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Shear Behavior of Fibrous Self Compacting Concrete Deep Beams

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Abstract :

Self compacting concrete (SCC) is a relatively new generation of concrete that is characterized by its liquid nature that makes it appropriate for cast the narrow members such as deep beams without vibration. The work aims to investigate the behavior of SCC deep beams and evaluate their shear capacity especially when steel fibers are used in their construction. The experimental work includes testing twelve reinforced concrete simply supported deep beams cast using self compacting concrete (SCC) with steel fibers to evaluate their shear behavior and strength. All tested beams have dimensions of (100×330×1050) mm and have been subjected to two point loads. The parameters considered are shear span to effective depth ratio (a/d), concrete compressive strength (f'_c) and steel fiber volumetric ratio (V_f). Test results indicated that the increase in (a/d) ratio from 0.6 to 1 leads to decreases in cracking and ultimate shear strengths by average ratios of 25.1 % and 20.6 % respectively. Increasing (f'_c) to the twice of the origin value leads to increases in the cracking and ultimate shear strengths by average ratios of 13.9 % and 48.1 % respectively. Using steel fibers in SCC deep beams improves cracking and ultimate shear strength by average ratios of 33.1 % and 11.4 % respectively when 0.4 % of steel fibers is used while they improve these shear strengths by average ratios of 64.4 % and 23 % when 0.8 % of steel fibers is used. The analytical work includes derivation of new equation for predicting ultimate shear strength of fibrous SCC deep beams depending on regression analysis of test results. The new proposed equation gives good agreement with the experimental results by comparison with the ACI318M-1999 Code equation and Rao-2012 Equation.

Keywords: self compacting concrete, shear, deep beams, steel fibers, high strength.

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سلوك القص لعتبات الخرسانة ذاتية الرص العميقة المسلحة بالألياف

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الخلاصة

الخرسانة ذاتية الرص عبارة عن جيل جديد نسبياً من الخرسانة التي تتميز بطبيعتها السائلة والتي تجعلها ملائمة لصب الاعضاء الانشائية الضيقة كالعتبات العميقة بدون الحاجة الى عملية الرص. يهدف العمل الى تحري السلوك الانشائي للعتبات العميقة المصنعة من هذا النوع من الخرسانة وتقييم تحملها لقوى القص خصوصاً عند استخدام الياف الحديد في انشاءها. يتضمن الجزء فحص اثنى عشر من العتبات الخرسانية المسلحة العميقة ذات الاستناد البسيط المصبوبة باستخدام الخرسانة ذاتية الرص مع استخدام الياف الحديد للتعرف على سلوك ومقاومة هذا النوع من العتبات. جميع العتبات كانت بإبعاد (100×330×1050) ملم ومعرضة لحملين مركزين. المتغيرات المعتبرة في هذه الدراسة هي نسبة فضاء القص الى العمق الفعال (a/d) ومقاومة انضغاط الخرسانة (f'_c) والنسبة الحجمية لالياف الحديد (V_f). نتائج الفحص دلت ان الزيادة في نسبة (a/d) من 0.6 الى 1 تؤدي إلى نقصان في مقاومة التشقق والمقاومة القصوى بمعدل نسب % 25.1 و % 20.6 على التوالي. الزيادة في (f'_c) الى ضعف القيمة الاصلية يؤدي إلى الزيادة في مقاومة التشقق والمقاومة القصوى بمعدل نسب % 13.9 و % 48.1 على التوالي. استخدام ألياف الحديد في العتبات العميقة المعدة باستخدام الخرسانة ذاتية الرص يحسن مقامة التشقق والمقاومة القصوى بمعدل نسب % 33.1 و % 11.4 على التوالي عند استخدام نسبة % 0.4 من ألياف الحديد بينما يحسن هذه المقاومات بمعدل نسب % 64.4 و % 23 عند استخدام نسبة % 0.8 منها. الجزء التحليلي من هذه الدراسة يتضمن اشتقاق معادلة جديدة لاحتساب مقاومة القص القصوى لهذا النوع من العتبات اعتمادا على التحليل الرجعي للنتائج العملية. المعادلة الجديدة المقترحة تعطي توافق جيد مع النتائج العملية بالمقارنة مع معادلة الكود الامريكي (ACI318M-1999 Code) ومعادلة مقترحة حديثا من قبل احد الباحثين (Rao-2012 Equation).

1. Introduction

Reinforced concrete deep beams are structural members having depth much greater than normal in relation to their span, while the thickness in the perpendicular direction is much smaller than either span or depth[1]. These members are used in many structural applications such as diaphragms, water tanks, foundations, bunkers, shear walls, girders used in multi story buildings to provide column offsets, and floor slabs under horizontal loads[1,2]. Usually, deep beams have narrow width and contain congested shear reinforcement. Therefore, the conventional concrete does not flow well when it travels to the web and does not completely fill the bottom part. This results in many problems in concrete such as, voids, segregation, weak bond with reinforcement bars and holes in its surface. Therefore, the self compacting concrete (SCC) is very appropriate type for casting these members.

2. Significant of Research[1]

Self compacting concrete, provides distinct advantages over conventional vibrated concrete due to liquid nature such as: elimination of above mentioned problems, low noise level in construction, faster construction and improving quality and durability, no need to vibration where it is able to fill all spaces in the formwork and passes through reinforcing bars by its own weight[3,4].

The difference in some properties between the conventional vibrated concrete and the self compacting concrete requires necessity to investigate the behavior and capacity of structural members constructed using this type of concrete. Therefore, the behavior of deep beams made using SCC is experimentally investigated in this research work[5]. Because of the lesser amount and smaller maximum size of coarse aggregate used in SCC compared with conventional vibrated concrete, one can expect that the shear strength of deep beams made by SCC is lesser than that carried out by deep beams made using conventional vibrated concrete, where the interlock mechanism of coarse aggregate is weaker which represents an important part of the total shear strength parts for these members. But the well self compaction and regularity of microstructure of this type of concrete reduce the weaken positions in it and may lead to an increase in its efficiency to resist the shear stresses.

This liquid property in SCC makes it appropriate to use steel fibers in its mix to improve its mechanical properties, where using them in SCC is easier than using it in conventional vibrated concrete[6]. Therefore, the use of steel fibers is one of the important parameters considered in this study. Because of weaker interlock mechanism of coarse aggregate in SCC, the steel fibers may have more prominent role in improving the shear strength of SCC deep beams compared with those made using conventional vibrated concrete.

* This research is taken from Ph.D. thesis referred to in the fifth reference of this research.

3. Experimental Program

The experimental program consists of testing twelve simply supported deep beams constructed using self compacting concrete. All beams have the same dimensions and amounts of the longitudinal and transverse reinforcement. They have an overall length of 1050 mm, a width of 100 mm and a height of 330 mm. In this study three important parameters are considered: shear span to effective depth ratio (a/d) , concrete compressive strength (f′c) , steel fiber volumetric ratio (V_f).

