement ratio =35%), led to reducing the ultimate deflection by 42 % while the ultimate load capacity increased by 10%. Moreover , adding steel bar of diameter 10mm to the beam that had three BFRP bars (by steel to BFRP reinforcement ratio =25%), led to reducing the ultimate deflection by 30 % while the ultimate load capacity increased by 8% . This shows that there is a direct relation between steel to BFRP reinforcement ratio and the reduction of deflection and the effect of adding steel bar is more pronounced on reducing ultimate deflection than increasing ultimate load capacity and hence enhancing serviceability of the beams.

Keywords: Concrete, Basalt FRP , Beams

INTRODUCTION

Basalt is a natural inorganic material that is found in volcanic rocks originating from frozen lava, with a melting temperature between 1500 ^{o}C and 1700 ^{o}C Militký & Kovacic (1996)[1]; (Militký et al.,(2002)[2].Studies on the mechanical and durability characteristics of Basalt fiber reinforced polymer (BFRP) have shown an acceptable performance overall. BFRP was shown to have good thermal resistance and excellent performance under the accelerated weathering test (Sim et al., 2005)[3]. In addition, BFRP was shown to have excellent freezing-and-thawing resistance and good resistance to hostile acidic environments (Wei et al., 2010)[4]. Basalt fibers lie between glass and carbon for both stiffness and strength (Brik, 2003)[5].The good properties of basalt fiber(Patnaik et al., 2004)[6], combined with cost-effective manufacturing, have led to the development of BFRP bars as internal reinforcement for concrete structures (Patnaik, 2009)[7].Basalt fibers can be used for very low temperatures (i.e. about-200 °C) up to comparatively high temperatures (i.e. in the range of 600-800 °C) (Wu et al., 2012)[8]; (Scheffler et al., 2009)[9]; Deàk & Czigàny (2009)[10]; (Cao et al., 2009)[11]. (Ovitigala,2012)[12] investigated the flexural behaviour of eight BFRPRC beams of 203.2 mm width * 304.8 mm height * 3657.6 mm total length. All beams failed by crushing of the concrete at the mid span (as expected for over-reinforced section). This investigation concluded that when the area BFRP reinforcement increased seven times, the deflection was reduced by 63% and moment capacity was increased by 90%. Moreover, the serviceability criteria (deflection limits) can be achieved by increasing the area of BFRP reinforcement. However, the ultimate failure would be brittle in nature without prior warning due to lower deflection when the area of BFRP reinforcement increased. (Urbanski et al., 2013)[13] and Lapko & Urbanski (2015)[14] investigated the flexural performance of concrete beams (80 * 120 * 1200 mm) reinforced with BFRP bars 8mm in diameter with a tensile modulus of elasticity of 39.05 GPa. The results showed that the BFRP-RC beams did not fail suddenly since the beams transformed into a tie system because flexural reinforcement did not rupture. The deflection and crack width of the BFRP-RC beams were significantly higher than that of a steel-reinforced beam, due to the lower modulus of BFRP bars compared to that of steel bars. Tomlinson & Fam (2015)[15] assessed the flexural and shear performances of concrete beams (150 * 300 * 3100 mm) reinforced with BFRP bars and stirrups. The test results showed that the beams with BFRP flexural reinforcement and BFRP or steel stirrups had significantly higher strengths (2.6-2.9 times) than control steel reinforced counterparts having the same reinforcement ratio. Adhikari,2009[16] tested thirteen 200 x 180 mm(8 x 7 in.) concrete beams reinforced with 3, 5, and 7 mm BFRP bars. The flexural reinforcement to balanced ratio ρ_f/ρ_{fb} ranged between 0.43 and 3.53. The results have shown that when the reinforcement ratio ρ_f is equivalent to the balanced ratio ρ_{fb}, the ultimate moment at failure was more than three times the cracking moment. (Etman ,2011)[17] investigated the flexural behaviour of nine RC one-way slabs internally reinforced with innovative hybrid reinforcement system. It was revealed that the use of the innovative hybrid reinforcement system resulted in remarkable increases in section ultimate load capacity as well as ductility.

EXPERIMENTAL PROGRAM

Test specimens

Fig.1 shows the dimensions and reinforcement details of the tested beams.The experimental program consists of Four concrete beams reinforced with BFRP bars and two beams reinforced with hybrid (BFRP/steel)bars were tested . The tested beams were 150 mm wide, 300 mm high, and 2400 mm long. The beams were tested under four-point bending over a clear span of 2200 mm. They had a clear shear span of 962.5 mm (corresponding to a shear-span-to- depth ratio of about 3.7), while the distance between the two loading points was kept 275 mm (constant moment zone). The beams were extended 100 mm beyond the support to provide sufficient anchorage length to prevent slippage of main reinforcement. The tested specimens were divided into two groups . The first group consisted of four specimens (B-2-0 ,B-3-0 , B-4-0 and B-5-0) with basalt reinforcement ratio (ρ_f) 3.59 , 5.38 , 7.16 and 8.95 times the balanced ratio (ρ_{fb}) according to ACI 440.1R-06 respectively .The tested beams of the first group were designed to fail by concrete crushing in the constant moment zone as it was preferable and more ductile than FRP rupture according to ACI 440.1R-06 ,this was accomplished by using ρ_f greater than ρ_{fb} . The second group consisted of two hybrid specimens (B-2-1 and B-3-1) using hybrid (BFRP/steel)bars with ρ_f 3.59 and 5.38 times ρ_{fb} respectively in addition to one steel bar of diameter 10mm(by steel to BFRP reinforcement ratio (A_S/A_F) =35% and 25% respectively) as shown in Table 1. All beams were reinforced with two steel bars of diameter 10mm as top reinforcement. Steel stirrups of diameter 10 mm spaced at 100 mm were used as shear reinforcement in both shear spans to avoid undesirable brittle shear failure in all specimens . To eliminate the confining effect of the shear reinforcement on the flexural behaviour, no stirrups were used in the constant moment zone.

