Applied Mechanics and Materials
ISSN: 1662-7482, Vol. 660, pp 603-612
doi:10.4028/www.scientific.net/AMM.660.603

Submitted: 2014-06-05
Accepted: 2014-08-16
Online: 2014-10-31

Evaluation of Shear Strength of Concrete Beams With GFRP Reinforcement

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The author Dr. Stefano de Miranda was removed as he was not an author of this article and his name was listed by mistake by the corresponding author.

Keywords: Concrete Beams, GFRP Bars, Shear Cracks, Shear Strength.

Abstract: This research presents an experimental study related to the shear behavior of simply supported reinforced concrete beams reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. Four concrete beams reinforced with GFRP bars and four control concrete beams reinforced with steel bars were tested until failure. In order to realize the occurrence of shear failure, all tested beams were designed with longitudinal reinforcement only and without shear reinforcement. The test variables used in this study were the concrete strength, *f'c*, and longitudinal reinforcement ratio, ρ. The crack patterns, location of the diagonal crack and angle of the diagonal crack were also observed during the test. The shear design equations obtained from the codes and references were used to evaluate the data obtained from the test. Finally, based on the data obtained from experimental and theoretical analysis, comments and recommendation on the shear strength equations were suggested.

Introduction

Fiber reinforced polymer (FRP) bars are currently available as a substitute for conventional steel bars in concrete structures. There are several reasons why civil and structural engineers may need to use it as reinforcement in reinforced concrete structures. The primary reason it's corrosion resistant and electromagnetic neutrality. In addition, this material also has high tensile strength and is lightweight [1]. However, the behavior of reinforced concrete beams at failure in shear is distinctly different from their behavior in flexure [2]. A failure due to shear is sudden as compared to a failure due to flexure. This type of failure should be avoided in design of reinforced concrete structures. Due to the fact that FRP bars is brittle and has low modulus of elasticity, and the shear strength of beams reinforced with GFRP bears have not been adequately studied [3]. In order to observe the shear behavior of concrete beams reinforced with GFRP bars, two types of test variables were used in this study, i.e. three reinforcement ratio and two shear span-effective depth ratio. Crack patterns, location of the diagonal cracks and angle of the diagonal cracks were observed recorded during the test.

Research Significance

The lack of study on the shear behavior of reinforced concrete beams reinforced with FRP bars is an area of great interest most researchers. Although some equations for shear design have been provided in the most of the design codes, not all concrete beam reinforced with FRP bars have been covered especially on diagonal shear cracking load [4,5,6]. This paper highlights the shear behavior of simply supported beams reinforced with different ratios of GFRP bars and different concrete strength. The beams were designed without stirrups. An experimental work was conducted to study the different aspects of concrete beams reinforced with GFRP bars to that beams with steel reinforcement at shear failure mode. Test results focuses on crack patterns, mode of failure, location and angle of the diagonal shear crack and the diagonal shear cracking load. Moreover, the comparison of theoretical shear strength calculated using equations suggested from the codes with the experimental shear strength were also presented.

Review of Current Design Provisions

Due to the rapid increase of using FRP materials as reinforcement for concrete structures, there are international efforts to develop design guidelines. These efforts have resulted in the publishing of several codes and design guides. Most of the shear design provisions currently in effect for concrete structures reinforced with FRP bars are based on the design formulas of members reinforced with conventional steel considering some modifications to account for the substantial differences between FRP and steel reinforcement, method of shear design, which is based on the truss analogy. The nominal shear resistance at the ultimate limit state, V_n, of RC beams retrofitted in shear with FRP is generally calculated simply by adding the contribution of FRP to the shear resistance, V_{cf}, to that of concrete, V_c, and of stripes, V_s, as follows:

$$V_n = V_c + V_s + V_{cf} \tag{1}$$

The beams in this study were designed reinforced without stirrups, thus V_s was negligible. This study reviews the concrete shear strength component V_{cf} of members longitudinally reinforced with FRP bars as recommended by ACI 440.1R-03 [7], ACI 440.1R-06 [8], SIS-M03-01[9], and JSCE [10].

