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A MODIFIED FORMULA TO PREDICT THE ULTIMATE LOAD CAPACITY OF REINFORCED CONCRETE CORBELS

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Abstract: Various methods are used in designing reinforced concrete corbels. The aim of the present research is to provide a modified formula to predict the ultimate strength of reinforced concrete corbels using nonlinear regression analysis of experimental data available in the literature (245) specimen which include the variables that affect the ultimate shear strength. According to this research the proposed equation gives a good agreement with experimental data when compared with the existing equations and it is more accurate, safe and economic

Keywords: *corbel, reinforced concrete, shear, ultimate load.*

صيغة معدلة للتنبؤ بالحمل الاقصى للكتائف الخرسانية المسلحة

الخلاصة:هنالك طرق عديدة تستخدم في تصميم الكتائف الخرسانية المسلحة حيث يهدف هذا البحث لتقديم معادلة جديد لحساب مقاومة العظمى للكتائف الخرسانية المسلحة باستخدام التحليل الاحصائي (الانحدار اللاخطي) لـ (245) نموذج من الكتائف الخرسانية المسلحة والمتاحة ضمن الابحاث العلمية والتي تحتوي على الكثير من المتغيرات التي من شأنها التاثير على مقاومة الكتائف الخرسانية المسلحة والمشار اليها لاحقا. وبالاعتماد على نتائج البحث فان المعادلة المقترحة اعطت توافقا جيدا مع النتائج العملية بالمقارنة مع المعادلات الاخرى و المقترحة من قبل الباحثين الاخرين كما ان المعادلة المقترحة يمكن استخدامها في التنبأ بالمقاومة العظمى للكتائف الخرسانية المسلحة حيث ان النتائج التي يمكن الحصول عليها تكون اكثر دقة وامان بالاضافة الى العامل الاقتصادي.

1. Introduction

Corbels (or brackets) are very important structural members for supporting precast beams, gentry girders and bridges, which are usually built monolithically with columns (or walls) to support heavy concentrated loads, [1], Figure (1). Reinforced concrete corbels have become a common feature in building construction with the increasing use of precast reinforced concrete elements for the construction of buildings and bridges [2].

Because of the prevalence of precast concrete, the design of corbels has become increasingly important. The term “corbel” is generally restricted to cantilevers having shear span-depth ratios less than unity. Such a small ratio causes the strength of corbels to often be controlled by shear. Corbels are designed mainly to resist the vertical reaction Vu at the end of the supported beam, and sometimes they must also resist a horizontal force (Nuc) transmitted from the supported beam due to restrained shrinkage,

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creep, or temperature change, Figure (2). Typically, reinforcement for the corbel consists of primary tension steel, horizontal hoops and framing bars. [3 - 5]

Brackets and corbels tend to act as simple trusses or deep beams, rather than flexural members [5], therefore, it was widely assumed that reinforced concrete corbels are principally shear transfer members. Conventional design procedures provide horizontal stirrups throughout the corbel depth as shown in Figure (2), to improve their shear capacities and reduce the likelihood of sudden failure. The design of reinforced concrete corbels has continuously been changing in recent years. The changes relate mainly to stirrup design and contribution to corbel strength. However, sometimes it can be difficult to comply with ACI Building Code requirements of cover and amount of shear reinforcement, due to the complexity of detailing and congestion of reinforcement, also this congestion could lead to difficulties in achieving fully compacted concrete, and result in poorer bond between reinforcement and concrete. One solution to this problem is to replace the conventional secondary reinforcement, i.e., stirrups with steel fibers, (or use self-compact concrete). [6 - 8]

The addition of various types of fibers to concrete leads to improvements in apparent bond between steel and concrete, the compressive strength, tensile strength, flexural strength, impact resistance, fracture toughness, fatigue resistance, crack control characteristic and ductility of the concrete. [2, 9- 11]

The corbel shown in Figure (3) may fail by shearing along the interface between the column and the corbel, by yielding of the tension tie, by crushing or splitting of the compression strut, or by localized bearing or shearing failure under the loading plate [5].

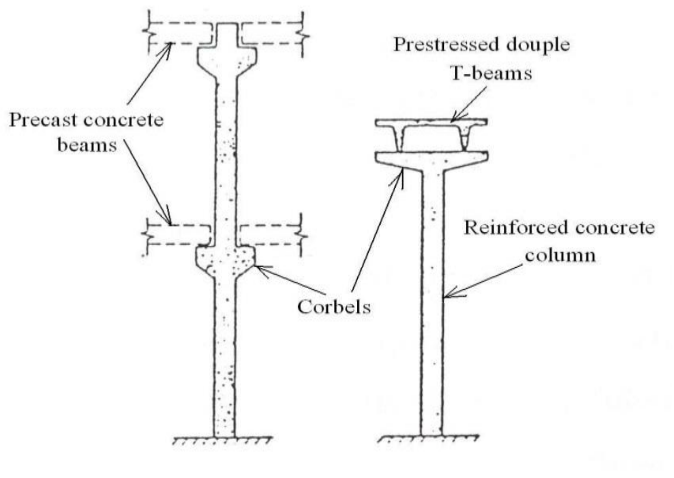

Figure 1 Precast concrete column and corbels. [2]

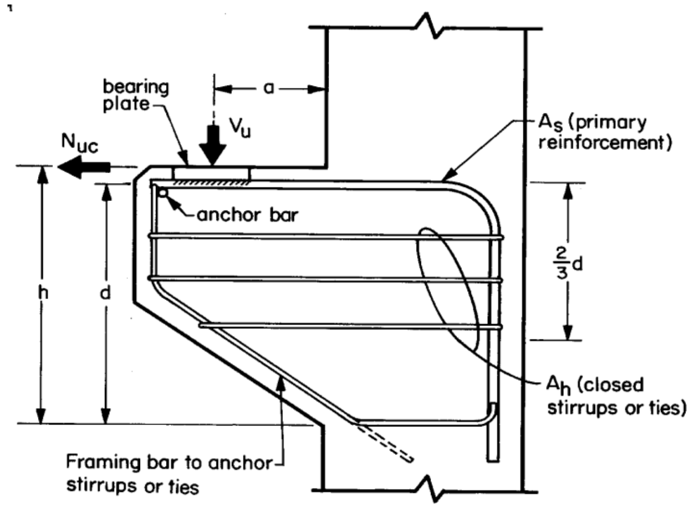

Figure 2 Typical reinforced concrete corbel. [4]

