Journal of Civil & Environmental Engineering

Chowdhury and Islam, J Civil Environ Eng 2015, 5:5
DOI: 10.4172/2165-784X.1000186

Research Article

Open Access

Shear Strength Prediction of FRP-reinforced Concrete Beams: A State-of-the-Art Review of Available Models

Md. Arman Chowdhury* and Md. Mashfiqul Islam

Ahsanullah University of Science and Technology Dhaka, Bangladesh

Abstract

The use of Fiber Reinforced Polymer (FRP) bars to reinforce concrete structures has received a great deal of interest in recent days due to their high tensile strength, corrosion resistance and good non-magnetization properties. Whether to pick FRP bars due to their low modulus of elasticity over conventional steel, to be used in beams, is the major concern of a designer. FRP bars show low strength in shear as they are more elastic than steel. Recently, researchers have developed a number of models to predict the shear strength of FRP-reinforced concrete, but none of them have yet been capable of determining the results satisfactorily. Here a comparative study among different codes and models as suggested by the researchers has been conducted to predict the shear strength of FRP reinforced concrete beams. To facilitate the comparison a database of 104 beams have been presented, which are composed of shear span-to-depth ratio, a/d ranged from 2.5 to 6.5, shear span, (a) ranges from, 600 to 1219, concrete compressive strength, (fc') 24.1Mpa to 81.4MPa, Modulus of elasticity of FRP bars, (Ef) varies between 32GPa to 145GPa, longitudinal reinforcement ratio, (Pf) varies between 0.25 to 3.02. The database contains beams and slabs without transverse reinforcement. The guidelines, codes and models that have been implemented and compared in this study consist of ACI 440.1R-03, CSA S806-06, CSA S806-08, CSA S806-11, JSCE-1997, ISIS-M03-01 2001, BISE guideline 1999. It was observed from the statistical analysis that model proposed by Kara 2011 exhibited the overall best performance to predict the shear strength of FRP-reinforced beams.

Keywords: Concrete beams; Elasticity; Non-magnetization; Reinforced

Introduction

Over the last couple of decades, fiber reinforced polymers (FRPs) have become alternatives to conventional steel reinforcement for concrete structures owing to their non-corrosive and non-magnetic properties [1-3]. Concrete members reinforced longitudinally with FRP bars develop wider and deeper cracks than those reinforced with steel due mainly to the relatively low elastic modulus of FRPs [4-13]. Wider cracks decrease the shear resistance contributions from aggregate interlock and residual tensile stresses, whereas deeper cracks reduce the shear resistance contribution from the uncracked concrete in compression [4,6]. Additionally, owing to the relatively wider cracks and small transverse strength of FRP bars, dowel action contribution to shear resistance can be very small compared with that of steel reinforcement [6]. Hence, the overall shear resistance of concrete members reinforced with longitudinal FRP bars is lower than that of concrete members reinforced with steel reinforcement.

Due to the difference in mechanical properties in between FRP bar and steel bars, the failure mode of FRP-reinforced concrete beams are different from that of RC beams [4]. This indicates the importance and the requirement of a design approach that can sufficiently predict the capacity of a FRP reinforced beam more specifically, the shear strength of that beam. Although a sufficient amount of research has been done on flexural capacities of FRP reinforced beams, due to their complex behavior in shear, they are in need of further evaluation. Over the last few decades a number of researches have been conducted to accurately predict the shear strength of FRP RC beams [4,14]. This paper will compare the available shear design and code equations with the experimental database collected from published literature. The compared code equations are: ACI 440.1R-03, CSA S806-06, CSA S806-08 and CSA S806-11 various models [5-7,11,13,15-22]. All the formulae required by the models for the calculation of the shear strength are included in the Appendix. The codes and models are evaluated and compared with the following performance check: Experimental shear strength over predicted shear strength by the model (V_{exp}/V_{pred}), Standard deviation (SD), Coefficient of Variation (COV) and Average Absolute Error (AAE). Since FRP is a relatively new material, standard guidelines are needed to overcome the additional cost that may be included due to the over conservativeness of the existing models. As most of the models and codes are based on the models that are available for concrete (ACI 318-02) [23], comparative study should be done using a large experimental database. This study considers all state of the art models and codes for predicting the shear strength of FRP RC beams and presents all the models/code equations in a systematic manner. The performance of these existing code equations and models are evaluated against the current and larger database.

Shear failure mechanism of FRP reinforced concrete beams

For FRP RC beams and one-way slabs (subsequently referred to as beams) without stirrups, shear failure generally occurs in association with the formation of one or more diagonal cracks, which for simplicity are assumed to form linearly as suggested by Hoang and Jensen [24], Hong and Nielsen [25], Jensen and Hoang [26], Jensen et al. [27]. Most of the shear predictions models and design procedures and standards assume that the shear resistance mechanisms for FRP RC beam will contribute in a similar manner to the nominal shear capacity of concrete member reinforced with steel [4]. These provisions use the well-known V_c+ V_s method of shear design, which is based on truss analogy [15].

***Corresponding author:** Md. Arman Chowdhury, Ahsanullah University of Science and Technology Dhaka, Bangladesh, Tel: (8802)8870422; E-mail: arman.chowdhury.ce@gmail.com

Received June 20, 2015; **Accepted** August 12, 2015; **Published** August 22, 2015

Citation: Chowdhury A, Islam M (2015) Shear Strength Prediction of FRP-reinforced Concrete Beams: A State-of-the-Art Review of Available Models. J Civil Environ Eng 5: 186. doi:10.4172/2165-784X.1000186

Concrete flexural members that are longitudinally reinforced with steel bars for flexure without stirrups resist the applied shear stresses via a number of mechanisms [3,4,6,15,22,28-30] including: (1) Shear resistance of uncracked concrete, (2)Interlocking action of aggregate, (3) dowel action of the longitudinal reinforcement, (4) arch action, and (5) residual tensile stresses across cracks. Shear contribution of concrete partly comes from friction forces, which are transferred over cracked surfaces and aggregate interlocking. Shear friction is affected by three properties, the aggregate size, the concrete strength and the crack width [29,30]. The dowel action refers to the shear force resisting transverse displacement between two parts of a structural element split by a crack that is bridged by the reinforcement [22]. As FRP is an anisotropic material with very low transverse stiffness, the dowel action of FRP reinforcement is negligible [22,30]. Arching action occurs in deep members or in the members in which the shear span-to-depth ratio (a/d) is less than 2.5 [22]. Compared to the amount of research on arc actions for flexural members that are longitudinally reinforced with steel bars, a limited number of studies have been done for the FRP reinforced beams [6]. The shear resistance also depends on concrete strength and the depth of an uncracked concrete section. Shear resistance increases as the concrete strength decreases and if the cracked section remains shallow. The basic explanation of residual tensile stresses is that when concrete first cracks, a clean break doesn't occur. Residual tension exists in cracked concrete for cracks less than 0.15 mm wide [4,15,22,28,31].

