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Evaluating the Ultimate Capacity of FRP Reinforced Concrete Beams by Using Eurocode 2 and ACI 440.1R-06

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Abstract: The most frequent cause of reinforced concrete deterioration is corrosion of the steel reinforcement, especially in harsh weather. One of the promising materials for structural applications is fiber-reinforced polymer (FRP) material because of its non-corrosive nature. One of the most productions of FRP material is FRP bars which are used in reinforced concrete structures. FRP bars have many advantages such as high strength to weight ratio. This research aims to evaluate the ultimate capacity of reinforced concrete beams with FRP bars by using available specimens in the literature against Eurocode 2 (EC2) specifications and compared with ACI-440.1R-06 code. The results showed that EC2 code overestimates the ultimate moment capacity for 5 samples only (4% of the examined specimens) for normal strength concrete, while EC2 code overestimates the ultimate moment capacity for 16 samples (14% of the examined specimens) for high strength concrete. Therefore, EC2 is more conservative for predicting moment capacity of reinforced concrete beams with FRP bars for normal strength concrete than high strength concrete. On the other hands, ACI 440.1R-06 underestimated the ultimate moment of all concrete beams reinforced with FRP bars. Accordingly, ACI 440.1R-06 is more conservative for predicting moment capacity than EC2.

Keywords: Flexural capacity; Shear capacity; FRP beams; Eurocode 2; ACI 440.1R-06.

1. Introduction

The design standards for steel reinforced concrete elements are no longer valid for FRP materials because it is a linear elastic brittle material. Multiple standards for the RC structures with FRP were published as a consequence of international research in this area through professional organizations. Utilizing of (GFRP, CFRP, and AFRP) is permitted by the design and construction guidelines (JSCE design recommendations of 1997[1]; CAN/CSA S806 2012[2]; ACI-440.1R-06[3]). In addition, the design codes (CAN/CSA S6 2014[4] and ACI 440.1R 2015[5]) and material specifications (CAN/CSA S807 2010[6]; ACI 440.6M 2008[7]) that are now in use enable engineers to design structural concrete elements reinforced with GFRP, CFRP, and AFRP. Therefore, multiple investigations have been conducted to study the accuracy of international codes to calculate the shear capacity and ultimate moment of FRP reinforced concrete beams. For instance, the literature found that ACI-440.1R-06 [3] predicts the shear capacity of FRP reinforced concrete beams with underestimation of the experimental results [8,9,10]. Also, ACI-440.1R-06 [3] underestimates the ultimate moment of reinforced concrete beams with FRP bars. [11,12]. Additionally, more investigations were carried out to study the accuracy of CAN/CSA S806-12 [2] to calculate the shear capacity and ultimate moment of reinforced concrete beams with FRP bars. The results showed that CAN/CSA S806-12[2] underestimates both shear and moment capacities of reinforced concrete beams with FRP bars [13,14].

However, the assessment of ultimate capacity for FRP reinforced concrete beams by using European standard is not available. Fib Bulletin No. 40[57] is the appropriate reference which is used instead of Eurocode 2 (EC2) [15] to design FRP reinforced concrete beams. Limited research investigate the accuracy of EC2 [15] for assessment the structural behaviour of flexural concrete members reinforced with FRP bars in terms of load capacity and deflection [16,17]. For instance, Barris et al. [17] collected the data obtained from twelve tests to assess the accuracy of EC2[15] for predicting the behaviour of reinforced concrete beams with FRP bars in terms of ultimate moment. The authors proved that EC2 forecast the flexural performance till the service load level accurately, while the prediction of ultimate moment was conservative. Cashell et al. [16] revealed that although, EC2[15] overestimates the flexural strength of concrete beams reinforced with BFRP bars, it provides an accurate forecast for deflection. In a more recent study, Borzovic et al [18] evaluated the reliability and precision of the second generation of EC2[15] for estimating the ultimate shear of reinforced concrete slabs with FRP bars by using statistical analyses. The authors came to the conclusion that by adjusting the ratio of reinforcement with the ratio of elastic modulus (GFRP to Steel), the design procedures that was initially designed for calculating the ultimate shear of steel reinforced concrete members could be successfully implemented to reinforced concrete members with FRP bars.

This research evaluates the load- carrying capacity of FRP reinforced concrete beams with massive available test data. The findings are compared with the provisions of EC2 [15] and ACI-440.1R-06[3].

2. RESEARCH SIGNIFICANCE

Most of previous research studied the accuracy of using American code (ACI-440.1R-06) [3] to evaluate the flexural performance of reinforced concrete beams with FRP bars in terms of moment capacity. However, there is a lack of knowledge for using Eurocode 2 (EC2) [15] to investigate the flexural performance of reinforced concrete beams with FRP bars. This research overcomes this problem by using the available data in the literature and making a comparison with EC2[15] and ACI-440.1R-06[3]. Based on the results, the code equations for predicting shear capacity, ultimate moment, and cracking moment were statistically evaluated.