ACI 440.1R-03 design guidelines [7]

To account for the axial stiffness of FRP longitudinal reinforcement, $A_f E_f$, as compared with that of steel reinforcement, $A_s\ E_s$, ACI Committee 440 recommended the following equation for calculating $V_{c,f}$

$$V_{cf} = \frac{\rho_f E_f}{\rho_s E_s} V_c \tag{2}$$

For practical design purposes, the value of ρ_s can be taken as half the maximum reinforcement ratio allowed by ACI 318[11] or $0.375\rho_{sb}$ and, considering a typical steel yield strength of 420 MPa for flexural reinforcement, the ACI Committee 440 recommended shear strength provided by concrete is as follows:

$$V_{cf} = \frac{\rho_f E_f}{90\beta_1 f'_c} \cdot \left(\frac{\sqrt{f'_c}}{6} b_w d \right) \le \frac{\sqrt{f'c}}{6} b_w d \tag{3}$$

ACI 440.1R-06 Guidelines [8]

The ACI 440.1R bases the design of cross sections subject to shear on the same approach used by the ACI 318-02 [11]: $\phi V_n \ge V_u$, where ϕ is the strength safety factor, V_u is the factored shear force at the section considered, and V_n is the nominal shear strength, computed as the sum of the shear resistance provided by concrete, V_c, and the FRP shear reinforcement, V_f. As for the computation of V_c, a new design method was proposed by Tureyen and Frosh [12] and adopted by the ACI 440.1R-06; according to this method V_c can be evaluated as follows:

$$V_c = \frac{2}{5}\sqrt{f'_c}\, b_w c \tag{4}$$

where f'_c =concrete compressive strength *(MPa)*; b_w=width of the web *(mm)*; and c=cracked transformed section neutral axis depth *(mm)*. For singly reinforced rectangular cross sections, $c=kd$ and k is calculated as follows:

$$k = \sqrt{2\rho_f n + (\rho_f n)^2} - \rho_f n$$

where ρ_f=FRP reinforcement ratio and $n=E_f/E_c$ ratio of the modulus of elasticity of longitudinal FRP bars to the modulus of elasticity of concrete.

ISIS-M03-01 design manual [9]

The shear resistance attributed to concrete, $V_{c,f}$, of members reinforced with FRP bars as flexural reinforcement is calculated according to the same principles as for steel reinforced concrete (CSA A23.3-94) [13] taking into account the difference in the modulus of elasticity between FRP and steel reinforcement as follows

$$V_{c,f} = 0.2\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_s}} \tag{5}$$

For sections with an effective depth greater than 300 mm, the concrete shear resistance $V_{c,f}$ is taken as:

$$V_{c,f} = \left(\frac{260}{1000+d}\right)\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_s}} \tag{6}$$

$$\geq 0.1\lambda\phi_c\sqrt{f'_c}\,b_w d\sqrt{\frac{E_f}{E_s}}$$

where λ is a modification factor for density of concrete and ϕ_c is a resistance factor for concrete.

JSCE design recommendations [10]

The concrete shear strength recommended by JSCE is given by the following equations:

$$V_{c,f} = \beta_d\beta_p\beta_n f_{vcd} b_w d/\gamma_b \tag{7a}$$

$$f_{vcd} = 0.2(f'_{cd})^{1/3} \leq 0.72MPa \tag{7b}$$

$$\beta_d = (1000/d)^{1/4} \leq 1.5 \tag{7c}$$

$$\beta_p = (100\rho_f E_f/E_s)^{1/3} \leq 1.5 \tag{7d}$$

$$\beta_n = 1 + M_o/M_d \leq 2 \; for N'_d \geq 0$$

$$\beta_n = 1 + 2M_o/M_d \geq 0 \; for N'_d < 0 \tag{7e}$$

Experimental Program:

An experimental work was conducted to investigate the shear behavior of concrete beams reinforced with GFRP bars, all tested beams were designed with longitudinal reinforcement only and without shear reinforcement.

