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Shear Strength and Behavior of High Strength Reinforced Concrete Beams without Stirrups

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Abstract

This paper presents test results of twelve high strength reinforced concrete (HSRC) beams without stirrups which were tested to investigate their shear strength and behavior under loading. The shear behavior, ultimate load-carrying capacity, and mode of failure are presented. The applicability the ACI 318M-11, Modified Zsutty, and Sudheer et al, the influences of shear span to effective depth ratio (a/d) and compressive strength (fc') on their shear strength are also presented. It is found that, In general, with increasing each of compressive strength and (a/d) ratio the failure loads and consequently the shear strength of the beams didn't increase significantly. It is also found that ACI 318 M-11 overestimates for some test results (unsafe) while Sudheer et al equation underestimates for all test results excessively. However, Modified Zsutty equation underestimates the tested values for all the tested beams and could estimate shear capacity satisfactorily within a reasonable factor of safety. A regression equation was proposed and it was found to be more reliable and safe in predicting shear strength of high strength reinforced concrete beams.

Key words : shear strength, high strength. Stirrups

1.Introduction

High-strength concrete is defined as concrete having a specified compressive strength of 40MPa and higher[1]. The use of High Strength Concrete is likely to increase further in 21st century with the construction of more high-rise buildings, long span pre-stressed bridges, and pre-cast elements in concrete structures. Concrete unlike steel is relatively non-homogenous material; hence its different structural properties are likely to change with increase in compressive strength. The high strength concrete is comparatively a brittle material as the sound matrix of aggregates and cement paste provides a smoother shear failure plane, which leads to its abrupt failure. Consequently the shear strength of high strength concrete does not increase in the same way, as its compressive strength. The limited experimental work on the high strength concrete makes it difficult to safely predict the shear capacity of reinforced concrete members which is presently evaluated on the basis of empirical equations proposed by different building codes with certain modifications in the equations for normal strength concrete. As most of these equations have been derived on the basis of experimental data of concrete with compressive strength of 40MPa or less, therefore their application to higher values of compressive strength always raise questions in the minds of researchers. To further rationalize and generalize these empirical equations for shear design of high strength reinforced concrete members, extensive research is required [2].

2.Objectives

1. To evaluate the shear strength of high strength reinforced concrete (HSRC) beams without web reinforcement.
2. To study the effects of various variables (a/d ratio and compressive strength fc') on the shear strength and behavior of high-strength reinforced concrete beams without stirrups under a concentrated load.
3. To compare the ultimate diagonal cracking shear strength obtained from test results with values calculated from ACI and other researcher's predictions.
4. To obtain an equation to predict the shear strength of high-strength reinforced

concrete beams and comparing with other researchers' data.

3. Experimental Program

In this work twelve high strength reinforced concrete beams without stirrups were cast and tested under a single central concentrated load. The beam specimens were divided into three series according to their compressive strength and a/d ratio (shear span to effective depth ratio). Each series comprised of four beams as shown in Table 1.

4. Materials

Cement Ordinary local Portland cement (Type I), Tasluja factory was used. All results compliant with ASTM C150 [3].
Silica Fume For achieving desired compressive strength microsilica as a mineral admixture was used in the mix. The product was ordered and tested outside of the country which compliant to ASTM1240-95[4]. Fine Aggregate (sand) The sand used in this work has a grading conforms to ASTM C33 [5] limits.

Coarse Aggregate (Gravel) The gravel with maximum size 19mm for series (S1) and 12.5mm for series (S2,S3) was used. The aggregate grading conforms to limits of ASTM C33[5]Standard Specification for Concrete Aggregates. Water Tap drinking water was used throughout this experimental work for washing, mixing of materials as well as for casting and curing. Chemical Admixture (HRWR) Superplasticizers used to make the concrete more workable. In this work a superpalsticizer which is commercially known as (Proplast PC260 EXTRA) was used. Reinforcement Steel Deformed Turkish made steel bars with nominal diameter 20mm were used as flexural reinforcement. All bars have been placed in the tension face of beams to avoid failing in flexure.

5. Mix Proportions

Three types of concrete mixes were used for casting all specimens. The selected mixes and their properties are summarized in Table 2.