3. EXAMINED DATA

The previous research of reinforced concrete beams with FRP bars was investigated carefully to obtain the results which served the current research. Forty nine references with 292 specimens were examined for load-deflection behaviour. The collected data involves beams with normal and high strength concrete with and without stirrups. FRP or steel stirrups were used as transverse reinforcement; while the main reinforcement was FRP bars. Additionally, the differences between the examined specimens were the beam geometry, ratio and mechanical properties of tensile and shear reinforcement. The type of loading is four - point bending for all the tested beams. Moreover, all concrete beams have rectangular cross section. Table 1 presents the examined FRP reinforced concrete beams from the literature relevant to the current study.

TABLE 1. The examined FRP reinforced concrete beams from the literature

References	No.	Compressive and tensile properties of concrete		Dimensions of the beam				Main longitudinal reinforcement				Shear reinforcement		
		f_c(MPa)	f_t(MPa)	b (mm)	d (mm)	a (mm)	a/d ratio	ρ_f(%)	f_{fu}(MPa)	E_f (GPa)	Main RFT	ρ_{fv}(%)	Shear RFT	f_u^{FRP} or f_u^s
Adam et al. [11]	4	19.85-60.26	2.1-5.8	120	250	1100	4.4	0.32 - 2.26	640	44	GFRP	0.56	Steel	500
Abed et al. [20]	10	47.5-70.5	4.5-6.8	180	182	750	4.1	0.45-1.84	1028 - 2068	42-131	BFRP-CFRP	0.87	Steel	460
Barris et al. [17]	2	56.3-61.7	5.2-5.9	140-160	142	600	4.2	1.77	995	64	GFRP	0.90-1.03	Steel	500
Cashell et al. [16]	2	33.5-35.9	3.5-3.7	125	162	650	4.0	0.78	1356 - 1565	54-56	BFRP	0.8	Steel	523
Theriault & Benmokrane [19]	4	52.1-97.4	5.3-8.8	130	129	500	3.9	1.23-2.83	773	38	GFRP	0.54	Steel	460
Pecce et al. [21]	2	30	2.8	500	145	1200	8.3	0.7-1.22	600	42	GFRP	0.2	Steel	500
Al-Sunna et al. [22]	4	37.67-44.87	3.5-4.2	150	193	767	4.0	0.28-3.93	665-1475	42-133	GFRP-CFRP	0.89	Steel	590
Elgabbas et al. [12]	5	42.5	3.9	200	233	1100	4.7	0.44-1.72	1162 - 1189	44 - 48	BFRP	0.79	Steel	450
Zhang et al. [23]	4	26.3-34	2.3-3.2	180	187	600	3.2	0.17-0.70	1075 - 1204	44 - 49	BFRP	0.56	Steel	335
Kassem et al. [24]	11	39.05-40.8	4.1-4.2	200	232	875	3.8	0.51-2.18	617-1988	36-122	GFRP-CFRP	0.98	Steel	460
Pawłowski et al. [25]	2	42.36	4.4	200	257	900	3.5	0.22-0.62	1185 - 1485	52 - 56	BFRP	0.5	Steel	500
Rafi et al. [9]	1	41.7	4.2	120	169	675	4.0	0.69	1676	135	CFRP	0.47	Steel	421
Alsayed et al. [26]	4	31.3-40.7	3.3-4.1	200	157	1250	8.0	1.15-3.60	700-886	35-43	GFRP	0.5	Steel	553

TABLE 1. The examined FRP reinforced concrete beams from the literature (continued)

