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Estimation of Maximum Shear Capacity of RC Deep Beams Strengthened by NSM Steel Bars

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Abstract

This work aims to estimate the maximum shear capacity of deep beams RC members strengthened by Near-Surface Mounted (NSM) steel bars. This is done by using an assumed semi-empirical formula that depends on experimental tests. This formula will cover many principal parameters such as shear span to effective depth ratios (a/d), orientation angle of NSM steel bars, concrete compressive strength (f′c), bar's diameter and their spacing. So, thirteen reinforced concrete deep beams with different (a/d) ratios equals (0.85, 1.136 and 1.42) were tested. These beams are categorized into three groups depending on (a/d) ratio, which contained one unstrengthen beam as a control specimen and others strengthened beams by different schemes of NSM steel bars.

A comparison between the calculated and experimental values shows good agreement with high coefficient of determination (R^2=95.4%). The proposed formula is also used to estimate shear capacity of some specimens that found in some previous literatures to confirm the validity of the formula in estimating shear capacity of different cases. Good agreement with low (COV) of the predicted shear capacity with the experimental values that found in literatures was obtained.

Keywords: Shear Capacity, RC Deep Beam, Near Surface Mounted, Strengthening, Steel Rebar.

الخلاصة

يهدف هذا البحث الى تخمين تحمل القص الاقصى للعتبات الخرسانية المسلحة العميقة والمقواة بتقنية التقوية قرب السطح باستخدام قضبان الحديد. من خلال اقتراح معادلة نصف وضعية بالاعتماد على نتائج مختبرية مع الاخذ بنظر الاعتبار مجموعة من المتغيرات المهمة و المؤثرة على سلوك هكذا عتبات مثل نسبة ذراع القص الى العمق الفعال (a/d ratio)، مقاومة الانضغاط للخرسانة، زاوية ميل القضبان المطمورة، قطر تلك القضبان والمسافات بينها. لذا تم فحص ثلاثة عشر نموذج من الاعتاب الخرسانية المسلحة ذات نسب ذراع قص الى العمق الفعال مختلفة (a/d= 0.85, 1.136 and 1.42) . اذ تم تقسيم النماذج الى ثلاثة مجاميع اعتمادا على نسبة (a/d)وكل مجموعة تتكون من نموذج واحد غير مقوى كنموذج سيطرة واخرى مقواة بأساليب مختلفة من قضبان الحديد المطمورة قرب السطح. عند مقارنة النتائج المحسوبة والنتائج العملية وجد ان هناك تطابق جيد بينهما وبمعامل تحديد عالي يساوي (%95.4)، ولتأكيد جودة الصيغة المقترحة في تقدير قدرة القص فقد تم استخدامها لتقدير تلك القيمة لعينات موجودة في بعض البحوث السابقة. حيث تم الحصول على توافق جيد في تخمين تحمل القص مع القيم العملية في تلك البحوث مع معامل تغاير (COV) منخفض.

كلمات المفتاحية: قابلية القص، الاعتاب الخرسانية العميقة المسلحة، التسليح المطمور قرب السطح، تقوية الاعتاب، حديد تسليح اعتيادي.

1. Introduction

Shear failure is a critical approach regards to concrete members because of its brittle nature. Conventional method of strengthening include different external bonded system techniques had dominate in shear improvement field for long area. Since the concrete structures had relatively long designed life, the future load demand still increasing and structures efficiency need to meet this new standard. In other cases accident may damage important structural member and innovative repairing techniques must apply to restore original member's performance. Meanwhile, errors of design and construction needs urgent strengthening even though before structures using. A strengthening process carried out in case of great performance level needed to reach, which include criteria like load carrying capacity, durability, change of structural function, etc. **(Yang *et.al.*, 2007)**.

A general term maintenance cover both strengthening and repairing which becomes a common successful solution for hold on critical structures in service, especially in case of non-economical removing or replacing of infrastructures. Choosing incompetent strengthen process may damage member and worsen its efficiency level. Many strengthening techniques were investigated experimentally and then implemented on existing RC structures **(Zararis *et.al.*, 2001)**.