6. Specimen Details

The beam specimens were divided into three series each of four beams according to their compressive strength and a/d ratio. The cross sectional dimension of all beams were same (200*400) mm but the length were varied between (2.00 to 2.80)m to achieve different a/d ratio. For all beams the amount of flexural reinforcements (which consists of 3-20mm dia.) were kept constant and this reinforcement amount was selected to be in acceptance with ACI318 [6] limits for minimum and maximum amounts of flexural reinforcement. Table 3 summarizes details of all beam specimens.

7. Test Procedure

All beams were tested after 28 days age. The digital dial gauge for measuring mid span deflection was erected as shown in Fig.1. Also, the available electrical (LVDT)s for measuring web shear crack width were erected on both sides (left side and right side)of the beam as shown in Fig.2. All beam specimens were tested as simply supported loaded by a single concentrated load at mid span. After these steps, the application of load was started in 4kN increments. At each load increment mid span dial gauge readings for deflection and (LVDT)s readings for web shear crack width at both sides of the beams were recorded. Furthermore, at each load increment, position, load magnitude, and cracks which appeared were marked and recorded carefully and these procedures were continued until failure. In parallel, the compressive strength test were carried out on standard (150*150*150)mm cubes together with the beams according to BS1881-116[7] to obtain the compressive strength value of each beam series. For each series of beams three cubes were tested. Moreover, splitting tensile test according to ASTM C496 [8] was carried out on cylindrical (150*300)mm specimens. For each series of beams three cylinders were tested and average values of (fsp) were recorded.

8. Experimental Results and Discussions

8.1 Midspan Deflection

After plotting load - deflection diagram, it was found that, in general, for the specified concrete compressive strength ,mid span deflection decreased as (a/d) ratio decreased. Fig.3 is presented for beams in (Series 2) . However, for the specified value of (a/d) ratio and different compressive strength, deflections were almost similar. Fig.4 is presented for beams (B2S1, B2S2, B2S3). In summary, it can be concluded that in this work (a/d) ratio factor has a greater effect on mid span deflection of the tested beams rather than compressive strength factor because when the latter factor is considered, the amount of longitudinal flexural reinforcement which was kept constant for all beams plays a vital role on deflection of the beams for different values of compressive strengths.

8.2 Mode of Failure

All the beams were failed in shear as shown in Fig. 5. In general, there are two modes of inclined cracking that were observed. In the first mode, the inclined (diagonal) crack was formed independent of flexural cracks, and is often referred to as a "web-shear crack". In the second mode, the inclined crack started as an extension of an already developed flexural crack, this is generally denoted as "flexural-shear crack". After the cracks developed and with increasing of applied load one of the following two failure modes were observed for each beam specimen:

a. Shear Compression Failure : After formation of the inclined crack (web shear crack or flexural shear crack) and with increasing of the applied load, the crack extended toward the point load and the support. After some stages, the concrete above the upper end of the inclined crack and at the point of application of the point load exhibited more cracks and subjected to crushing resulting in the "shear compression failure" of the beam. This mode of failure was seen in all tested beams except in (B4S3).

b. Shear Tension Failure : After formation of the inclined crack (web shear crack or flexural shear crack) and with increasing of the applied load, the crack extended toward the point load and the support. After some stages, some secondary cracks due to the dowel action of the longitudinal flexural reinforcement bars appeared at the lower end of the crack. These secondary cracks propagated backward along the longitudinal bars from the inclined crack to the support and caused loss of bond , splitting of the concrete, further propagation of the cracks, and an anchorage failure of the longitudinal bars. This failure is called "shear tension failure", and it was observed in (B4S3).

8.3 Web-Shear Crack Width

For measuring the web-shear crack width of the beam specimens, available (LVDT)s were fixed on right and left sides of each tested beam at the mid height of its depth as shown in Fig.2. Through the (LVDT)s readings, web-shear crack width of the concrete beams was measured progressively with the load increments. For illustrating the effects of varying (a/d) ratio and compressive strength (fc') on web-shear crack width, load versus web-shear crack width diagrams considering these two variables for each beam series and its individuals are plotted. For example, in Fig.6 load versus web shear crack width for beams in (series 1) is illustrated for a specific value of fc' (74.58MPa) and different a/d ratio, and in Fig.7 load versus web shear crack width for beams (B2S1, B2S2, B2S3) is illustrated for a specific value of a/d (2.86) and different fc'. It can be concluded that for a specific compressive strength (fc') and different (a/d) ratio, as much as (a/d) ratio decreased, web-shear crack width of the concrete beams decreased. On the other hand, for a specific value of (a/d) ratio, beams with higher compressive strength (fc'), exhibited larger web-shear crack width and more brittle behavior accompanied by brisker failure.