The specimens are divided into four groups (A , B , C , and D). These groups are classified according to shear span to effective depth ratio (a/d) and concrete compressive strength (f′c) values. Group (A) relates to small value of shear span to effective depth ratio (a/d = 0.6) and normal concrete compressive strength (f′c < 41 MPa) according to ACI 363R[6]. Group (B) relates to larger value of shear span to effective depth ratio (a/d = 1) and normal concrete compressive strength. Group (C) relates to a/d = 0.6 and high concrete compressive strength (f′c > 41 MPa)[7] while group (D) relates to a/d = 1 and high concrete compressive strength.

Each group involves three different beams, where the first beam of each group is non fibrous beam have approximately minimum vertical reinforcement ratio according to ACI318M-2011[8] provisions (ρ_v = 0.0025). The second beam of each group is a fibrous beam similar to the first beam but with volumetric ratio of steel fibers of 0.004. The third beam of each group is a fibrous beam similar to the first beam but with volumetric ratio of steel fibers of 0.008. **Table (1)** shows details about all twelve beams with their related parameters. The normal strength SCC will be denoted by (NSCC) and high strength SCC will be denoted (HSCC).

4. Materials:

4.1 Cement

Ordinary Portland cement (type I) of Tasluja Factory is used in the present study. Test results of chemical composition and physical properties of the used cement tested by National Center for Construction Laboratories and Researches in Baghdad comply with the requirements of I.Q.S. No.5, 1984[9].

4.2 Fine Aggregate

Al-Ukhaider natural sand is used in concrete mix. Before using it, the sieve analysis is performed at Material Laboratory in Engineering College of Al- Mustansiriya University to ensure its validity for mixing. The fineness modulus, depending on this analysis, is 2.78. The sieve analysis results of the sand comply with the limits of the Iraqi Specification No.45/1984[10].

Table .(1) Details of tested beams and research parameters

Group	Beam design-ation	Total Length (mm)	Cross Section Dimensions mm	Conc. Type	a/d	Steel fibers %
A	A1	1050	100 × 330	NSCC	0.6	0
	A3	1050	100 × 330	NSCC	0.6	0.4
	A4	1050	100 × 330	NSCC	0.6	0.8
B	B1	1050	100 × 330	NSCC	1	0
	B3	1050	100 × 330	NSCC	1	0.4
	B4	1050	100 × 330	NSCC	1	0.8
C	C1	1050	100 × 330	HSCC	0.6	0
	C3	1050	100 × 330	HSCC	0.6	0.4
	C4	1050	100 × 330	HSCC	0.6	0.8
D	D1	1050	100 × 330	HSCC	1	0
	D3	1050	100 × 330	HSCC	1	0.4
	D4	1050	100 × 330	HSCC	1	0.8

4.3 Coarse Aggregate (Gravel)

Crushed gravel of maximum size of 10 mm brought from Al-Niba'ee region is used. Before using it, the sieve analysis is performed at Material Laboratory in Engineering College of Al-Mustansiriya University to ensure its validity for mixing and choosing the primary proportions of mix materials. The grading of this aggregate conforms to the Iraqi specification No.45/1984[10].

4.4 Limestone Powder

Limestone powder is locally named "Al-Gubra" brought from Al-Mousel district and has been used as a filler for concrete production for many years. The particle size of the limestone powder is less than 0.125 mm, which satisfies EFNARC 2002[11] recommendations.

4.5 Super Plasticizer

In this work, the super plasticizer used is known commercially as "GLENIUM51". It is a new generation of modified polycarboxylic ether. It is compatible with all Portland cements that meet recognized international standards. Super plasticized concrete exhibits a large increase in slump without segregation. However, this provides enough period after mixing for casting and finishing the concrete surface.

4.6 Steel Reinforcing Bars

Deformed steel bars are used in this work with nominal diameters of 16 mm and 10 mm for longitudinal reinforcement in tension side (bottom side) and plain bars of diameter 4 mm are used for longitudinal reinforcement in compression side (top side) while deformed bars of 4 mm is used as vertical shear reinforcement. Tensile tests of steel reinforcement are carried out at the laboratory of Materials at the College of Engineering in AL-Mustansiriya University to determine the average yield stress and the ultimate stress. The test results are listed in **Table (2).** Steel reinforcing cages are shown in **Figure (1).**

Table .(2) Properties of reinforcing steel bars

Nominal bar diameter (mm)	Bar area (mm^2)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation at ultimate stress (%)
16	201	671	831	6.6
10	78.5	650	807	9.7
4	12.6	406	534	3.4
4 plain	12.6	413	521	3.1

Fig .(1) Steel reinforcement cage

5. Steel Fibers

Adding steel fibers to SCC is very suitable without needing to vibration because of its high workability. Hooked ends mild steel fibers are used in cast of fibrous self compacting concrete with volumetric ratio of 0.4 % and 0.8 %. **Table (3)** gives properties of the steel fibers taken from manufacture catalog.

6. Concrete Mix Proportions

To determine mix proportions for different types of concrete adopted in this study, the tables of mix proportion suggested by Al-jadiri[12] in her research carried out in 2008 is adopted with some modifications after performing many trial mixes. **Table (4)** gives the final quantities by weight of materials used in preparation of self compacting concrete per cubic meter for the different mixes adopted in this work.

Table .(3) Mechanical properties of steel fibers

Property	Specifications
Density	7860 kg/m^3
Ultimate strength	2000 MPa
Modulus of Elasticity	$200x10^3$ MPa
Strain at proportion limit	5650 $x10^{-6}$
Poisson's ratio	0.28
Average length	30 mm
Nominal diameter	0.375 mm
Aspect ratio (L_f/D_f)	80

Table (4) Proportions of SCC mixes per cubic meter

Mix name	Cement (kg)	Limestone powder (LSP) (kg)	Water (liter)	Sand (kg)	Gravel (kg)	Super plasticizer (liter)	Steel fibers (kg)
NSCC	400	170	190	797	767	7.5	0
NSCC-0.4	400	170	190	797	767	8.5	31.4
NSCC-0.8	400	170	190	797	767	10	62.8
HSCC	550	50	165	855	767	20	0
HSCC-0.4	550	50	165	855	767	22	31.4
HSCC-0.8	550	50	165	855	767	25	62.8

7. Tests on Fresh Concrete

In this work, consideration of concrete mix as a self compacting concrete is verified by three standard tests: Slump flow, $T_{50\ cm}$ slump flow and L-box as shown in **Figures (2) and (3).**

Fig .(2) Spreading concrete in Slump Flow test of SCC

Fig .(3) Flowing of concrete in horizontal section in L-box test of SCC

8. Mixing

The procedure of mixing is stated as follows:

1. The fine aggregate is added to the mixer with 1/3 quantity of water and mixed for 1 minute.
2. The cement and limestone powder are added with another 1/3 quantity of water. Then, the mixture is mixed for 1 minute.
3. The coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of super plasticizer, and the mixing time lasts for 1½ minutes then the mixer is left for 1/2 minute to rest.
4. Then, the 2/3 of the leftover of the dosage of super plasticizer is added and mixed for 1½ minutes.
5. The concrete is then discharged for performing fresh properties and casting.