Materials

Reinforcements: One type of FRP bars was used as longitudinal reinforcement: E-Glass FRP. The GFRP reinforcement bars used in this study are manufactured by FIDIA global service, Milano, Italy. The glass FRP bars were used in two sizes: No. 12 (d_b = 12.70 mm) and No. 16 (d_b = 15.88 mm). the deformed steel bars had also two different sizes: (d_b = 11.30 mm) and (d_b = 15.96 mm) were used in reinforcing the control beams. The mechanical properties of the reinforcing bars were determined by performing tensile tests on representative specimens. The characteristics of the glass FRP and steel reinforcement used in this study are summarized in Table 1 and Table 2.

Fig. 1: GFRP bar used in this study

Table 1: Mechanical properties for GFRP bar

Properties	**Ø 12**	**Ø 16**
Cross Sectional Area (mm²)	113.14	201.14
Nominal Diameter, ∅ (mm)	12.70	15.88
Modulus of Elasticity, E_f (GPa)	52.315	56.715
Tensile Strength, f_{fu} (MPa)	860.15	920
Ultimate Strain, ε_f (%)	1.65	1.84

Table 2: Mechanical properties for Mild Steel bar

Properties	**Ø 12**	**Ø 16**
Cross Sectional Area (mm²)	113.04	201.14
Nominal Diameter, ∅ (mm)	11.3	15.96
Modulus of Elasticity, E_s (GPa)	209	209
Yield Strength, f_y (MPa)	453	460
Ultimate Strain, ε_y (%)	0.23	0.23

Concrete: Two types of concrete compressive strength, f'_c, used in this study were 28.5 MPa and 49.1 MPa. The concrete was supplied by GAMA company. The concrete mix design computation and characteristics of concrete used in this study are summarized in Table 3 and Table 4.

Table 3: Concrete mix design computation

Materials		Specified 49.1 MPa	Specified 28.5 MPa
Cement Content (kg/ m^3)		430	318
Free W/C Ratio Specified		0.36	0.49
Coarse Aggregate	4.75≈19.0mm(kg/ m^3)	560	670
	4.75≈12.5mm (kg/ m^3)	560	450
Fine Aggregate Content (kg/ m^3)		682	700
Free Water (kg/ m^3)		155	157
Concrete Density (kg/m3)		2387	2295

Table 4: Mechanical properties for Concrete

Properties	28.5 MPa	49.1 MPa
Compressive Strength, f'_c (MPa)	28.5	49.1
Modulus of Elasticity, E_c (GPa)	25.1	32.9
maximum usable compressive strain in concrete, ε_c	0.0016	0.0023
Poisson's Ratio, μ	0.200	0.200
Tensile Strength, f_t (MPa)	2.239	3.218

Research Design

Four concrete beams reinforced with GFRP bars and four control concrete beams reinforced with steel bars were tested until failure. In order to realize the occurrence of shear failure, all tested beams were reinforced with longitudinal reinforcement only and without shear reinforcement.

All beams were simply supported and subjected to two point loads and known as four point bending test in laboratory, see Fig. 2. The deflection of beam was monitored by the linear variable differential transducer (LVDT's) placed at the side of mid-span of beam. A data logger was recorded and stored the test data for each load increment at a frequency of one reading per second. All beam dimensions were similar in terms of length, width and depth at 2000 mm, 200 mm and 250 mm, respectively. Table 5 summarizes the test variables of all beams tested.