A new technique called Near Surface Mounted (NSM) involve cutting grooves in concrete cover and implement rebar into it, with special groove filler (epoxy or cement mortar) proved its efficiency as an effective technique. Although NSM strengthening technique is considered as new repairing system, but its first use was in early 50’s **(Asplund, 1949)**. At the first appears of NSM technique, steel bars embedded with cement mortar was the basic concept of strengthening. Later, outside bars cover with shotcrete is adopted. However, this procedure failed to improve good bond strength and in some cases it is not practical to cast concrete around the whole strengthen members. At early 60’s of past century epoxy’s industry implemented in structural filled and move NSM technique step further by using resins as groove filler **(Rahal and Rumaih, 2011)**.

A higher bond strength available with expansion of NSM as effective strengthening system and it is appropriate for different criteria, corrosion problem of steel bars lead to use epoxy coated steel and replacing it by different FRP product like carbon fiber reinforced polymer bars, sheet and laminate. Also glass and basalt reinforced polymer rebars were used **(Täljsten *et.al.*, 2003)**

Many literature were studied shear and flexural strengthening with FRP NSM in addition to bond strength investigation such as (De Lorenzis *et.al.*, 2000 ; Blaschko and Zilch, 1999 ; Barros and Dias, 2003 ; El-Hacha and Rizkalla, 2004 ; Rizzo and De Lorenzis, 2009 ; Proia and Matthys, 2017). Meanwhile rare researches were found on NSM steel rebars (Rahal and Rumaih, 2011 ; Aiswarya and Prabhakaran, 2017)**.**

The RC members shear strength usually computed by summing concrete and internal stirrups shear strength components. But in case of external strengthening the role of independent shear capacity of each component is not valid since the strength worked in interaction manner in this case (Kim *et.al.*, 2017). The brittle failure almost sudden and there is no ability of warning like flexural failure. Although extensive studies made on shear failure in beams, but international concrete design codes still depend on semi-empirical model for shear design. So, it becomes necessary to assume a new empirical formula that gives a better estimation of shear capacity for strengthened members rather than conservative way.

This study aims to propose a semi-empirical formula for estimating shear capacity of RC deep beams strengthening with NSM technique, and comparing estimated results with the current experimental values and other found in previous literatures.

2. Experimental Program

In this work, thirteen simply supported deep beams were strengthened with NSM steel bars in shear. All specimens have the same dimensions and flexural reinforcement. The beams had a length of 1500 mm, with 200 mm width and 400 mm height and reinforced by (3ϕ16) bars as longitudinal reinforcements. They were casted and designed to fail in shear adopting Strut and Tie model **(ACI 318-14)**. So beam with no stirrups were used. The specimens were divided into three groups according to their (a/d) ratios, that less than two as recommended by the provisions **(ACI 318-14)** for deep beam requirements (f′c= 45 MPa). Two-point load with an overall clear span of 1300 mm were used for testing beams. Beams dimensions and details are shown in Figures (1) and (2) and Table (1).

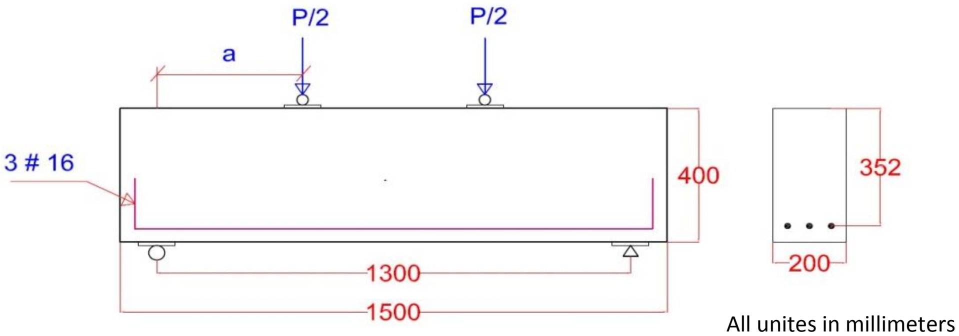

Figure (1) The Dimensions and Details of a Typical Specimen of RC Deep Beams

After curing for 28 days in wet condition, the beams were marked in the desire spacing and inclination to have a groove dimension equal two times bars diameters. The cutting process was made by electric saw-cut then the groove cleaned by air and washed by water jet to get small particles and concrete powder out of groove as shown in Figure (3). Then rebars embedded into the groove and emerged with epoxy, see Figure (4).