However, for mixes containing steel fibers, the fibers are added during step 4 and mixed for 2 minutes to achieve homogenous distribution of fibers.

9. Test procedure and Measurements

All beams were tested using a hydraulically universal testing machine of 3000 kN capacity under monotonic loads up to ultimate load at the Structural Laboratory of the College of Engineering of Al-Mustansiriya University. Vertical deflections are measured at beam midspan using digital gauge of (0.01 mm) accuracy. Loading was applied at increments of 10 kN. At each load stage the deflection readings at the midspan of beam are recorded. When the first crack appeared, the corresponding load is recorded.

Fig .(4) Digital gauge location

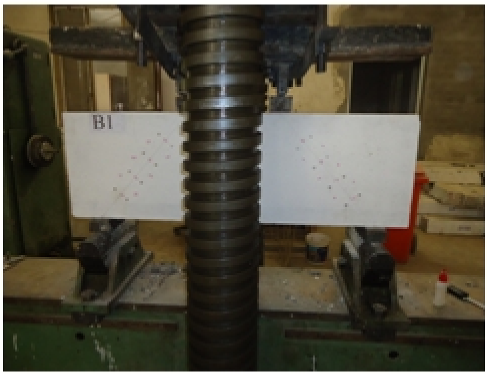

Fig .(5) Deep beam setup

10. Fresh SCC Properties Results

Table (5) illustrates the results of the three tests that carried out on SCC mixes and the comparisons with the standard limitations are also presented. From this table, one can notice that the results of all mixes tests satisfy the requirements of EFNARC[11] specifications except the last mix (HSCC-0.8) which exceeds the limitations by small margins in slump flow test and T_{50} slump flow test. The deviation is acceptable according ACI-237R-07[13] which gives limitation of 450-760 mm for slump flow test and according to Advanced Concrete Masonry Center[11] which suggests a value of > 600 mm for slump flow and a value of < 7 sec for T_{50} slump flow test for mixes which are designed with characteristic cube strength not less than 60 MPa.

Table .(5) Tests results of fresh SCC properties

Mix name	Slump flow (mm)	T_{50} (sec)	L – box (H_2/H_1)
NSCC	770	2.5	1
NSCC-0.4	740	3	0.97
NSCC-0.8	700	4	0.90
HSCC	730	4	0.92
HSCC-0.4	690	4.5	0.88
HSCC-0.8	640	6	0.81
Limits of EFNARC[10]	650-800	2-5	0.8-1

11. Hardened SCC Mechanical Properties Results

Table (6) shows test results of mechanical properties obtained for the two mixes. These properties are concrete compressive strength (f'_c), splitting tensile strength (f_t), modulus of rupture (f_r) and modulus of elasticity (E_c). Each value presented in this table represents the average value of three specimens.

Table .(6) Tests results of mechanical properties for hardened SCC

Mix name	f'_c (MPa)	f_t (MPa)	f_r (MPa)	E_c (MPa)
NSCC	32.84	3.12	4.41	24897
NSCC-0.4	33.29	3.78	6.32	25365
NSCC-0.8	34.54	4.15	7.02	26184
HSCC	64.65	4.56	6.80	35287
HSCC-0.4	67.39	5.43	8.21	36436
HSCC-0.8	66.35	5.92	8.83	35618

The concrete mixes give normal compressive strength about 32.84 MPa while high compressive strength about 64.65 MPa. This means that good design of mixes can achieve the requirements of both types of concrete: NSCC and HSCC. The increase in (f'_c) from 32.84 MPa to 64.65 MPa (97% increase) leads to increases in (f_t) from 3.12 MPa to 4.56 MPa (46% increase), in (f_r) from 4.41 MPa to 6.8 MPa (54% increase) and in (E_c) from 24897 MPa to 35287 MPa (42% increase).

The effect of steel fibers on concrete compressive strength and modulus of elasticity seems to be very small for both NSCC and HSCC. The splitting tensile strength and modulus of rupture are significantly affected by using steel fibers.

12. Test Results of SCC Deep Beams

Table (7) summarizes the results of first cracking load (P_{cr}) and ultimate load (P_u) for all tested beams together with their modes of failure.

Table .(7) Tests results of SCC deep beams

Beam name	a/d	f′c (MPa)	% V_f	P_{cr} kN	P_u kN	Mode of shear failure
A1	0.6	32.84	0	165	485	Diagonal splitting
A3	0.6	33.29	0.4	210	515	Diagonal splitting
A4	0.6	34.54	0.8	280	560	Diagonal splitting
B1	1	32.84	0	125	370	Diagonal splitting with crushing of nodal zone
B3	1	33.29	0.4	170	395	Diagonal splitting
B4	1	34.54	0.8	210	465	Diagonal splitting
C1	0.6	64.65	0	195	695	Diagonal splitting
C3	0.6	67.39	0.4	260	775	Diagonal splitting
C4	0.6	66.35	0.8	310	820	Diagonal splitting
D1	1	64.65	0	140	520	Diagonal splitting with crushing of nodal zone
D3	1	67.39	0.4	190	630	Diagonal splitting
D4	1	66.35	0.8	225	690	Diagonal splitting

13. Behavior of SCC Deep Beams

Figures (6), (7) and (8) show the crack patterns for some SCC deep beams after testing . At low load levels, all the tested beams behaved in an elastic manner where no defects in their structure and the cracks did not appear at any place and the deflections at midspan are small and proportional to the applied load. Generally, the first diagonal crack (shear crack) appears at the middle third of the diagonal region bounded by load and support positions at a loading level ranges between 27% and 50 % of the ultimate load. The first flexure crack is observed in the lower part of the beam at the middle region between load positions. As the load is further increased, the inclined cracks expand and extend toward the support and load positions, also new cracks form parallel to the first crack and new cracks form near support.