References	No.	f_c(MPa)	f_t(MPa)	b (mm)	d (mm)	a (mm)	a/d ratio	ρ_f(%)	f_{fu}(MPa)	E_f (GPa)	Main RFT	ρ_v(%)	Shear RFT	f_u^{FRP} or f_u^s
Sun et al. [27]	2	39.53	4	220	252	600	2.4	0.62-1.70	907-2550	46-147	BFRP-CFRP	0.57	Steel	500
Barris et al. [28]	5	32.1-54.5	3.3-5.6	140-160	144	600	4.2	0.98-2.66	1015-1321	63-64	GFRP	0.90-1.03	Steel	500
Oh et al. [29]	7	28.6	2.9	180	185	680	3.7	0.47-0.93	841-1200	42	GFRP	1.45-2.18	Steel	500
Kalpana & Subramanian [30]	4	20-60	2.1-5.9	200	198	550	2.8	0.99-1.57	600	55	GFRP	0.28	Steel	500
Erfan et al. [31]	8	30-60	2.9-5.9	150	208	600	2.9	0.31-1.63	1400	56	BFRP	0.45-1.34	Steel	500
Yang et al. [32]	1	75.9	7.7	230	206	800	3.9	1.6	941	48	GFRP	0.85	Steel	477
Thiagarajan et al. [33]	6	43.88-53.31	4.5-5.5	152	122	508	4.2	0.36-0.76	1900	140	CFRP	0.65	Steel	415
Khorasani et al. [34]	20	30	2.9	250	211	800	3.8	0.72-1.45	775-825	42-46	GFRP	0.57-1.15	Steel	462-473
Tomlinson & Fam [35]	6	48-60	4.9-6.1	150	250	1100	4.4	0.13-0.84	1158	68	BFRP	0.17-0.68	Steel/ FRP	485-1158.5
Duranovic et al. [36]	9	24-34.72	2.5-3.6	150	215	512	2.4	0.88-1.33	1000	45	GFRP	0.38-1.68	Steel/ FRP	600-1000
Toutanji & Deng [37]	3	35	3.5	180	255	1200	4.7	0.53-1.10	695	40	GFRP	1.26	FRP	695
Jumaa et al. [38]	4	73	7.4	200	234	610	2.6	3	1089	58	BFRP	0.25-0.63	FRP	1100
Wang et. [13]	1	32.5	3.4	120	212	700	3.3	0.88	826	109	CFRP	0.4	FRP	826
Said et al. [8]	10	19.85-60.26	2.1-6.2	120	250	500	2.0	1.13-2.26	640	44	GFRP	0.39-0.84	FRP	640
Massam [39]	6	35-49	3.6-5.1	450	404	3050	7.5	0.48-2.23	517	40	GFRP	0.079-0.16	FRP	517
Zhao et al. [40]	9	34.3	3.6	150	250	750	3.0	1.51-3.02	1124	105	CFRP	0.41	FRP	1100-1300
Issa et al. [41]	9	35.9	3.7	200-300	165	397	2.4	0.78-3.97	1050-1070	48-53	BFRP	0.31	FRP	1070
Nagasaka et al. [42]	12	22.9-36.7	2.4-3.7	250	253	480	1.9	1.9	1000	56	AFRP	0.5-1.5	FRP	690
Maruyama & Zhao [43]	13	27.5-38.3	2.9-3.9	150	250	750	3.0	0.55-2.11	1170	94	CFRP	0.12-0.24	FRP	690
Alkhrdaji et al. [44]	3	24	2.5	178	279	750	2.7	2.3	690	40	GFRP	0.40-0.52	FRP	690
Niewels [45]	8	43-48	4.4-5.1	300	412	1302	3.2	3.25-3.65	690	63	GFRP	0.14-0.54	FRP	690
Razaqpur et al. [10]	7	40-49	3.9-4.8	200	225	410	1.8	0.22-0.78	2250	145	CFRP	NA	NA	NA
Ashour [46]	12	27-47	2.6-4.6	150	164	666	4.1	0.14-1.38	650-705	32-38	GFRP	NA	NA	NA
El Refai & Abed [47]	8	49	5.1	152	206	545	2.6	0.33-1.45	1168	50	BFRP	NA	NA	NA
Kim & Jang [48]	12	30-403	3.1-4.2	150-200	213	625	2.9	0.30-0.83	900-2130	40-147	CFRP/ GFRP	NA	NA	NA

*NA stands for no stirrups were used as shear reinforcement.

4. EUROCODE 2 (EC2) DESIGN

4.1 CRACKING MOMENT

The cracking moment (M_{cr}) of reinforced concrete beams with FRP bars can be estimated using the following equation (1) [15]:

$$M_{cr} = \frac{f_r\, I_g}{y_t} \quad (1)$$

Where (f_r) stands for the modulus of rupture of concrete and could be estimated using equation (2), (y_t) is the distance between the extreme tension fibers of concrete and the neutral axis of the cross section, and (I_g) indicates the gross moment of inertia.

$$f_{r,\,EC2} = 0.3\, (f_c)^{2/3} \quad (2)$$

Where (f_c) is the compressive strength of the cylindrical concrete.

4.2 ULTIMATE CAPACITY

4.2.1 FLEXURAL CAPACITY

The term of ultimate capacity of reinforced concrete beams with FRP bars refers to shear and bending capacities. The flexural failure takes place due to rupture of FRP bars or crushing of concrete at the extreme compressive fibers, depending on the ratio of reinforcement. If the ratio of FRP reinforcement (ρ_f=A_f/bd) is less than the balanced ratio (ρ_b), the flexural failure is rupture of FRP bars (FRP bars reaches the ultimate strain), otherwise, the flexural failure takes place due to crushing of concrete (the compressive concrete fibers reaches the ultimate compressive strain=0.003). Depending on EC2[15], the balanced ratio of reinforcement (ρ_b) can be calculated using equation (3):

$$\rho_{b,EC2} = \frac{\lambda \eta f_c \varepsilon_{cu}}{f_{fu}(\varepsilon_{fu} + \varepsilon_{cu})} \quad (3)$$

Where (η) and (λ) are factors of the rectangular stress block and can be calculated from equation (4) and equation (5):

$$\eta = 1 - \frac{f_c - 50}{200} \quad (4)$$

$$\lambda = 0.8 - \frac{f_c - 50}{400} \quad (5)$$

(ε_{cu}) is the compressive strain of concrete at ultimate (i.e., crushing strain) and it equals 0.003 according to EC2, (ε_{fu}) is the ultimate tensile strain of FRP bars and it equals ($\frac{f_{fu}}{E_f}$).

