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Strain Distribution on Reinforcement of Concrete Beams Reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars

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Abstract. This paper presents a part of the results from an experimental study of strain distribution on reinforcement of concrete beams reinforced with glass fiber-reinforced polymer (GFRP) bars. Under static loading conditions, eight concrete beams reinforced with GFRP bars were tested and as comparison eight beams with steel reinforcement were also tested. All of the beams were prepared with varying ratios of longitudinal reinforcement bars and stirrups. The effect of shear span-effective depth ratio on strain distribution of longitudinal reinforcement was also observed. Furthermore, the behavior of strain on stirrups due to different materials of longitudinal reinforcement was also discussed in this report. The test results show that the ratio of longitudinal reinforcement significantly influence the strain distributions on reinforcement where the beams with higher ratio exhibit higher strain. Moreover, it was also obtained that the different types of longitudinal reinforcement considerably influences the strain behavior on stirrups as higher strain was observed in beams reinforced with GFRP bars.

Introduction

FRP development in construction industry is strongly influenced by their physical and mechanical properties. Other factor is due to their durability in an alkaline environment which makes them as an alternative reinforcing material to the solution problems in concrete structures. As early in 1990s, the use of FRP as internal and external reinforcement in reinforced concrete (RC) structures commenced and recently the innovative of hybrid structures as the combination of FRP bars with other dissimilar reinforcing materials such steel become the major concerns [1–3]. Although FRP bars have higher strength and lighter than steel bars, but their modulus of elasticity such very low compared to steel bars hence exhibit linear stress-strain behavior up to failure [4]. Moreover, with no yielding plateau, large deflection was recorded as that the influence of reinforcement ratios, concrete strength and shear span-effective depth ratios (a/d) plays an important role in restraining the safety margin against failure [5]. Since FRP characteristic is slightly differ from steel, ACI 440 [6] recommended the design of FRP structures to be over-reinforced so that the structure fails by concrete crushing rather than FRP rupture. The limits also prescribed on shear reinforcement, as shear failure are more catastrophic [7]. In this paper, the strain distribution on reinforcing bars is studied by changing the reinforcement ratios, stirrups spacing and shear span-effective depth ratios, and comparison were made for steel RC beams (BSS) and GFRP RC beams (BGS). Two design codes of “Structural Use of Concrete – BS8110-1:1997” [8] and “Building Code Requirements for Structural Concrete and Commentary – ACI 318-08” [9] were used for the design of steel RC beams. While “Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars - ACI 440-1R-06” [6] are referred for the design of FRP RC beams.

Experimental Program

Test Specimens. In this experimental program, totally eight steel RC beams and eight GFRP RC beams which identified as BSS and BGS were constructed and tested under static loading conditions. All beams were designated with different amount and types of longitudinal reinforcement bars, shear span-to-depth ratios (a/d) and steel stirrup ratios. According to the different shear span length (a_{V1} = 550 mm and a_{V2} = 1100 mm), they have been grouped into two types of beam length which are 2000 mm and 3000 mm long with a rectangular cross section of 200 mm x 400 mm as illustrated in Fig. 1. BSS specimens were longitudinally reinforced by two to three numbers of 16 mm diameters of steel bars at the tension and compression face. While for BGS, the beams were reinforced by GFRP bars with similar diameter, in equivalent numbers and positions as BSS beams in an attempt to replace the traditional reinforcing bars with non-corrosive GFRP bars. The details of test specimens are summarized in Table 1.

