

# Shear Strength Prediction for Concrete Beams Reinforced with GFRP Bars

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**Abstract.** This study presents a shear strength prediction model for concrete beams reinforced with GFRP bars. An empirical equation is developed using multiple regression analysis from the experimental results of 16 RC beams with GFRP bars. The proposed equation involved the parameters that affected the shear strength of beams such as compressive concrete strength, shear span ratio, longitudinal reinforcement ratio and modulus elasticity of the reinforcement. The accuracy of the proposed equation was verified by predicting the available experimental data from the literature. Furthermore, the predictions of shear capacities were compared with the current shear design code of ACI 440.1R-06. As a result, the ACI 440 provides very conservative prediction, while a better prediction is obtained from the shear strength prediction model in the present study.

## 1 Introduction

Glass fiber-reinforced polymer (GFRP) bars have emerged as an alternative reinforcement material to steel reinforcement due to certain advantages especially in terms of overcoming corrosion and repairing works [1]. In addition, GFRP bars possess higher tensile strength and are lighter than steel bars. However, the brittle behaviour and low modulus of elasticity of GFRP bars remain a matter of concern for concrete structure design.

Recently, the American Concrete Institute [2] has published design guidelines relevant to the use of GFRP bars as the main reinforcement in concrete structures. Accordingly, their design provisions for flexural and shear design followed the conventional reinforced concrete design guidelines. The shear design of reinforced concrete beam considered the contributions of concrete shear strength and shear resistance of stirrups,  $V_c+V_s$ , as the total shear resistance,  $V$ . However, with respect to different mechanical properties of GFRP, some modifications were made in the calculation of concrete shear strength,  $V_c$  of beams reinforced with GFRP bars. The concrete shear strength equation,  $V_c$  recommended by the ACI 440 design method [2] consisted of variables such as modulus elasticity of longitudinal

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reinforcement ( $E_f$ ), longitudinal reinforcement ratio ( $\rho_f$ ), concrete compressive strength ( $f_{cu}$ ), beam width ( $b_w$ ) and neutral axis depth ( $c$ ). It was indicated that no shear span to depth ratio ( $a/d$ ) was included in the equation. Previous studies found that the ACI 440 design method was very conservative and more research is needed with respect to beams with a shear span ratio less than 2.5 [2-4]. Moreover, recent studies [5, 6] have also found that the concrete shear strength estimated by ACI 440 provided the most conservative predictions compared to other existing shear strength model. Consequently, a high amount of reinforcements will be required thereby increasing the cost of building structures.

In this paper, a new concrete shear strength prediction model for concrete beams reinforced with GFRP bars is developed based on the experimental results of this study. Furthermore, the accuracy of the proposed concrete shear strength equations was verified with the test results obtained from the literature. The performance of the proposed equations was also compared with current shear design guidelines of ACI 440 [2].

## 2 Test Program

### 2.1 Material properties

As shown in Fig. 1, the sand-coated GFRP bars with a diameter of 16 mm were used as longitudinal reinforcement bars in concrete beams. From the tensile tests on three GFRP samples, the mechanical properties of GFRP bars were obtained. Accordingly, the tensile strength and modulus elasticity of GFRP bars were 766 MPa and 56.6 GPa, respectively. All the tested beams were provided with steel stirrups with a diameter of 8 mm within the shear span. The yield strength and modulus elasticity of stirrups were 454 MPa and 162 MPa respectively. The beams were constructed using two grades of concrete with compressive strengths measuring 24 MPa and 36 MPa respectively.