Table 1: Description of test specimens

Group	Beam	Main reinforcement BFRP	Main reinforcement Steel	ρ_f / ρ_{fb}	$(A_S/A_F)\%$	objectives
Group 1	B-2-0	2Ø12	_	3.59	-	Study the effect of increasing reinforcement ratio on the flexural behaviour of the specimens.
	B-3-0	3Ø12	_	5.38	-	
	B-4-0	4Ø12	_	7.16	-	
	B-5-0	5Ø12	_	8.95	-	
Group 2	B-2-1	2Ø12	1Ø10	3.59	35	Study the effect of adding different ratios of steel to BFRP bars (A_S/A_F)on enhancing deflection
	B-3-1	3Ø12	1 Ø10	5.38	25	

Material properties

Concrete

The test specimens were made of normal strength concrete(NSC) with a target compressive strength of 30 MPa after 28 days . The mix proportions of the used NSC were 350 kg/m^3 of cement, 560 kg/m^3 of sand, and 1120 kg/m^3 of aggregate with a water/cement ratio (w/c) of .5 .The maximum aggregate size was 20 mm.

Reinforcing bars

Basalt-fiber-reinforced polymer (BFRP) bars of diameter 12mm were used as tension reinforcement in the tested beams. The bars had a helical wire wrapping to enhance the bond between the bars and the surrounding concrete as shown in Fig.2. 10 mm steel bars were used as transverse and top reinforcement in all beams. The elastic modulus of BFRP bars is 55 GPa while the ultimate strength and strain are 1100 MPa and 2.8% respectively as given by manufacturer . The elastic modulus of steel bars is 200 GPa while the yield strength is 360 MPa as given by manufacturer .