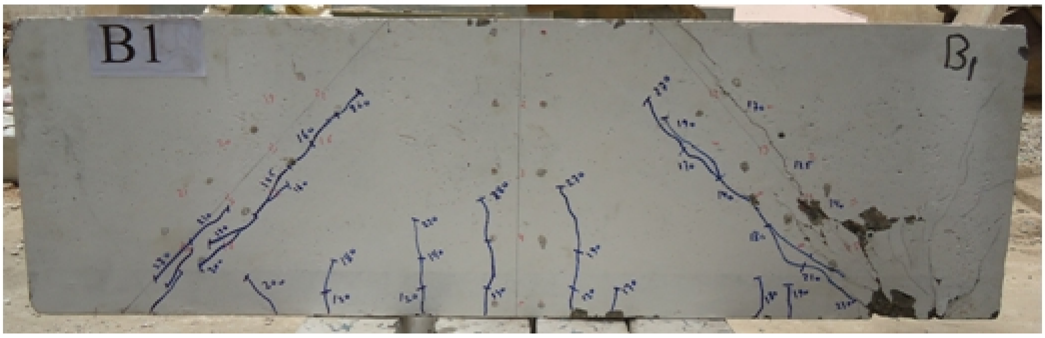

Fig .(6) Crack pattern after testing deep beam (B1)

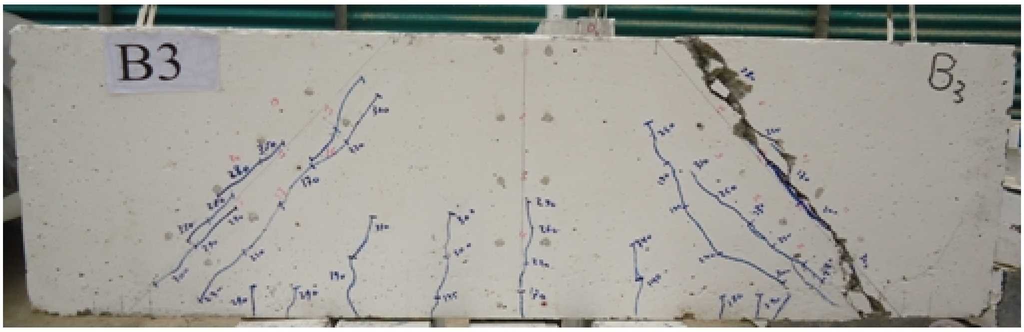

Fig .(7) Crack pattern after testing deep beam (B3)

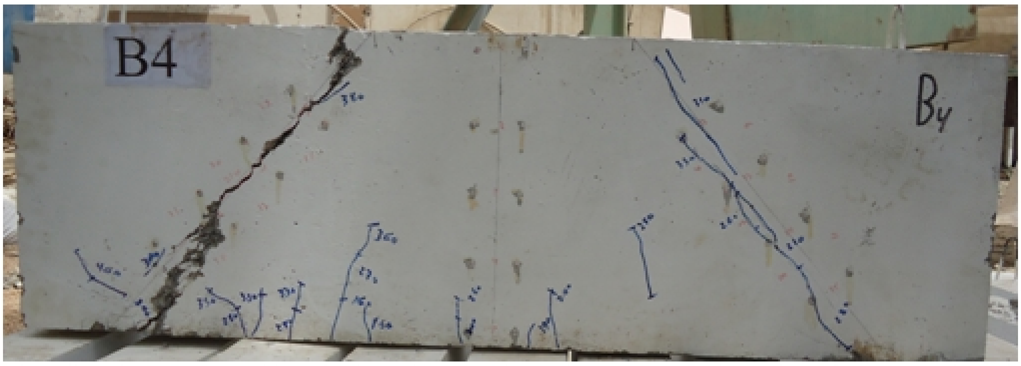

Fig .(8) Crack pattern after testing deep beam (B4)

Eventually, the diagonal cracks are many and one or more of these cracks might propagate into the compression zone at the loading position. Failure occurs by splitting the beam into two parts approximately along the line joining the edge steel blocks at the support and loading positions (diagonal splitting mode). Also the stirrups intersecting the splitting line are yielded or ruptured.

The splitting lines for beams of groups B and D are more pronounced than those of beams of group A and C because of higher tension stresses due to higher value of (a/d) ratio. At failure, number and length of flexural cracks in beams of group B and D are more than these in beams of group A and C because the higher bending moment due to higher value of (a/d).

The presence of steel fibers contributes in delaying appearance of cracks and hampers their development. It is clear in **Figures (7) and (8)** where the cracks are few and short especially at the mid span of beams (B3) and (B4) in comparison with crack pattern of beams (B1).

14. Effect of Shear Span to Effective Depth Ratio (a/d)

Effect of increasing (a/d) from 0.6 to 1 on cracking and ultimate loads and the ratio between them for all tested beams are detailed in **Table (8).** The reduction in cracking load due to increasing (a/d) ratio ranges from 19 % to 28.2 % (average of reduction is 25.1 %). The reduction occurring in HSCC beams is slightly larger than that occurring in NSCC beams. The reduction in the ultimate load due to increasing the (a/d) ratio from 0.6 to 1 ranges from 15.9 % to 25.2 % (average of reduction is 20.6 %). The reduction occurring in fibrous beams is smaller than that occurring in non fibrous beams and this reduction becomes smaller as (V_f) increase. The ratio between cracking and ultimate loads ranges from 0.28 to 0.5 for a/d = 0.6 while it ranges from 0.27 to 0.45 for a/d = 1, i.e., generally this ratio decreases as the (a/d) ratio increases.

Table .(8) Effect of the (a/d) ratio on cracking and ultimate loads

Strength type	V_f %	a / d = 0.6			a / d = 1			% Variation due to increasing (a/d)	
		P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} kN	P_u kN	P_{cr}/P_u	DP_{cr} %	DP_u %
Normal Strength	0	165	485	0.34	125	370	0.34	-24.2	-23.7
	0.4	210	515	0.41	170	395	0.43	-19	-23.3
	0.8	280	560	0.5	210	465	0.45	-25	-17
High Strength	0	195	695	0.28	140	520	0.27	-28.2	-25.2
	0.4	260	775	0.34	190	630	0.3	-26.9	-18.7
	0.8	310	820	0.38	225	690	0.33	-27.4	-15.9

From the **Figure (9),** it is clear that the increase in the (a/d) ratio significantly increases the deflection value for all load stages. This increase becomes larger as the applied load increases. The increase is more pronounced for HSCC beams but less pronounced as steel fibers content increases.