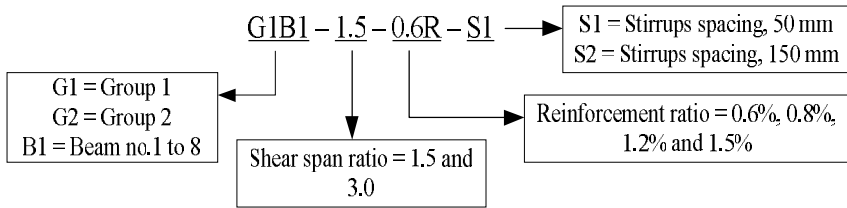


**Fig. 1.** Glass fiber reinforced polymer (GFRP) bars.

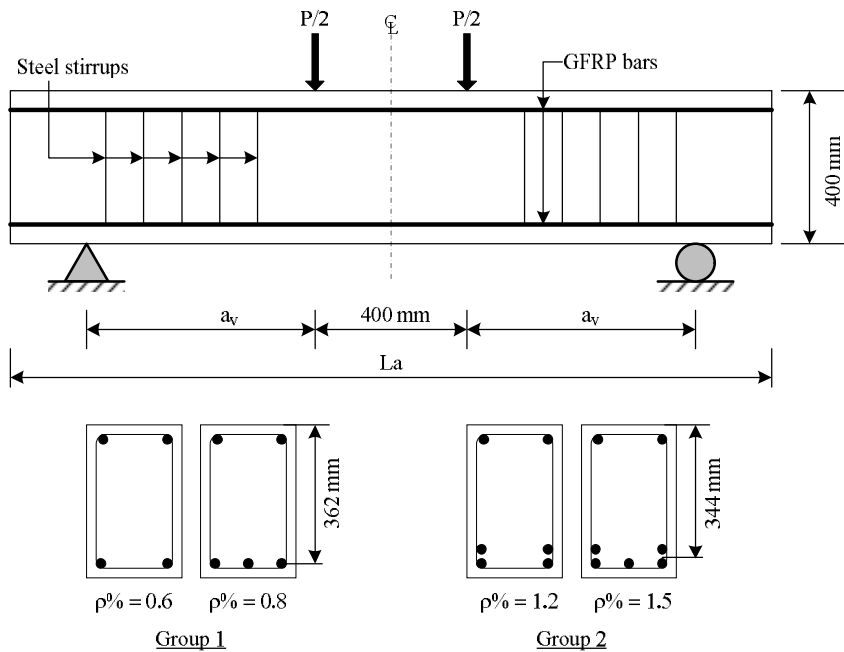
### 2.2 Test specimens and instrumentation

This investigation evaluates the contribution of concrete to the shear resistance of concrete beams reinforced with GFRP bars. The test variables consisted of longitudinal reinforcement ratio, shear span ratio and stirrups spacing. As shown in Table 1, a total of sixteen concrete beams were constructed and tested up to failure. The tested beams were divided into two groups: beams with reinforcement ratios of 0.6% and 0.8% (Group 1) and

beams with reinforcement ratios of 1.2% and 1.5% (Group 2). All beams measured 200 mm in width with different beam depths of 362 mm (Group 1) and 343 mm (Group 2) as illustrated in Fig. 2. Each group included beams with shear span ratios of 1.5 and 3.0 with steel stirrups spacing of 50 mm and 150 mm. The beams were labelled systematically and can be explained as follows:



As shown in Fig. 2, all beams were tested over a simply supported with constant clear span of 400 mm. The beams were tested under four point loading. To investigate the stress-strain relationships, two electrical-resistance strain gauges were bonded on the top concrete surface at the middle of beam span. The strain gauges were also bonded on the longitudinal reinforcement bars and stirrups. While, the displacements were measured by using three linear variable displacement transducers (LVDTs) with a 50 mm stroke, that were placed at the mid-span and under the load positions. During testing, all the crack formations on each side of the beam surface were marked.