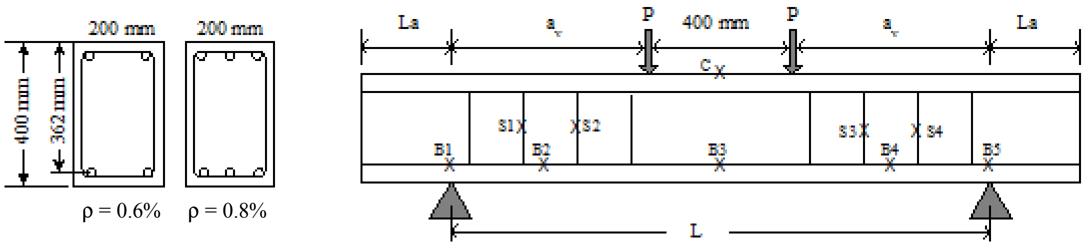

Fig. 1. Cross-section detail and test scheme

Table 1. Summary of test specimens

	Dimensions				Ratio	Reinforcement				
Specimen No.	a_v (mm)	L_a (mm)	L (mm)	L_{total} (mm)	a/d	Stirrups (mild steel 8 mm dia.) spacing (mm)	ρ (%)	Longitudinal Reinforcement Bars Type	N	ρ and ρ' (%)
BSS-01	550	250	1500	2000	1.5	50	1.01	Steel	2	0.6
BSS-02	550	250	1500	2000	1.5	50	1.01	Steel	3	0.8
BSS-03	550	250	1500	2000	1.5	150	0.34	Steel	2	0.6
BSS-04	550	250	1500	2000	1.5	150	0.34	Steel	3	0.8
BSS-05	1100	200	2600	3000	3.0	50	1.01	Steel	2	0.6
BSS-06	1100	200	2600	3000	3.0	50	1.01	Steel	3	0.8
BSS-07	1100	200	2600	3000	3.0	150	0.34	Steel	2	0.6
BSS-08	1100	200	2600	3000	3.0	150	0.34	Steel	3	0.8
BGS-01	550	250	1500	2000	1.5	50	1.01	GFRP	2	0.6
BGS-02	550	250	1500	2000	1.5	50	1.01	GFRP	3	0.8
BGS-03	550	250	1500	2000	1.5	150	0.34	GFRP	2	0.6
BGS-04	550	250	1500	2000	1.5	150	0.34	GFRP	3	0.8
BGS-05	1100	200	2600	3000	3.0	50	1.01	GFRP	2	0.6
BGS-06	1100	200	2600	3000	3.0	50	1.01	GFRP	3	0.8
BGS-07	1100	200	2600	3000	3.0	150	0.34	GFRP	2	0.6
BGS-08	1100	200	2600	3000	3.0	150	0.34	GFRP	3	0.8

Material Properties. The sand-coated glass FRP bars used in the study was supplied by Concrete Protection Products Inc. North Carolina. The bars are made of continuous E-glass fibres impregnated with a vinylester resin by using a pultrusion process. Both top and bottom longitudinal bars in BGS beams were made up of 16 mm diameter of GFRP bars which having different mechanical characteristic compared to conventional steel bars as listed in Table 2 and the stress-strain behavior for all the reinforcing bars are shown in Fig. 2. As a brittle reinforcing material, there is no observation of yielding plateau as the FRP bars behave linearly elastic up to failure. Each of the beams was cast on the same day from the same ready-mix concrete batch with a normal compressive strength concrete of 24 N/mm^2, with a crushed aggregate of a maximum size of 20 mm. All beams were confined with 8 mm diameter closed rectangular steel stirrups with varying of 50 mm and 150 mm spacing in the shear span zone. These two types of spacing were obtained according to BS8110 [8] in order to provide the minimum and sufficient amount of stirrups.

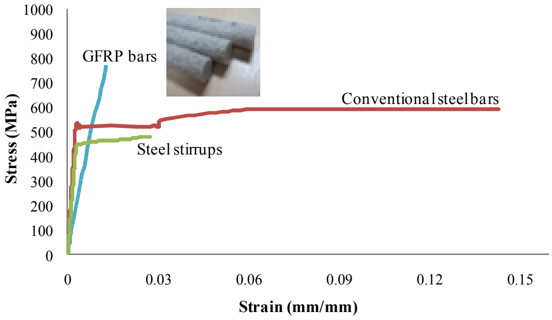

Fig. 2. Stress-strain behavior of reinforcing bars

Table 2. Mechanical properties of specimens

Rebars	Diameter (mm)	Tensile strength, (Mpa)	Modulus of elasticity (Gpa)	Ultimate strain
GFRP	16	771	57.3	0.013
Steel	16	512	207	0.0026
Steel	8	440	162	0.0028

Instrumentations. The test scheme of beam is shown in Fig. 1, where each beam was instrumented by electrical-resistance strain gauges as well as linear variable displacement transducers (LVDT). Totally ten strain gauges were bonded along the tensile bars (B1, B2, B3, B4 and B5) which 2 numbers of strain gauges were located at every locations. The strain gauge was denoted as SG and bonded on selected stirrups. In addition, two strain gauges were also bonded on the top concrete faces at mid-span section and denoted as C. Three LVDTs with a 50 mm stroke were installed: one at the mid-span section and another two under the load positions. At each load increment, all crack development and its propagation on the both sides of beam surfaces were recorded and carefully observation on the initial crack, ultimate load and type of failure were examined.

