Proposed Design Methods for High-Strength Epoxy-Modified Reinforced Concrete Beams

Abstract:

Epoxy-modified concrete (EMC) is made by partially replacing ordinary Portland cement with epoxy by weight. This paper presents first simple modification of ACI approach for the analysis of ultimate moment capacity of high-strength epoxy-modified reinforced concrete (EMRC) beams. Such modified approach was based on strain compatibility and equilibrium conditions for EMRC section in combined with suitable idealized compression and tension stress blocks. The stress blocks were given by suitable empirical functions for the compressive and post-cracking strengths of EMRC. It was found that the modified ACI approach was successful in calculating the ultimate moment capacity of EMRC beams with good accuracy, and there was a good agreement between the computed ultimate moments by the proposed flexural approach and the experimental results of several sources of literature. Secondly, this paper concerned with the prediction of the ultimate shear strength of high-strength EMRC beams based on an empirical relation. The comparison of the analytical predictions with several experimental data, presented for a wide range of variables in fourteen different investigations, confirms that the ultimate shear strength of EMRC beams with or without stirrups can be conservatively evaluated using the proposed analytical approach.

Keywords:

Reinforced Concrete; Structural Behavior; Epoxy-Modified Concrete; Beams

1. Introduction:

Concrete made with Portland cement has been a popular for the past ninety years or more. However, cement concrete have some disadvantages such as delayed hardening, low tensile strength, large drying shrinkage, and low chemical resistance. Many attempts to use polymers and epoxy resins have been made in order to improve the properties of hardened concrete [1-3]. One of the most important applications of epoxy resins is the using of epoxy as a supplementary cementing material for producing epoxy-modified concrete (EMC). The partial replacing of cement by epoxy resin was found [4-7] to improve tensile and compressive strengths, ductility, chemical resistance, and durability of concrete. A very good performance was also reported [8-10] for EMC in the marine environment and hot Arabian Gulf region. The uses of epoxy in producing reinforced concrete beams has many beneficial effects such as the increasing of the flexural and shear strengths, ductility, and bond strength between tension steel bars and concrete [1-4, 11]. However, limited research programs are reported in the literature for the behavior of normal-strength EMRC beams in flexure [12-14], and shear [15-18]. It was found that the flexural and shear strengths are gradually increased with increasing epoxy-cement ratio and remarkably improved at polymer-cement ratio of 20%. Recently, comprehensive experimental programs were performed [19] for testing epoxy-modified high-strength reinforced concrete beams in flexure and shear. Different material and structural variables were considered in the testing programs.

The present paper is concerned with the development of design approaches for high-strength EMRC beams in flexure and shear…………

2. Proposed Design Method for Flexure

2.1 Evaluation of Compressive and Tensile Strengths

For design studies, the compressive and tensile strengths of EMRC are derived using empirical functions. Eighty-two standard EMC cubes have been tested with different epoxy weight ratios. From the testing results, least square fitting linear relation was developed to determine compressive strength (f_{cup}) of EMC in terms of conventional HSC compressive strength (f_{cu}) and epoxy weight ratio (W_e) as follows:

$$f_{cup} = f_{cu}(1.0 + 0.019 \; W_e) \tag{1}$$

Similarly, forty-eight standard concrete cylinders have been tested to determine the concrete splitting tensile strength (f_{tup}) of EMC in terms of the tensile strength of conventional HSC (f_{tu}) and epoxy weight ratio (W_e). The least square fitting of testing data gives the following linear equation for f_{tup}

$$f_{tup} = f_{tu}(1.0 + 0.013 \; W_e) \tag{2}$$

2.2 Prediction of Ultimate Moment Capacity

To predict the ultimate moment capacity of EMRC beam section (M_u), the proposed stress and strain distributions are shown in Fig. (1). ACI design approach [20] for high strength concrete sections under flexure was modified as follows:

a- For EMC in compression, the stress distribution is idealized by the equivalent rectangular stress block with (0.67 f_{cup}) stress and (a_c) depth.
b- To account for the improved tensile strength and post-cracking strength for EMC, a tension stress block is used with a (0.3 f_{tup}) stress and (t-c) depth.
c- For the steel reinforcement in tension and compression, an elasto-plastic relation is used taking into consideration the strain hardening after the yielding point.