**Fig. 2.** Details of test specimens and test setup

**Table 1(a).** Beam details and test results.

Group	Beam	$a_v$ (mm)	L (mm)	$f_{cu}$ (N/mm <sup>2</sup> )	Longitudinal reinforcement ratio (%)	Stirrups spacing (mm)
1	G1B1-1.5-0.6R-S1	550	2000	24	0.6	50
	G1B2-1.5-0.8R-S1	550	2000	24	0.8	50
	G1B3-1.5-0.6R-S2	550	2000	24	0.6	150
	G1B4-1.5-0.8R-S2	550	2000	24	0.8	150
	G1B5-3.0-0.6R-S1	1100	3000	24	0.6	50
	G1B6-3.0-0.8R-S1	1100	3000	24	0.8	50
	G1B7-3.0-0.6R-S2	1100	3000	24	0.6	150
	G1B8-3.0-0.8R-S2	1100	3000	24	0.8	150
2	G2B1-1.5-1.2R-S1	550	2000	36	1.2	50
	G2B2-1.5-1.5R-S1	550	2000	36	1.5	50
	G2B3-1.5-1.2R-S2	550	2000	36	1.2	150
	G2B4-1.5-1.5R-S2	550	2000	36	1.5	150
	G2B5-3.0-1.2R-S1	1100	3000	36	1.2	50
	G2B6-3.0-1.5R-S1	1100	3000	36	1.5	50
	G2B7-3.0-1.2R-S2	1100	3000	36	1.2	150
	G2B8-3.0-1.5R-S2	1100	3000	36	1.5	150

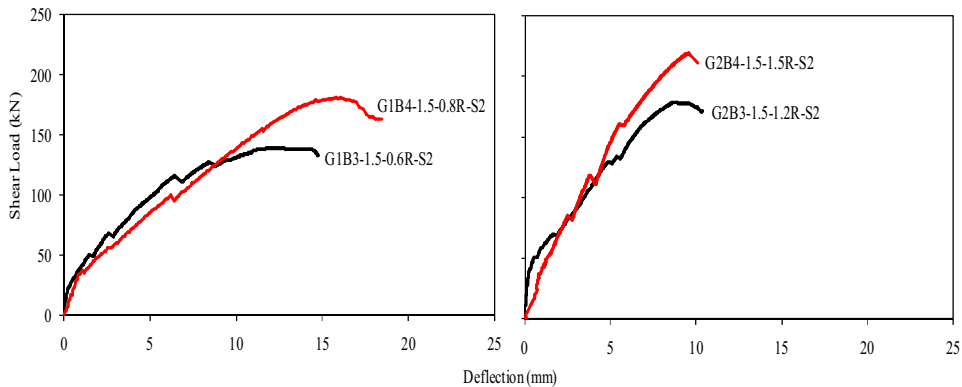
**Table 1(b).** Beam details and test results.

Group	Beam	Test results		
		First diagonal crack load, $V_{c,exp}$ (kN)	Shear load, P/2 (kN)	Failure mode
1	G1B1-1.5-0.6R-S1	41.3	233.2	Flexure
	G1B2-1.5-0.8R-S1	42.7	281.6	Flexure
	G1B3-1.5-0.6R-S2	37.1	139.0	Shear
	G1B4-1.5-0.8R-S2	55.8	181.3	Shear
	G1B5-3.0-0.6R-S1	27.4	99.0	Flexure
	G1B6-3.0-0.8R-S1	24.7	132.1	Flexure
	G1B7-3.0-0.6R-S2	14.4	92.8	Flexure
	G1B8-3.0-0.8R-S2	21.3	125.6	Flexure
2	G2B1-1.5-1.2R-S1	39.0	255.0	Shear
	G2B2-1.5-1.5R-S1	54.0	280.2	Flexure
	G2B3-1.5-1.2R-S2	43.5	179.3	Shear
	G2B4-1.5-1.5R-S2	64.5	219.3	Shear
	G2B5-3.0-1.2R-S1	32.5	151.3	Flexure
	G2B6-3.0-1.5R-S1	30.5	164.4	Flexure
	G2B7-3.0-1.2R-S2	36.0	138.5	Flexure
	G2B8-3.0-1.5R-S2	31.5	140.1	Shear

### 3 Results and discussion

The test results on first diagonal crack load, shear load and failure mode for each tested beam in this study are listed in Table 1. Typical load-deflection curves between beams with the same shear span ratio and stirrups spacing, but different longitudinal reinforcement ratios of GFRP bars are shown in Fig. 3. It is shown that the shear capacity increases as the longitudinal reinforcement ratios increases. It also revealed that an increase in reinforcement ratio influences the stiffness of the beams. In addition, all beams experienced bilinear load-deflection behaviour after the formation of the first flexural crack within moment region.