The mode of failure will be crushing of concrete in the extreme compressive fibers when $\rho_f \geq \rho_{b,2}$,and the ultimate moment ($M_{ult,EC2}$) can be determined depending on EC2 by using equation (6):

$$M_{ult,EC2} = (\lambda\xi)\, \eta\, f_c\, b\, d^2\, (1 - \frac{\lambda\xi}{2}) \quad (6)$$

Where:

$$\xi = \frac{\varepsilon_{cu}}{\varepsilon_f + \varepsilon_{cu}} \quad (7)$$

$$\varepsilon_f = \frac{-\varepsilon_{cu} + \sqrt{\varepsilon_{cu}^2 + \frac{4 f_c \eta \lambda \varepsilon_{cu}}{\rho_f E_f}}}{2} \quad (8)$$

Where ε_f is the actual FRP strain during crushing of concrete.

The mode of failure will be rupture of FRP bars when $\rho_f < \rho_{b,2}$,and the ultimate moment ($Mult,EC2$) can be determined depending on EC2 by using equation (9):

$$M_{ult,EC2} = A_f\, f_{fu}\, (1 - \frac{\xi}{2}) \quad (9)$$

Where (A_f) stands for area of FRP bars.

To calculate the compressive strain of concrete (ε_c) at the moment of rupture of FRP bars, the following equations could be used (10-13).

$$\xi = \frac{\varepsilon_c}{\varepsilon_c + \varepsilon_{fu}} \quad (10)$$

$$F_c = F_T \;>>\; bd\xi \frac{\int_0^{\varepsilon_c} \sigma_c\, \varepsilon_c\, d}{\varepsilon_c} = A_f\, f_{fu} \quad (11)$$

$$\sigma_c = f_c\, [\, 1 - (1 - \frac{\varepsilon_c}{\varepsilon_{c2}})^n \qquad 0 \leq \varepsilon_c \leq \varepsilon_{c2} \quad (12)$$

$$\sigma_c = f_c \qquad \varepsilon_{c2} < \varepsilon_c \leq \varepsilon_{cu2} \quad (13)$$

(ε_{c2}) and (ε_{cu2}) can be determined by using EC2 [15].

4.2.2 ULTIMATE SHEAR CAPACITY

The ultimate shear capacity (V) can be estimated by the contribution of the stirrups (V_f) and the concrete (V_{cf}) for resisting shear stresses and can be calculated using equation (14).

$$V = V_{f,EC2} + V_{cf,EC2} \quad (14)$$

The concrete shear capacity ($V_{cf,EC2}$) can be determined by equation (15) which depends on the axial stiffness (EA) of the main reinforcement of FRP bars

$$V_{cf,EC2} = 0.12bd\, (1 + \sqrt{\frac{200}{d}})\, (100\, \frac{A_f}{bd} \frac{E_f}{E_s} \emptyset_\varepsilon f_c)^{1/3} \quad (15)$$

Where (ϕ_ε) is the permitted strain ratio in the FRP bars (ε_f), and could be taken as 0.004, and the yield strain of the steel bars (ε_y) is 0.2% according to EC2.

The stirrups shear capacity ($V_{f,EC2}$) can be determined by equation (16)

$$V_{f,EC2} = \frac{A_{fv}\, f_{fv}\, d}{s} \quad (16)$$

$$f_{fv} = 0.0045\, E_{fv} \quad (17)$$

Where f_{fv} is developed stress in the stirrups and can be calculated using equation (17), A_{fv} is area of FRP stirrups, S is spacing between FRP stirrups and E_{fv} is the elastic modulus of FRP stirrups.

5. ACI-440.1R-06 CODE

5.1 CRACKING MOMENT

The cracking moment (M_{cr}) of reinforced concrete beams with FRP bars can be estimated using equation (1) , where (fr) is can be determined according to ACI 440.1 R-06 [3] by using equation (18):

$$f_r = 0.62\, (f_c)^{1/2} \quad (18)$$

5.2 ULTIMATE CAPACITY

5.2.1 FLEXURAL CAPACITY

The balanced reinforcement ratio can be determined according to ACI 440.1 R-06 [3] by using equation (19):

$$\rho_{b,ACI} = 0.85\, \beta_1\, \frac{\varepsilon_{cu}\, f_c}{(\varepsilon_{cu} + \varepsilon_{fu}) f_{fu}} \quad (19)$$

where (ε_{cu}) can be defined as the ultimate compressive strain of concrete and equals to 0.003 as determined by ACI-440-1R-06, and the factor (β_1) can be determined by using equation (20):

$$\beta_1 = 0.85 - 0.05\,\frac{f_c - 27.6}{6.9} \qquad (20)$$

Accordingly, if $\rho_f \geq \rho_b$ then the mode of failure is concrete crushing, and the ultimate moment (M_{ult}) can be determined according to ACI 440.1 R-06 [3] by using equation (21):

$$M_{ult,ACI} = \rho_f\, f_f \left(1 - 0.59\,\frac{\rho_f f_f}{f_c}\right) b d^2 \qquad (21)$$