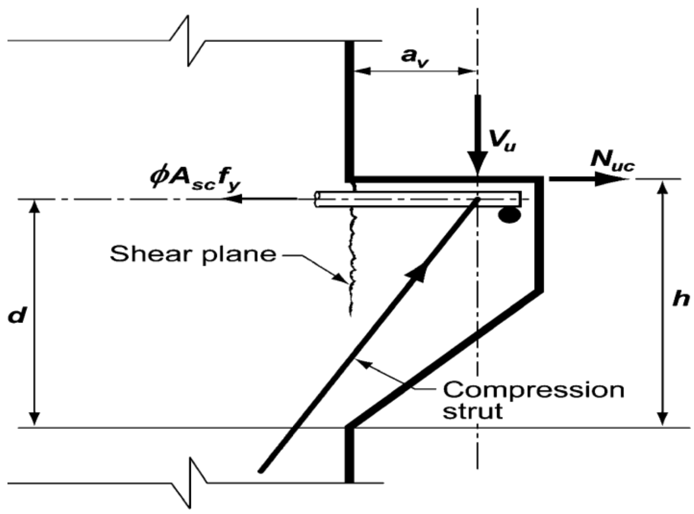

Figure 3 Structural action of a corbel. [4]

2. Research Significance

Many researchers and committees present formulas that deal with nominal shear strength of reinforced concrete corbels to obtain accurate values that predict the load carrying capacity of reinforced concrete corbels. Therefore, the aim of the present research is to provide a new equation to predict the ultimate strength of reinforced concrete corbels, the proposed equation must be accurate, safe, economic, and reflects the behavior of reinforced concrete corbels.

3. Relevant Analysis Approaches

Methods for computing the nominal shear capacity of reinforced concrete corbels using the ACI 318-2014 Code [4] and those proposed by other researches and the expressions proposed in the present research are discussed.

3.1. ACI 318-2014[4] Code Procedure

The ACI 318-2014 Code permits the smaller values of the following equations for the upper limit of the load carrying capacity of reinforced concrete corbels equations.

$$V_n = 0.2f'_c\, b_w\, d \qquad (1)$$

$$V_n = (3.3 + 0.08f'_c)b_w\, d \qquad (2)$$

$$V_n = 11\, b_w\, d \qquad (3)$$

where:

Vn : nominal capacity of reinforced concrete corbel.

f'c : compressive strength of concrete.

bw : width of corbel.

d : effective depth of corbel.

Also, the Code provides that the area of primary tension reinforcement (As) in a corbel or a bracket shall not be less than the larger of Equation (4) or Equation (5).

$$A_{sc} = (A_f + A_n) \qquad (4)$$

$$A_{sc} = (2A_f/3 + A_n) \qquad (5)$$

$$A_{vf} = (V_n/\mu f_y) \qquad (6)$$

where:

A_{sc}: area of primary tension reinforcement in a corbel or bracket, mm^2.

A_f : area of reinforcement in bracket or corbel resisting factored moment, mm^2 .

A_n : area of reinforcement in bracket or corbel resisting tensile force Nuc, mm^2.

A_{vf} : area of shear friction reinforcement, mm^2.

μ : coefficient of friction.

f_y : specified yield strength of reinforcement, MPa.

To evaluate the nominal shear strength of reinforced concrete corbel, the shear strength can be calculated based on flexural requirements as:

$$V_n = \frac{M_n}{a} \qquad (7)$$

$$V_n = \frac{A_{sc}\, f_y\, (d - \beta\frac{c}{2})}{a} \qquad (8)$$

where :

$A_{sc} = A_f$

$$V_n = (A_{sc} + A_h)f_y\, \mu \qquad (9)$$

The minimum steel ratio of the flexural (A_{sc}/bd) shall not be less than $(0.04(f'_c/f_y))$.

Closed stirrups or ties parallel to as should be distributed uniformly within (2/3) d adjacent to primary tension reinforcement with a total area A_h given by:

$$A_h = 0.5(A_{sc} - A_n) \quad (10)$$

where:

A_h : total area of shear reinforcement parallel to primary tension reinforcement in a corbel or bracket, mm^2.

3.2. Fattuhi in 1994 [13]

Fattuhi proposed an empirical equation that takes into account different factors that affect corbel strength. The strength estimation equation set out is based on tests reported in his work. The expression is presented in the following general form

$$V_n = k_1\ (b\,h)^{k_2}\,(f_{ct})^{k_3}\,(\frac{a}{d})^{k_4}\,(\frac{As}{b\,d})^{k_5}\,(10)^{k_6(\frac{H}{V})}\left(\frac{f_y}{f_{cu}}\right)^{k7}\left(\frac{d}{h}\right)^{k8} \quad (11)$$

3.3. Siao 1994 [14]

Siao in 1994 introduced formula to evaluate the nominal shear strength using a refined strut-and-tie system. The ultimate shear force may be given by:

$$Vn = 1.8\ ft\ b\ d \quad (12)$$

3.4. Muhammad in 1998[15]

In 1998, Muhammad proposed an equation, which is based on nonlinear regression analysis carried out on the available test results in his study for predicting the ultimate shear strength of reinforced concrete corbels.

$$V_n = 74\left[(1+F)(\frac{f'_c}{f_y})\right]^{0.4}(\frac{A_s+A_h}{b\,d})^{0.5}(\frac{d}{a})^{0.7}\,b\,h \quad (13)$$

3.5 Aziz in 2001[16]

Based on the data available in literature, Aziz proposed equation (14) for predicting the nominal shear strength of reinforced concrete corbels.

$$Vn = 2.38\left[\frac{f'c\,\frac{k}{d}(pw+ph)}{\frac{a}{d}}\right]^{0.175} b\,d \quad (14)$$

3.6 Zrar in 2005 [17]

Zrar proposed equation (15) to predict the ultimate shear strength of the reinforced concrete corbels. He concluded that the proposed equation (15) has the lowest coefficient of variation C.O.V. values and the safety factor to calculate the ultimate shear strength of the reinforced concrete corbels.

$$Vn = 0.0863\left[\left(\frac{f'_c\, b\, d}{100}\right)(pw\, f_y\, d + 440\, ph\, f_{yh})\frac{d}{a}\right]^{0.4626} \quad (15)$$

3.7 Al-Zahawi in 2011[18]

Based on Al-Zahawi investigation and the data available in literature, a linear and nonlinear expression was proposed for predicting the nominal shear strength of the fibrous and non-fibrous reinforced concrete corbels. The expression used in the work is:

$$V_n = \frac{1}{30}(b_w d)^{0.45} f_{ct}^{\,0.75}\left[\left(\frac{\rho_w f_y\, d}{90} + 1000\,\rho_h\, f_{yh}\right)\frac{d}{a}\right]^{\frac{1}{3}} \quad (16)$$

3.7 Aliewi in 2014[9]

Aliewi carried out experimental and theoretical investigations to study the behavior and load carrying capacity of fibrous and non-fibrous self-compacting reinforced concrete corbels subjected to vertical loading and proposing of useful expressions to predict the nominal shear strength of fibrous and non-fibrous self-compacting reinforced concrete corbels based on the experimental data.

$$V_n = \left(\frac{1}{200}\right)\left(f_c'^{\,1.75} + 200(\,\rho wfy + \rho hfyh)\right)(2.4)^{-\frac{a}{d}}(1 + 0.4F)bd \quad (17)$$

4. Proposed Equations for Predicting The Ultimate Shear Capacity Vn

An attempt has been made to provide expressions for computing the nominal shear strength of reinforced concrete corbels based on the available results obtained from nonlinear regression analysis for the available data in literature [9, 13, 15, 16, 18-27].