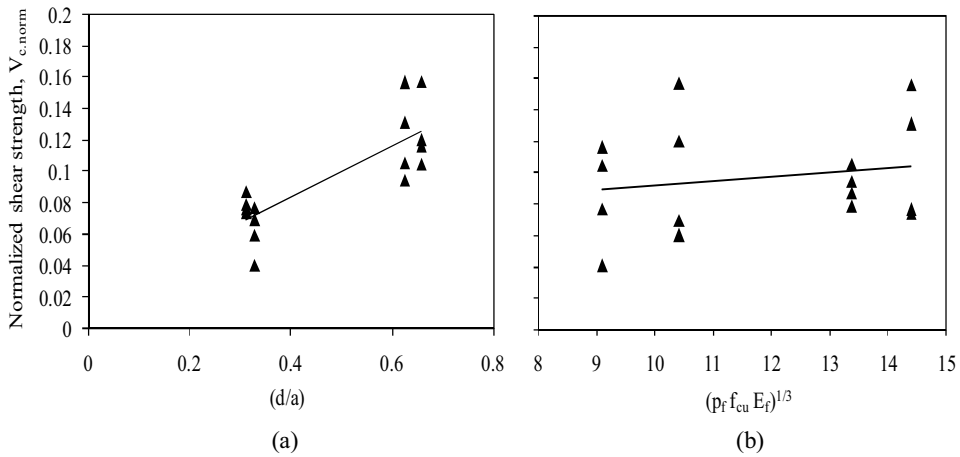
Two types of failure were observed namely shear failure and flexure failure. Flexure failure was indicated by excessive concrete crushing at the top concrete sections of the middle beam span. Flexure failure was sudden especially in beams that experienced bar rupture, such in beams G1B1-1.5-0.6R-S1, G1B5-3.0-0.6R-S1, G1B6-3.0-0.8R-S1 and G1B7-3.0-0.6R-S2. The shear failure was exhibited by severe diagonal cracks within the shear span. The failure was also sudden and generally occurred in beams that had stirrups spacing of 150 mm within the shear span ratio of 1.5 such in beams G1B3-1.5-0.6R-S2, G1B4-1.5-0.8R-S2, G2B3-1.5-1.2R-S2 and G2B4-1.5-1.5R-S2.



**Fig. 3.** Typical load-deflection curves of beams with the same shear span ratio of 1.5, stirrups spacing of 150 mm but different reinforcement ratios within 0.6% to 1.5%.

### 4 Proposed shear design equation

The derivation of the shear design equation,  $V_c$  was obtained from the test results of this study. This proposed equation includes the effects of test variables of shear span ratio, reinforcement ratio, modulus of elasticity and concrete compressive strength. The relationship between the test results and variables is plotted in Fig. 4(a) and (b). In the figures, the test results of shear capacity,  $V_{c,exp}$  was normalized by the square root of concrete strength,  $\sqrt{f_{cu}}$  and the cross section area of the beam,  $b_w d$  [7-9]. It was discovered that the normalized shear strength,  $V_{c,norm}$  increases as the shear span ratio of  $(d/a)$  increases as shown in Fig. 4(a). A linear relationship was also indicated in Fig. 4(b) between normalized shear strength with combination variables of  $(p_f E_f f_{cu})^{1/3}$ . A similar relationship was reported in the literature for beams reinforced with longitudinal GFRP and CFRP bars. However, the effect of concrete compressive strength was not considered.



**Fig. 4.** Relationship between Normalised Shear Strength and Test Variables

Hence, the basic expression for deriving the concrete shear capacity of beams can be written as:

$$V_c = \beta \sqrt{f_{cu}} b_w d \quad (1)$$

In the above equation,  $\beta$  is the correction factor which incorporated the test variables of  $(d/a)$  and  $(p_f E_f f_{cu})^{1/3}$  which influenced the shear strength of beams reinforced with GFRP bars. Based on the relationship, the following expression is proposed:

$$\beta = k_1 (p_f E_f f_{cu})^{1/3} + k_2 \left( \frac{d}{a} \right) \quad (2)$$