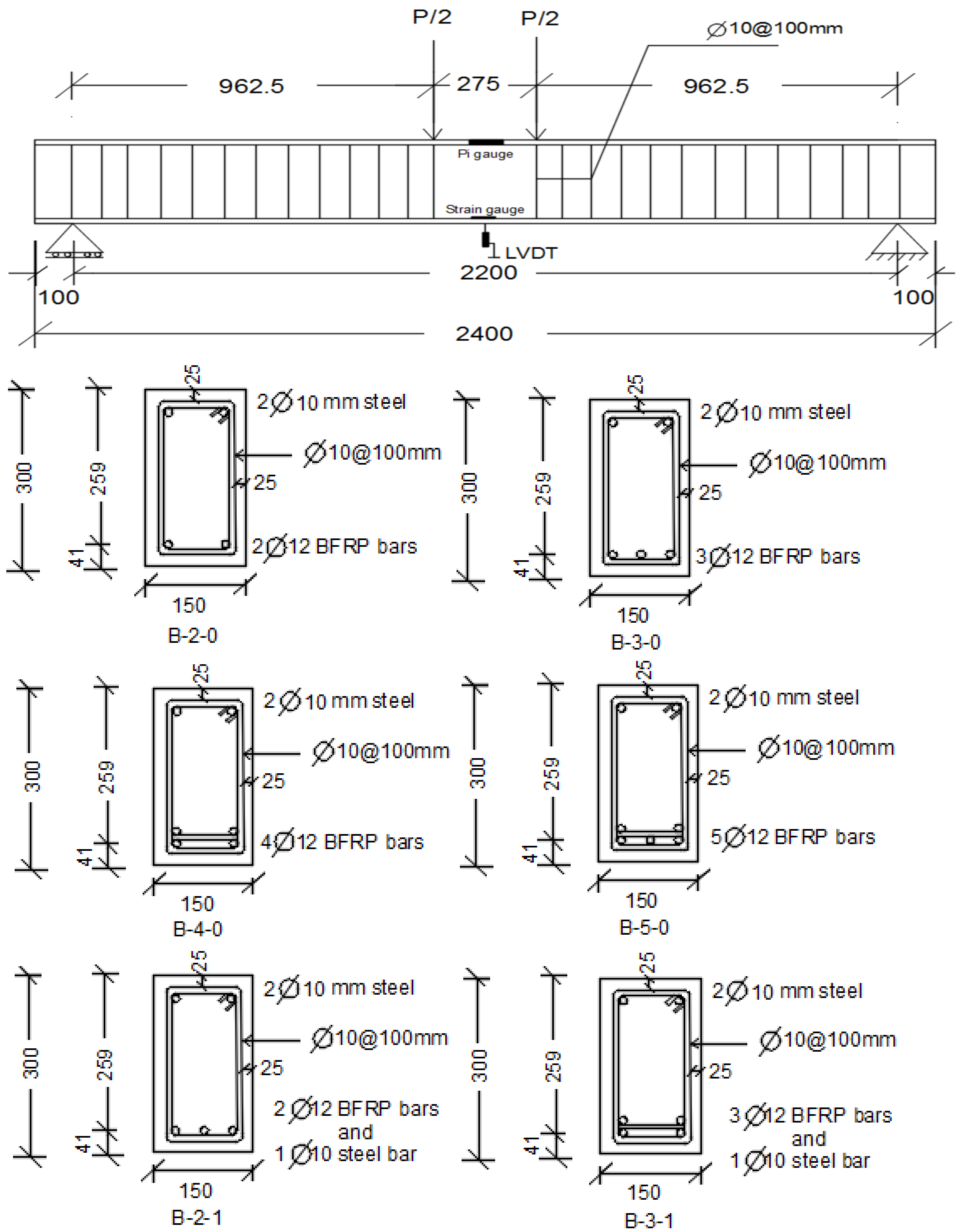

Fig.1: Dimensions and reinforcement details of tested beams (all dimensions are in mm)

Fig.2: BFRP bars

Test setup and procedures

Four point bending setup consisted of a wide flange spread beam placed on two steel plates covering the entire width of the beam . The beams are hinged at one end and roller at the other end. The load was generated by a hydraulic jack located at the center of the spread beam and applied to the wide flange . The midspan deflections were measured using linear variable differential transformer (LVDT). Pi- gauge was mounted on the top concrete surface at the midspan of the beam to measure the compressive strain in concrete. In addition, strain gauge of 6mm length was attached on flexural main reinforcement at midspan . Data logger system was used to collect the data from all the instrumented equipments. The test setup and instrumentation are shown in Fig. 3 .

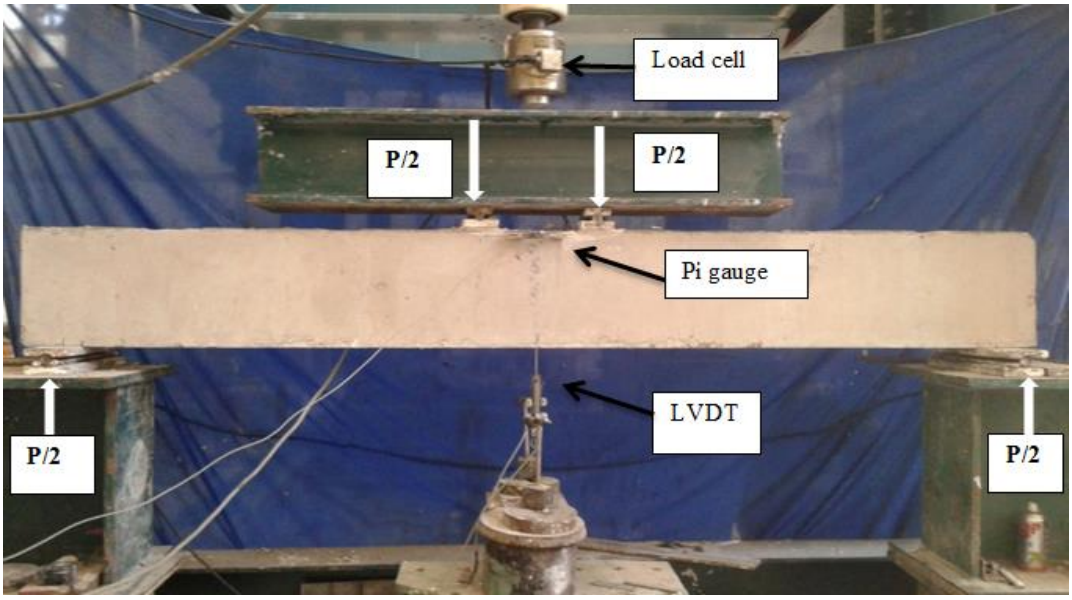

Fig.3: Test setup and instrumentation

TEST RESULTS AND DISCUSSION

The flexural behaviour of BFRP RC beams will be discussed in terms of, crack pattern and failure mode, crack width, load-deflection behaviour, cracking load, load capacity and developed strain in concrete and BFRP bars .

Crack pattern and mode of failure

For the beams reinforced with only BFRP bars, the first flexural crack initiated in the middle of the constant moment region. Beyond the first cracking load, additional flexural cracks were developed along the beam length within the constant moment region. With the increase in loading, the flexural cracks propagated toward the top fiber and cracks started to develop in the shear region .As shown in Table 2, the number of flexural cracks inside the constant moment region at 67% of the ultimate load (where no more cracks were appeared after this load level and only widening of the existing cracks could be observed)was 2,3,4 and 5 for beams B-2-0 , B-3-0 , B-4-0 and B-5-0 respectivey . The crack patterns in Fig.4 confirm that beams with higher reinforcement ratios exhibited improved patterns characterized by better distribution , which could be captured by comparing the crack patterns of the tested beams to that of beam B-2-0 (lowest reinforcement ratio). Moreover, increasing the reinforcement ratio while keeping the mechanical properties unchanged helped enhance the cracking performance (distribution) due to prevent localization of stresses .
For beam B-2-0 ,approaching beam ultimate capacity , some longitudinal cracks at the level of the reinforcement appeared between two vertical cracks, but did not affect the failure mode.These cracks are mainly due to the high deformation of the bars, which led to slippage between the reinforcement bars and surrounding concrete (i.e., bond failure). All the beams continued to sustain the load until it reached the maximum flexural capacity, at which the concrete in the constant moment region at the compression zone crushed as shown in Fig. 4.