The regression analysis has been carried out on (245) reinforced concrete corbel, the proposed formula of nominal shear strength will consist of three parts. The first part depends on material properties, the second part depends on corbels geometry, shear span and effective depth ratio and outer face depth to total depth and the third part depends on steel fibers properties, the steel fiber parameter is expressed in parts of the factor (F).

The first part can be represented as:

$$c_1(f_c'^{\,c_2} + c_3(\,\rho w\, fy + \rho h\, fyh))$$

The second part can be represented as

$$(c_4)^{-a/d} * \left(\frac{k}{h}\right)^{c5}$$

The third part can be represented by

$$(1 + c_6 F)$$

$$F = (\ell_f/d_f)V_f\beta$$

where

F: fiber factor

ℓ_f/d_f: fiber aspect ratio
V_f: fiber volumetric ratio
β :bond factor

So, the proposed formula can be represented as shown below.

$$V_n = c_1\left(f_c'^{c_2} + c_3\ \rho wfy\right)(c_4)^{-\frac{a}{d}} * \left(\frac{k}{h}\right)^{c5} * (1 + c_6F)bd \qquad (18)$$

The coefficients values (C1, C2, C3, C4, C5, and C6) of this proposed formula are determined using regression analysis. Data Fit program and Excel Microsoft Office have been used to perform the regression analysis. Equation (19) shows values of these coefficients and final formula of proposed equation after approximation of these coefficients values to simple values that have an insignificant effect on their accuracy.

$$V_n = \left(\frac{27}{800}\right)\left(f_c'^{1.31} + 24(\ \rho wfy + \rho hfyh)\right)(2.8)^{-\frac{a}{d}} * (\frac{k}{h})^{0.015} * (1 + 0.4F)bd \qquad (19)$$

Results of the proposed formula equation (19) show a very good agreement with experimental results. Table (1) shows the results of adopted statistical properties for analysis of (245) corbels by the proposed equation. The equation show small values for standard deviation (S.D.), coefficient of variation (C.O.V), and range and high values for coefficient of Correlation (C.C.). Values of Avg., Max. and Min. are closer to unity. This reflects a good accuracy of these equations.

Table (1) statistical properties for the proposed equation

Method	Avg.	S.D.	C.O.V.	C.C.	Max.	Min.	Range
Proposed Equ.	1.492397	0.27154	18.19488	0.957106	2.443273	1.004305	1.438968

5. Comparisons between Proposed and Existing Equations of (Vn)

Tables (2), present detailed results of statistical properties (Avg., S.D. and C.O.V.) for all existing expressions in this research (ACI 318M-14 [4], Mahmmud [13], Aziz [14], Zrar [17], Fattuhi [13], Siao [14], Al-Zahawi [18] and Aliewi [9]) and the proposed equations (19).

Table (2) statistical properties for all existing and proposed equations

method	AVg.	S.D.	C.O.V.	C.C.	MAX	MIN	Range
Proposed Equ. (Eq. 19)	1.4924	0.27154	18.1949	95.7106	2.44327	1.00431	1.43897
Aliewi (Eq. 17)	1.37147	0.2736	19.9492	94.0366	2.28637	0.91976	1.36661
Al-Zahawi (Eq. 16)	1.87305	0.36053	19.2483	93.6201	3.23204	1.01228	2.21976
ACI 318-2014	1.15614	0.45767	39.5863	78.8909	2.59363	0.372	2.22163
Siao (Eq. 12)	1.00716	0.34282	34.0384	80.9614	1.96811	0.36481	1.6033
Aziz (Eq. 14)	3.45882	1.34428	38.8653	73.8817	8.49387	1.3195	7.17437
Zrar (Eq. 15)	1.14064	0.30255	26.5244	82.6466	2.07886	0.51902	1.55984
Mahmmud (Eq. 13)	1.21114	0.42143	34.7956	78.3942	2.23563	0.35134	1.88429
Fattuhi (Eq. 11)	1.00033	0.33377	33.3658	73.0181	2.01966	0.27214	1.74752

Figures (4 – 12) shows comparison between experimental and predicted ultimate shear strengths (Vn) for existing and proposed equation (19). It can be observed that there is a good correlation between the experimental and the predicted results for the proposed equation in comparison with the existing equations and proposed equation is very convergent and consistent as compared with other proposed equation obtained by different researchers.

Figures (13 - 21) show values of the shear strength ratio (Vn Experimental / Vn Predicted.), for the available data in the literature [9, 13, 15, 16, 18-27]. Figure (21), shows that the vast majority of the strength ratios for the proposed equation (9) is greater than unity and Figure (9) shows the values are convergent and consistent for all values of ratio between experimental and predicted ultimate shear strengths (Vn) for the proposed equation, so that the proposed equation can be adopted to predict the nominal load of reinforced concrete corbels.