8.4 Failure Loads

a. Effects of (a/d) : Failure loads versus (a/d) ratios for all beams of the three series are plotted in Fig. 8 to visualize how the (a/d) ratio affects failure loads. It can be seen that for a specified value of compressive strength, variation of (a/d) ratio has a direct effect on failure loads of the tested beam such that with increasing (a/d) ratio failure loads decreased.

b. Effects of (fc') : All tested beams were failed in shear, and their failure loads were dependant mostly on the value of compressive strength. For different values of (a/d) ratios, the effect of variation of the compressive strength on the tested beams is illustrated in Fig.9. It can be concluded that, in general, with increasing compressive strength the failure loads decreased. However, there is some irregularity in beams of series 2 (S2) which can be justified by the different properties of these beams due to the existence of larger amount of silica fume and superplasticizer in their concrete mixture. It was also observed that with increasing the compressive strength, the tested beams behaved in brittle manner which results in more brisker failure of them.

9.Comparing test results with other provisions

The following three common equations were used for the purpose of comparison of test results:

ACI 318M-11 Equation for Shear Prediction[6]. For members subjected to shear and flexure only, ACI 318M-11 propose the following equation for predicting shear strength of reinforced concrete beams

$$Vc = [0.16\,(fc')0.5 + 17\rho(Vu\ d/Mu)]bwd$$

$$\text{but } \leq 0.29\,(fc')0.5\ bw\ d \qquad \ldots\ldots\ldots(1)$$

where:

Vc = Nominal shear strength provided by concrete, N

fc' = Compressive strength of concrete (N/mm2)

ρ = Flexural reinforcement ratio As/ (bw d)

Vu = Factored shear force at the section considered, N

Mu = Factored moment at the section considered, N.mm

bw , d = Web width, effective depth, mm.

Modified Zsutty Equation for Shear Prediction[9]

Wafa, et al proposed some modifications for Zsutty Equations to predict shear strength of high strength concrete beams at different (a/d) ratio. For limits of normal beams (a/d >2.5) , the following equation was proposed:

$$Vc = 2.1\,(fc'\ \rho\ d/a)0.33\ bwd \quad \text{for } a/d > 2.5 \qquad \ldots(2)$$

where:

Vc = Nominal shear strength provided by concrete. N

fc' = Compressive strength of concrete (N/mm2)

ρ = Flexural main reinforcement ratio [As/ (bw d)]

a = Shear span, mm

bw , d = Web width, effective depth, mm

The equation proposed by Sudheer et al [10] .

Sudheer et al, in 2010, proposed a linear regression equation in power series to estimate the shear resistance (Vc) of high strength reinforced concrete beams as shown below:

$$Vc = 32\,(ft\ \rho\ /\ (a/d)\ )0.8\ bw\ d \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

where

Vc = Nominal shear strength provided by concrete ,N

ft = Tensile strength of concrete in (N/mm2).

a/d = Shear span to effective depth ratio.

ρ = Flexural main reinforcement ratio [As/ (bw d)]

bw ,d = Web width, effective depth, mm

On the bases of test results (Vtest) and the predicted values (Vpredict) from each equations, the statistical parameters were calculated for the three beam series of the work as shown in Table 4.