Experimental database

In order to study the shear behavior of FRP RC beams and check the performance of the available design codes and models, a database of 104 beams reinforced with FRP bars and those that failed in shear was compiled [3,15,18,29,32-38]. Only slender beams (a/d>2.5) were considered in this study. In the CAN/CSA-S806 recommendation, a coefficient λ_d is used to consider the concrete density effect; a value of λ_d =1.0 was used in this research (see also Liu and Pantelides [39], Machial et al. [4]. The specimens included 91 beams and 13 one way slabs; all were simply supported and were tested either in three point or four point bending. These specimens included 2 specimens reinforced with aramid FRP bars, 42 specimens reinforced with carbon FRP bars and 60 specimens reinforced with glass FRP bars. All specimens had zero transverse reinforcement (Table 1).

Parameter that Influence Shear Strength

While considerable research activities have been conducted to quantify the flexural behavior of FRP-reinforced members, considerably less is known about the shear behavior of FRP-reinforced concrete beams [10,15,20,21,40,41]. Based on the provided database from literature this section will analyze and compare the existing models and codes. The effect of different controlling parameters on those models and codes will also be analyzed in detail.

Shear span-to-depth ratio (a/d)

The shear span to the effective depth ratio, (a/d) is an important parameter that influences the shear strength. Considering 100 data points, Figure 1b shows the scatter of experimental shear strength with varying the span to depth ratio (a/d) of the beams. Experimental data showing a decreasing trend with increasing ratio which is supported by the theoretical prediction in Figure 1a.

Effective depth, d

The shear strength contribution of FRP-RC beams was found to be directly related to the effective depth of the beams. The entire model assumes that shear strength increases linearly with increasing effective depth as shown in Figure 2a and Experimental shear strength also shows an increase in compressive strength with effective depth in Figure 2b. The mechanical explanation for this is that, due to the increase concrete compressive zone, resistance against shear force increases. ACI 440 shows conservative response comparative to the other models.

Shear Span, a

Most of the design guidelines and models assume that there is no significant effect of the shear span on shear strength of FRP RC beams. Design codes and models: CSA S806-11, Machial et al. [4], Machida A [42], ISIS-M03-01 [43], BISE guideline [44], Razaqpur et al. [20], CSA S806-06 [45], Hoult et al. [21] shows no response with the varying shear span while Wegian et al. [7], Zhao et al.[19], Kara [22] shows non-linear response with a decreasing rate with the increasing shear strength. Experimental result showing a decreasing trend in Figure 3a and 3b so all other codes and models has the scope to improve in this part.

Axial stiffness of reinforcing bars, $p_f E_f$

Axial stiffness of reinforcement is determined by multiplying the reinforcement ratio and the modulus of elasticity (E) of the reinforcement, i.e. $p_f E_f$. The lower the axial stiffness the greater the tensile strain in the longitudinal reinforcing bars. This in turn will cause a reduction in the compression zone leading to wider shear cracks and overall reduction in V_c. In another study, El-sayed et al. [15], found that the concrete shear strength is a function of the longitudinal stiffness. Longitudinal stiffness of FRP RC beam increases as the concrete shear strength increases and it is evident from experimental results in Figure 4a and 4b.

Compressive strength of concrete

To investigate the effect of concrete compressive strength on shear a strength prediction a number of compressive strength is selected and evaluated with the design of guidelines and codes. The shear design method provided by ACI 440.1R-03 assumes that the shear strength of FRP-reinforced concrete beams decrease with the increase in concrete compressive strength, but all other model assume that the shear strength of FRP RC beams increase with the increasing concrete compressive strength as shown in Figure 5a. Experimental result shows an increasing trend in shear strength with the increasing concrete compressive strength in Figure 5b.

Longitudinal reinforcement ratio, p_f

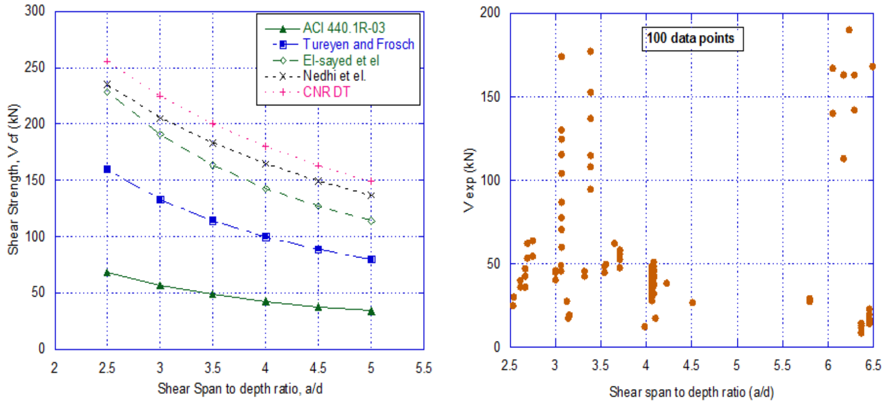
The longitudinal reinforcement ratio, p_f is the area of the longitudinal reinforcement divided by the beam width and the effective depth of the beam. Several researcher observed that p_f is related to the concrete shear strength V_c in a non-linear manner [4,13,15,16,29,32] as also showed in the Figure 6a and 6b. Crack depth and crack width decrease with the increase in longitudinal reinforcement ratio [15] and this reduction in the crack depth increases the shear resistance of the uncracked concrete block. Razaqpur et al. [29] and Gross et al. found a relationship between longitudinal reinforcement ratio and the concrete shear strength which is later on implemented by CSA-S806-02 [46], Kara [22], JSCE-97 [47], Alam and Hussein [48], El-sayed et al. [15], Wegian et al. [7] applied the same factor which is cubic root of reinforcement ratio in modelling shear strength. Nedhi et al. [13] determined the relationship between reinforcement ratio and concrete strength by a power of 0.3 which is replaced by 0.23 in further study. CNR DT suggests a linear relationship between p_f and V_c. From Figure