From strain compatibility and equilibrium conditions, the ultimate moment capacity of the EMRC beam section is derived in [19] as:

$$M_u = T_s\left[d - \beta c/2\right] + Tp\left[(t + c - \beta c)/2\right] \tag{3}$$

$$T_s = f_s \; A_s \tag{4}$$

$$T_p = 0.3 \; f_{tup} \; b \; (t - c) \tag{5}$$

$$c = \frac{T_s + T_p}{0.67 \ \ f_{cup} \ \ b \ \ \beta} \qquad (6)$$

$$\beta = 1.05 - 0.05(f_{cup} / 6.9) \qquad 0.65 \le \beta \le 0.85 \qquad (7)$$

$$f_s = Es \ \ \varepsilon_s \qquad \varepsilon_s < \varepsilon_y \qquad (8-a)$$

$$f_s = f_y + E_{sh}(\varepsilon_s - \varepsilon_y) \qquad \varepsilon_s \ge \varepsilon_y \qquad (8-b)$$

$$\varepsilon_s = 0.003 \ \ [(d/c) - 1] \qquad (9)$$

where A_s is the tension steel area, E_s is the elasticity modulus of steel; taken as ($2x10^5$ MPa), and c is the depth of the neutral axis. E_{sh} is the slope of the stress-strain curve in the hardening range after yielding; which can be taken as (0.1 E_{se}) or less [21].

3. Proposed Design Method for Shear

3.1 Shear Resistance Mechanisms in R.C. Beams

In a concrete beam reinforced with web reinforcement as stirrups, the total shear force (V_u) is resisted by the concrete (V_c) and the stirrups (V_s). The shear resistance of concrete (V_c) is due to the shear force carried by concrete in compression zone, shear frictional resistance of aggregate interlock action, and shear dowel resistance of longitudinal tension reinforcement. At first upon loading, the shear force is carried only by concrete. Once formation of the first inclined crack, redistribution of the shear stresses occur, with some part of the shear being carried by concrete and the rest being carried by stirrups. Inclined cracking is assumed to occur when the predominant inclined crack crosses the mid-height of the beam section. Upon the formation of inclined cracks, the contribution of concrete shear resistance remains nearly constant, and the increasing shear force is resisted by stirrups. The shear carrying capacity is reached once the stirrups have yielded.

The ultimate shear force V_u carried by the section can be determined by

$$V_u = V_c + V_s \qquad (10)$$

And by stress units as follows:

$$v_u = v_c + v_s \qquad (11)$$

where v_u is the ultimate shear strength of the beam, v_c is the ultimate shear strength of concrete, and v_s is the ultimate shear strength of web reinforcement. In the literature, several experimental investigations were performed for determining the concrete shear contribution and many empirical equations were proposed for concrete shear strength. The shear stress carried by vertical stirrups is evaluated by the truss analogy as:

$$v_s = \frac{n\ A_{st}\ f_{yv}}{b\ s} \quad (12)$$

where A_{st} is the area of one branch of the stirrup, n is the number of stirrup branches, f_{yv} is the yield stress of web reinforcement, b is the width of beam web, and s is the spacing between shear reinforcement in the longitudinal direction of the beam.

3.2 Evaluation of Concrete Shear Contribution

In order to predict the ultimate shear strength of the high-strength EMRC beams, the method followed by Zsutty [22] was adopted as illustrated in Fig. (2). Based on the experimental results of the eighteen tested beams in shear, the least square fitting linear relation was used to determine the concrete shear strength. The least square fitting linear relation was found to be sensible and straightforward. The following general relation was used:

$$\frac{v_{c\ proposed}}{\sqrt{f_{cu}}} = x + y\ \frac{\rho_L}{(a/d)\sqrt{f_{cu}}} \quad (13)$$

where f_{cu} is the standard concrete compressive strength in MPa, ρ_L is the percentage ratio of the longitudinal tensile steel reinforcement, and (a/d) is the shear span-to-depth ratio. The factors (x) and (y) are the constants of the linear fitting equations. The factor (x) was 0.18, and the factor (y) which expresses the slope of the linear equations, was found to be 0.26. Then the final proposed equation of the concrete shear strength can be written as follows:

$$v_{c\ proposed} = 0.18\ \sqrt{f_{cu}} + 0.26\ \frac{\rho_L}{(a/d)} \quad (14)$$