Where f_f is the stress in the FRP bars at the point of concrete crushing, and can be determined by using equation (22):

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85\,\beta_1 f_c}{\rho_f} E_f \varepsilon_{cu}} - 0.5(E_f \varepsilon_{cu}) \; < f_{fu} \qquad (22)$$

if $\rho_f < \rho_b$ then the mode of failure is rupture of FRP bars, and the ultimate moment (M_{ult}) can be determined according to ACI 440.1 R-06 [3] by using equation (23):

$$M_{ult,ACI} = A_f\, f_{fu} \left(d - \frac{\beta_1\, c_b}{2}\right) \qquad (23)$$

The neutral axis depth (c_b) can be determined from equation (24):

$$c_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}\right) d \qquad (24)$$

5.2.2 SHEAR CAPACITY

The ultimate shear capacity (V) can be estimated by the contribution of the stirrups (V_f) and the concrete (V_{cf}) for resisting shear stresses and can be calculated using equation (14). The contribution of concrete to shear capacity can be determined according to ACI 440.1 R-06 [3] by using equation (25):

$$V_{cf,ACI} = \frac{2}{5}\sqrt{f_c}\, b\, c \qquad (25)$$

The contribution of shear reinforcement to shear capacity can be determined according to ACI 440.1 R-06 [3] by using equation (16) and the stress in the stirrups can be determined by using equation (26):

$$f_{fv} = 0.004\, E_{fv} \qquad (26)$$

6. RESULTS AND DISCUSSION

6.1 EC2 CODE

6.1.1 ULTIMATE SHEAR

Figure 1 demonstrates the comparison of the experimental results of the literature with predicted results using EC2 for 95 reinforced concrete beams with FRP bars and without stirrups. The average values of the standard deviation, variance and relative error were 14.5%, 2.1%, and -16.3%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 20.1%, 4.0%, and -25.3%, respectively for high strength concrete . It should be mentioned that the comparison was conducted by using the relative error between the predicted results and the experimental results. Therefore, the positive and negative values of relative error indicate that EC2 code overestimates or underestimates the shear capacity, respectively compared to experimental results. For normal strength concrete, the minimum relative error was -53.6%, while the maximum was 21.2%. For high strength concrete, the minimum relative error was -72.8%, while the maximum was 31.2%. EC2 code overestimates the ultimate shear capacity for fourteen samples only (9% of the examined specimens without stirrups) for normal strength concrete, while EC2 code overestimates the ultimate shear capacity for 25 samples (17% of the examined specimens without stirrups) for high strength concrete . The Root Mean Squared Error (RMSE) values for the prediction of EC2 code were 23.2 and 25.2 kN for normal and high strength concrete, respectively. Table 2 presents the statistical parameters obtained from the current study.

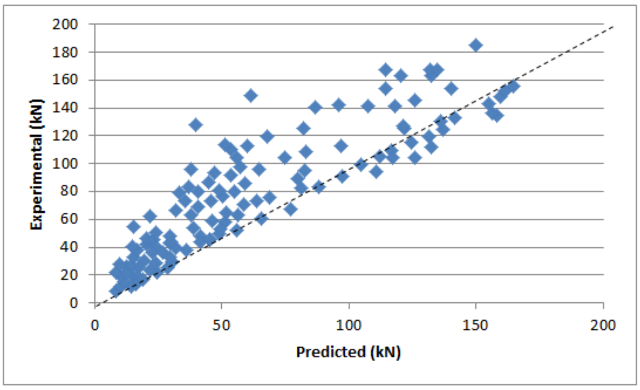

FIGURE 1. Experimental vs. predicted ultimate shear strength of the examined specimens without stirrups (EC2 code).

Figure 2 demonstrates the comparison of the experimental results of shear capacity vs. predicted results using EC2 for reinforced concrete beams with FRP bars and with stirrups. The average values of the standard deviation, variance and relative error were 16.1%, 2.6%, and -24.8%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 19.8%, 3.9%, and -31.9%, respectively for high strength concrete. For normal strength concrete, the minimum relative error was -69.3%, while the maximum was 14.8%. For high strength concrete, the minimum relative error was --79.3%, while the maximum was 16.8%. EC2 code overestimates the ultimate shear capacity for four samples only (3% of the examined specimens with stirrups) for normal strength concrete, while EC2 code overestimates the ultimate shear capacity for 18 samples only (12% of the examined specimens with stirrups) for high strength concrete. Therefore, the most of samples reinforced with FRP bars and with stirrups were underestimated by EC2. The Root Mean Squared Error (RMSE) values of the samples reinforced with FRP bars and with stirrups for the prediction of EC2 code were 61.15 and 81.2 kN for normal and high strength concrete, respectively as presented in Table2.