The crack propagation for the hybrid beams followed the traditional flexural-cracking patterns in the first group beams as shown in Fig. 4. The first cracks always appeared in the constant moment region of the beams, starting from the beam bottom surface and extending vertically toward the compression zone. As the load increased, the cracks extended further away from the constant-moment region towards the supports.
As shown in Table 2 and comparing beam B-2-1 with B-2-0 that had the same BFRP reinforcement ratio in addition to one steel bar of diameter 10mm and yield strength 360 MPa ,the number of flexural cracks inside the constant moment region at 67% of the ultimate load increased from 2 cracks for beam B-2-0 to 4 cracks for beam B-2-1. Comparing beam B-3-1 with B-3-0 that had the same BFRP reinforcement ratio in addition to one steel bar of diameter 10mm and yield strength 360 MPa ,the number of flexural cracks inside the constant moment region at 67% of the ultimate load increased from 3 cracks for beam B-3-0 to 6 cracks for beam B-3-1. This showed that using steel bar of diameter 10 mm prevented localization of stresses and make a good distribution of elongation at different positions . The beams continued to sustain the load until it reached the maximum flexural capacity, at which the concrete in the constant moment region at the compression zone crushed as shown in Fig. 4.

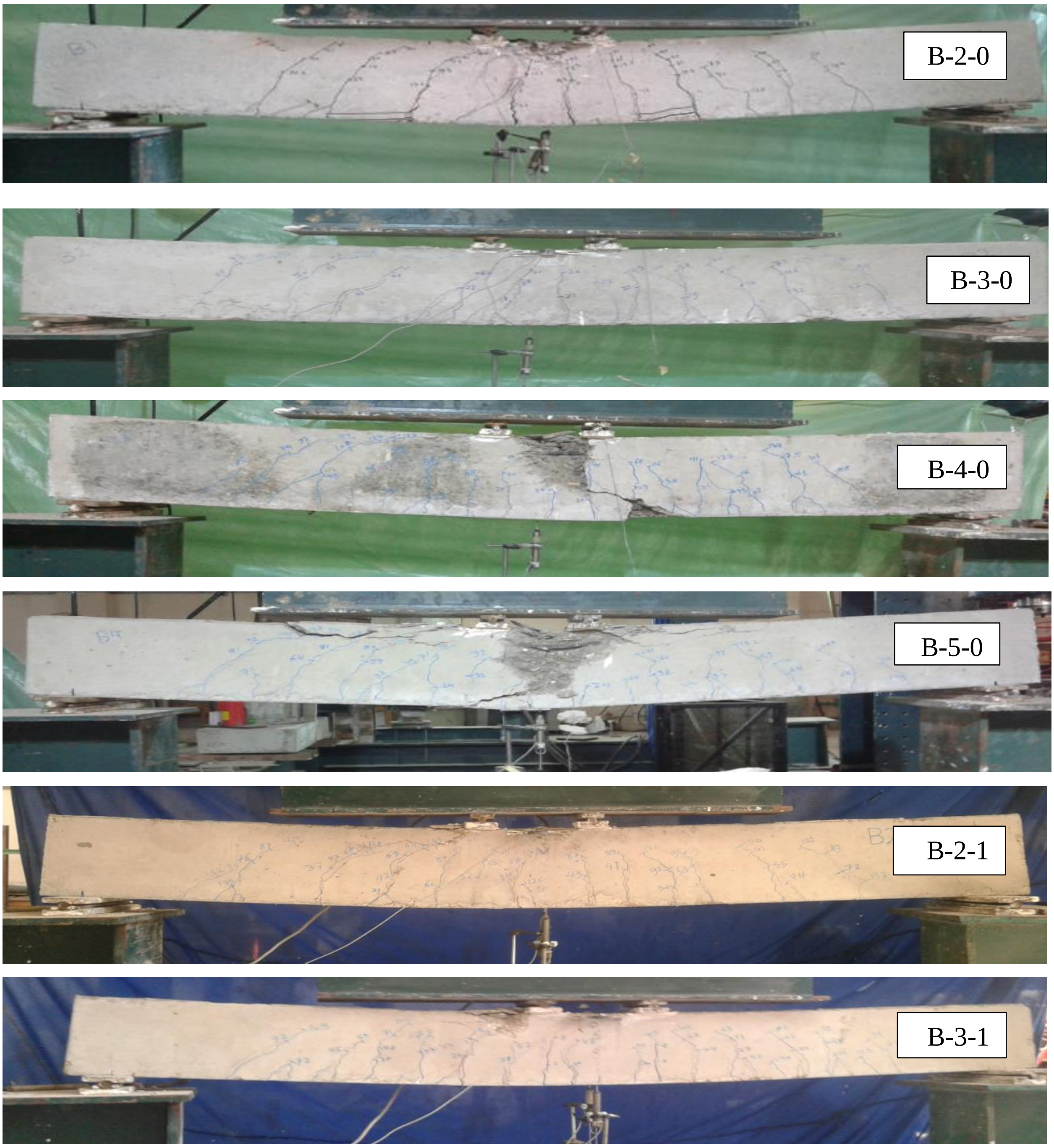

Fig.4: Crack pattern and mode of failure of tested beams

Crack width

For the beams reinforced with only BFRP bars ,Table 2 provides the maximum crack width at service load(30% of the ultimate load) in each beam. 30% of the ultimate load represented the service load level according to ACI 440.1R-06 .The maximum flexural crack width within constant moment region at service load was 1.0 ,0.8 ,0.7 and 0.5mm for beams B-2-0 , B-3-0 ,B-4-0 and B-5-0 respectively. It should be noted that the beam B-5-0 is the only beam that satisfied service limiting for crack width according to (ACI 440.1R-06). It can be concluded that increasing reinforcement ratio from 0.0058 for beam B-2-0 to 0.0145 for beam B-5-0 (increased by 150%) ,led to reducing the crack width by 50%. It's clear that there is an inverse relation between the reinforcement ratio and the crack width. The reduction of crack width caused by increasing reinforcement ratio was attributed to the restriction that made by reinforcement bars since there is a direct relation between the strain in the reinforcing bars and the crack width .

For hybrid beams Table 2 provides the maximum crack width at service load. The maximum flexural crack width within constant moment region was 1.0 mm and 0 .5 mm for beam B-2-0 and B-2-1 ,respectively at service load. This showed that adding steel bar of diameter 10mm to beam B-2-0 (by steel to BFRP reinforcement ratio =35%) led to decreasing crack width by50% . Moreover ,the maximum flexural crack width within constant moment region was 0.8 mm and .45 mm for beam B-3-0 and B-3-1 ,respectively at service load. This showed that adding steel bar of diameter 10mm to beam B-3-0 (by steel to BFRP reinforcement ratio =25%) led to decreasing crack width by40% . It's clear that there is a direct relation between steel to BFRP reinforcement ratio and the reduction of crack width.