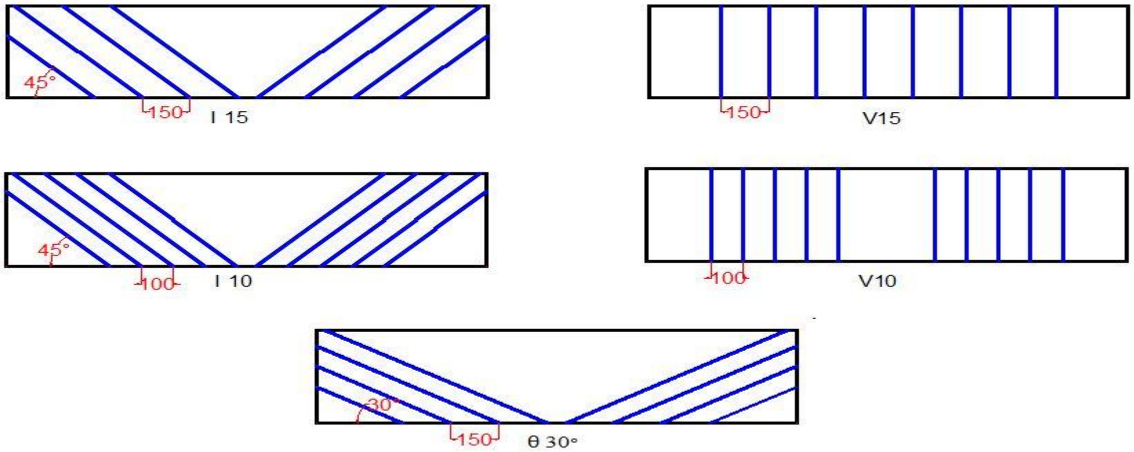

Figure (2) NSM Strengthening Scheme

Table (1) Details of the Tested Deep Beams

Group no	Beam designation*	Beam type	(a/d) ratio	Steel NSM Properties		
				Angle of NSM bars	Spacing of NSM bars (mm)	NSM bars diameter (mm)
One	BC3	Control	0.85	-	-	-
	BS3 –V15	Strengthening	0.85	90 °	150	8
	BS3 – V10	Strengthening	0.85	90 °	100	8
	BS3 – ϕ12	Strengthening	0.85	90 °	150	12
	BS3 – I15	Strengthening	0.85	45 °	150	8
	BS3 – I10	Strengthening	0.85	45 °	100	8
Two	BC4	Control	1.136	-	-	-
	BS4 –V15	Strengthening	1.136	90 °	150	8
	BS4 –V10	Strengthening	1.136	90 °	100	8
	BS4 –I15	Strengthening	1.136	45 °	150	8
	BS4 –θ 30 °	Strengthening	1.136	30 °	150	8
Three	BC5	Control	1.42	-	-	-
	BS5 –I15	Strengthening	1.42	45 °	150	8

*Designation: (C) control, (S) Strengthening, (3, 4 and 5) refer to load arm distances (300, 400 or 500 mm), (I) inclined NSM rebars and (V) vertical, Meanwhile (15 and 10) indicate NSM spacing (150 or 100 mm) respectively.

Figure (3) Groove Cutting Process

Figure (4) Imbedded Bars into Grooves

3. Test Results

The test results of failure loads and modes of failure are listed in Table (2). The results showed significant competence of NSM method in strengthening shear capacity of RC deep beams member by (7.35, 20.6 %) over unstrengthen members. Loading capacity increased by (9.33 and 6.01 %) when adopting inclined NSM rebars rather than vertical for group one and two respectively.

Table (2) Experimental Test Results

Beam	a/d Ratio	Max. Load (kN)	Increase in Max Load %	Mode of Failure
BC3	0.85	680	__	**Shear**
BS3-V 15	0.85	730	7.35	**Shear & Debonding**
BS3-V 10	0.85	750	10.29	**Shear & Debonding**
BS3-ϕ12	0.85	780	14.706	**Shear & Debonding**
BS3-I 15	0.85	775	13.97	**Flexural**
BS3- I 10	0.85	820	20.6	**Flexural**
BC4	1.136	615	__	**Shear**
BS4-V 15	1.136	665	8.13	**Flexural & Cover Separation**
BS4-V 10	1.136	690	12.2	**Flexural**
BS4-I 15	1.136	705	14.63	**Flexural & Debonding**
BS4-θ30	1.136	710	15.45	**Flexural**
BC5	1.42	460	_	**Shear**
BS5-I 15	1.42	500	8.7	**Flexural**

It also found that the shear failure that happened in specimens which having no or vertical strengthening bars is transformed into flexural failure when adopting inclined strengthening bars. When reducing rebars spacing from (150 to 100 mm) failure load enhanced by (5.8 and 3.76%) for group one and two respectively, in addition to (6.85 %) increase in maximum load if (ϕ12) bars used instead of (ϕ8).