Using a regression analysis, the constant values of  $k_1$  and  $k_2$  are obtained. By substituting Equation (2) into (1), the proposed shear strength equation can be written as follow:

$$V_{c.pred} = \left[ 0.00203 (p_f E_f f_{cu})^{1/3} + 0.153 \left( \frac{d}{a} \right) \right] \sqrt{f_{cu}} b_w d \quad (3)$$

## 5 Evaluation of the proposed shear design equation

In order to verify the proposed equation, Equation (3) was compared with the test results of this study and available test results in the literature [3, 6–11] as listed in Table 2. All 42 beams were reinforced with different reinforcement ratios of GFRP and CFRP bars with shear span ratios within 2.3 to 5.0.

In Table 2, the comparison of shear strength predictions according to the proposed equation and current design codes of ACI 440 [2] were compared. The mean value of average ( $V_{exp}/V_{norm}$ ) for the proposed Equation (3) is 1.12 with a standard deviation of 0.21 and a coefficient of variation of 19%. These low values show that the predictions are close to the real values which provide the most accurate prediction. On the other hand, the predicted shear capacities corresponding to ACI 440 provide the most conservative results compared to the prediction results by Equation (3) with a mean value of 1.57.

**Table 2.** Verification of proposed shear strength equation.

Sources	Specimens	Types of bar	a/d	b	d	$f_{cu}$	Longitudinal Reinforcement		$V_{c,exp}$ (kN)	Normalised, $V_{c,nom}$	ACI 440.1R (2006)		Proposed Equation (3)	
							$\rho_f$ (%)	$E_f$ (Mpa)			$V_{c,pred}$ (kN)	$V_{c,nom}/V_{c,pred}$	$V_{c,pred}$ (kN)	$V_{c,nom}/V_{c,pred}$
Present Study	G1B1-1.5-0.6R-S1	GFRP	1.5	200	362	24	0.6	56522	41.3	0.12	0.06	1.92	0.12	0.98
	G1B2-1.5-0.8R-S1	GFRP	1.5	200	362	24	0.8	56522	42.7	0.12	0.07	1.65	0.12	0.99
	G1B3-1.5-0.6R-S2	GFRP	1.5	200	362	24	0.6	56522	37.1	0.10	0.06	1.73	0.12	0.88
	G1B4-1.5-0.8R-S2	GFRP	1.5	200	362	24	0.8	56522	55.8	0.16	0.07	2.16	0.12	1.29
	G1B5-3.0-0.6R-S1	GFRP	3.0	200	362	24	0.6	56522	27.4	0.08	0.06	1.28	0.07	1.12
	G1B6-3.0-0.8R-S1	GFRP	3.0	200	362	24	0.8	56522	24.7	0.07	0.07	0.95	0.07	0.97
	G1B7-3.0-0.6R-S2	GFRP	3.0	200	362	24	0.6	56522	14.4	0.04	0.06	0.67	0.07	0.59
	G1B8-3.0-0.8R-S2	GFRP	3.0	200	362	24	0.8	56522	21.3	0.06	0.07	0.82	0.07	0.84
	G2B1-1.6-1.2R-S1	GFRP	1.6	200	343	36	1.2	56522	39.0	0.09	0.08	1.22	0.12	0.77
	G2B2-1.6-1.5R-S1	GFRP	1.6	200	343	36	1.5	56522	54.0	0.13	0.09	1.53	0.12	1.05
	G2B3-1.6-1.2R-S2	GFRP	1.6	200	343	36	1.2	56522	43.5	0.11	0.08	1.36	0.12	0.86