Load –deflection behaviour

For the beams reinforced with only BFRP bars ,the Load-deflection curves are shown in Fig. 5 . The load –deflection curve for each beam can be divided into two stages .The first stage is the stage before cracking of the beams and the slope of the curve in this stage is called pre-cracking stiffness Benmokrane et al.(2016) . The second stage is the stage after cracking of the beams and the slope of the curve in this stage is called post-cracking stiffness Benmokrane et al.(2016) . Before cracking, the deflection of the beams was minimal and showed similar pre-cracking stiffness, regardless of their reinforcement ratio. For the post-cracking region , the load-deflection curves can be distinguished between four specimens according to reinforcement ratio .

As shown in Table 2 , increasing BFRP reinforcement ratio led to increasing the load capacity at a deflection of L/180 . The L/180 deflection is considered the least conservative deflection limitation under service loading in design provisions (ACI 440.1R-06). The load capacity at a deflection of L/180 was ٢٥,٦١,٦٧ and ٨٤ kN for beams B-2-0 ,B-3-0 ,B-4-0 and B-5-0 respectively. Comparing beam B-5-0 with B-2-0, the load of B-5-0 at a deflection of L/180 was more than three times that of B-2-0 . This shows that increasing BFRP reinforcement ratio has significant effect on post- cracking stiffness and enhancing the serviceability of the beams .

For the hybrid beams as shown in Fig.5 ,the load –deflection curve of the second group can be divided into three stages . The first stage is the stage before cracking of the beams and the slope of the curve in this stage is called pre-cracking stiffness . The second stage is the stage after cracking of the beams and before yielding of steel bar, the slope of the curve in this stage is called post-cracking stiffness .The third stage is the stage after yielding of steel bar , the slope of the curve in this stage is called post-cracking stiffness but with a value less than the previous value of post-cracking stiffness. For the post-cracking region of the second group, the effect of adding steel bar of diameter 10mm with yield strength 360 MPa to beams B-2-0 and B-3-0 is obvious in post- cracking stiffness . The beam B-2-1 has a post- cracking stiffness more than B-4-0 until yielding of steel bar .The load of B-2-1 at a deflection of L/180 was 2.4 times that of B-2-0. Moreover,The beam B-3-1 has a post- cracking stiffness more than B-5-0 until yielding of steel bar. The load of B-3-1 at a deflection of L/180 was 1.3 times that of B-3-0 . This shows that , adding steel bar of diameter 10 mm with yield strength 360 MPa has significant effect on post- cracking stiffness and enhancing the serviceability of the beams .