4. Validation and Comparative Studies for Flexure

A comparative study was performed to predict the ultimate moment capacity of EMRC beams using the proposed approach, the design equation of ACI Code [20], and the finite element prediction [19]. Table (1) compares the measured flexural moment in [19] to the calculated moment values as predicted by the three methods**.** It is obvious that the proposed approach is capable of predicting the ultimate moment of reinforced concrete beams with good accuracy. The average value of $M_{u\ exp.}/M_{u\ anal.}$ ratio (Ave.) is 1.05 and the standard deviation (st.d.) is 0.04. For ACI results, the mean value of the ratio $M_{u\ exp.}/M_{u\ ACI}$ is 1.18 and the standard deviation 0.06. Finally, the average of the moment ratio is 1.09 and 0.04 as the standard deviation for the finite element prediction. The predictions of the proposed method are more accurate because of accounting for the post-cracking strength of EMC.

In order to validate and generalize the proposed flexural design approach for normal-strength and high-strength concrete beams, the correlation between the predicted ultimate moment of several reinforced concrete beams are compared with the experimental results in twelve sources of literature [19,23-33]. These beams were tested in many countries. In Fig. (3), the predicted ultimate moments are compared with the experimental results for 157 beams. It is clear that despite the difference in test specimens, the proposed approach predicts their ultimate moment capacity reasonably well. Data cover a wide range of reinforced concrete beams variations in concrete strength ($21.5 \le f_{cu} \le 101$ MPa), yield stress of tensile steel reinforcement ($240 \le f_y \le 511$ MPa), epoxy weight ratio (0% ≤ W_e ≤ 10%), and moment capacities (3.25 ≤ M_u ≤ 1440 m.kN). The mean value of the ratio between the measured and calculated moment capacities is 1.13 and the standard deviation is 0.23.

5. Validation and Comparative Studies for Shear

In Table (2), a comparative study was performed to predict the ultimate shear capacity of EMRC beams; tested in [19], using the proposed approach, ACI Code design equation [20], and the finite element prediction [19]. It is obvious that the proposed approach is capable of predicting the shear strength of reinforced concrete beams with and without web reinforcement. The average value of the ratio between the measured and predicted shear strength using the present approach is 1.06 with 0.06 as standard deviation. The predicted shear strengths of ACI Code are conservative where the average of the strengths ratio is 1.30 and 0.12 as the standard deviation. Finally, the average of the strengths ratio is 1.07 and 0.06 as the standard deviation for the finite element method.

To validate and generalize the applicability of the proposed shear design equation, the correlation between the calculated shear strength of several normal-strength and high-strength concrete beams are compared with experimental results of 218 beams reported in literature. These beam specimens were tested by several researchers all over the world [19, 15, 16, 34-44]. As shown in Fig. (4), satisfactory results were obtained from the comparison of measured and computed shear strengths of the specimens. The average value of the ratio between measured to calculated shear strengths is 1.31 and the standard deviation is 0.36. Despite the difference in test specimens, the proposed equation predicts their shear strengths reasonably well. Data cover a wide range of reinforced concrete beams variations in concrete strength (16.5 ≤ f_{cu} ≤ 90 MPa), tensile steel reinforcement ratio (0.6 % ≤ ρ_L% ≤ 8.16 %), epoxy weight ratio (0 % ≤ w_e ≤ 20 %), ratio of vertical stirrups (0 % ≤ ρ_v% ≤ 1.2 %), and shear span-to-depth ratio (2.0 ≤ a/d ≤ 6.0).

6. Conclusions

1- By including the post-cracking strength of EMC, the modified ACI approach was successful in calculating the ultimate moment capacity of EMRC beams with good accuracy. For the proposed method, the mean value of $M_{uexp.}$ / $M_{uanal.}$ ratio is 1.05 and the standard deviation is 0.04.
2- There is a good agreement between the computed ultimate moments by the proposed flexural approach for EMRC beams, and the experimental results of several sources of literature. Despite the difference in test specimens, concrete strength, reinforcement details, and epoxy weight ratio parameters, the proposed approach predicts the ultimate moment capacity reasonably well and proves the suitability as a general design and analysis tool. The mean value of the ratio between the measured and calculated moments is 1.13 and the standard deviation is 0.23.
3- An empirical relation is proposed to predict the ultimate shear strength of normal-strength and high-strength EMRC beams. The proposed approach is capable of predicting the shear strength of reinforced concrete beams with and without web reinforcement accurately. The average value of the ratio between the measured and predicted shear strength is 1.06 and 0.06 as standard deviation.
4- Satisfactory results were obtained from the comparison of measured and computed shear strengths of 218 tested beams from different sources using the proposed approach. Although the difference in test specimens, the proposed equation predicts their shear strengths reasonably

well. The average value of the ratio between measured to calculated shear strengths is 1.31 and the standard deviation is 0.36.