No	Reference	Beam	f_c' (MPa)	b_w (mm)	*d*(mm)	*a* (mm)	Reinforcement		$V_{exp}(kN)$
							$\rho_f(\%)$	$E_f(GPa)$	
1	**Yost et al. [3]**	1FRPa	36.3	229	225	914	1.11	40.3	39.1
2		1FPRb	36.3	229	225	914	1.11	40.3	38.5
3		1FPRc	36.3	229	225	914	1.11	40.3	36.8
4		2FRPa	36.3	178	225	914	1.42	40.3	28.1
5		2FRPb	36.3	178	225	914	1.42	40.3	35
6		2FRPc	36.3	178	225	914	1.42	40.3	32.1
7		3FRPa	36.3	229	225	914	1.66	40.3	40
8		3FRPb	36.3	229	225	914	1.66	40.3	48.6
9		3FRPc	36.3	229	225	914	1.66	40.3	44.7
10		4FRPa	36.3	279	225	914	1.81	40.3	43.8
11		4FRPb	36.3	279	225	914	1.81	40.3	45.9
12		4FRPc	36.3	279	225	914	1.81	40.3	46.1
13		5FRPa	36.3	254	224	914	2.05	40.3	37.7
14		5FRPb	36.3	254	224	914	2.05	40.3	51
15		5FRPc	36.3	254	224	914	2.05	40.3	46.6
16		6FRPa	36.3	229	224	914	2.27	40.3	43.5
17		6FRPb	36.3	229	224	914	2.27	40.3	41.8
18		6FRPc	36.3	229	224	914	2.27	40.3	41.3
19	**El-sayed et al. [15]**	S-C1	40	1000	165.3	1000	0.39	114	140
20		S-C2B	40	1000	165.3	1000	0.78	114	167
21		S-C3B	40	1000	160.5	1000	1.18	114	190
22		S-G1	40	1000	162.1	1000	0.86	40	113
23		S-G2	40	1000	159	1000	1.7	40	142
24		S-G2B	40	1000	162.1	1000	1.71	40	163
25		S-G3	40	1000	159	1000	2.44	40	163
26		S-G3B	40	1000	154.1	1000	2.63	40	168
27	**El-sayed et al. [15]**	CN-1	50	250	326	1000	0.87	128	77.5
28		GN-1	50	250	326	1000	0.87	39	70.5
29		CN-2	44.6	250	326	1000	1.24	134	104
30		GN-2	44.6	250	326	1000	1.22	42	60
31		CN-3	43.6	250	326	1000	1.72	134	124.5
32		GN-3	43.6	250	326	1000	1.71	42	77.5
33	**Razaqpur et al. [29]**	BR1	40.5	200	225	600	0.25	145	36.1
34		BR2	49	200	225	600	0.5	145	47
35		BR3	40.5	200	225	600	0.63	145	47.2
36		BR4	40.5	200	225	600	0.88	145	42.7
37		BA3	40.5	200	225	800	0.5	145	49.7
38		BA4	40.5	200	225	950	0.5	145	38.5
39		Beam1	28.9	150	167.5	666.67	0.45	38	12.5
40		Beam3	28.9	150	212.3	666.67	0.71	32	17.5
41		Beam5	28.9	150	263	666.67	0.86	32	25
42		Beam7	50.15	150	162.6	666.67	1.39	32	17.5
43		Beam9	50.15	150	213.3	666.67	1.06	32	27.5
44		Beam11	50.15	150	262.12	666.67	1.15	32	30
45	**El-sayed et al. [15]**	CH-1.7	63	250	326	1000	1.71	135	130
46		GH-1.7	63	250	326	1000	1.71	42	87
47		CH-2.2	63	250	326	1000	2.2	135	174
48		GH-2.2	63	250	326	1000	2.2	42	115.5
49	**Gross et al. [24]**	8-2a	60.3	127	143	910	0.33	139	14.3
50		8-2b	60.3	127	143	910	0.33	139	12.9
51		8-2c	60.3	127	143	910	0.33	139	14.7
52		8-3a	61.8	159	141	910	0.58	139	19.8
53		8-3b	61.8	159	141	910	0.58	139	23.1
54		8-3c	61.8	159	141	910	0.58	139	17
55		11-2a	81.4	89	143	910	0.47	139	8.8
56		11-2b	81.4	89	143	910	0.47	139	11.7

No	Reference	Beam	$f_c^{'}$ (MPa)	b_w (mm)	*d*(mm)	*a* (mm)	Reinforcement		$V_{\exp}(kN)$
							$\rho_f(\%)$	$E_f(GPa)$	
57		11-2c	81.4	89	143	910	0.47	139	8.9
58		11-3a	81.4	121	141	910	0.76	139	14.3
59		11-3b	81.4	121	141	910	0.76	139	15.3
60		11-3c	81.4	121	141	910	0.76	139	16.6
61	**Gross et al. [50]**	1a-26	79.6	203	225	914	1.25	40.3	41.6
62		1b-26	79.6	203	225	914	1.25	40.3	30.4
63		1c-26	79.6	203	225	914	1.25	40.3	42.1
64		2a-26	79.6	152	225	914	1.66	40.3	31
65		2b-26	79.6	152	225	914	1.66	40.3	33.1
66		2c-26	79.6	152	225	914	1.66	40.3	33.5
67		3a-27	79.6	165	224	914	2.10	40.3	38.4
68		3b-27	79.6	165	224	914	2.10	40.3	32.2
69		3c-27	79.6	165	224	914	2.10	40.3	36.7
70		4a-37	79.6	203	224	914	2.56	40.3	48.3
71		4b-37	79.6	203	224	914	2.56	40.3	45.7
72		4c-37	79.6	203	224	914	2.56	40.3	45.2
73	**Tariq and Newhook [33]**	G07N1	37.3	160	346	951.5	0.72	42	54.5
74		G07N2	37.3	160	346	951.5	0.72	42	63.7
75		G10N1	43.2	160	346	1149	1.1	42	42.7
76		G10N2	43.2	160	346	1149	1.1	42	45.5
77		G15N1	34.1	160	325	1150.5	1.54	42	48.7
78		G15N2	34.1	160	325	1150.5	1.54	42	44.9
79		C07N1	37.3	130	310	949	0.72	120	49.2
80		C07N2	37.3	130	310	949	0.72	120	45.8
81		C10N1	43.2	130	310	1150	1.1	120	47.6
82		C10N2	43.2	130	310	1150	1.1	120	52.7
83		C15N1	34.1	130	310	1150	1.54	120	55.9
84		C15N2	34.1	130	310	1150	1.54	120	58.3
85	**Tureyen and Frosch [16]**	V-G1-1	39.7	457	360	1219.2	0.96	40.5	108.1
86		V-G2-1	39.9	457	360	1219.2	0.96	37.6	94.7
87		V-A-1	40.3	457	360	1219.2	0.96	47.1	114.8
88		V-G1-2	42.3	457	360	1219.2	1.92	40.5	137
89		V-G2-2	42.5	457	360	1219.2	1.92	37.6	152.6
90		V-A-2	42.6	457	360	1219.2	1.92	47.1	177
91	**Alkhrdaji et al. [35]**	BM7	24.1	178	279	750	2.3	40	53.4
92		BM8	24.1	178	287	750	0.77	40	36.1
93		BM9	24.1	178	287	750	1.34	40	40.1
94	**Deitz et al.**	GFRP1	28.6	305	157.5	710	0.73	40	26.8
95		GFRP2	30.1	305	157.5	913	0.73	40	28.3
96		GFP3	27	305	157.5	913	0.73	40	29.2
97		Hybrid1	28.2	305	157.5	913	0.73	40	28.5
98		Hybrid2	30.8	305	157.5	913	0.73	40	27.6
99	**Mizukawa et al. [36]**	No.1	34.7	200	260	700	1.3	130	62.2
100	**Duranovic et al. [37]**	GB6	32.9	150	210	766.5	1.36	130	62.2
101	**Swamy and Aburawi [38]**	F-6-GF	39	154	222	700	1.55	34	19.5
102	**Zhao et al.**	No.1	34.3	150	250	750	1.51	105	45
103		No.6	34.3	150	250	750	3.02	105	46
104		No.15	34.3	150	250	750	2.27	105	40.5