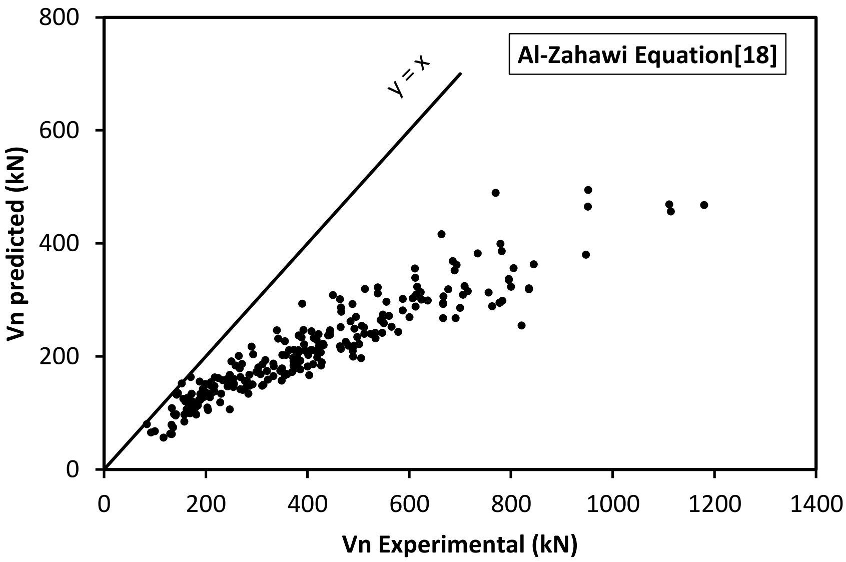

Figure 4 Experimental and Predicted Ultimate Shear Strengths (Vn) For Al-Zahawi Equation

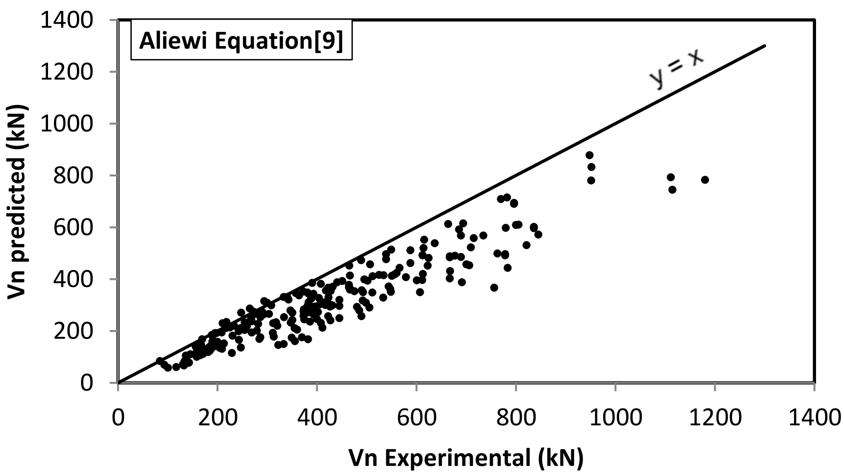

Figure 5 Experimental and Predicted Ultimate Shear Strengths (Vn) For Aliewi Equation

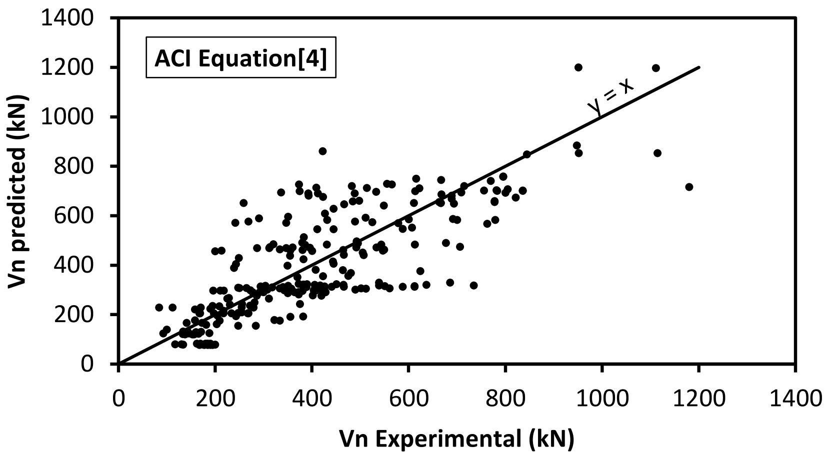

Figure 6 Experimental and Predicted Ultimate Shear Strengths (Vn) For ACI Equation

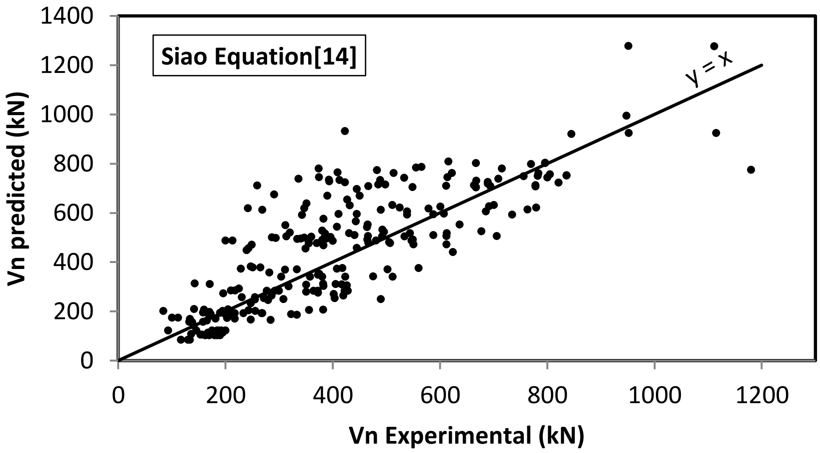

Figure 7 Experimental and Predicted Ultimate Shear Strengths (Vn) For Siao Equation

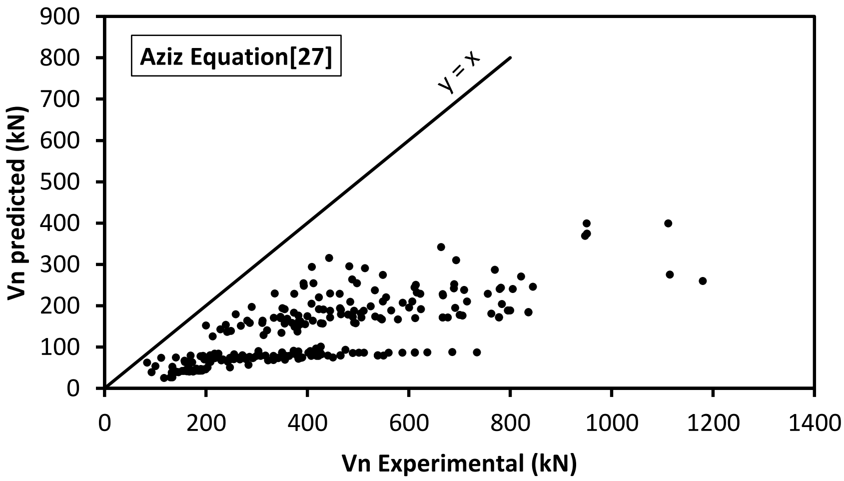

Figure 8 Experimental and Predicted Ultimate Shear Strengths (Vn) For Aziz Equation