The strengthened beams showed smaller diagonal cracks width that appeared at greater loading values of about (6.25, 32%) compared with the corresponding control specimens. The failure modes and cracks pattern of the three groups are shown in Figure (5).

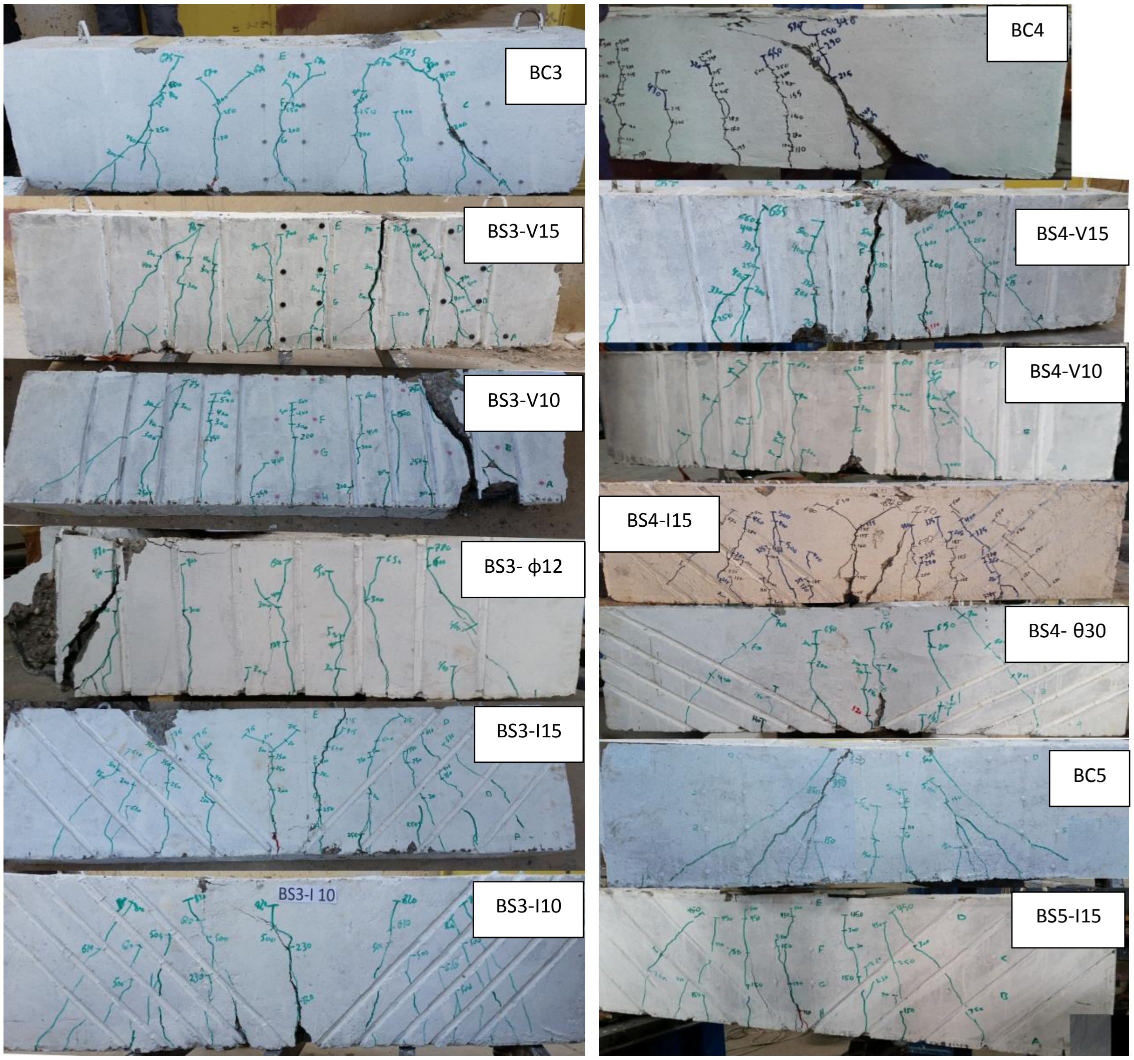

Figure (5) Beams Failure Modes and Cracking Patterns

4. Proposed Model for Maximum Shear Capacity

The worldwide concrete design codes are more conservative in case of shear design, because of the brittle nature of this failure. However the need of accurate model to estimate failure load could not found in these codes ***(Kim et al., 2017)***. So, depending on the experimental results the following formula is suggested to compute the shear capacity of RC deep beam strengthened by NSM steel bars.

A new model is proposed that can estimate the maximum shear capacity of deep beam by making use of the equation that originally adopted by (***ACI 318-14)***. The proposed formulae and corresponding factors are:

$$\boldsymbol{V_n = k * V_c + m * V_s} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, (V_n) refers to the nominal shear capacity of strengthened beam, (V_c) concrete shear strength, (V_s) NSM steel bar portion in load capacity, (k) and (m) are correction factors. Whereas the suggested equation for estimating concrete shear strength which depends on the compressive strength of concrete instead of its square root as in ***(ACI-318-14)*** code is:

$$\boldsymbol{V_c = f'_c * b * d} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, (f'_c) Concrete compressive strength (MPa), (b) Beam width (mm), and (d) Beam effective depth (mm).

And the NSM steel bar contribution (which is the same of equation 22.5.10.5.4 in the ***(ACI-318-14)*** to calculate steel reinforcement shear resistance) is:

$$\boldsymbol{V_s = \frac{A_v * f_y * (sin\theta + cos\theta) * d}{s}} \quad \text{……………..(3)}$$