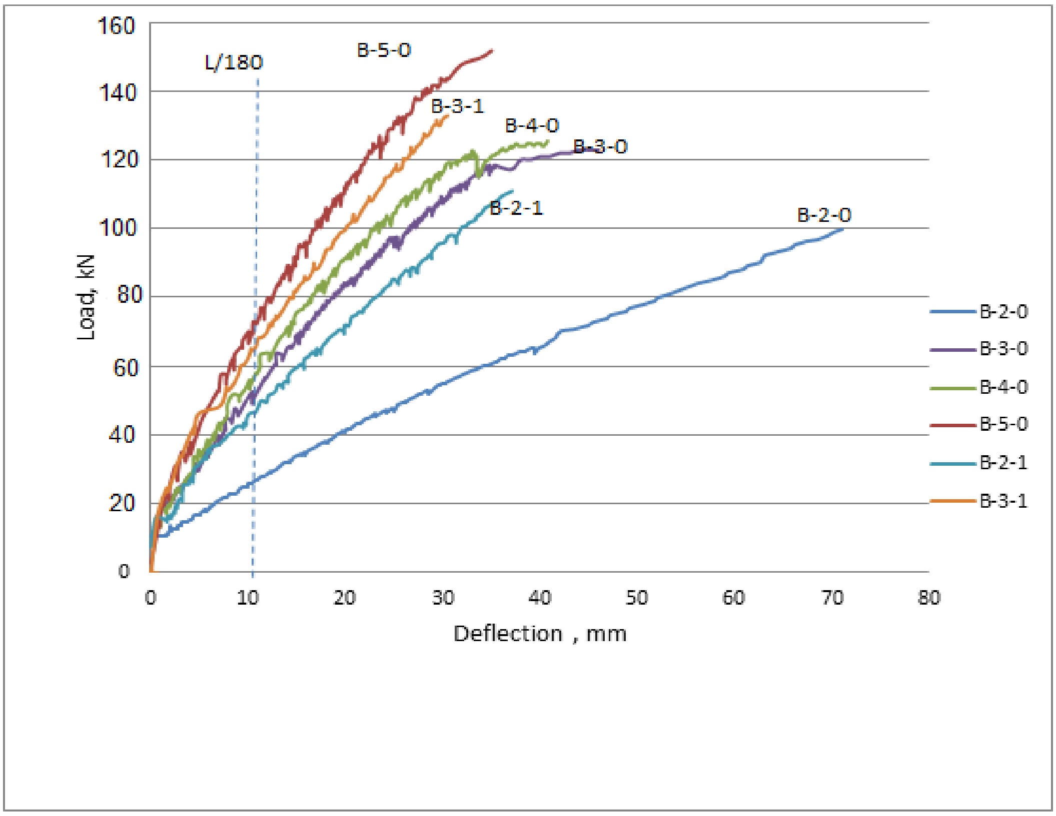

Fig.5 :Load-deflection curves

Cracking load

For the beams reinforced with only BFRP bars all beams behaved similarly until first cracking. Their cracking loads and pre-cracked stiffness were essentially the same regardless of reinforcement ratio . Table 2 provides the cracking loads of all tested beams. The reported cracking load , excluding the self-weight of the beams, ranged from 14.80 for beam B-2-0 to 14.90 kN.m for beam B-5-0 with an average of 14.85 kN.m . This value is approximately 11 % of the average ultimate load capacity.It can be concluded that increasing reinforcement ratio has no effect on the cracking load.
For hybrid beams as shown in Table 2 the cracking load for B-2-1 and B-3-1 was nearly unaffected by adding steel bar of diameter 10mm to B-2-0 and B-3-0 .The cracking load for B-2-1 increased by 1 % compared to B-2-0 Moreover, the cracking load for B-3-1 increased by 1% compared to B-3-0, so this value can be neglected.

Load capacity

For the beams reinforced with only BFRP bars ,the load capacities and deflection at the ultimate condition are presented in Table 2. Inspection of Table 2 shows that the experimental ultimate load capacity was 118,131,145 and 165 kN for beams B-2-0,B-3-0,B-4-0and B-5-0 respectively .Moreover ,the ultimate defelction was 72,49,43 and 35 for beams B-2-0,B-3-0, B-4-0and B-5-0 respectively. This shows that increasing reinforcement ratio by 150% (B-2-0 to B-5-0) caused an increase in the ultimate load by 40% and decrease in the deflection at ultimate by 50%. Fig.6 and Fig.7 show the normalized ultimate load and normalized ultimate deflection versus the ρ_f / ρ_{fb} curves respectively . For the beams that had ρ_f / ρ_{fb} less than or equal to 7 , the increase in the ρ_f / ρ_{fb} from 3.59 (B-2-0) to 5.38 (B-3-0) and 7.16(B-5-0) reduced the ultimate deflection by 40% but showed a slight increase in the load capacity (20%).

However, the beam with ρ_f / ρ_{fb} greater than 7.0 beam (B-5-0) has more pronounced increasing in the load capacity (increased by 40%). It can be concluded that in case of ρ_f / ρ_{fb} is less than or equal to 7.0, it has more influence on reducing the deflection than increasing the load capacity, as is the case for B-2-0, B-3-0 and B-4-0 . However, beams with ρ_f / ρ_{fb} greater than 7.0 revealed better influence on the load capacity than the ultimate deflection.

For hybrid beams as shown in Table 2 ,the ultimate load and ultimate deflection for B-2-1 were 129 kN and 42 mm respectively . while the ultimate load and ultimate deflection for B-3-1was 142kN and 35mm respectively . The test results showed that Adding steel bar of diameter 10mm and yield strength 360 MPa to the beam that had two BFRP bars (by steel to BFRP reinforcement ratio =35%), led to reducing the ultimate deflection by 42 % while the ultimate load capacity increased by 10%. Moreover, Adding steel bar of diameter 10mm and yield strength 360 MPa to the beam that had three BFRP bars (by steel to BFRP reinforcement ratio =25%), led to reducing the ultimate deflection by 30 % while the ultimate load capacity increased by 8% .This shows that there is a direct relation between steel to BFRP reinforcement ratio and the reduction of deflection .Moreover, the effect of adding steel bar of diameter 10 and yield strength 360 MPa more pronounced on reducing ultimate deflection than increasing ultimate load capacity and hence enhancing serviceability of the beams.