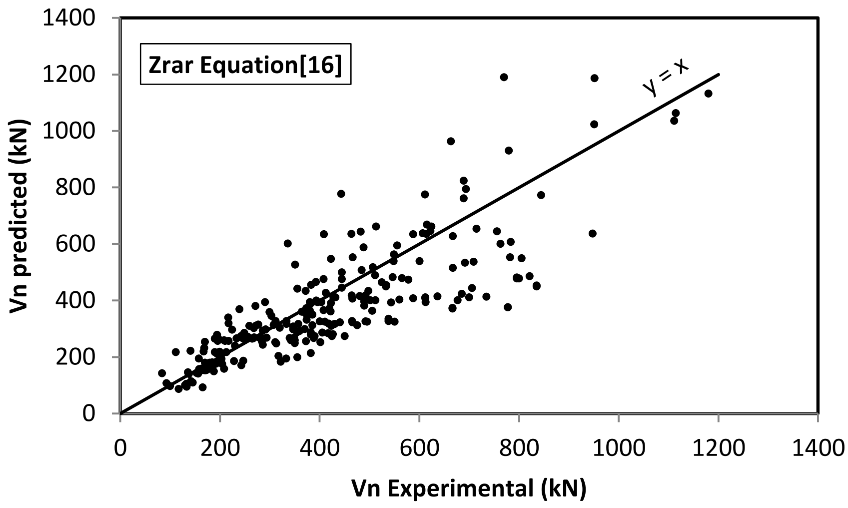

Figure 9 Experimental and Predicted Ultimate Shear Strengths (Vn) For Zrar Equation

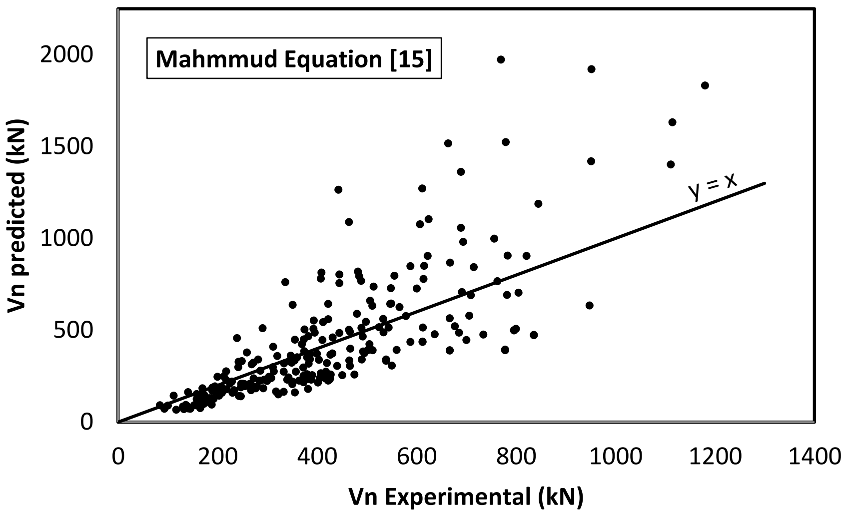

Figure 10 Experimental and Predicted Ultimate Shear Strengths (Vn) For Mahmmud

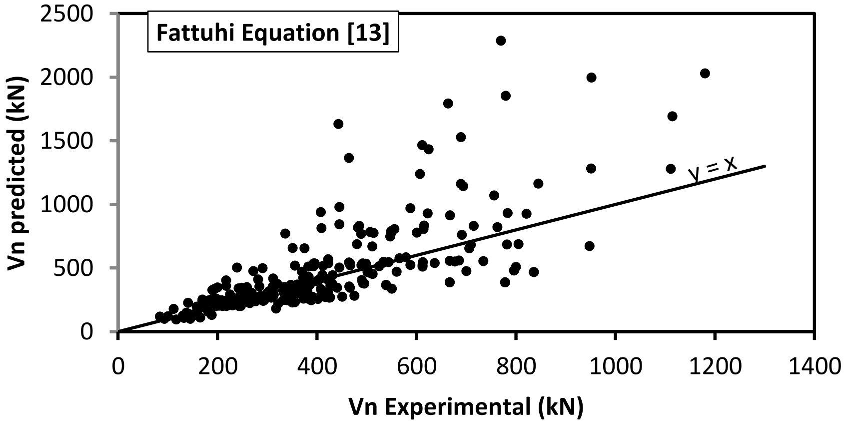

Figure 11 Experimental and Predicted Ultimate Shear Strengths (Vn) For Fattuhi Equation

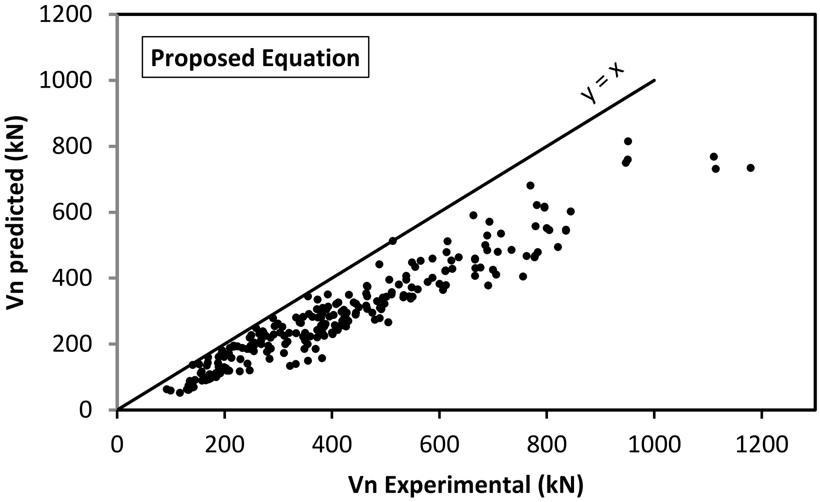

Figure 12 Experimental and Predicted Ultimate Shear Strengths (Vn) For Proposed Equation (Eq. No.19)