	G2B4-1.6-1.5R-S2	GFRP	1.6	200	343	36	1.5	56522	64.5	0.16	0.09	1.83	0.12	1.26
	G2B5-3.2-1.2R-S1	GFRP	3.2	200	343	36	1.2	56522	32.5	0.08	0.08	1.02	0.07	1.05
	G2B6-3.2-1.5R-S1	GFRP	3.2	200	343	36	1.5	56522	30.5	0.07	0.09	0.87	0.08	0.96
	G2B7-3.2-1.2R-S2	GFRP	3.2	200	343	36	1.2	56522	36.0	0.09	0.08	1.13	0.07	1.17
	G2B8-3.2-1.5R-S2	GFRP	3.2	200	343	36	1.5	56522	31.5	0.08	0.09	0.89	0.08	0.99
Alam and Hussein (2012)	G-0.5-500	GFRP	2.5	250	455	37.4	0.4	46300	68.0	0.10	0.04	2.44	0.08	1.25
	G-500	GFRP	2.5	250	440	44.7	0.9	46300	77.2	0.10	0.06	1.76	0.09	1.22
	C-0.5-350	CFRP	2.5	250	310	42.4	0.2	144000	58.7	0.12	0.05	2.40	0.08	1.42
	C-0.5-500	CFRP	2.5	250	460	42.4	0.2	144000	70.3	0.09	0.05	1.76	0.08	1.12
	C-500	CFRP	2.5	250	460	42.4	0.5	144000	74.1	0.10	0.07	1.34	0.09	1.10
	C-2.5-500	CFRP	2.5	250	439	42.4	0.7	144000	82.5	0.12	0.09	1.33	0.09	1.24
Ashour and Kara (2014)	B-400-2	CFRP	2.7	200	370	27	0.1	141400	32.9	0.09	0.04	1.93	0.07	1.18
	B-400-4	CFRP	2.7	200	370	27	0.2	141400	36.1	0.09	0.06	1.54	0.08	1.23
Zeidan et al. (2011)	A-I-2.5	CFRP	2.5	150	280	24	0.1	148000	22.5	0.11	0.04	2.51	0.08	1.44
	A-II-2.5	CFRP	2.5	150	280	45	0.1	148000	22.5	0.08	0.04	2.12	0.08	1.01
	A-II-5.0	CFRP	5.0	150	280	49	0.1	148000	12.5	0.04	0.04	1.15	0.05	0.87
	B-II-2.5	CFRP	2.5	150	280	46	0.2	148000	27.5	0.10	0.05	1.86	0.08	1.15
Ashour (2006)	Beam 5	GFRP	2.5	150	269	34	0.9	32000	25.0	0.11	0.05	2.02	0.08	1.31
	Beam 11	GFRP	2.5	150	269	59	1.2	32000	30.0	0.10	0.05	1.83	0.09	1.11
El-Sayed et al. (2006)	GN-2	GFRP	3.1	250	326	44.6	1.2	42000	60.0	0.11	0.07	1.68	0.08	1.44
Melo and Rayol (2002)	Beam 1	GFRP	2.5	150	270	50	0.9	48000	35.0	0.12	0.06	2.05	0.09	1.40
	Beam 2	GFRP	2.5	150	270	50	0.9	48000	35.0	0.12	0.06	2.05	0.09	1.40
	Beam 3	GFRP	2.5	150	270	50	1.6	48000	20.0	0.07	0.08	0.91	0.09	0.75
	Beam 4	GFRP	2.5	150	270	50	2.1	48000	30.0	0.10	0.09	1.22	0.10	1.09
	Beam 5	GFRP	2.5	150	270	50	2.7	48000	30.0	0.10	0.10	1.09	0.10	1.06
	Beam 6	GFRP	2.5	150	270	50	3.3	48000	35.0	0.12	0.10	1.17	0.10	1.20
	Beam 7	GFRP	2.5	150	270	50	3.3	48000	30.0	0.10	0.10	1.00	0.10	1.03
Rendy et al. (2011)	BGN-05	GFRP	2.3	130	210	34	0.6	51500	19.6	0.12	0.06	2.23	0.09	1.42
	BGN-11	GFRP	3.0	130	210	34	0.6	51500	13.6	0.09	0.06	1.55	0.07	1.20
Kim and Jang (2013)	C-2.5-R2-2	CFRP	2.5	150	216	30	0.4	146200	21.6	0.12	0.08	1.53	0.09	1.41
	G-2.5-R1-1	GFRP	2.5	200	216	30	0.3	48200	24.7	0.10	0.04	2.50	0.08	1.36
Total Specimens	42 beams	GFRP and CFRP	2.3 - 5.0	150 - 250	210 - 460	20 - 59	0.11 - 3.26	32000 - 148000	Mean		1.57		1.12	
									STDEV		0.51		0.21	
									CoV (%)		32		19	