Results and Discussion

Fig. 3 and Table 3 shows the load-deflection curves and comparative study between theoretical predictions and experimental results in terms of load at first crack (P_{cr}), ultimate load (P_u) and their corresponding deflections (Δ_{max}). As expected, the concrete beams reinforced with GFRP behave linearly up to the first crack, P_{cr} and after cracking, they behaved linearly up again but with reduced stiffness. Beams BGS showed higher load capacity and larger deflection compared to beam reinforced with steel bars, BSS. This behavior is attributed to the low modulus of elasticity of GFRP bars. However, less shear strength was examined in the beams failed on shear (BGS-03 and BGS-04) than that beams reinforced with steel bars (BSS-03 and BSS-04). As it has been reported from previous experimental results [10-11], at the same load level, the strains distribution and curvatures on GFRP RC beams were much higher than in beam reinforced with CFRP and steel. Overall, similar behavior was observed in both types of beam that an increase amount of tensile reinforcement to ρ = 0.8%, leads to increase ultimate capacity, P_u of the beam as summarized in Table 3. In case of beams with higher shear span-effective depth ratio, the ultimate capacity of the beam decreases compared to that beams with shorter shear span.

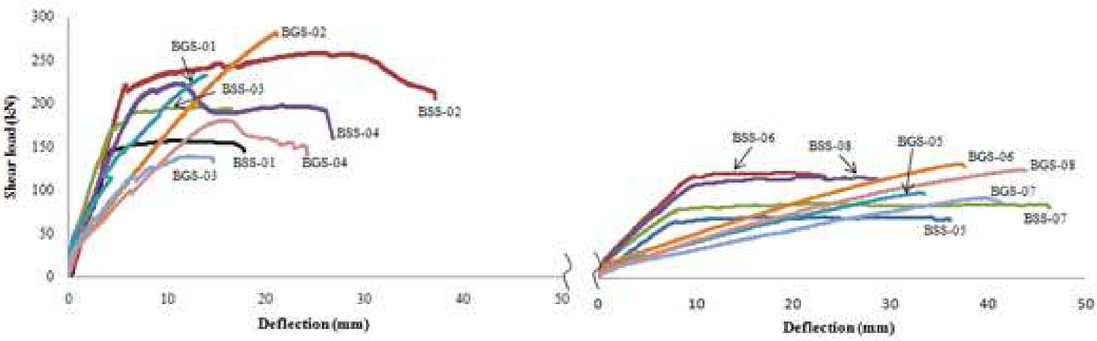

Fig. 3. Load-deflection behavior of beams

Table 3. Experimental results and analytical predictions

Specimen No.	Test results				Calculated values			
	P_{crack} (kN)	$P_{ultimate}$ (kN)	Δmax (mm)	Failure mode	P_{crack} (kN)	*ACI 318-08* *Pf (kN)*	*BS 8110-01:1997* *Pf (kN)*	*ACI 440.1R-06* *Pf (kN)*
BSS-01	39.1	157.6	10.92	Flexure	34.7	126	124	-
BSS-02	48.5	258.7	25.47	Flexure	37.0	182	176	-
BSS-03	44.4	195.5	13.66	Shear	34.7	126	124	-
BSS-04	56.5	223.3	11.35	Shear	37.0	182	176	-
BSS-05	47.6	71.8	34.17	Flexure	17.3	63	62	-
BSS-06	30.4	122.3	19.18	Flexure	18.5	91	88	-
BSS-07	25.2	86.4	23.97	Flexure	17.3	63	62	-
BSS-08	27.3	117.3	21.85	Flexure	18.5	91	88	-
BGS-01	31.3	233.2	14.41	Flexure	30.8	-	-	157
BGS-02	34.3	281.6	21.06	Flexure	31.2	-	-	183
BGS-03	33.6	139.0	12.63	Shear	30.8	-	-	157
BGS-04	45.6	181.3	16.08	Shear	31.2	-	-	199
BGS-05	15.9	99.0	33.06	Flexure	15.4	-	-	85
BGS-06	15.6	132.1	37.07	Flexure	15.6	-	-	99
BGS-07	5.8	92.8	39.88	Flexure	15.4	-	-	85
BGS-08	20.2	125.6	43.74	Flexure	15.6	-	-	99

The theoretical flexural strength was predicted according to the ACI 318-08 [9], BS8110 [8] and ACI 440-1R-06 [6] design guidelines. It is clear that the experimental ultimate load in all beams were higher than the theoretical flexural load except in beam BGS-03 and BGS-04 which were failed on shear. Two types of failure mode were observed from the test i.e. shear and flexural failure. Fig. 4 shows the typical rupture of the FRP bars and shear failure of beam.