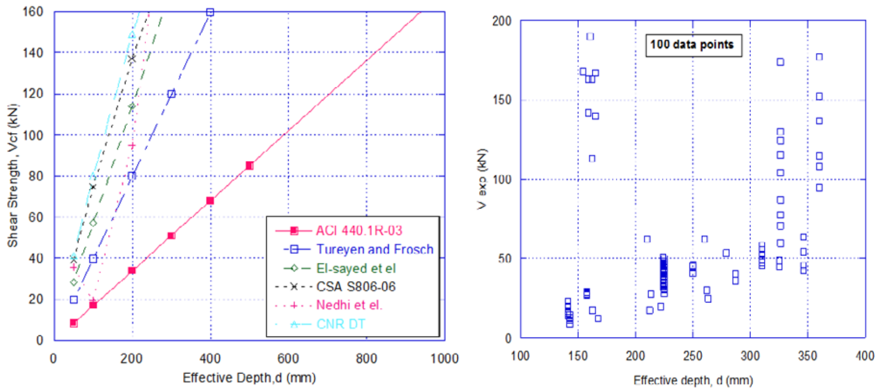
Table 1: Database of Experimental shear capacities of beam reinforced with FRP bars without web reinforcement.

Citation: Chowdhury A, Islam M (2015) Shear Strength Prediction of FRP-reinforced Concrete Beams: A State-of-the-Art Review of Available Models. J Civil Environ Eng 5: 186. doi:10.4172/2165-784X.1000186



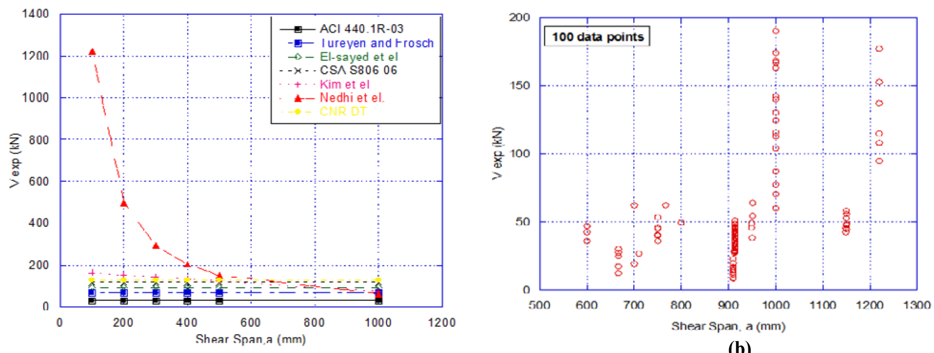
(a) (b)

Figure 1: Effect of Shear span to depth ratio on the shear strength of FRP-RC beams.



(a) **(b)**

Figure 2: Effect of Effective depth on the shear strength of FRP-RC beams.



(a) **(b)**

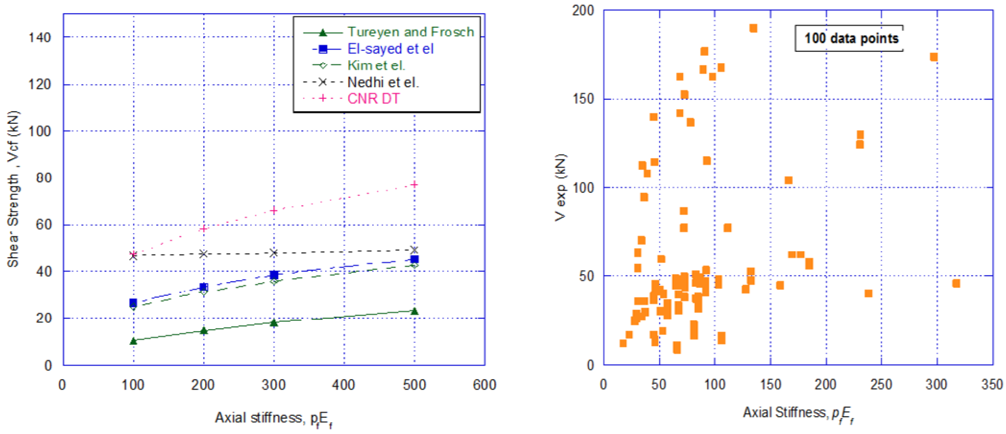
Figure 3: Effect of Shear Span on the shear strength of FRP-RC beams.

6b it is not clear whether this relationship is linear or non-linear but the increasing trend in the experimental results agree with the theoretical predictions by different models and codes.