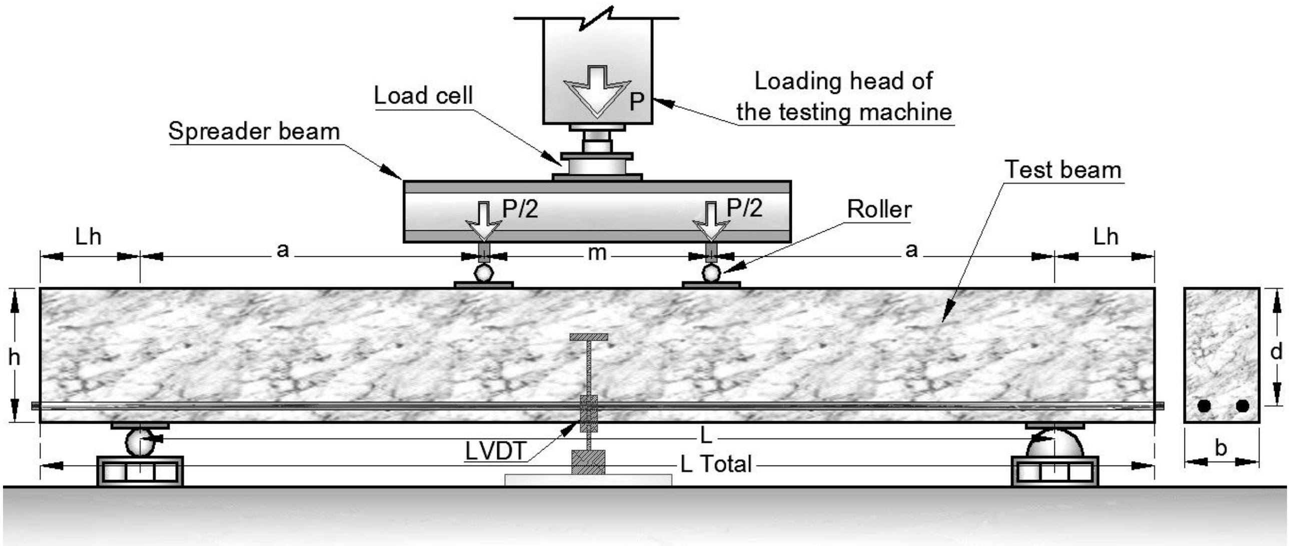


Fig. 2: Schematic of the test setup for beam

Table 5: Detail of beam and test variables

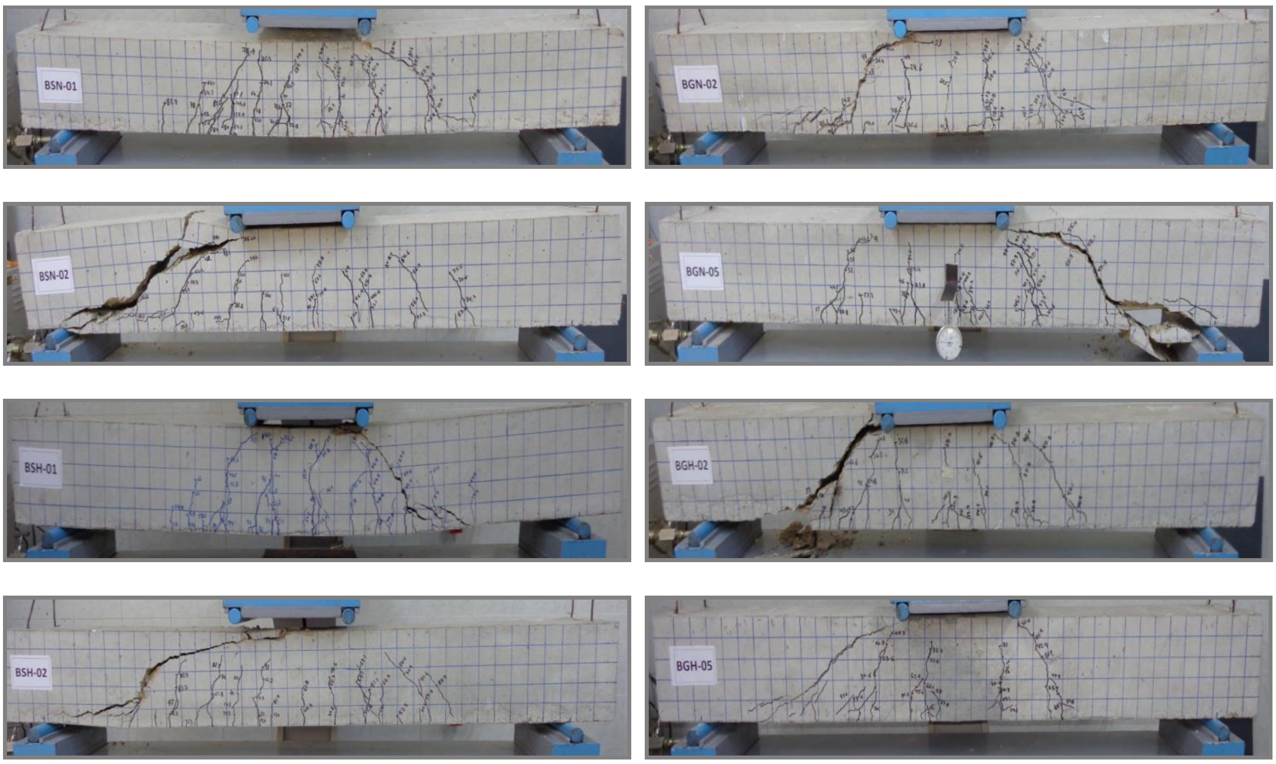
Beams	Reinf.	*f'c* Mpa	*b* (mm)	*h* (mm)	*m* (mm)	*d* (mm)	*a* (mm)	*L* (mm)	*Lh* (mm)	*L Total* (mm)	*Longitudinal Reinforcement*			
											Quantity	d_b (mm)	*As* (mm^2)	ρ (%)
BSN-01	Steel	28.5	200	250	350	219	670	1690	155	2000	2	12	226.2	0.52
BGN-02	GFRP	28.5	200	250	350	219	670	1690	155	2000	2	12	226.2	0.52
BSN-02	Steel	28.5	200	250	350	217	670	1690	155	2000	2	16	402.1	0.93
BGN-05	GFRP	28.5	200	250	350	217	670	1690	155	2000	2	16	402.1	0.93
BSH-01	Steel	49.1	200	250	350	219	670	1690	155	2000	2	12	226.2	0.52
BGH-02	GFRP	49.1	200	250	350	219	670	1690	155	2000	2	12	226.2	0.52
BSH-02	Steel	49.1	200	250	350	217	670	1690	155	2000	2	16	402.1	0.93
BGH-05	GFRP	49.1	200	250	350	217	670	1690	155	2000	2	16	402.1	0.93

Test Results and Discussion

Eight concrete beams consisting of four steel reinforced beams and four GFRP reinforced beams were tested in the present experimental program. The ultimate flexural strength, crack patterns, mode of failure, location and angle of the diagonal shear crack and load-deflection performance of the beams have been predicted and compared with the theoretical values.

1. Behavior of The Test Beams

During the loading stage of the beams, the crack pattern was monitored closely by drawing lines along the cracks and the load values that caused such cracks at the crack tip were recorded. In the initial stages of loading (for all the beams) cracks