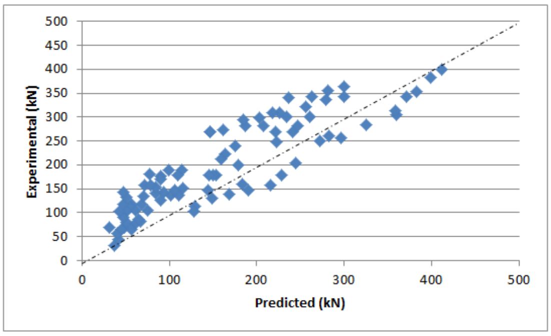

FIGURE 2. Experimental vs. predicted ultimate shear strength of the examined specimens with stirrups (EC2 code).

6.1.2 ULTIMATE MOMENT CAPACITY

One hundred and fifteen tested specimens were used to calculate their moment capacities by EC2 code [15]. Figure 3 demonstrates the comparison of the experimental results of ultimate moment capacity vs. predicted results using EC2 for reinforced concrete beams with FRP bars. The average values of the standard deviation, variance and relative error were 15%, 2.2%, and -10.7%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 16.5%, 2.7%, and -11.7%, respectively for high strength concrete. For normal strength concrete, the minimum relative error was –51.8%, while the maximum was 39.6%. For high strength concrete, the minimum relative error was --61.7%, while the maximum was 49.5%. EC2 code overestimates the ultimate moment capacity for 5 samples only (4% of the examined specimens) for normal strength concrete, while EC2 code overestimates the ultimate moment capacity for 16 samples (14% of the examined specimens) for high strength concrete.

The Root Mean Squared Error (RMSE) value of the ultimate moment for the prediction of EC2 code were 7.3 and 9.28 kN for normal and high strength concrete, respectively as presented in Table2.

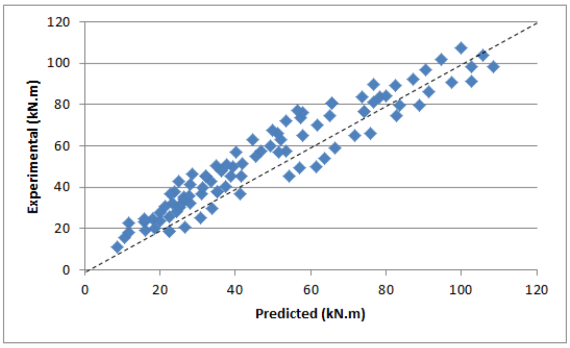

FIGURE 3. Experimental vs. predicted ultimate moment capacity of the examined beams reinforced with FRP bars (EC2 code).

6.1.3 CRACKING MOMENT

Figure 4 shows the relationship between experimental and theoretical cracking moment of 195 reinforced concrete beams with FRP bars. The average values of the standard deviation, variance and relative error were 55.7%, 31.1%, and 11.5%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 64.4%, 41.5%, and 13.4%, respectively for high strength concrete. For normal strength concrete, the minimum relative error was –74.9%, while the maximum was 27.9%. For high strength concrete, the minimum relative error was –85.3%, while the maximum was 38.1%. EC2 code overestimates the cracking moment capacity for 6 samples only (3% of the examined specimens) for normal strength concrete, while EC2 code overestimates the cracking moment capacity for 12 samples (6% of the examined specimens) for high strength concrete. The Root Mean Squared Error (RMSE) value of the cracking moment for the prediction of EC2 code were 3.54 and 4.83 kN for normal and high strength concrete, respectively as presented in Table2.

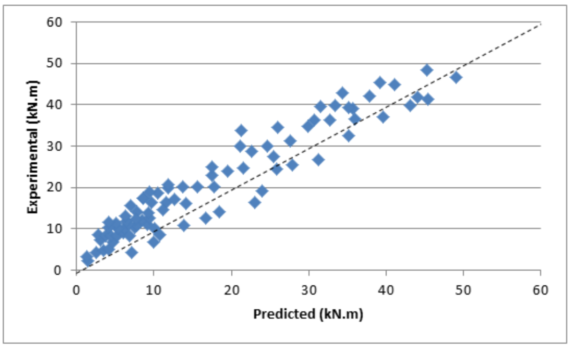

FIGURE 4. Experimental vs. predicted cracking moment of the examined beams reinforced with FRP bars (EC2 code).

6.2 ACI-440.1R-06 CODE

6.2.1 ULTIMATE SHEAR

Figure 5 demonstrates the comparison of the experimental results of the literature with predicted results by using ACI-440.1R-06 for 95 reinforced concrete beams with FRP bars and without stirrups. The average values of the standard deviation, variance and relative error were 13.8%, 1.9%, and -15.2%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 14.1%, 2.0%, and -17.3%, respectively for high strength concrete . All theoretical results predicted by ACI-440.1R-06 are in safe side because the relative errors are negative values (range between -51.0% and -8.3% for normal strength concrete and -62.0% and -14.3% for high strength concrete). Therefore, ACI 440.1R-06 [3] underestimated the ultimate shear of all concrete beams reinforced with FRP bars and without stirrups. Table 3 presents the statistical parameters obtained from the current study.