Fig. 4. Beam failure

In Fig. 5 the development of strain distributions along tensile bars were plotted at different load increment at each strain gauges position of B1, B2, B3, B4 and B5 as marked in Fig. 1. As illustrated, the selected beams with short shear span, a/d = 1.5 (BSS-02 and BGS-02) were compared with high shear span, a/d = 3.0 (BSS-06 and BGS-06). As expected, the maximum strain value was occurred at the mid-span of beam. The dashed line represents the value of yield and rupture strain for steel and FRP bars and it was found that the strain development in all GFRP RC beams significantly distributed at higher strain value rather than steel RC beams. Large strain values also detected at the support of beam which is comparable to the level of strain in beam reinforced with steel. The ultimate strains recorded in BGS-02 and BGS-06 reached a value of 0.013 and 0.015 respectively. While in case of BSS beams, strain distribution is very low and stop to increase after the bar yield. However, a high strain value was occurred at the middle gauges position once failure and considerably exceeded the ultimate strain values in BGS beams. The strain distribution developed in the stirrups (refer Fig. 6) shows that the highest strain value was developed on stirrups located in BGS beams (about 0.0018) which higher strain distribution experienced in beams with larger stirrup spacing compared to beams with closely spacing. Significant development was also observed between the closest stirrups at point load and support which associated with diagonal cracks at failure. Generally, the level of strains reduces as the shear span increases, this behavior is clearly seen in steel RC beams.