Where, (Av) Area of NSM bars (2- Legs) (mm^2)**,** (fy) Yield tensile strength of NSM bars (MPa), (s) Horizontal spacing center to center of NSM bars (mm), and (θ) Inclination angle with respect to horizontal axis of beam.

The factor (k) in equation (1) depends on the (a/d) ratio which may be considered the most effective parameter in load capacity.

$$\boldsymbol{k = \frac{1}{n} * [\, 0.5238 - 0.1865 * \log\left(\frac{a}{d}\right) \,]} \quad \text{…………..(4)}$$

Where (n) in equation (4) is a constant that also influenced by the (a/d) ratio and suggested to be:

$$\boldsymbol{n = \begin{cases} 5.11 \text{ , } \mathit{For} \left(\frac{a}{d}\right) < 1.136 \\ \\ 7.2 \text{ , } \mathit{For} \left(\frac{a}{d}\right) \geq 1.136 \end{cases}} \quad \text{…………..(5)}$$

While factor (m) in equation (1) is a constant value and depend on type of NSM components materials that equals:

$$\boldsymbol{m = \begin{cases} 0.2128 \text{ , } \mathit{For\ Steel\ rebars} \\ \\ 0.35 \text{ , } \mathit{For\ \ FRP\ Components} \end{cases}} \quad \text{…………….(5)}$$

Table (3) shows very good match between proposed model and experimental result of strengthened beams with coefficient of determination (R^2=0.954), and low coefficient of variation (COV=0.032).

Table (3) Compression between Experimental and Proposed Model Results

Specimen	**$P_{exp.}$**	**Exp. Shear Strength (Vn kN)**	**Predicted Shear Strength**			**$V_{m.}/V_n$**
			$k*V_c$	**$m*V_s$**	**Vmodel V_m (kN)**	
BC3	680	340.00	665.59	0.00	332.79	0.979
BS3-V 15	730	365.00	665.59	51.21	358.40	0.982
BS3-V 10	750	375.00	665.59	76.82	371.20	0.990
BS3-φ12	780	390.00	665.59	115.22	390.40	1.001
BS3-I 15	775	387.50	665.59	72.42	369.01	0.952
BS3- I10	820	410.00	665.59	108.63	387.11	0.944
BC4	615	307.50	636.70	0.00	318.35	1.035
BS4-I 15	705	352.50	636.70	72.42	354.56	1.006
BS4-V15	665	332.50	636.70	51.21	343.95	1.034
BS4-V10	690	345.00	636.70	76.82	356.76	1.034
BS4-θ30	710	355.00	636.70	69.95	353.33	0.995
BC5	460	230.00	435.95	0.00	217.98	0.948
BS5-I 15	500	250.00	435.95	72.42	254.19	1.017