Beam width (b_w)

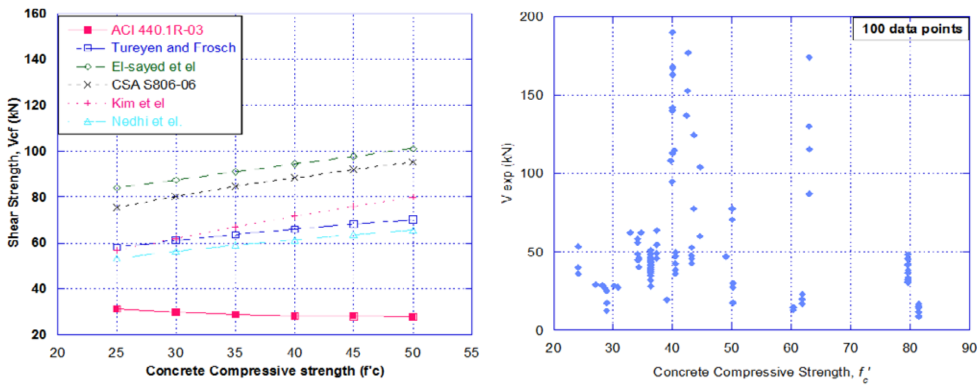
All available models and codes assume a linear relationship between Concrete shear strength and beam width (ACI 440.1R-03 [1], CSA S806-06, CSA S806-08, CSA S806-11, JSCE-1997 [47], ISIS-M03-01 [43], BISE guideline [44], El-sayed et al.[15], Tureyen and Frosch [16], Wegian et al. [7], Michaluk et al. [17], Deitz et al. [18], Nedhi et al. [13], Zhao et al. [19], Razaqpur et al. [29], CNR-DT 203 [49], Hoult et al. [21], Kara [22], Nasrollahzadeh et al. [5], Kim et al. [11], and Lee and Lee [6]. It was observed from the statistical analysis that model proposed by Kara [22]) and this relationship is visible from Figure 7

Citation: Chowdhury A, Islam M (2015) Shear Strength Prediction of FRP-reinforced Concrete Beams: A State-of-the-Art Review of Available Models. J Civil Environ Eng 5: 186. doi:10.4172/2165-784X.1000186



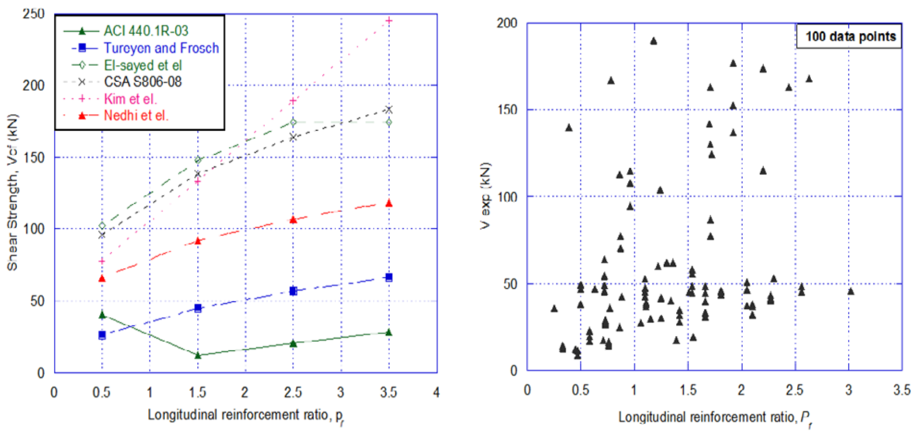
(a) (b)

Figure 4: Effect of Axial stiffness of reinforcing bar on the shear strength of FRP-RC beams without stirrups.



(a) (b)

Figure 5: Effect on concrete compressive strength on the shear strength of FRP-RC beams without stirrups.



(a) (b)

Figure 6: Effect of longitudinal reinforcement ratio on the shear strength of FRP-RC beams without stirrups.

a and 7b.

Modulus of elasticity of FRP bar, E_f (GPa)

Modulus of Elasticity of FRP bar is an important parameter to predict the shear strength of FRP-RC beams. The difference between the modulus of elasticity of steel and FRP bar has become the point of interest for the researchers. ACI 440 guidelines assumed a linear relationship between concrete shear strength and the FRP bar but

Citation: Chowdhury A, Islam M (2015) Shear Strength Prediction of FRP-reinforced Concrete Beams: A State-of-the-Art Review of Available Models. J Civil Environ Eng 5: 186. doi:10.4172/2165-784X.1000186

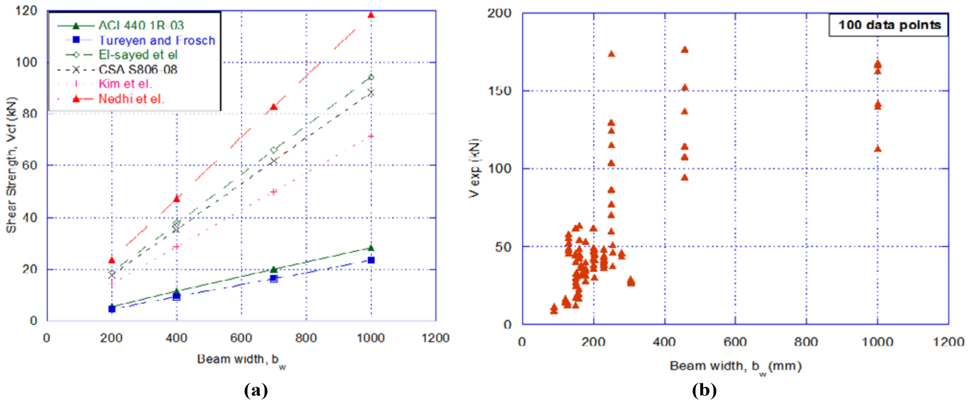


Figure 7: Effect of beam width on the shear strength of FRP-RC beams without stirrups.

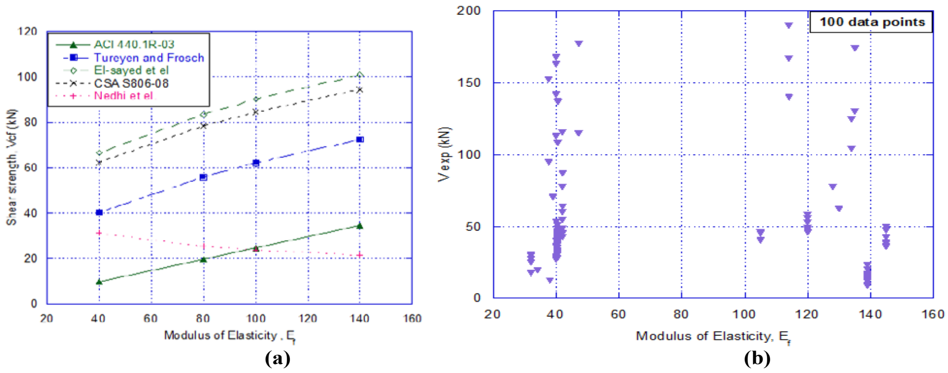


Figure 8: Effect of Modulus of Elasticity on the shear strength of FRP-RC beams without stirrups.