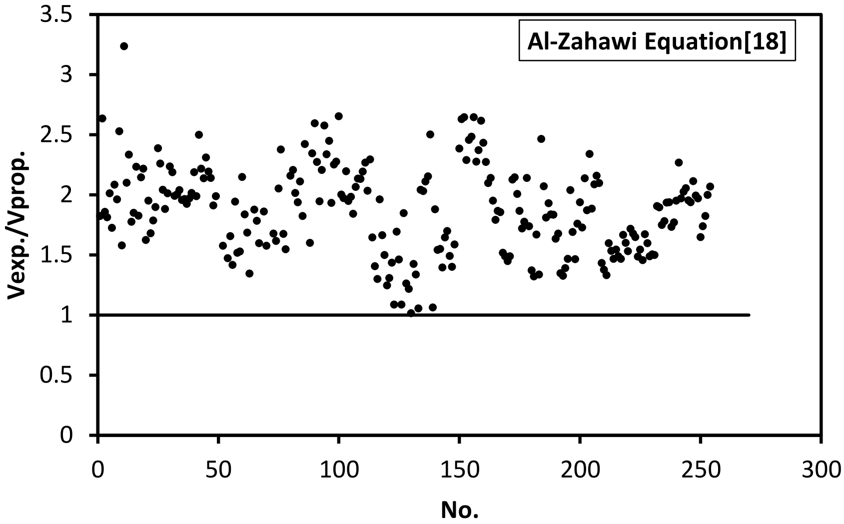

Figure 13 Nominal Strength Ratio for Al-Zahawi Equation

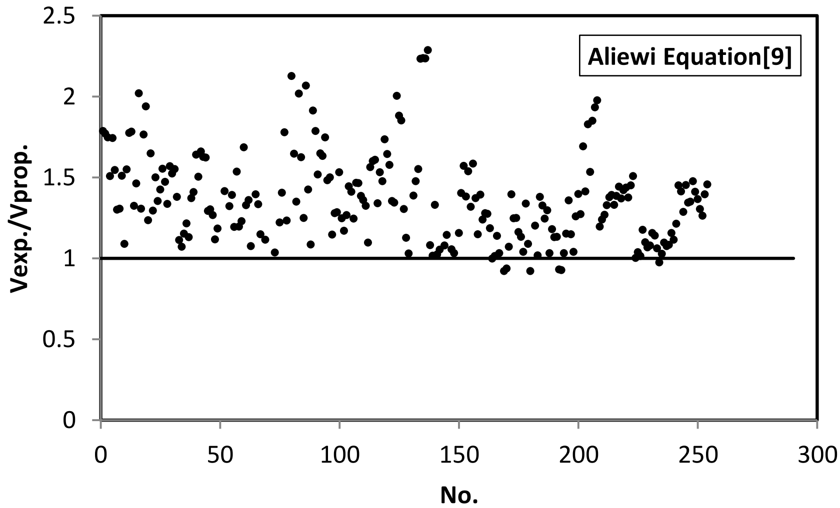

Figure 14 Nominal Strength Ratio for Aliewi Equation

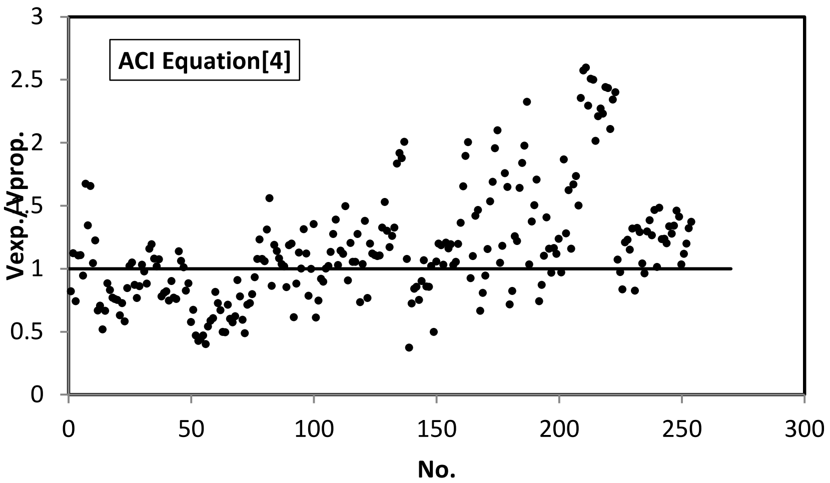

Figure 15 Nominal Strength Ratio for ACI Equation

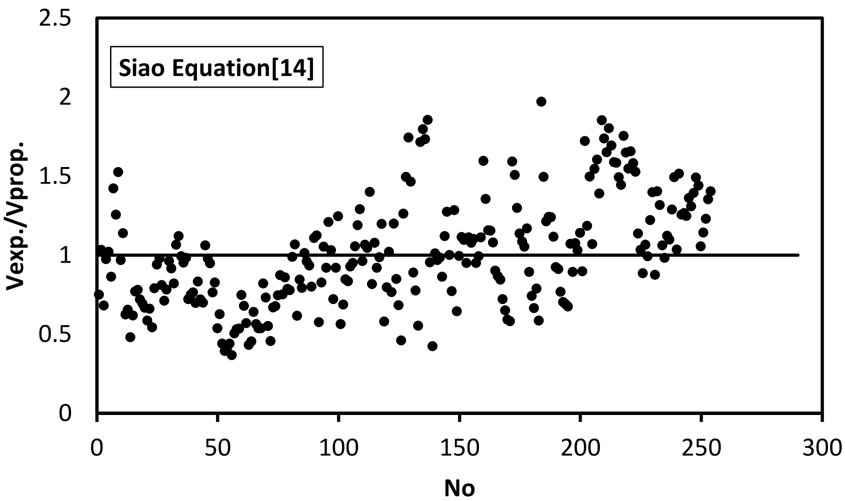

Figure 16 Nominal Strength Ratio for Siao Equation

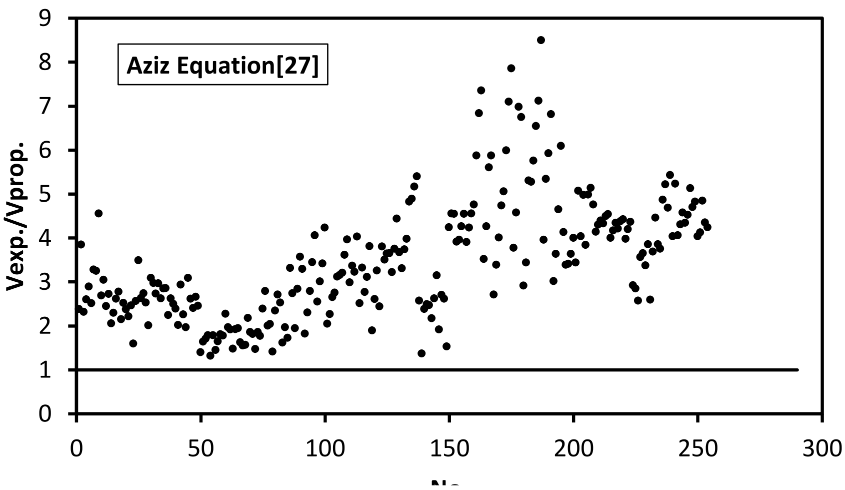

Figure 17 Nominal Strength Ratio for Aziz Equation

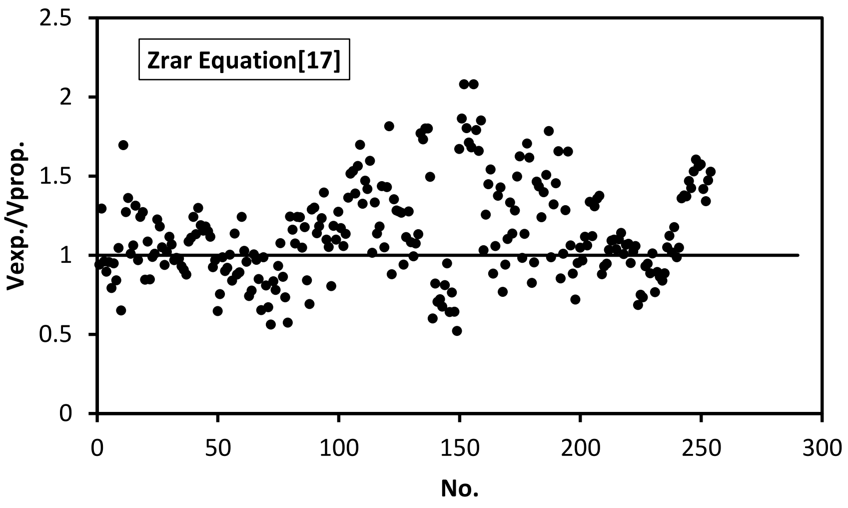

Figure 18 Nominal Strength Ratio for Zrar Equation

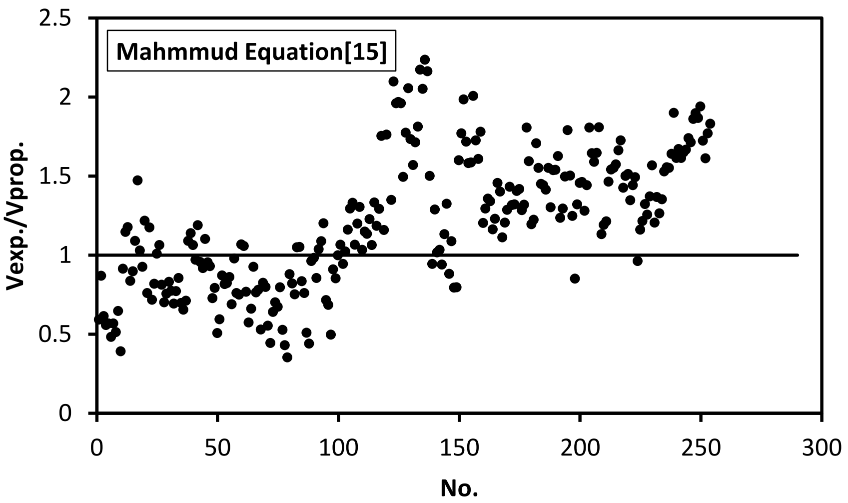

Figure 19 Nominal Strength Ratio for Mahmmud Equation

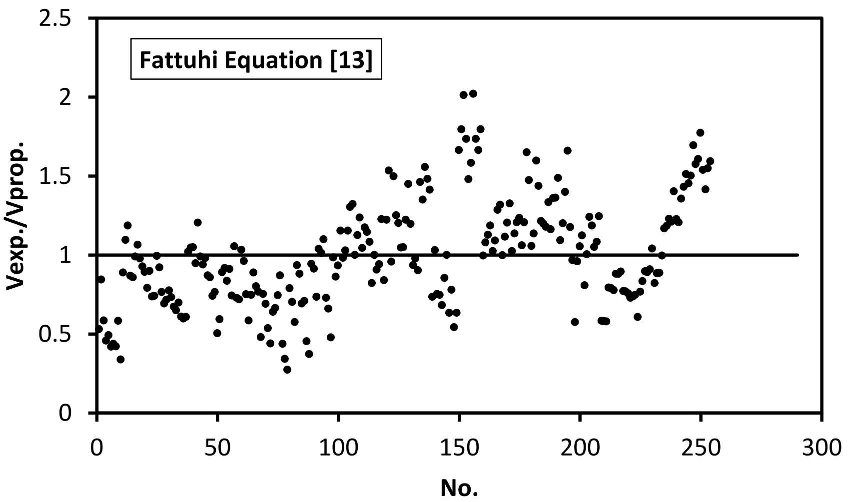

Figure 20 Nominal Strength Ratio for Fattuhi Equation