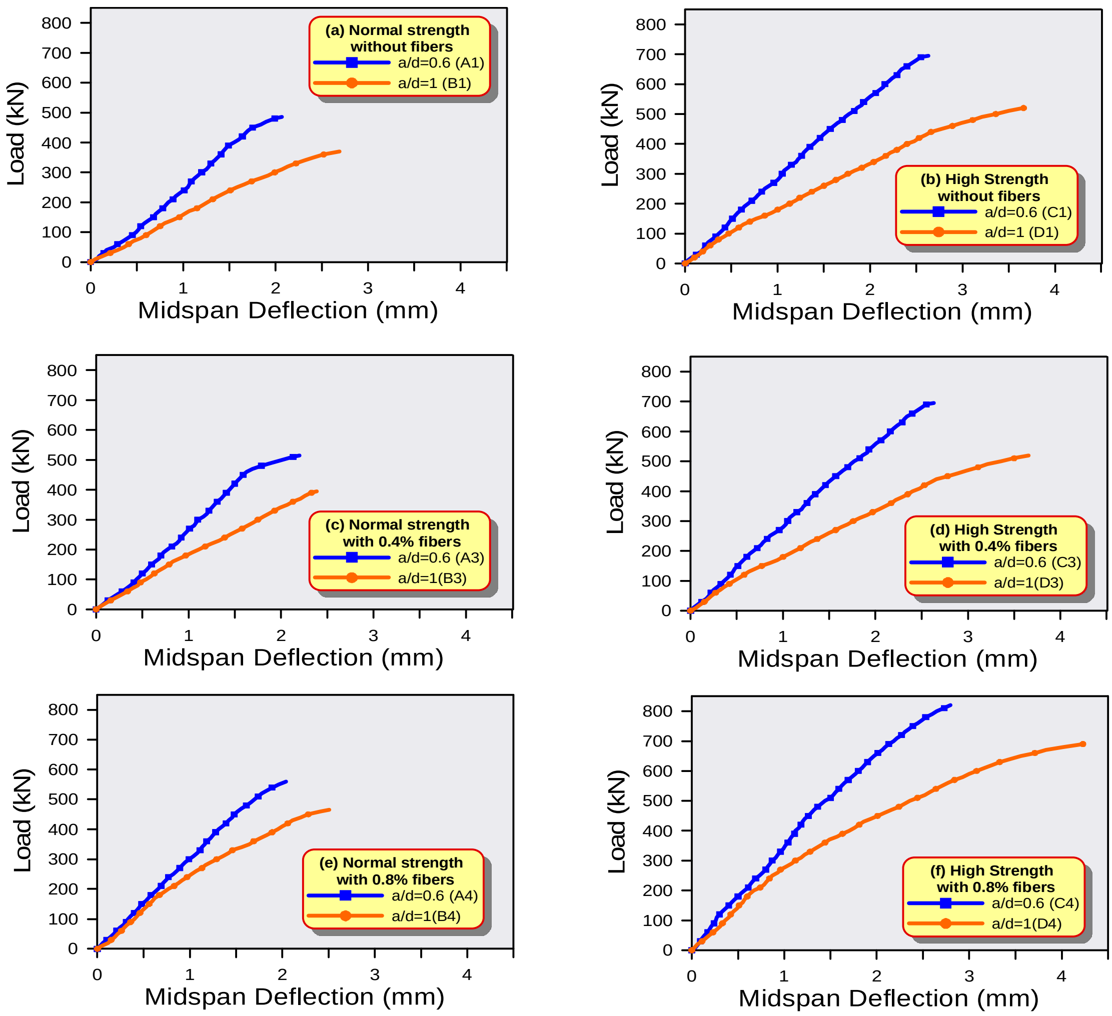

Fig .(9) Effect of the (a/d) ratio on load – midspan deflection curve

15. Effect of Concrete Compressive Strength (f'_c)

Effect of (f'_c) on cracking and ultimate loads and the ratio between them for all tested beams are detailed in **Table (9).** The improving in ultimate load due to doubling the (f′c) value ranges from 40.5 % to 59.5 % (average increase is 48.1 %). This improvement is approximately similar for the two considered values of (a/d) ratio. Also, this improvement increases when the steel fibers are present. The improvement in cracking load due to doubling the (f'_c) value ranges from 7.1 % to 23.8 % (average increase is 13.9 %). This improvement in cracking load becomes smaller as the (a/d) ratio increases. The ratio between the cracking and ultimate loads ranges from 0.34 to 0.5 for NSCC beams while it ranges from 0.27 to 0.38 for HSCC beams, i.e., this ratio decreases as (f'_c) increases.

From the **Figure (10),** it is clear that the increase in (f'_c) value reduces the deflection for all load stages. The reduction in deflection as a result of rising (f'_c) is insignificant. The increase in (f'_c) value results in higher modulus of elasticity then result in higher flexural rigidity (EI), therefore, the deflection is smaller (positive action). But this increase in (f'_c)

value results in decreasing the compression zone depth because of rising the neutral axis according to equilibrium of internal forces. This leads to smaller moment of inertia for beam section, thereby this leads to a reduction in flexural rigidity (EI) and an increase in the deflection (negative action). The two contradictory actions of (f'_c) lead to insignificant effect on deflection value.

Table .(9) Effect of (f'_c) on cracking and ultimate loads

	V_f %	Normal Strength			High Strength			% Variation due to increasing (f'_c)	
		P_{cr} kN	P_u kN	P_{cr} /P_u	P_{cr} kN	P_u kN	P_{cr} /P_u	DP_{cr} %	DP_u %
a / d = 0.6	0	165	485	0.34	195	695	0.28	+18.2	+43.3
	0.4	210	515	0.41	260	775	0.34	+23.8	+50.5
	0.8	280	560	0.5	310	820	0.38	+10.7	+46.4
a / d = 1	0	125	370	0.34	140	520	0.27	+12	+40.5
	0.4	170	395	0.43	190	630	0.3	+11.8	+59.5
	0.8	210	465	0.45	225	690	0.33	+7.1	+48.4