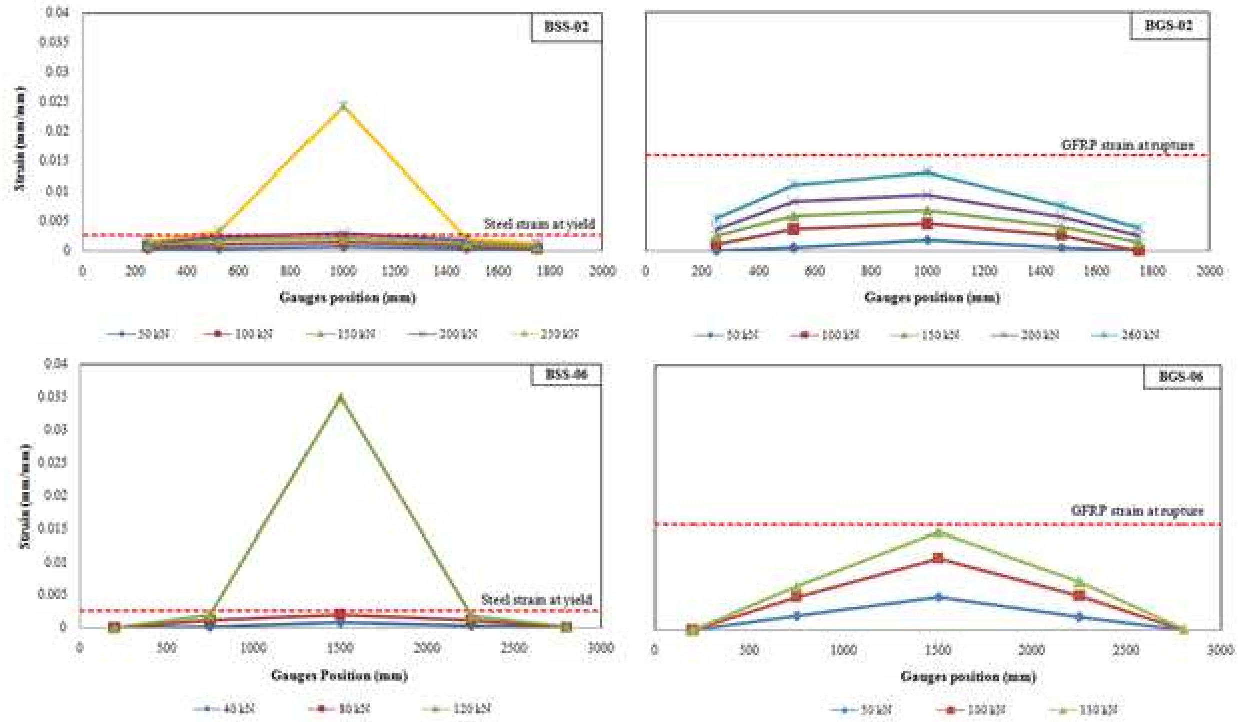

Fig. 5. Development of strain distributions on longitudinal reinforcement bars

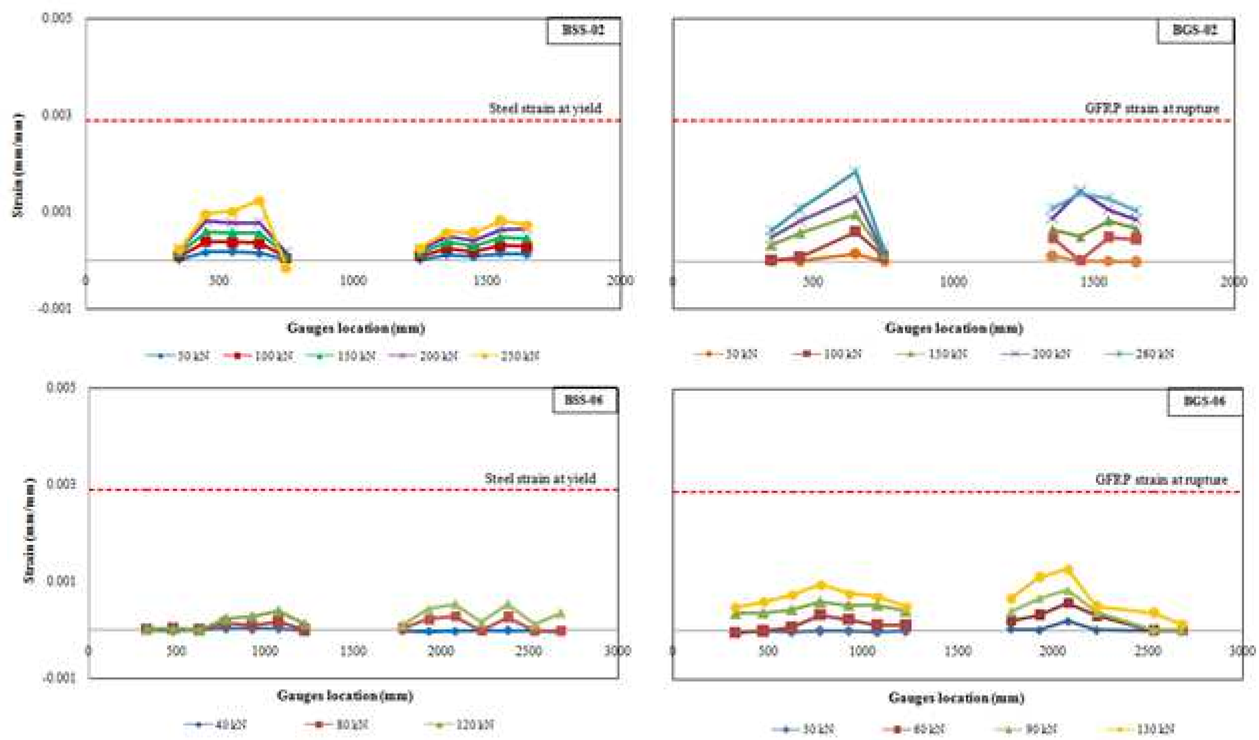

Fig. 6. Development of strain distributions on stirrups

Conclusions

The beam reinforced with GFRP bars behaved linearly up until failure with reduced stiffness compared to beam reinforced with steel bars. All of the test variables such as reinforcement ratios shear span and stirrup ratios significantly influence the strain distribution on reinforcement of the beams. The level strains developed along longitudinal GFRP bars significantly higher than that steel bars. In addition, larger strain values were developed at the beam supports hence sufficient length at hanging region is very important to avoid any bond failure. However, as the shear span increases, the development of strain distribution at the support is not significant. This behavior is in similar manner with steel RC beams such lesser strain values were developed at the support after the steel bar yielded. Strain value in stirrups also higher in GFRP RC beams than that steel RC beams. Higher strain was recorded in a stirrup which closest to the point load positions which associated with the diagonal shear cracks, however, the level of strain reduces as the shear span and shear link spacing increases.

Acknowledgements

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