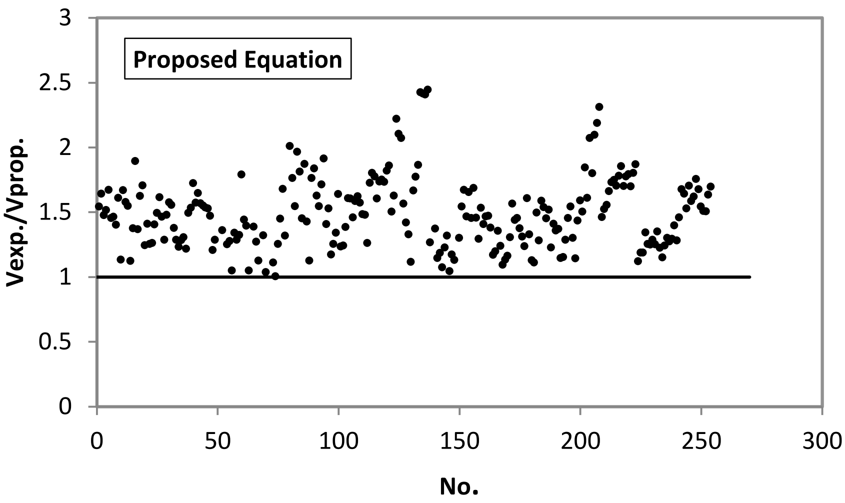

Figure 21 Nominal Strength Ratio for Proposed Equation (Eq. No.19)

6. Statistical Results

Each expression present in this research can be used to predict the nominal capacity of the reinforced concrete corbels available in the literature. Comparisons were made for each expression among the other using statistical method. Table (2) and Figures (22-24) show that the proposed equation (9) has the lowest coefficient of variation (C.O.V) value, the lowest standard deviation (S.D) and highest value of Correlation coefficient (C.C.) among all the equation proposed by the other researchers so that the proposed equation (9) can be used to predict the ultimate shear strength of reinforced concrete corbel with more accuracy, safe and economic.