Method	Vexp/V pred		COV (Coefficient of Variation)	Min	Max	AAE % (Average Absolute Error)
	Mean	SD (Standard Deviation)				
ACI 440.1R-06 [1]	3.5	1.459394	41.69696	1.15	9.83	66.73
El-sayed et al. [15]	1.32	0.245486	18.59746	0.89	2.33	23.43
Turyen and Frosch [34]	1.88	0.326777	**17.38178**	1.33	3.51	45.37
Wegian et al. [7]	0.84	0.149269	17.77007	0.56	1.44	24.63
Michaluk et al. [17]	0.75	0.326563	43.54175	0.16	1.64	86.52
Deitz et al. [18]	0.25	**0.108854**	43.54175	0.05	0.54	442.83
CSAS6-08 [51]	1.29	0.39038	30.26203	0.76	2.74	21.65
JSCE -97 [47]	1.1	0.232971	21.17919	0.73	2.03	13.92
ISIS Canada 2001 [43]	0.8	0.409619	51.20243	0.23	2.06	73.63
BISE 1999	0.74	0.17603	23.78784	0.42	1.45	43.31
Kim et al.	1.05	0.326485	31.09381	0.56	2.13	25.15
Nedhi et al.	1.09	0.382181	35.06247	0.55	2.16	23.81
Nedhi et al.	1.25	0.459646	36.77165	0.63	2.49	23.85
Zhao et al.	0.711	0.142059	19.98012	0.46	1.26	46.69
Razaqpur et al.	2.07	0.518543	25.05038	1.17	4.45	48.95
CSA-S806-11	1.15	0.227476	19.78052	0.73	2.09	15.76
CNR DT 2006	1.37	0.311411	22.7307	0.78	2.58	25.91
Hoult et al. 2008	1.32	0.452308	34.26576	0.67	3.18	24.05
CSA S806-06	2.08	0.654444	31.46365	0.69	4.09	48.61
Kara 2011	**1.03**	0.191787	18.62009	0.69	1.81	**13.78**
Nasrollahzadeh and Basiri	0.97	0.30181	31.11442	0.46	1.95	29.21
Lee and Lee	1.93	0.90000	46.6800	0.77	5.72	41.35

Table 2: Statistical Analysis results for Different Models and codes.

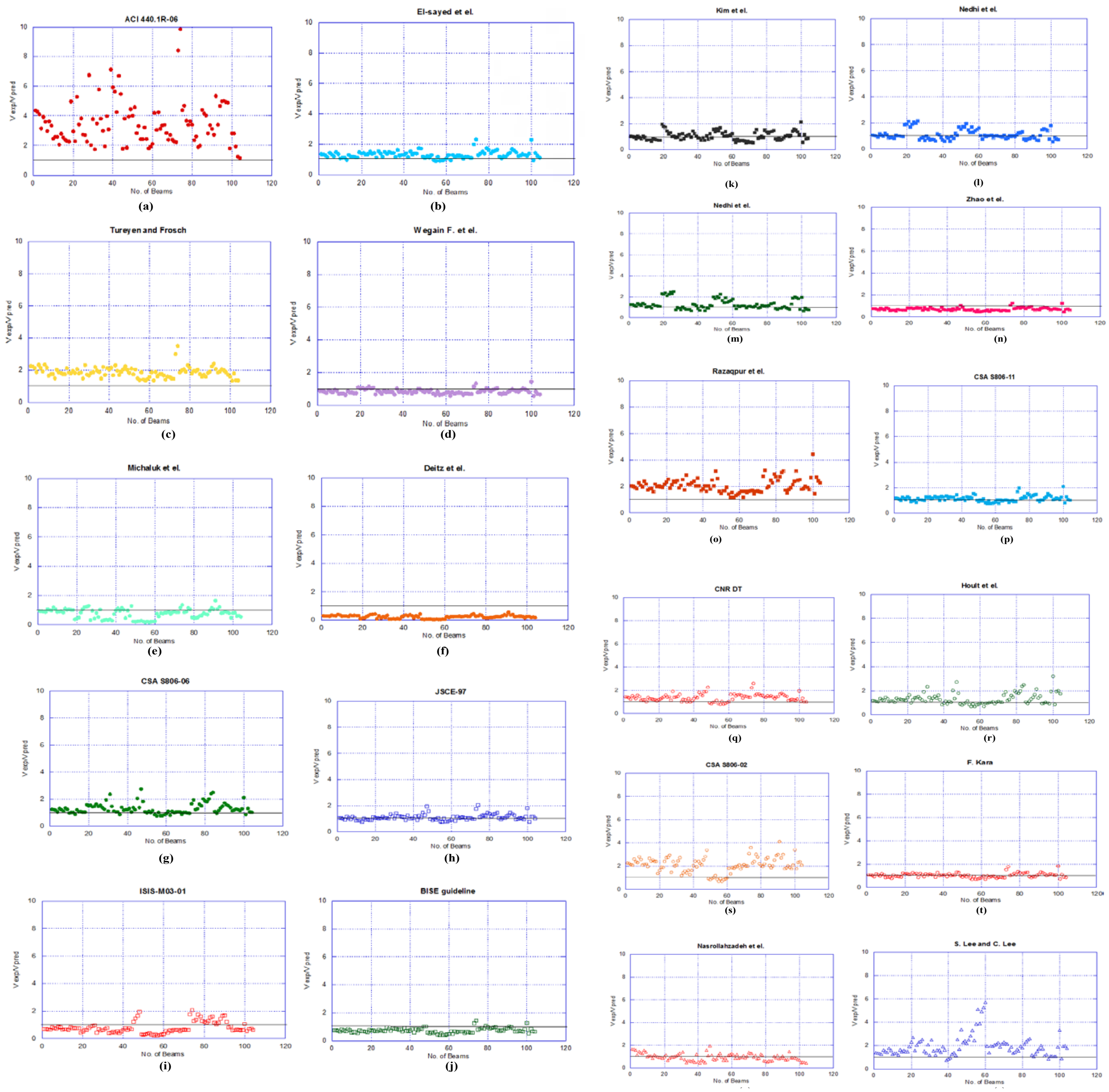


Figure 9: V_{exp}/V_{pred} to No of beams graph for all available models.

most of the research shows a cubic root relationship between them (CSA S806-02 [46], Kara [22], JSCE-97 [42], Alam and Hussein [48], El-sayed et al. [15], Wegian et al. [7], CNR DT 203 [49], BISE design guideline [44], Razaqpur et al. [29]) and some other assumed a square root relationship (CSA S806-06, CNR DT 203 [49], ISIS-M03-01 [43] design manual). Figure 8a and 8b shows the increasing tendency of the FRP RC beams shear strength with the increasing modulus of elasticity of FRP bars.