7. References

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serial	Beam	W_e%	f_{cu} (MPa)	f_y (MPa)	b (mm)	d (mm)	As (mm^2)	$M_{u\ exp.}/M_{u\ anal.}$	$M_{u\ exp.}/M_{u\ ACI}$	$M_{u\ exp.}/M_{u\ finite}$
1	A7	0	66	420	120	170	226	1.04	1.18	1.08
2	B7	5	72	420	120	170	226	1.06	1.22	1.12
3	C7	10	77	420	120	170	226	1.08	1.26	1.12
4	A8	0	66	430	120	170	402	1.04	1.09	1.08
5	B8	5	72	430	120	170	402	1.05	1.11	1.01
6	C8	10	77	430	120	170	402	1.06	1.13	1.04
7	D1	0	66	420	120	170	226	1.03	1.14	1.08
8	E1	10	77	420	120	170	226	1.08	1.21	1.11
9	D2	0	66	420	120	170	226	1.06	1.17	1.10
10	E2	10	77	420	120	170	226	1.10	1.24	1.14
							Ave.	**1.06**	**1.18**	**1.09**
							st. d.	**0.02**	**0.06**	**0.04**

Table (1) Comparison of the Experimental Test Results to the Calculated Ultimate Moment Capacities

serial	Beam	W_e%	a/d	d (mm)	ρ_L %	ρ_v %	f_{cu} (MPa)	$v_{u\ exp.}/v_{u\ prop.}$	$v_{u\ exp.}/v_{u\ ACI}$	$v_{u\ exp.}/v_{u\ finite}$
1	A1	0	2.5	208	3.00	0.24	66	1.00	1.08	1.06
2	A2		2.5	208	3.00	0	66	1.02	1.23	1.10
3	A3		3.5	192	4.40	0.24	66	1.03	1.24	1.04
4	A4		3.5	192	4.40	0	66	1.07	1.38	1.10
5	A5		3.5	192	4.40	0.48	66	0.97	1.12	1.13
6	A6		4.5	186	6.80	0	66	1.09	1.41	1.13
7	B1	5	2.5	208	3.00	0.24	72	1.00	1.14	0.95
8	B2		2.5	208	3.00	0	72	1.06	1.22	1.09
9	B3		3.5	192	4.40	0.24	72	1.09	1.32	1.04
10	B4		3.5	192	4.40	0	72	1.10	1.42	1.11
11	B5		3.5	192	4.40	0.48	72	1.02	1.18	1.12
12	B6		4.5	186	6.80	0	72	1.12	1.45	1.17
13	C1	10	2.5	208	3.00	0.24	77	1.06	1.28	1.07
14	C2		2.5	208	3.00	0	77	0.98	1.27	1.06
15	C3		3.5	192	4.40	0.24	77	1.14	1.38	1.10
16	C4		3.5	192	4.40	0	77	1.14	1.47	0.98
17	C5		3.5	192	4.40	0.48	77	1.11	1.30	1.11
18	C6		4.5	186	6.80	0	77	1.14	1.47	0.95
							Ave.	**1.06**	**1.30**	**1.07**
							st. d.	**0.06**	**0.12**	**0.06**

Table (2) Comparison of the Experimental Test Results to the Calculated Ultimate Shear Capacities