first appeared in the constant moment zone. As the load increased, additional cracks developed in the mid span and new vertical cracks formed in the shear span. In the case of BGN-02 and BGH-02 with ρ_f = 0.52% , the secondary cracks were developed for both sides. A number of random cracks was also detected in the concrete around the longitudinal tension reinforcement for both sides. One of the vertical cracks in the shear span became critical and extended towards the load point at the ultimate stage. These beams failed at a load lower than the design load and the failure was observed to be mainly due to the low modulus of elasticity of the GFRP bars. For beam BSN-01 and BSH-01 with ρ_s = 0.52%, the initial shear cracking in the specimen behaves similarly as the previous specimens. The secondary crack also propagates for both sides shown in Fig. 3. The failure of the beams BGN-05, BGH-05, BSN-02 and BSH-02 with ρ = 0.93%, the diagonal crack started first and when force was increased development of secondary cracks propagated on one side of the beam. Cracks in concrete beams develop when the principal tensile stresses exceed the tensile strength of concrete. Although vertical cracks and inclined cracks were the main cracks that developed during the loading stage in all the beams tested, some steel reinforced beams and GFRP reinforced beams exhibited horizontal cracks along the reinforcement. The crack width in the shear span in the beams with GFRP bar was observed to be more when compared to that in the corresponding beams with steel bar.