Mean	0.994
Standard Deviation	0.032
COV	0.032

5. Assessment of Proposed Model with Some Previous Works

A comparative study would be carried out on some experimental results that is found in previous literatures for assessing the validity of proposed model in estimating shear capacity of different cases. The dimensions and strengthening process of the selected specimens are close to the current data as listed in Table (4). Experimental shear capacity from **(Arabzadeh *et.al.*, 2011;Raj & Surumi, 2012;Mezher, 2015;Abdul-Samad *et.al.*, 2017)** were compared using proposed model in the following sections.

5.1 Experimental Data by (Arabzadeh *et.al.*, 2011)

Sixteen specimens with (8 cm × 40 cm) cross section and (1.2 m) clear span were tested by **(Arabzadeh *et.al.*, 2011** under two points load. Different main steel reinforcement was used with constant shear span over effective depth ratio (a/d=1.1). The tested beams classified into four series depending on web steel bar configurations. They were: (A) vertical steel distribution over whole length, (B) steel bars within shear span only, (C) net of vertical and horizontal bars and (D) inclined in (45°) rebars. The shear capacities of specimens for all series are calculated using the proposed model assuming that the reinforcement stirrup will participate in the shear capacity of RC beam as calculated by Eq.3. The suggested model shows very good prediction of shear capacity of the considered specimens, especially in series (B) which contain reinforcement in only the shear span. The max difference among predicted value with the experimental values in series (B) does not exceed (±1%) and this value slightly increased for another series with acceptable value of (COV=0.102).

5.2 Experimental Data by (Raj & Surumi, 2012)

Twelve RC deep beams having (1.4 m) length and (17.5 cm ×25 cm) cross section were tested under four points bending with (a/d =1.84) by Raj and Surumi. The compressive strength of concrete was (34.88 MPa). The tested beams contain one unstrengthened beam as control and eleven specimens that classified into two groups. Group One consisted of four beams that two of them embedded with (φ6 mm) GFRP bars in two configurations angle (90 ° and 45 °). The same configuration schemes were used in the other two beams but replacing of bars by (3 mm × 10 mm) GFRP laminates. Constant center to center spacing of bars or laminate that equal (100 mm) were provided for this group. Whereas Group Two, that having seven beams, contained both mentioned configurations of GFRP laminate (but there is no GFRP bars) that spaced by (75mm, 100mm and 125 mm) and last one with U-warped GFRP sheet over shear span.

It was found that the proposed model gives very good prediction of shear capacity for specimens that strengthened with bars rather than those with laminate. Adopting GFRP material instead of steel bars has insignificant effect on the accuracy of the calculated shear strength which may be considered slightly over estimated. Whereas the COV of all specimens is about (0.133).

5.3 Experimental Data by (Mezher, 2015)

Mezher tested twelve RC members strengthened or repaired by using different inclination and spacing of CFRP NSM bars. High tensile strength of CFRP bars used in this work gives large deviation than other data. However the interaction between CFRP and internal stirrups or CFRP is more complicated, and the combined strengthening system contrasts independence shear contribution theory. So, two values for ($\boldsymbol{m}$) are suggested. They are, ($\boldsymbol{m}$=0.2128) for internal steel stirrups and ($\boldsymbol{m}$=0.35) for NSM CFRP bars. Good conceding between numerical model and experimental result with (COV = 0.129) is obtained.

5.4 Experimental Data by (Abdul-Samad *et.al.*, 2017)

Five specimens were prepared in this study with variable spacing between anchored NSM bars. The (***m***) factor was used in similar value to those suggested for calculating shear capacity of the specimens that tested by **(Mezher, 2015)** for both internal steel stirrups and NSM CFRP bars. High conceding in shear capacity with the experimental results is obtained when adopting the suggested model with (COV = 0.047).

Table (4) shows summary of the properties of beams that tasted in the mentioned literatures as well as the obtained statistical values. Meanwhile Fig. (6) shows variation of analyzed data from proposed formula values.