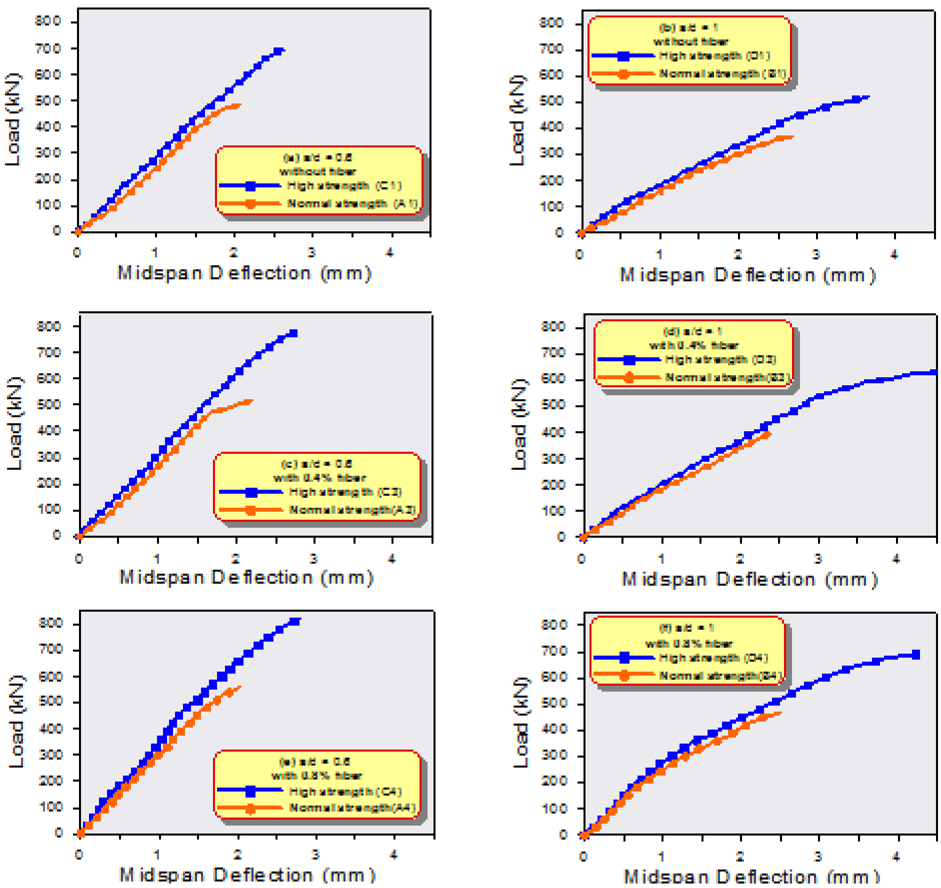

Fig .(10) Effect of the (f'_c) ratio on load – midspan deflection curve

16. Effect of Volumetric Steel Fiber Ratio (V_f)

Effect of (V_f) on cracking and ultimate loads and the ratio of them for all tested beams are detailed and **Tables (10) and (11).** The improvement in ultimate load value due to increasing (V_f) from 0 % to 0.4 % ranges from 6.2 % to 21.2 % (11.4 % as a typical average improvement for all four cases). The improvement becomes larger as the (a/d) ratio increases. The improvement in HSCC beams is larger than the improvement in NSCC beams. The improvement in ultimate load due to increasing (V_f) from 0 % to 0.8 % ranges from 15.5 % to 32.7 % (23 % as a typical average improvement for all four cases).

The improvement in cracking load due to increasing (V_f) from 0.0 % to 0.4 % ranges from 27.3 % to 36 % (33.1 % as a typical average improvement for all four cases). the improvement becomes slightly higher as the (a/d) ratio increases. The improvement in cracking load due to increasing (V_f) from 0 % to 0.8 % ranges from 59 % to 69.7 % (64.4 % as typical average improvement for all four cases). Generally, the improvements in NSCC beams are higher than the improvements in HSCC beams.

The presence of steel fibers result in a delay in crack initiation and propagation where they hold concrete particles and prevent them from initial separation. Therefore, the first crack in fibrous concrete beams appears at a load level appreciably higher than the load which causes crack initiation in non fibrous concrete beam. After cracking, the steel fibers prevent the crack widening and delay its growth by absorption a portion of tension stresses carried by concrete i.e., this action reduces the tension stresses applied to concrete. Therefore, the failure takes place in fibrous concrete beams at a load level higher than the failure load of non fibrous concrete beams. The ratio between cracking and ultimate loads increases with increasing steel fiber ratio, where it ranges from 0.27 to 0.34 for non fibrous concrete beams and ranges from 0.3 to 0.43 for fibrous concrete beams with 0.4 % of steel fibers. While the ratio ranges from 0.33 to 0.5 for fibrous concrete beams with 0.8 % of steel fibers.

Table .(10) Effect of using 0.4 % of steel fibers on cracking and ultimate loads

	Strength type	V_f= 0.0 %			V_f= 0.4 %			% Variation due to increasing (% V_f)	
		P_{cr} kN	P_u kN	P_{cr}/P_u	P_{cr} kN	P_u kN	P_{cr}/P_u	DP_{cr} %	DP_u %
a / d = 0.6	NSCC	165	485	0.34	210	515	0.41	+27.3	+6.2
	HSCC	195	695	0.28	260	775	0.34	+33.3	+11.5
a / d = 1	NSCC	125	370	0.34	170	395	0.43	+36	+6.8
	HSCC	140	520	0.27	190	630	0.3	+35.7	+21.2

Table .(11) Effect of using 0.8 % of steel fibers on cracking and ultimate loads

	Strength type	V_f= 0.0 %			V_f= 0.8 %			% Variation due to increasing (% V_f)	
		P_{cr} kN	P_u kN	P_{cr} /P_u	P_{cr} kN	P_u kN	P_{cr} /P_u	DP_{cr} %	DP_u %
a / d = 0.6	NSCC	165	485	0.34	280	560	0.5	+69.7	+15.5
	HSCC	195	695	0.28	310	820	0.38	+59	+18
a / d = 1	NSCC	125	370	0.34	210	465	0.45	+68	+25.7
	HSCC	140	520	0.27	225	690	0.33	+60.7	+32.7

From **Figure (11),** it is clear that the increase in (V_f) reduces the deflection at all load stages. This reduction in deflection due to presence of steel fibers is fairly considerable for all cases and for all load stages especially when 0.8 % of steel fibers is used. The effect of steel fibers in reducing the deflection at any load stage becomes larger as the (a/d) ratio increases.