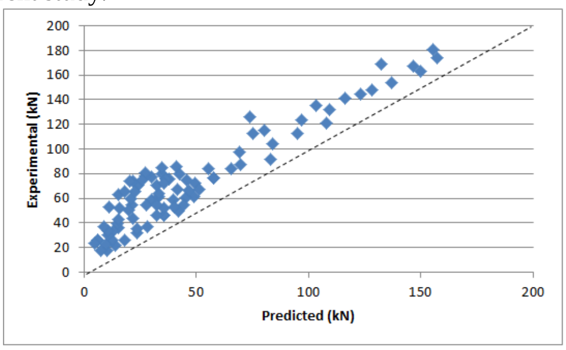

FIGURE 5. Experimental vs. predicted ultimate shear strength of the examined specimens without stirrups (ACI-440.1R-06 code).

TABLE 2. Statistical analysis of the experimental and theoretical results (EC2 code).

Concrete type	Parameter	Ultimate shear of the beams without stirrups	Ultimate shear of the beams with stirrups	Ultimate moment	Cracking moment
Normal Strength Concrete (NSC)	Correlation Coefficient (R2)	0.88	0.82	0.93	0.74
	Average Error %	-16.3	-24.8	-10.7	11.5
	Mean Absolut Error MAE	13.2	62.5	8.3	1.5
	S.D. %	14.5	16.1	15	55.7
	Var. %	2.1	2.6	2.2	31.1
	Max Error %	21.2	14.8	39.6	27.9
	Min Error %	-53.6	-69.3	-51.8	-74.9
	RMSE	23.21	61.15	7.3	3.54
High Strength Concrete (HSC)	Correlation Coefficient (R2)	0.76	0.68	0.82	0.61
	Average Error %	-25.3	-31.9	-11.7	13.4
	Mean Absolut Error MAE	16.7	71.3	9.7	2.9
	S.D. %	20.1	19.8	16.5	64.4
	Var. %	4	3.9	2.7	41.5
	Max Error %	31.2	16.8	49.5	38.1
	Min Error %	-72.8	-79.3	-61.7	-85.3
	RMSE	25.21	81.2	9.28	4.83

Figure 6 reveals the relationship between the experimental results of the literature and the predicted results by using ACI-440.1R-06 for reinforced concrete beams with FRP bars and with stirrups. The average values of the standard deviation, variance and relative error were 15.8%, 2.5%, and -11.8%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 16.7%, 2.8%, and -13.5%, respectively for high strength concrete . All theoretical results predicted by ACI-440.1R-06 are safe because the relative errors range between -42.5% and -15.3% for normal strength concrete and -51.7% and -17.8% for high strength concrete. Therefore, ACI 440.1R-06 [3] underestimated the ultimate shear of all concrete beams reinforced with FRP bars and with stirrups. Table 3 presents the statistical parameters obtained from the current study.

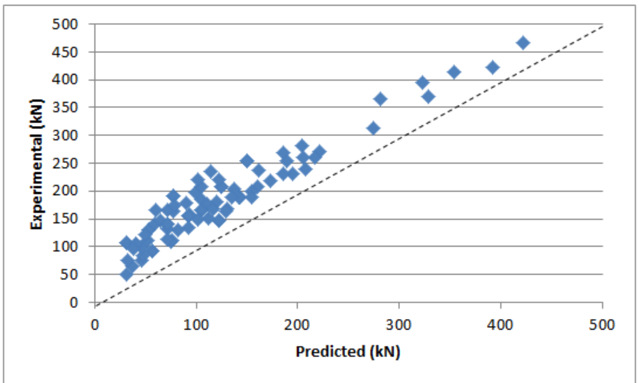

FIGURE 6. Experimental vs. predicted ultimate shear strength of the examined specimens with stirrups (ACI-440.1R-06 code).

6.2.2 ULTIMATE MOMENT

One hundred and fifteen tested specimens were used to calculate their moment capacities by ACI-440.1R-06 code [3]. Figure 7 demonstrates the comparison of the experimental results of the literature and the predicted results for reinforced concrete beams with FRP bars. The average values of the standard deviation, variance and relative error were 18.4%, 3.4%, and -15.3%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 20.5%, 4.2%, and -19.5%, respectively for high strength concrete. All theoretical results predicted by ACI-440.1R-06 are safe because the relative errors range between -38.5% and -8.3% for normal strength concrete and -63.5% and -12.7% for high strength concrete. Therefore, ACI 440.1R-06 [3] underestimated the ultimate moment of all concrete beams reinforced with FRP bars. Table 3 presents the statistical parameters obtained from the current study.

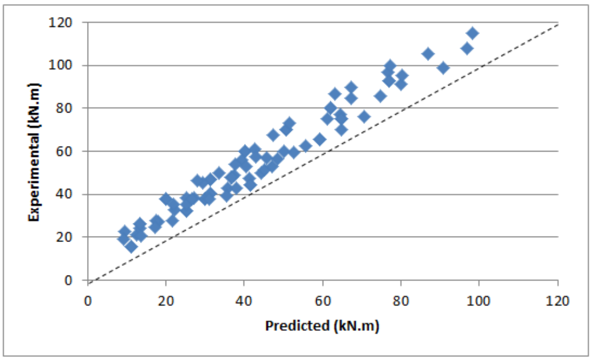

FIGURE 7. Experimental vs. predicted ultimate moment of the examined beams reinforced with FRP bars (ACI-440.1R-06 code).