(a) Concrete beams reinforced with steel bars (b) Concrete beams reinforced with GFRP bars

Fig. 3: Crack pattern in test beams at ultimate stage.

Based on data from Table 6, all the beams failed in shear at an ultimate load close to the design load. the mechanism of failure in GFRP reinforced concrete beams was due to the low modulus of elasticity of the GFRP bar. In addition, bonding of the secondary surface deformations from the GFRP bar surface was observed at ultimate stages of the loading. The variation of angle shear cracking and distance of diagonal shear crack, also change due to ratio of reinforcement. The distance of diagonal shear crack has increased following the rate increasing of reinforcement ratio but for the angle shear cracking remained.

Table 6: Summary of test results

Beam	Reinf.	*f'c* Mpa	Slope of crack in shear span zone (Deg)		Crack distance from support (mm)		Shear Crack start at load level kN		Flexure Crack start at load level kN	Failure load, kN	Experimental shear strength V_{exp}, kN	Mode of Failure
			Left	Right	Left	Right	Left	Right				
BSN-01	Steel	28.5	58	56	493	402	16.1	19.4	10.30	62.5	31.25	SF
BGN-02	GFRP	28.5	61	62	449	536	13.3	14.3	8.90	51.8	25.90	SF
BSN-02	Steel	28.5	43	55	192	289	17.35	18.55	14.80	85.6	42.80	SF
BGN-05	GFRP	28.5	69	55	448	337	14.9	13.3	9.10	71.2	35.60	SF
BSH-01	Steel	49.1	46	46	533	332	17.2	13.2	11.80	71.36	35.68	SF
BGH-02	GFRP	49.1	39	48	332	383	15	16.4	10.45	59.52	29.76	SF
BSH-02	Steel	49.1	54	50	274	426	19.65	22.75	16.95	89.6	44.80	SF
BGH-05	GFRP	49.1	31	61	204	503	15	17.95	12.50	74.2	37.10	SF