Model and Codes Comparison: Results and Discussion

In order to compare the performance of existing codes and models in predicting the shear strength of FRP RC beams, a total of five performance checks were utilized: Standard Deviation (SD), Coefficient of Variation (COV), Mean and Average Absolute Error (AAE). The AAE gives an indication of total error that, the design algorithm produced with the database.

$$AAE = \frac{1}{n}\sum \frac{\left|V_{exp} - V_{pred}\right|}{V_{exp}} \times 100$$

The performance of design equations in predicting the concrete contribution to shear strength is presented in Figure 9a-9v and Table 2. The design equation provided by Kara 2011 had the most accurate prediction with a mean of 1.03 and AAE of 13.78%. CSA S806 [46] and Tureyen and Frosch 2001 has the least scattered results compared to others models and equations, and had a mean of 2.08 and 1.88, AAE 45.37% and 15.76% respectively. Tureyen and Frosch 2001 also show a best balance of results with a lowest COV (Coefficient of Variation). Kara [22], El-sayed et al. [15] and Wegian et al. [7] have the second best COV as 17.77%, 18.59% and 18.62%. Although Nasrollahzadeh 2014 have a lower AAE and lesser scatter of results it shows an over estimation in predicting the result by a mean value of 0.97. All other values obtained from the statistical analysis are given in Table 2 and bolded values indicating the minimum value in that column.

Conclusion

The paper has presented an overview of analytical models developed to predict the shear capacity of FRP reinforced concrete beams. A through literature review was conducted on the shear strength of concrete beams reinforced with FRP-RC beams. A database of 104 beams was composed and used in statistical analysis for comparing the performance of existing models and codes. Moving from the first theoretical studies, all of which were based on empirical model only considering the difference between modulus of elasticity of steel and FRP bars, the paper highlights the work done by successive researchers to improve the accuracy of predictions for analysis and design purposes.

Many published provisions and methods for shear resistance of FRP reinforced concrete members (ACI 440.1R-03, CSA S806-06, CSA S806-08, CSA S806-11, JSCE-1997 [47], ISIS-M03-01 [43], BISE guideline [44], El-sayed et al. [15], Tureyen and Frosch [34], Wegian et al. [7], Michaluk et al. [17], Deitz et al. [18], Nehdi et al. [41], Nedhi et al. [13], Zhao et al. [19], Razaqpur et al. [29], CNR-DT 203 [49], Hoult et al. [21], Kara [22], Nasrollahzadeh [5], Kim et al. [11], and Lee and Lee [6] have been considered in this study.

Kara [22] shows the all-round best performance to predict the shear strength of FRP RC beams although improvement may be made to minimize the Average Absolute Error (AAE) and also the COV (Coefficient of Variation). Genetic programming used by Kara [22,50] shows significant improvement over conventional models based on truss analogy and other empirical methods. So, Research should be done on implementing this approach in much more accurate way.

However, more experimental testing of both slender and deep beams reinforced with FRP for longitudinal reinforcement would assist in developing models that can accurately predict the shear strength.

References

1. ACI Committee 440 (2006) Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars.
2. Bashir R, Ashour A (2012) Neural Network modeling for shear strength of concrete members reinforced with FRP bars. Compos: Part B 4: 33198-3207.
3. Yost JR, Gross SP, Dinehart DW (2001) Shear Strength of Concrete Beam Reinforced with Deformed GFRP Bars," ASCE J Compos Construct 5: 268-275.
4. Machial R, Alam MS, Rteil A (2012) Revisiting the shear design equations for concrete beams reinforced with FRP rebar and stirrups. Mater Struct 45.
5. Nasrollahzadeh K, Basiri MM (2014) Prediction of shear strength of FRP reinforced concrete beams using fuzzy inference system. Expert Systems with Applications 41: 1006-1020.
6. Lee S, Lee C (2014) Prediction of shear strength of FRP-reinforced concrete flexural members without stirrups using artificial neural networks. Eng Struct 61: 99-112.
7. Wegian FM, Abdalla HA (2005) Shear capacity of concrete beams reinforced with fiber reinforced polymers. Compos Struct 71: 130-138.
8. Zeidan M (2011) Evaluation of Concrete Shear Strength for FRP Reinforced Beams. Structures Congress, pp: 1816-1826.
9. Matta F, Nanni A, Galati N (2005) Size effect on shear strength of concrete beams reinforced with FRP bars. Aci Structural Journal 110.
10. Zhang T, Oehlers DJ, Visintin P (2014) Shear Strength of FRP RC Beams and One-Way Slabs without Stirrups. J Compos Constr 18.
11. Kim CH, Jang HS (2012) Concrete Shear Strength of Normal and Lightweight Concrete Beams Reinforced with FRP Bars. J Compos Constr 2-10.
12. Guadagnini M, Pilakoutas K, Waldron P (2006) Shear Resistance of FRP RC Beams: Experimental Study. J Compos Construct 10: 464-473.
13. Nedhi M, El Chabib H, Saïd A (2007) Proposed Shear Design Equations for FRP-Reinforced Concrete Beams Based on Genetic Algorithms Approach. J Mater Civil Eng 19: 1033-1042.
14. Tottori S, Wakui H (1993) Shear Capacity of RC and PC Beams Using FRP reinforcement. American Concrete Institute, ACI SP-138, edited by A. Nanni and C.W. Dolan 615-631.
15. El-Sayed A, El-Salakawy E, Benmokrane B (2005) Shear strength of concrete beams reinforced with FRP bars: Design method. Proceedings of the 7th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures - FRPRCS-7: 955-974.
16. Tureyen AK, Frosch RJ (2002) Shear Tests of FRP-Reinforced Concrete Beams without Stirrups. ACI Struct J 99: 427-434.
17. Michaluk R, Rizkalla S, Tadros G, Benmokrane BM (1998) Flexural behavior of one-way concrete slabs reinforced by fiber reinforced plastic reinforcement. ACI Struct J 95: 353-65.
18. Deitz DH, Harik IE, Gesund H (1999) One-Way Slabs Reinforced with Glass Fiber Reinforced Polymer Reinforcing Bars. Proceedings of the 4th International Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures, MI., 279-286.
19. Zhao XL, Zhang L (2007) State-of-the-art review on FRP strengthened steel structures. Eng Struct 29: 1808-1823.
20. Razaqpur AG, Shedid M, Isgor B (2011) Shear Strength of Fiber-Reinforced Polymer Reinforced Concrete Beams Subject to Unsymmetric Loading. J Compos Construct 15: 500-512.
21. Hoult NA, Sherwood EG, Bentz EC, Collins MP (2008) Does the use of FRP reinforcement change the one-way shear behavior of reinforced concrete slabs? J Compos Constr 12: 125-133.
22. Kara IF (2011) Prediction of shear strength of FRP-reinforced concrete beams without stirrups based on genetic programming. Advances in Engineering Software 42: 295-304.
23. ACI Committee 318 (2002) Building code requirement for Structural Concrete (318-02) and Commentary (318-02). American Concrete Institute, Farmington Hills, Michigan, 443.
24. Hoang LC, Jensen UG (2010) Rigid plastic solutions for the maximum shear capacity of confined RC members. Mag Concr Res 62: 625-636.
25. Hoang LC, Nielsen MP (1998) Plasticity approach to shear de-sign. Cem Concr Comp 20: 437-453.
26. Jensen UG, Hoang LC (2009) Shear strength prediction of circular RC members by the crack sliding model. Mag Concr Res 61: 691-703.
27. Jensen UG, Hoang LC, Joergensen HB, Fabrin LS (2010) Shear strength of heavily reinforced concrete members with circular cross section. Eng. Struct 32: 617-626.
28. ACI-ASCE Committee 445 on Shear and Torsion (1998) Recent approaches to shear design of structural concrete. J Struct Eng 124: 1375-1417.
29. Razaqpur AG, Isgor BO, Greenaway S, Selley A (2004) Concrete Contribution to the Shear Resistance of Fiber Reinforced Polymer Reinforced Concrete Members. J Compos Construct 8: 452-460.
30. Machiel R, Alam MS, Rteil A (2010) Shear strength contribution of transverse FRP reinforcement in bridge girders. IABSE-JSCE 978-984.
31. Fico R, Prota A, Manfredi G (2008) Assessment of Eurocode-like design equations for the shear capacity of FRP RC members. Compos Part B: Eng 39: 792-806.
32. Gross SP, Dinehart DW, Yost JR, Theisz PM (2004) Experimental Tests of