6.2.3 CRACKING MOMENT

Figure 8 shows the relationship between experimental and theoretical cracking moment of 195 reinforced concrete beams with FRP bars. The average values of the standard deviation, variance and relative error were 17.6%, 3.1%, and -14.5%, respectively for normal strength concrete, while the average values of the standard deviation, variance and relative error were 22.1%, 4.9%, and -18.7%, respectively for high strength concrete. For normal strength concrete, the minimum relative error was –72.5%, while the maximum was -28.6%. For high strength concrete, the minimum relative error was –81.3%, while the maximum was -32.5%. Accordingly, the most theoretical results predicted by ACI-440.1R-06 are safe because it underestimated the cracking moment of the most concrete beams reinforced with FRP bars.

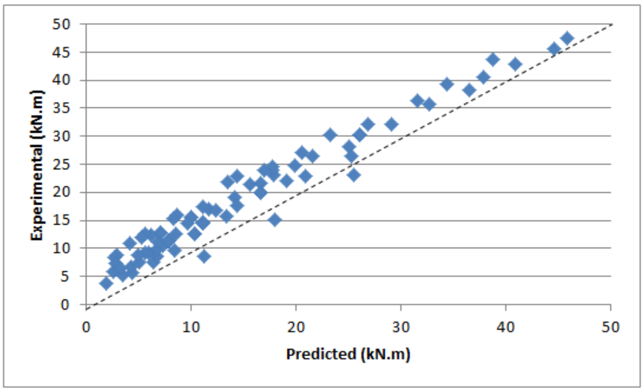

FIGURE 8. Experimental vs. predicted cracking moment of the examined beams reinforced with FRP bars (ACI-440.1R-06 code).

TABLE 3. Statistical analysis of the experimental and theoretical results (ACI-440.1R-06 code).

Concrete type	Parameter	Ultimate shear of the beams without stirrups	Ultimate shear of the beams with stirrups	Ultimate moment	Cracking moment
Normal Strength Concrete (NSC)	Correlation Coefficient (R2)	920.	910.	40.9	820.
	Average Error %	-15.2	-11.8	-15.3	-14.5
	Mean Absolut Error MAE	15.5	42.5	12.4	5.6
	S.D. %	13.8	15.8	18.4	17.6
	Var. %	1.9	2.5	3.4	3.1
	Max Error %	-8.3	-15.3	-8.3	-28.6
	Min Error %	-51	-42.5	-38.5	-72.5
High Strength Concrete (HSC)	Correlation Coefficient (R2)	0.91	0.88	0.91	0.81
	Average Error %	-17.3	-13.5	-19.5	-18.7
	Mean Absolut Error MAE	18.7	62.5	14.7	8.6
	S.D. %	14.1	16.7	20.5	22.1
	Var. %	2.0	2.8	4.2	4.9
	Max Error %	-14.3	-17.8	-12.7	-32.5
	Min Error %	-62.0	-51.7	-63.5	-81.3

7. CONCLUSIONS

This research aims to assess the accuracy of EC2 and ACI-440.1R-06 for predicting the ultimate capacity (shear capacity and moment capacity) in addition to cracking moment for 292 concrete beams reinforced with FRP bars. Depending on the results, the following conclusions can be written:

1- The statistical results proved that EC2 is more conservative for predicting moment capacity of reinforced concrete beams with FRP bars for normal strength concrete than high strength concrete with a reasonable prediction. Therefore, EC2 equations can be used safely for predicting moment capacity of concrete beams reinforced with FRP bars for normal strength. However, a modification on EC2 equations should be applied for predicting moment capacity of concrete beams reinforced with FRP bars for high strength concrete.

2- The statistical results revealed that EC2 is more conservative for predicting shear capacity of reinforced concrete beams with FRP bars for normal strength concrete than high strength concrete. Accordingly, EC2 equations can be applied without modifications for predicting shear capacity of concrete beams reinforced with FRP bars for normal strength.

3- ACI 440.1R-06 underestimated the ultimate shear of all concrete beams reinforced with FRP bars with a reasonable prediction. Therefore, ACI-440.1R-06 equations can be applied safely for predicting ultimate shear of concrete beams reinforced with FRP bars for normal and high strength concrete.

4- ACI 440.1R-06 predicted the ultimate moment of all concrete beams reinforced with FRP bars reasonably. Accordingly, ACI-440.1R-06 equations can be applied without a modification for predicting ultimate moment of concrete beams reinforced with FRP bars for normal and high strength concrete.

8. Recommendations for future research

Statistical analysis should be carried out by making a comparison between ACI and EC2 codes to investigate their accuracies for predicting deflections of concrete beams reinforced with FRP bars at different loading stages. Moreover, a modification on EC2 equations should be applied for predicting moment capacity of concrete beams reinforced with FRP bars for high strength concrete.

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