Table (4) Pervious Works Specimens Properties

Literature	**Beams' cross-section (h×b) (cm×cm)**	**Beam length (m)**	**Clear span (m)**	**f'c (MPa)**	**a/d**	**Strengthening Type**	**Mean**	**Standard Deviation**	**COV**
Arabzadeh et. al	40×8	1.6	1.2	60	1.08	No strengthening but using Internal Steel	0.980	0.104	0.102
Raj & Surumi	25×17.5	1.4	1.2	34.88	1.84	NSM GFRP Bars & Laminate	1.010	0.134	0.133
Mezher	40×15	1.3	1.0	30	1.158	NSM CFRP Bars	1.065	0.137	0.129
Abdul-Samad et al	45×14	1.2	1.0	25.8	0.864	NSM anchored CFRP Bars	0.970	0.046	0.047

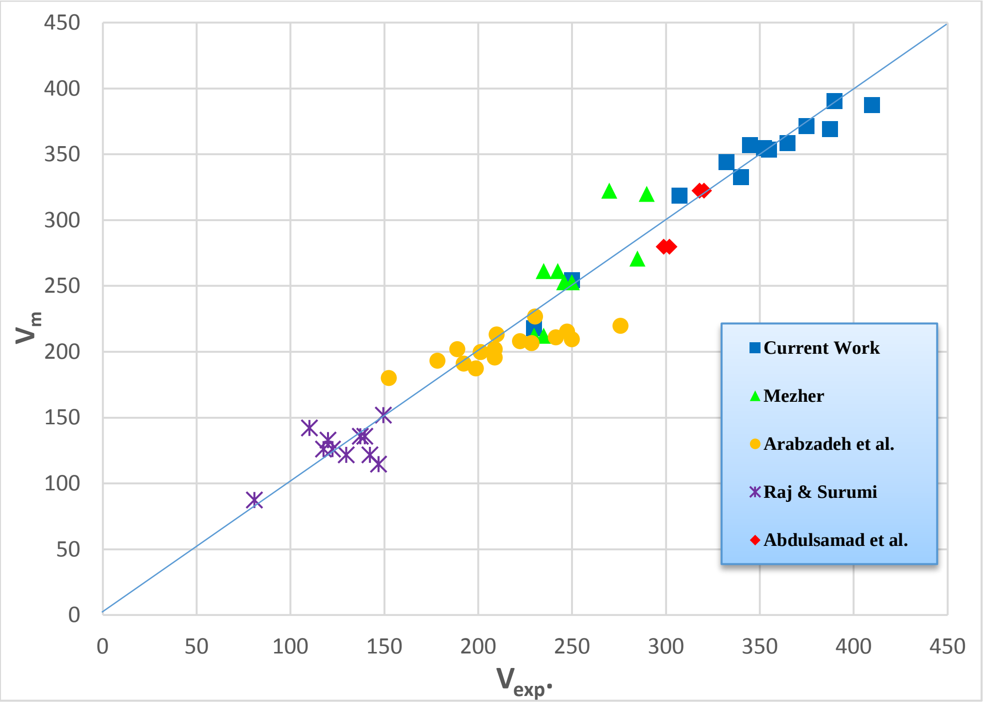

Fig. (6) Experimental versus Predicted Shear Strength

6. Conclusion

The proposed model proved its significant ability in estimating shearing capacity for different shear strengthening schemes and the following general points could be summarized from this investigation:

1. The validity of model in predicting the shear strength of RC deep beams having wide range of concrete compressive strength (30 – 60 MPa).
2. Acceptable accuracy in estimating shear strength of beams with adopting different shapes of NSM (rebars or laminates) and different materials (Steel, CFRP and BFRP) that having varied range of tensile strength is obtained.
3. The model is able to estimate shear capacity even when using internal steel stirrups instead of or as well as to NSM bars.
4. Validity of estimating different arrangement of stirrups or NSM strengthening bars.
5. The model has good efficiency in estimating the shear capacity of strengthened as well as repaired (rehabilitated) deep beams with different NSM distribution.
6. Good accuracy is obtained in estimation of different specimens' dimensions with different clear span range (1.0 -1.4 m), as well as large (a/d) ranged between (0.85-1.84).
7. Estimating shear capacity of anchored and non-anchored NSM bars.

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