High-Strength Concrete Beams Reinforced with CFRP Bars. Proceedings of the 4 th International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS-4), Calgary, Alberta, Canada 8: 20-23.

33. Tariq M, Newhook JP (2003) Shear Testing of FRP reinforced Concrete withou Transverse Reinforcement. Proceedings of CSCE 2003-Anuual Conference, Moncton, NB, Canada.

34. Tureyen AK, Frosch RJ (2003) Concrete Shear Strength: Another Perspective. ACI Struct J 100: 609-615.

35. Alkhrdaji T, Wideman M, Belarbi A, Nani A (2001) Shear strength of GFRP RC Beams and Slabs. Proceeding of the International Conference, Composites in Construction-CCC 2001, Porto/Portugal 409-414.

36. Mizukawa Y, Sato Y, Ueda T, Kakuta Y (1997) A Study on Shear Fatigue Behavior of Concrete Beams with FRP Rods. Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3), Japan Concrete Institute, Sapporo, Japan 2: 309-316.

37. Duranovic N, Pilakoutas K, Waldron P (1997) Tests on Concrete Beams Reinforced with Glass Fibre Reinforced Plastic Bars. Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3), Japan Concrete Institute, Sapporo, Japan 2: 479-486.

38. Swamy N, Aburawi M (1997) Structural Implications of Using GFRP Bars as Concrete Reinforcement. Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3), Japan Concrete Institute, Sapporo, Japan 2: 503-510.

39. Liu R, Pantelides CP (2013) Shear Strength of GFRP reinforced precast lightweight concrete panels. Construct Build Mater 48: 51-58.

40. Bousselham A, Chaallal O (2004) Shear Strengthening Reinforced Concrete Beams with Fiber-Reinforced Polymer: Assessment of Influencing Parameters and Required Research. ACI Struct J 101: 219-227.

41. Nehdi M, El Chabib H, Aly Said A (2006) Predicting the effect of stirrups on shear strength of reinforced normal-strengthconcrete (NSC) and high-strength concrete (HSC) slender beams using artificial intelligence. Canadian J Civil Eng 33: 933-944.

42. Machida A (1997) Recommendation for Design and Construction of Concrete Structures Using Continuous Fibre Reinforcing Materials. Concrete Engineering Series 23, Japan Society of Civil Engineers, JSCE, Tokyo, Japan 325.

43. ISIS-M03-01 (2001) Reinforcing Concrete Structures with Fiber Reinforced Polymers. The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures, ISIS Canada, University of Winnipeg, Manitoba 81.

44. British Institution of Structural Engineers (BISE) (1999) Interim guidance on the design of reinforced concrete structures using fiber composite reinforcement. IStructE, SETO Ltd., London.

45. Canadian Standard Association CSA (2006) CAN/CSA S6-06, Canadian Highway Bridge DesignCode, Rexdale, Ontario.

46. CSA S806-02 (2002) Design and Construction of Building Components with Fibre Reinforced Polymers. Canadian Standards Association, Rexdale, Ontario 177.

47. Japan Society of Civil Engineers JSCE (1997) Recommendation for Design and Construction of Concrete Structures using Continuous Fiber Reinforcing Materials. A Machida (eds.), 164 Concrete Eng Series 3.

48. Alam MS, Hussein A (2011) Experimental investigation on the effect of longitudinal reinforcement on shear strength of fibre reinforced polymer reinforced concrete beams. Can J Civil Eng 38: 243-251.

49. CNR-DT-203,Guide for the design and construction of concrete structures reinforced with fiber reinforced ploymer bars (2006) CNR Advisory Committee on Technical Recommendations fro design and construction. Rome, Italy.

50. Gross SP, Yost JR, Dinehart DW, Svensen E, Liu N (2003) Shear Strength of Normal and High Strength Concrete Beams Reinforced with GFRP Reinforcing Bars. Proc. of the Int. Conference on High Performance Mater in Bridges ASCE 426-437.