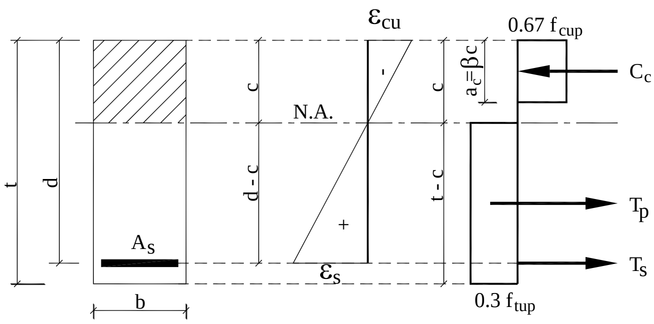

Figure (1) Ultimate Stress and Strain Distributions

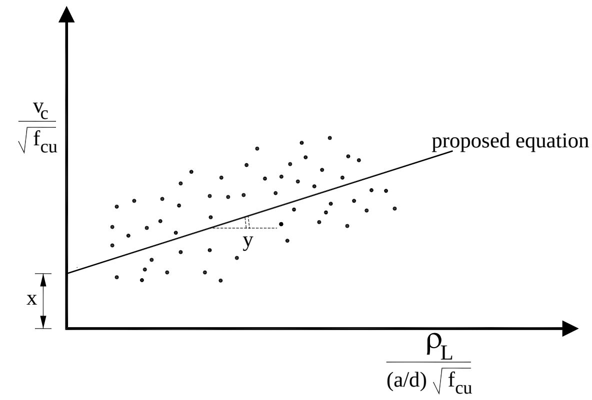

Figure (2) Followed Method to Predict Concrete Shear Strength

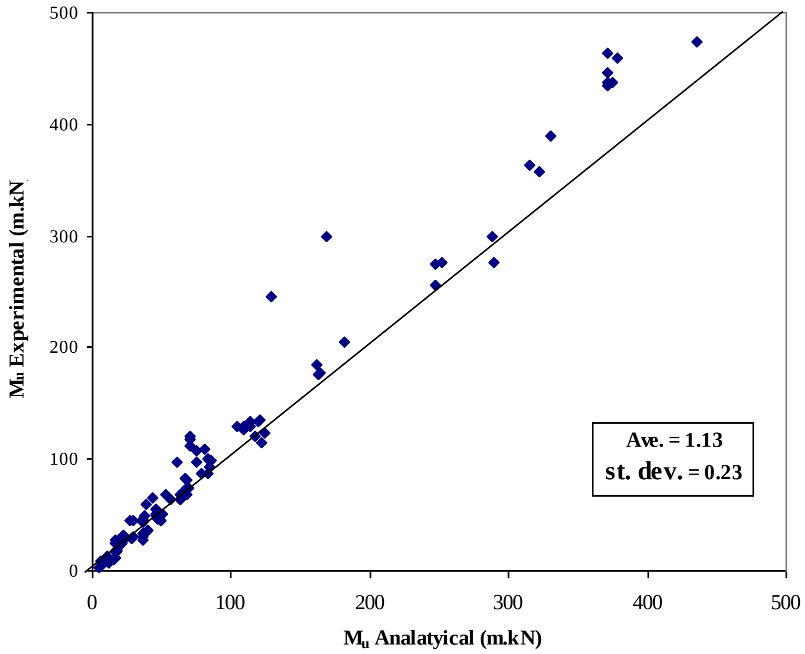

Figure (3) Correlation of the Experimental and Analytical Ultimate Moment

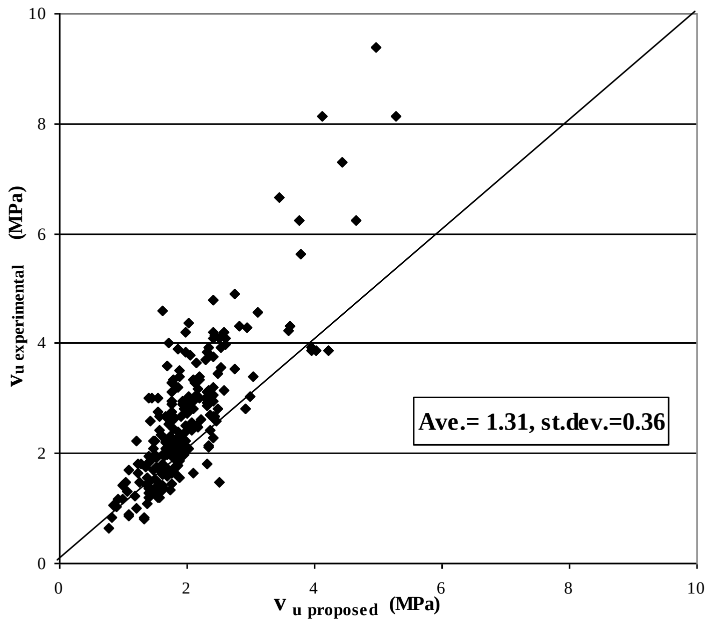

Figure (4) Correlation of Experimental and Predicted Shear Strengths