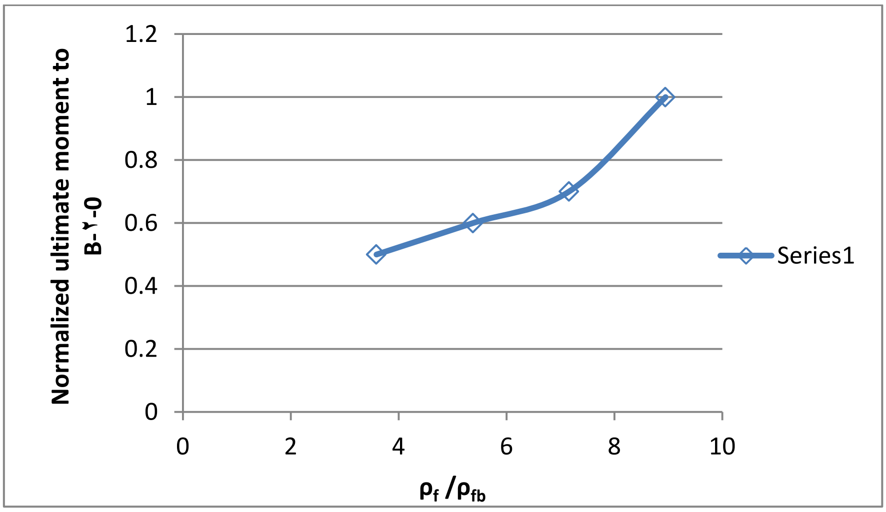

Fig.6 :Normalized ultimate load vs. ρ_f / ρ_{fb}

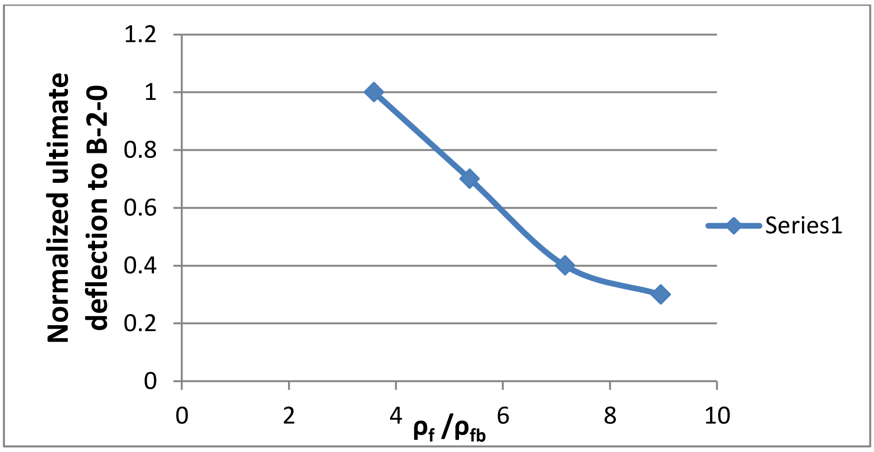

Fig.7 :Normalized ultimate deflection vs. ρ_f / ρ_{fb}

Reinforcement and concrete Strain

For the beams reinforced with only BFRP bars as shown in Fig.8, none of the BFRP strain gauges in the four beams registered noticeable reading before the initiation of the first beam crack. However, once the first crack initiated, a sudden jump in the strain took place without showing an increase in the load which reflects the sudden change in the stiffness at cracking. Moreover, the plotted data shows that, after beam cracking, the reinforcement tensile strains varied linearly with the increased load up to failure. The relationship of the load versus strain curves were typical bilinear curves with a sharp increase in the reinforcement strains, especially in the beams with low reinforcement ratios due to relatively low stiffness . As shown in Fig. 9, all beams of the first group reached ultimate strain capacity of concrete.at which the concrete in the constant moment region at the compression zone crushed .

For hybrid beams as shown in Fig.8 ,the load –versus- strain curve in BFRP bars had the same behaviour of the beams reinforced with only BFRP until initiation of the first crack . After that, the strain in BFRP bars increased until the concrete in the compression zone reached εcu at which the concrete in the constant moment region crushed as shown in Fig.9 .The positive effect of adding steel bar appeared in reducing the strain in BFRP bars at the samre load level which led to smaller cracks width since there is a direct relation between developed strain in BFRP bars and crack width .