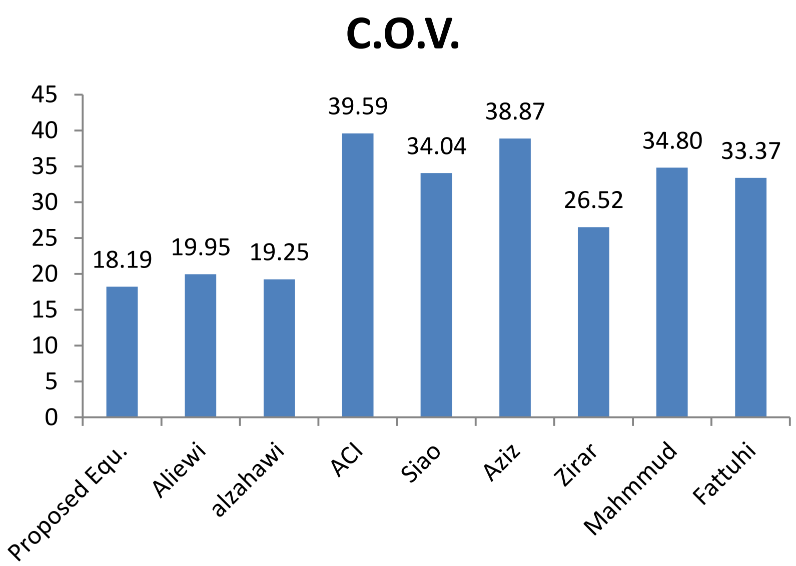

Figure 22 C.O.V values obtained by using regression analysis for (245) corbels for different methods

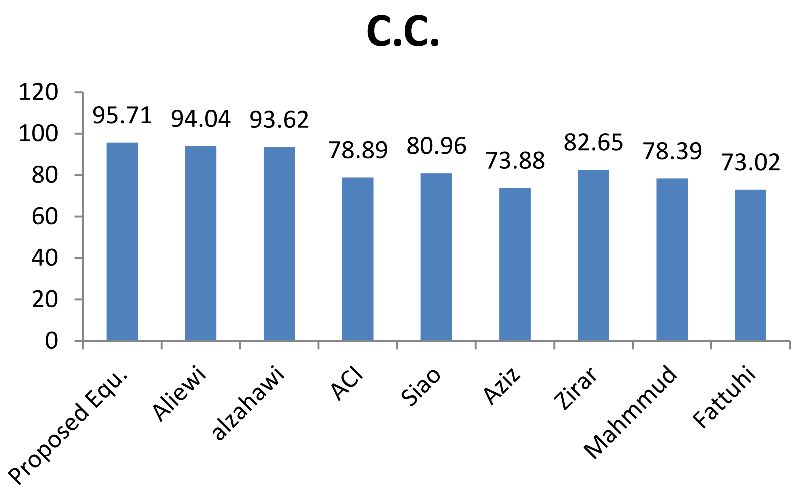

Figure 23 C.C values obtained by using regression analysis for (245) corbels for different methods

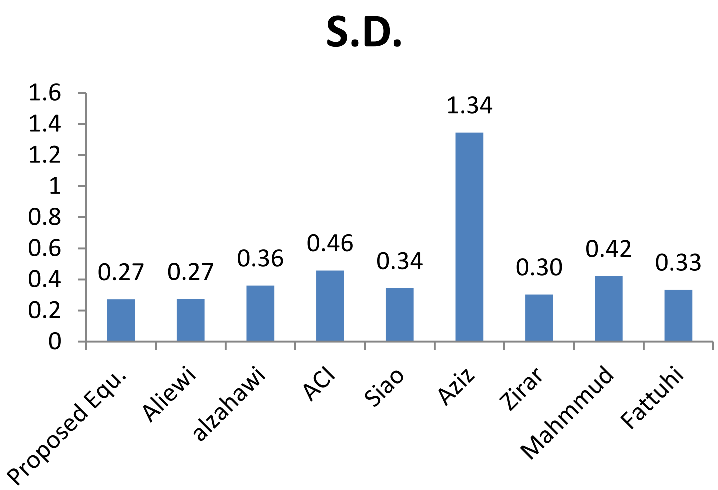

Figure 24 S.D values obtained by using regression analysis for (245) corbels for different methods

7. Conclusions

1. The proposed equation to predict the ultimate shear strength (Vn) based on regression analysis of experimental data which include the variables that affect the ultimate shear strength, is more accurate, safe and economic than existing equations when compared with the proposed equation**.**
2. The proposed equation gives good agreement with experimental data when compared with the existing equations.
3. The proposed equation gives average (Avg.) values of ratio of experimental to predicted ultimate shear strengths value (1.492397), coefficient of variation (C.O.V) of ratio of experimental to predicted ultimate shear strength value (18.19488) and the

correlation (C.C.) of ratio of experimental to predicted ultimate shear strength value (95.7106 %), and standard deviation (S.D.) of ratio of experimental to predicted ultimate shear strength value (0.27154)

8. Notations

a = Shear span, mm

A_f = Area of reinforcement in bracket or corbel resisting factored moment.

A_h = Total area of shear reinforcement parallel to primary tension reinforcement in a corbel or bracket (stirrups).

A_n = Area of reinforcement in corbel or bracket resisting tensile force N_{uc}.

A_s = Area of main tension bars in corbel or bracket.

A_{sc} = Area of primary tension reinforcement in corbel or bracket.

A_{vf} =Area of shear friction reinforcement.

b = Width of corbel.

b_f = Bond factor

d = Corbel effective depth.

d_f = Diameter of fiber

Ec = Elastic modulus of concrete.

Es = Elastic modulus of steel.

F = Fiber factor

f'_c = Compressive cylinder strength of concrete.

ft = Splitting cylinder strength of concrete

f_{yh} = Specified yield strength of horizontal reinforcement (stirrups).

f_{cu} = Cube compressive strength of concrete

f_t = Splitting tensile strength of concrete

f_y = Specified yield strength of reinforcement.

h = Corbel's overall depth.

Hu = Horizontal tensile force at the ultimate load.

Nu = Horizontal force.

V_u = Shear force at the ultimate load.

$\frac{a}{d}$ = Shear span to effective depth ratio.

$\frac{H_u}{V_u}$ = Ratio of horizontal ultimate load to vertical ultimate load

ρ_h = Reinforcement ratios of horizontal bars

9. Abbreviations

ACI	American Concrete Institute
C.C.	Correlation coefficient
C.O.V.	Coefficient of variation
Max.	Maximum value of tested to calculated shear strengths ratios
Min.	Minimum value of tested to calculated shear strengths ratios
S.D.	Standard deviation

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