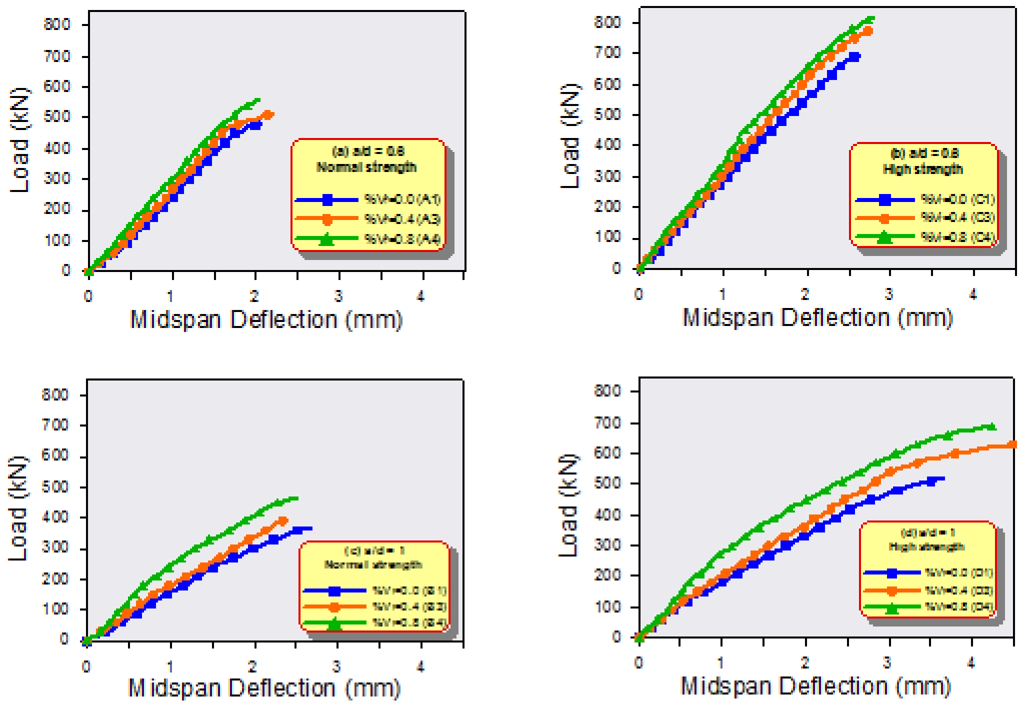

Fig .(11) Effect of the (%V_f) ratio on load – midspan deflection curve

17. Proposed equation for Analysis of SCC Deep Beams

The analytical part of this study includes the attempt to derive an mathematical expression for predicting the ultimate shear strength (V_n) of SCC deep beams so that it reflect the behavior of them accurately depending on regression analysis of test data. The expression of ultimate shear stress of concrete (n_c) will consist of three terms. The first term depends on material properties (compressive strength of concrete and ratio of tension reinforcement). It is proposed to be as follows:

$$\boldsymbol{first\ term} = \boldsymbol{a_1 (f'^{\,a_2}_c + a_3\, \rho)} \qquad \text{.......................... (1)}$$

The second term depends on beam geometry or load path (shear span and effective depth). It is proposed to be as follows:

$$\boldsymbol{second\ term} = \frac{\boldsymbol{1}}{\boldsymbol{1+b_1(a/d)}} \qquad \text{..........................(2)}$$

The third terms depends on fibers properties (fiber factor) and is proposed to be as follows:

$$\boldsymbol{third\ term} = \boldsymbol{(1 + c_1 \tfrac{a}{d} F)} \qquad \text{..........................(3)}$$

$$\boldsymbol{F = (\ell_f / d_f) V_f \beta} \qquad \text{..........................(4)}$$

where: ℓ_f / d_f = fiber aspect ratio

V_f =fiber volumetric ratio

β = bond factor taken as 0.75 (for hooked type of steel fibers)

The ultimate shear stress of web reinforcement is proposed to be as follows:

$$\boldsymbol{v_s} = \boldsymbol{\left(d_1 \tfrac{a}{d} \rho_v f_{yv} + (d_2 - \tfrac{a}{d}) \rho_h f_{yh}\right)} \qquad \text{..........................(5)}$$

The total shear strength of deep beams will be as combination of concrete and reinforcement strengths as follows:

$$\boldsymbol{V_n = (v_c + v_s) bd} \qquad \text{.......................... (6)}$$

The final expression of proposal will be as follows:

$$\boldsymbol{V_n} = \boldsymbol{\left[\frac{a_1 (f'^{\,a_2}_c + a_3\, \rho)(1 + c_1 \frac{a}{d} F)}{1 + b_1 \left(\frac{a}{d}\right)} + d_1 \frac{a}{d} \rho_v f_{yv} + (d_2 - \frac{a}{d}) \rho_h f_{yh}\right] bd} \qquad \text{................(7)}$$

Experimental results of twelve beams tested in this study and another fourteen beams available in literature[14] were adopted for regression analysis by Data Fit program for determination of coefficients (a_1, a_2, a_3, b_1, c_1, d_1 and d_2). All these coefficients are calculated by calibration of equation results with test results. The values of these coefficients are as follows after approximation of them to familiar values : a_1= 0.4 , a_2= 1, a_3= 1500, b_1= 4, c_1= 2/3, d_1= 1, and d_2= 3. Therefore the final expression of proposed equation is as follows:

$$V_n = \left[\frac{0.4(f'_c+1500\,\rho)(1+\frac{2a}{3d}F)}{1+4\left(\frac{a}{d}\right)} + \frac{a}{d}\rho_v f_{yv} + (3-\frac{a}{d})\rho_h f_{yh}\right] bd \quad \text{..................... (8)}$$

18. ACI Code-1999 equation[15] for Analysis of SCC Deep Beams

In this code, the total shear strength of deep beams is calculated by:

$$V_n = V_c + V_s \quad \text{..................... (9)}$$

$$V_c = \left(3.5 - 2.5\frac{M_u}{V_u d}\right)\left[\sqrt{f'_c} + 120r\,\frac{V_u d}{M_u}\right] b_w d/7 \quad \text{..................... (10)}$$

$$V_s = f_y d\left[\frac{A_v}{s_v}\frac{1}{12}\left(1+\frac{\ell_n}{d}\right) + \frac{A_{vh}}{s_{vh}}\frac{1}{12}\left(11-\frac{\ell_n}{d}\right)\right] \quad \text{..................... (11)}$$

In the above equations, the following conditions should be satisfied:

$$\left(3.5 - 2.5\frac{M_u}{V_u d}\right) \le 2.5 \quad \text{.....................(12)}$$

$$V_c \le 0.5\sqrt{f'_c}\,b_w d \quad \text{.....................(13)}$$

$$V_n \le \frac{1}{18}(10 + \frac{\ell_n}{d})\sqrt{f'_c}\,b_w d \quad \text{..................... (14)}$$

19. Rao-2012 Equation for Analysis of SCC Deep Beams

In 2012, Rao and Sundaresan[16] developed size-dependent shear strength expression for reinforced concrete deep beams as follows:

$$V_n = \left[\frac{11.4\rho^{0.35}\sqrt{f'_c}}{1+2\left(\frac{a}{d}\right)}\left(0.38 + \frac{1}{\sqrt{1+\frac{d}{25d_a}}}\right) + 0.02\,\rho^{-0.08}\rho_h f_y\left(\frac{d}{a}\right) + 0.31\rho_h f_y\left(\frac{a}{d}\right)\right] bd \quad \text{....(15)}$$

where: d_a = maximum size of coarse aggregate

20. Results of analysis

Experimental results of twelve beams (beams from A1 to D4 in **Table 12)** tested in this study and another fourteen beams (beams from B1 to B14 in Table 12) available in literature[14] are adopted for checking the validity of derived equation. **Table (12)** gives ratios of experimental to predicted results of shear strength values obtained by the proposed equation , the ACI- Code equation and Rao's equation. The proposed equation gives ratios that are close to unity for all beams. This means that the analytical results of the proposed equation have a good correlation with experimental results. This reflects the accuracy and rationality of the proposed equation. The results show that the ACI Code equation is very conservative. This means that the ACI Code equation significantly underestimate the ultimate shear capacity. The ACI Code equation is less accurate than the proposed equation. Rao's equation is safe and more accurate than the ACI Code equation but less accurate than the proposed equation. This is evident through the statistical results listed at bottom of **Table (12).**

Also, **Figure (12)** shows a comparison between experimental and predicted ultimate shear strengths (V_n) for the proposed equation, the ACI Code equation and Rao's equation. This figure shows the good correlation between the experimental and analytical results obtained for proposed equation in comparison with the ACI Code equation where its data points are less dispersant and closer to the 45^o line than data points of the ACI Code equation. Also, the figure shows underestimation or conservation of the ACI Code equation where the fit line of their data lies away from the 45^o line. Rao's equation have results that are less dispersant than the ACI Code equation results and its data fit line is fairly close to the 45^0 line.