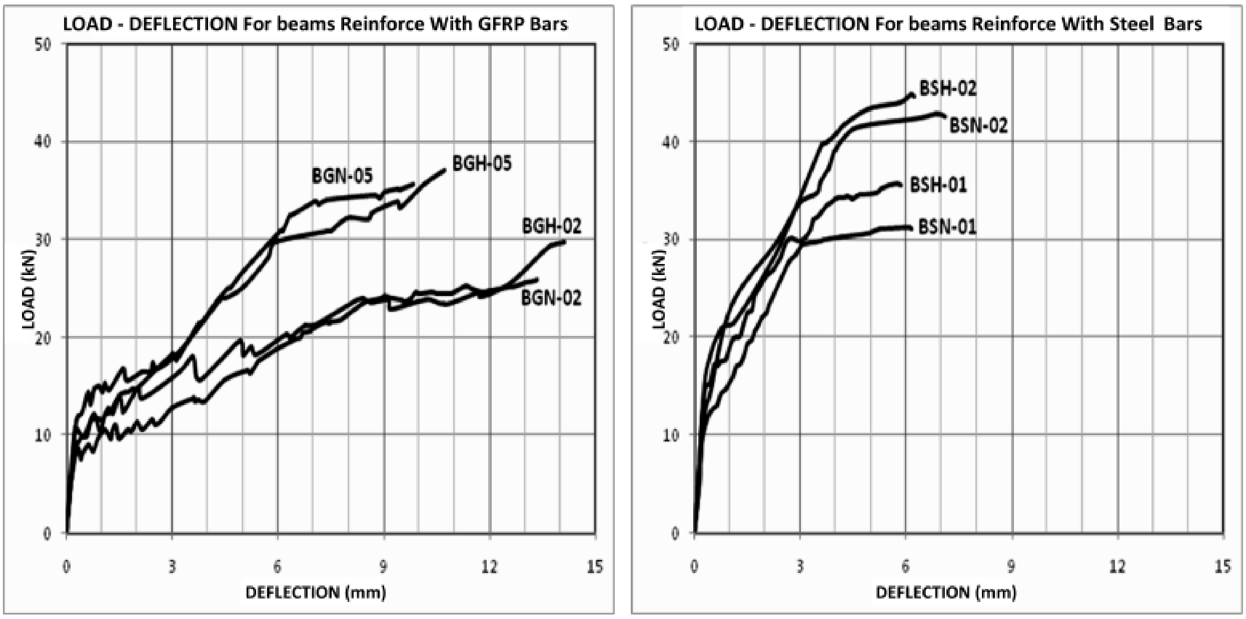
Notes: SF = shear failure

2. Load Deflection

The ultimate load carried by each beam and the deflection corresponding to the Ultimate load are presented in Table 7 whereas Fig. 4, shows the load-deflection curves for beams with steel bar compared with load-deflection curves for beams with GFRP bar, occurred at mid-span. It can be seen that all beams behaved linear elastic at the beginning, and as the load increases, the beam starts to behave non-linear due to the development of cracks until failure occurred. The deflection behavior of the GFRP bar reinforced concrete beam had higher deflection compared to both steel and GFRP bar reinforced concrete beams. However, the relatively low modulus of elasticity of GFRP bar was found to be an important factor in increasing the deflection of GFRP reinforced concrete beams.

Table 7: Comparison ultimate load and deflection at ultimate load

Beam	Reinf.	fc' (Mpa)	a_v/d	ρ (%)	Failure load, kN	Experimental shear strength V_{exp}, kN	Deflection at Ultimate Load (mm)
BSN-01	Steel	28.5	3.06	0.52	62.5	31.25	6.08
BGN-02	GFRP	28.5	3.06	0.52	51.8	25.90	13.35
BSN-02	Steel	28.5	3.09	0.93	85.6	42.80	6.88
BGN-05	GFRP	28.5	3.09	0.93	71.2	35.60	9.84
BSH-01	Steel	49.1	3.06	0.52	71.36	35.68	5.74
BGH-02	GFRP	49.1	3.06	0.52	59.52	29.76	14.12
BSH-02	Steel	49.1	3.09	0.93	89.6	44.80	6.12
BGH-05	GFRP	49.1	3.09	0.93	74.2	37.10	10.71



(a) (b)

Fig. 4: Load-deflection behavior (a) beams with steel bar (b) beams with GFRP bar.

3. Comparison Of Experimental Shear Strength With Theoretical Values

The shear strengths of the tested beams reinforced with FRP bars were predicted using the shear design provisions of ACI 440.1R-03 design guidelines [7], ACI 440.1R-06 Guidelines [8], ISIS-M03-01 design manual [9], and JSCE design recommendations [10].

Table 8: Comparison of experimental shear strength with theoretical values

Beam	Experimental shear strength V_{exp}, kN	ACI 440.1R-03		ACI 440.1R-06		ISIS-M03-01		JSCE	
		V_{theor},kN	V_{exp} /V_{theor}	V_{theor},kN	V_{exp} /V_{theor}	V_{theor},kN	V_{exp} /V_{theor}	V_{theor},kN	V_{exp} /V_{theor}
BGN-02	25.90	4.80	5.40	12.90	2.01	23.4	1.11	19.8	1.31
BGN-05	35.60	9.30	3.83	17.10	2.08	24.1	1.48	24.5	1.45
BGH-02	29.76	4.50	6.61	14.80	2.01	30.7	0.97	23.3	1.28
BGH-05	37.10	8.60	4.31	19.90	1.86	31.6	1.17	28.9	1.28
Mean			5.04		1.99		1.18		1.33

The predicted shear strengths were compared with the experimental values as given in Table 8. For β_1= According to ACI 440.1R-03, the factor β_1 in the denominator of Eq. 3, is a function of the concrete compressive strength. It can be simply expressed by the following equation:

$$0.85 \geq \beta_1 = 0.85 - 0.007(f'_c - 28) \geq 0.65.$$

Eq. 4, was used to predict the concrete shear strengths of the tested FRP reinforced beams according to ACI 440.1R-06. For predictions using the ISIS-M03-01 design manual Eq. 5, considering λ and φ_c equal to 1.0. Eq. 7, was used for predicting the shear strengths according to the JSCE method. It should be pointed out that the member safety factor γ_b was taken equal to 1.0 and the design axial compressive force Nd' as well as the decompression moment Mo was taken equal to zero.