## 6 Conclusions

The following conclusions can be drawn from this study:

- (i) Shear strength of the tested beams is proportional to the longitudinal reinforcement ratio and shear span ratio. The stirrups spacing also influence the shear strength of the beams.
- (ii) The stiffness of tested beams slightly increases with increasing longitudinal reinforcement ratio after the occurrence of the first flexure crack.
- (iii) Proposed Eq. (3) provides a reliable and accurate estimation of the shear strength of beams reinforced with GFRP bars with a mean value of 1.12. The equation accounts for the effect of the longitudinal reinforcement ratio, shear span ratio, modulus elasticity of bars and concrete compressive strength.
- (iv) The ACI 440.1R-06 provided very conservative prediction results for all beams reinforced with GFRP bars with a mean value of 1.57.

## References

- [1] N. Salleh, A. Rahman, M. Sam and J.M. Yatim, Flexural behavior of GFRP RC beam strengthened with carbon fiber reinforced polymer (CFRP) plate: Cracking behavior, *Appl. Mech. Mater.*, **752-753**, 610–616 (2015)
- [2] American Concrete Institut (ACI), *Guide for the design and construction of structural concrete reinforced with FRP bars (440-1R-06)*, Farmington Hills, MI (2006)
- [3] A.G. Razaqpur, B.O. Isgor, A.M. Asce, S. Greenaway and A. Selley, Concrete contribution to the shear resistance of fiber reinforced polymer reinforced concrete members, *J. Compos. Constr.*, **8**, 452–460 (2004)
- [4] N.A.A. Hamid, R. Thamrin, A. Ibrahim and H.A. Hamid, Strain distribution on reinforcement of concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars, *Key Eng. Mater.*, **595**, 812–817 (2014)
- [5] A.F. Ashour and I.F. Kara, Size effect on shear strength of FRP reinforced concrete beams, *Compos. Part B Eng.*, **60**, 612–620 (2014)
- [6] N.A.A. Hamid, A. Ibrahim, T. Rendy and H.A. Hamid, Effect of longitudinal reinforcement ratio on shear capacity of concrete beams with GFRP bars, *Proc. of the Inter. Civil and Infrastructure Eng. Conference*, Springer, 587–599 (2015)
- [7] C.H. Kim and H.S. Jang, Concrete shear strength of normal and lightweight concrete beams reinforced with FRP Bars, *J. Compos. Constr.*, **18**(2), 2–10 (2014)
- [8] M.S. Alam and A. Hussein, Unified shear design equation for FRP reinforced concrete members without stirrups, *J. Compos. Constr.*, **17**(5), 575-583 (2013)
- [9] A.K. El-sayed, E.F. El-salakawy and B. Benmokrane, Shear strength of FRP-reinforced concrete beams without transverse reinforcement, *ACI Struct.*, **103**(2), 235–243 (2006)
- [10] M. Zeidan, M.A. Barakat, Z. Mahmoud and A. Khalifa, Evaluation of concrete shear strength for FRP reinforced beams, *Proc. of the Struct. Congr.*, ASCE, 1816–1826 (2011)
- [11] A.F. Ashour, Flexural and shear capacities of concrete beams reinforced with GFRP bars, *Constr. Build. Mater.*, **20**, 1005–1015 (2006)
- [12] R. Thamrin, A.A.A. Samad, A. David, Y.E.C. David, N.A.A. Hamid and I. Ali, Experimental study on diagonal shear cracks of concrete beams without stirrups, *Proc. of the fib Symposium PRAGUE*, Czech Concrete Society, 1–8 (2011)
- [13] G.S. Melo and J.A. Rayol, Shear resistance of GFRP reinforced concrete beams, *Proc. of the Rehabilitating and Repairing Buildings and Bridges*, ASCE, 47–64 (2002)