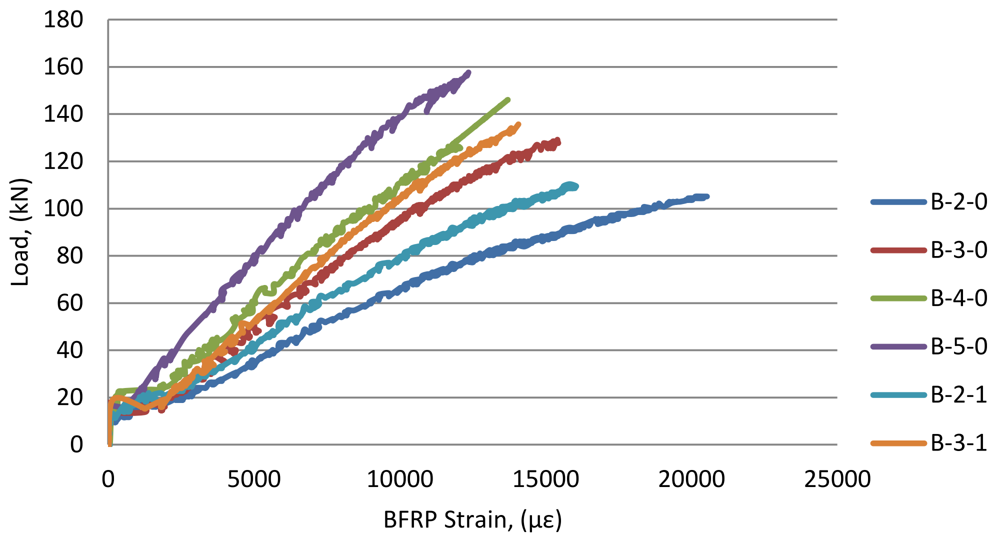

Fig.8: Load -BFRP strain

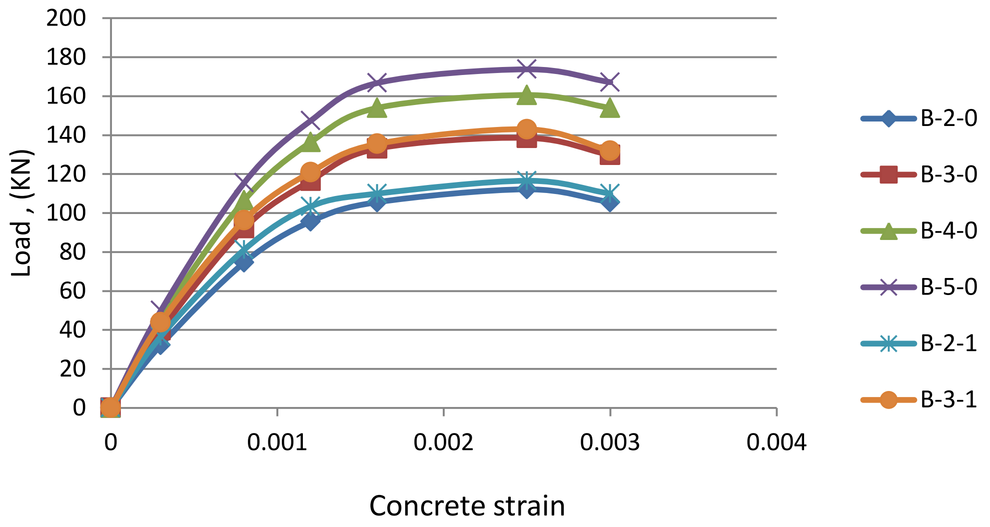

Fig.9: Load -concrete strain

Table 2 :Experimental results

Beam	Number of flexural cracks at 67%P_u	Crack width at 30%P_u (m.m)	Cracking load (kN)	Ultimate load (kN)	Load at L/180 (kN)	Ultimate deflection (Δ, mm)	Ultimate strain in BFRP (με)
B-2-0	2	1	14.80	118	٢٥	72	20100
B-3-0	3	.8	14.85	١٣١	٦١	49	15700
B-4-0	4	.7	14.87	١45	٦٧	43	13400
B-5-0	5	.5	14.90	١٦٥	٨٤	35	11800
B-2-1	4	.5	14.86	١29	٦٠	42	19200
B-3-1	6	.45	14.90	142	٨٢	35	13100

CONCLUSION

The flexural behaviour of six 150 x 300 x 2400mm concrete beams reinforced with basalt FRP (BFRP) bars were investigated. The beams were divided into two groups , the first group consisted of four beams reinforced with only BFRP bars with reinforcement ratios (ρ_f) ranged from 3.59 to 8.95 times the balanced ratio (ρ_{fb}) and the Second group consisted of two hybrid beams reinforced with BFRP and steel bars .Based on the test results and discussion presented herein, the following conclusions are drawn:

1- The pre-cracking response and cracking loads of the beams were nearly unaffected by the reinforcement ratio. After cracking, The load capacity at a deflection of L/180 (service limit according to ACI 440.1R-06) was 25,61,67 and 84 kN for beams

B-2-0 ,B-3-0 , B-4-0 and B-5-0 respectively. Comparing beam B-5-0 with B-2-0, the load of B-5-0 at a deflection of L/180 was more than three times that of B-2-0 . This shows that increasing BFRP reinforcement ratio has significant effect on post- cracking stiffness and enhancing the serviceability of the beams .

2- The reinforcement ratio significantly affected the general behaviour of the BFRP-RC beams. Increasing reinforcement ratio by 150% (B-2-0 to B-5-0) caused an increase in the ultimate load by 40% and decrease in the deflection at ultimate by 50% .

3- Adding steel bar of diameter 10mm and yield strength 360 MPa to the beam that had two BFRP bars (by steel to BFRP reinforcement ratio =35%), led to reducing the ultimate deflection by 42 % while the ultimate load capacity increased by 10%. Adding steel bar of diameter 10mm and yield strength 360 MPa to the beam that had three BFRP bars (by steel to BFRP reinforcement ratio =25%), led to reducing the ultimate deflection by 30 % while the ultimate load capacity increased by 8% . This shows that there is a direct relation between steel to BFRP reinforcement ratio and the reduction of deflection .Moreover, the effect of adding steel bar of diameter 10mm and yield strength 360 MPa more pronounced on reducing ultimate deflection than increasing ultimate load capacity and hence enhancing serviceability of the beams

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