Table .(12) Result of analysis by proposed Eq., ACI-1999 Eq. and Rao's Eq.

Beam Name	V_n Exp. (kN)	$V_{n\ Exp.} / V_{n\ Predicted}$			Beam Name	V_n Exp. (kN)	$V_{n\ Exp.} / V_{n\ Predicted}$		
		ACI 1999	Rao 2012	Proposed Equation			ACI 2011	Rao 2012	Proposed Equation
A1	242.5	2.629	1.036	1.065	B2	375	1.902	1.237	1.006
A3	257.5	2.774	1.092	1.031	B3	444	2.199	1.283	1.045
A4	280	2.967	1.167	1.018	B4	300	1.883	1.162	1.039
B1	185	2.005	1.043	1.071	B5	265	1.745	1.027	0.987
B3	197.5	2.128	1.107	1.003	B6	250	1.73	0.97	1.007
B4	232.5	2.464	1.28	1.039	B7	235	1.714	0.913	1.031
C1	347.5	2.764	1.065	1.035	B8	280	1.885	1.037	1.043
C3	387.5	3.023	1.163	1.028	B9	265	1.831	0.997	1.039
C4	410	3.222	1.241	1.014	B10	253.5	1.775	0.961	1.021
D1	260	2.068	1.061	1.054	B11	248	1.751	0.945	1.016
D3	315	2.457	1.26	1.091	B12	245	1.739	0.937	1.015
D4	345	2.711	1.39	1.034	B13	315	1.974	1.183	1.066
B1	335	1.962	1.237	1.018	B14	265	1.787	1.012	1.013
Avg.		2.196	1.108	1.046					
S.D.		0.462	0.126	0.0236					
C.O.V.		21.06%	11.34%	2.26%					
C.C.		0.572	0.857	0.994					

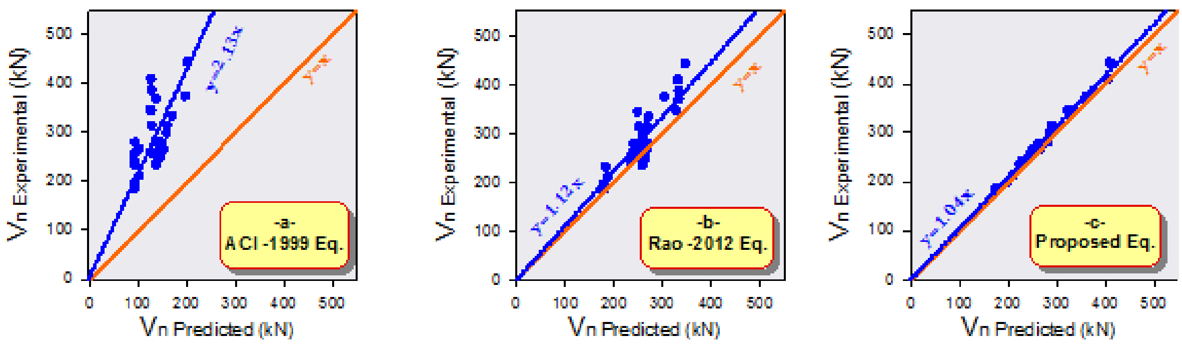

Fig .(12) Comparison between experimental and predicted ultimate shear strengths (V_n)

21. Conclusions

1- All tested SCC deep beams were failed by shear. The shear failure took place by diagonal splitting mode for all tested beams.

2- It was found that for all tested beams the increase in the shear span to effective depth ratio (a/d) from 0.6 to 1 reduces the cracking load by a range of 19 % to 28.2 % (average of reduction is 25.1 %). The reduction occurring in HSCC beams is slightly larger than that occurring in NSCC beams.

3- The increase in the (a/d) ratio from 0.6 to 1 reduces the ultimate load with a range of 15.9 % to 25.2 % (average of reduction is 20.6 %). The reduction occurring in fibrous beams is smaller than that occurring in non fibrous beams.

4- For all tested beams, the increase in the concrete compressive strength (f'_c) to the twice of the origin value improves the cracking load by a range of 7.1 % to 23.8 % (average increase is 13.9 %). This improvement in cracking load becomes smaller as the (a/d) ratio increases.

5- By increasing (f'_c) to the twice of the origin value, the ultimate load improves with a range of 40.5 % to 59.5 % (average increase is 48.1 %). This improvement increases when the steel fibers are present.

6- It was found that the use of 0.4 % of steel fibers increases the cracking load by a range of 27.3 % to 36 % for all cases (the average of increase is 33.1 %). While, the use of 0.8 % of steel fibers increases the cracking load with a range of 59 % to 69.7 % for all cases (the average of increase is 64.4 %). The improvements are generally larger in NSCC beams when compared with HSCC beams.

7- The presence of 0.4 % of steel fibers increases the ultimate load by a range of 6.2 % to 21.2 % for all cases (the average of increase is 11.4 %). While using of 0.8 % of steel fibers increases the ultimate load with a range of 15.5 % to 32.7 % for all cases (the average of increase is 23 %). The enhancement is larger in HSCC beams when compared with NSCC beams. Also, the enhancement becomes larger as the (a/d) ratio increases.

8- Values of cracking to ultimate load ratio range from 0.27 to 0.5 for all beams. This ratio is slightly decreased with increasing (a/d) ratio. Also, this ratio decreases with increasing (f'_c) but increases with increasing (V_f).

9- The load- deflection response of SCC deep beams is significantly affected by (a/d) ratio. The response becomes appreciably nonlinear as the (a/d) ratio increases. Load- deflection response is slightly affected by the compressive strength of concrete (f'_c). It was found that the response is slightly stiffer as (f'_c) increases. Also, The response becomes stiffer as fiber content increases especially when 0.8 % ratio of steel fibers is used.

10- An analytical equation to predict (V_n) is derived based on regression analysis of test results. It was found that the proposed equation give results that very close to test results of 26 SCC deep beams by comparison with results of the ACI-2011 Code equation and Rao's equation. Equation of the ACI Code is very conservative. The proposed equation gives Avg. = 1.046 and C.O.V. = 2.26 % While the ACI Code equation gives Avg. = 2.196 and C.O.V. = 20.06 %. Rao's equation gives Avg. = 1.108 and C.O.V. = 11.34 %.

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