It can be noticed from Table 8 that both ISIS and JSCE predicted values (V_{pred}) are in good agreement with the experimental results (V_{exp}). This is evident from Table 8 as the mean values of V_{exp}/V_{pred} were 1.18 and 1.33 for the ISIS and JSCE methods, respectively.

The JSCE design method has more advantage over the ISIS method as it accounts for the two components of axial stiffness (E_f and A_f) of the reinforcing bars, whereas the ISIS method does not account for the reinforcement ratio.

The ACI 440.1R-06 gives reasonable but rather conservative results as the mean value of V_{exp} /V_{pred} was 1.99. However, the predicted values obtained from the ACI 440.1R-03 were clearly conservative and underestimates the shear strength for all concrete beams reinforced with GFRP bars as shown in Table 8.

Conclusion

The shear strength and behavior of concrete beams reinforced with FRP bars were evaluated. Eight reinforced concrete beams without stirrups consisting of four concrete beams reinforced with GFRP bars and four control concrete beams reinforced with steel bars were tested until failure. The test variables were the reinforcement ratio and the modulus of elasticity of the longitudinal reinforcing bars. The experimental test results were compared to the available shear design provisions. The main findings of this investigation can be summarized as follows:

1. Beam reinforced with GFRP bars showed similar shear behaviour than that of beam reinforced with steel. However the shear strength of beams reinforced with GFRP bars is lower than that beams reinforced with steel bars. This fact is due to the low elastic modulus of GFRP bars.
2. The ratio of longitudinal reinforcement, ρ is directly proportional with the capacity of beam. The value of angle shear cracking also reduced when the ratio of longitudinal reinforcement ρ is increased.
3. Due to the low modulus of elasticity of the reinforcement, the beams reinforced with longitudinal GFRP reinforcement exhibited much greater deflections than those with steel reinforcement. In addition, shear crack widths, measured at the same load levels, were also generally larger for the GFRP RC beams than those observed in the equivalent steel RC beams.
4. ISIS-M03-01and JSCE design methods, for beams without stirrups resulted in good predictions for beams reinforced with glass FRP bars. The design equation by the ACI 440.1R-06 gives reasonable but rather conservative results. On the other hand, the ACI 440.1R-03 design method provided very conservative results for beams reinforced with glass FRP bars. Generally, better predictions can be obtained by both the ISIS design method (ISIS-M03-01) and JSCE design recommendations; and

Acknowledgement

This study was financially supported by Ministry of Higher Education, Malaysia. Through University Tun Hussein Onn Malaysia, UTHM, (GIPS Grant , Project Vot No. 1241). The GFRP reinforcement bars used in this study are manufactured by FIDIA global service, Milano, Italy. and ready mix concrete was supplied by GAMA company. And we would like to express sincere gratitude and appreciation to Laboratory technicians at the University, UTHM. And all friend who provided academic opinions and support to author, and all support is thankfully acknowledged.

List of Symbols And Abbreviations

FRP	-	Fibre Reinforced Polymer
GFRP	-	Glass Fibre Reinforced Polymer
a_v/d	-	Shear span/effective depth
f_{cu} ,f'_c ,	-	cylinder compressive strength of

f_{ck}		concrete
v	-	Shear stress
V	-	Shear Force
ρ	-	Ratio of longitudinal reinforcement
ρ_f	-	FRP flexural reinforcement ratio
E_f	-	Modulus elasticity of FRP
E_s	-	Modulus of elasticity for steel
A_s	-	Area of steel reinforcement
A_f	-	Area of FRP reinforcement
b_w	-	Beam width
d	-	Effective depth
SF	-	Shear Failure
mm	-	Millimeter

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