10. Proposed regression equation for predicting shear strength of beams without stirrups

On the bases of the test results of the twelve reinforced concrete beams of this study, a regression analysis is performed to formulate a predictive equation for the ultimate shear strength of high strength reinforced concrete beams without stirrups. The equation is as follows:

$$Vc = 1.378(fc'\ \rho/\{ft\ (a/d)2\} + ft/(a/d))1.393\ bw\ d \quad \ldots\ldots\ (4)$$

Vc = Nominal shear strength provided by concrete, N

ρ = Flexural main reinforcement ratio

fc' = Compressive strength of concrete (N/mm2)

a/d = Shear span to effective depth ratio

ft = Tensile strength of concrete in (N/mm2)

bw d = Web width, effective depth, mm

Table 5 presents the predicted results of the tested beams on the bases of Eq. (4) and comparison between predicted and test results.

11. Comparing the proposed and other equations based on the other researchers' data

The proposed and other mentioned equations are applied on the data of the twelve tested beams of this study and the data of other 121 tested beams selected from other researchers' investigations. The compressive strength of the selected beams are between 41.45 MPa $\leq$ fc'$\leq$ 97.70 MPa and (a/d) ratio are between 2.43$\leq$ (a/d) $\leq$6. Summary of the results of the calculated statistical parameters is summarized inTable6.

12. Conclusions

Based on the results and the theoretical analysis of the twelve tested beams of this study and 121 beams from other researchers' data, and by taking into account the effects of (a/d) ratio and compressive strength on shear strength and behavior of high strength reinforced concrete beams without stirrups, the following conclusions could be drawn:

1. 1.High-strength reinforced concrete beams without web reinforcement presented a very fragile behavior. The higher the concrete compressive strength is, the brisker the failure will be (more brittle behavior).
2. Both (a/d) ratio and compressive strength affect the mid span deflection and first flexural crack loads of the tested beams. However, (a/d) ratio factor has a more direct and regular effect rather than compressive strength factor because when the latter factor is considered, other factors such as the amount of longitudinal flexural reinforcement (which was kept constant for all beams in this study) and the different properties of the concrete mixtures due to existence of different contents of silica fume and superplasticizer also play vital roles on the deflection and consequently the first flexural load of the beams for different values of compressive strength.
3. In general, with increasing each of compressive strength and (a/d) ratio, the failure loads and consequently the shear strength of the tested beams decreased or in best case did not increase significantly.
4. For a specific value of compressive strength (fc') and different (a/d) ratio, as much as (a/d) ratio decreased, web-shear crack width of the concrete beams decreased. Meanwhile, for a specific value of (a/d) ratio, beams with higher compressive strength (fc'), exhibited larger web-shear crack width and more brittle behavior accompanied by brisker failure.
5. On the bases of results of this study, for each one of ACI 318M-11, Modified Zsutty, and Sudheer et al equations as much as the compressive strength and (a/d) ratio increased, the values of the [V(predict) / V(test)] also increased which indicates that the equations become less conservative.
6. ACI 318M-11 equation underestimates the tested values for almost all the tested beams which means that this equation is slightly conservative for the tested beams, and with increasing compressive strength and (a/d) ratio, it loses its conservation.
7. Modified Zsutty equation underestimates the tested values for all the tested beams and could estimate shear capacity satisfactorily within a reasonable factor of safety.
8. Sudheer et al equation underestimates excessively the tested values for all the tested beams and provides excessive factor of safety for the values.
9. Neither the three selected equations (ACI 318M-11, Modified Zsutty, and Sudheer et al), nor the current proposed equation (Eq.4) are totally conservative for all the beams tested by other researchers in predicting the shear capacity of reinforced high strength concrete beams.
10. Both Modified Zsutty and the proposed (Eq.4) equations could estimate the shear strength of reinforced concrete beams of other researchers more accurately and safely comparing to other equations because they overestimated for fewer number of beams.
11. ACI 318M-11 equation has lower degree of safety and accuracy in predicting the shear capacity of reinforced high strength concrete beams of other researchers comparing to other equations.
12. Even though Sudheer et al equation is excessively conservative on the bases of test results of this study, it could not predict the shear strength results of the other researchers safely and overestimates for larger number of beams comparing to modified Zsutty and the proposed (Eq.4) equations.

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سلوك ومقاومة القص للعتبات الخرسانية المسلحة ذات المقاومة العالية بدون حديد القص

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المستخلص :
معظم المعادلات التى تستخدم لحد الان لتخمين مقاومة القص (Shear Strength) للعتبات الخرسانية المسلحة عالية المقاومة هي حصيلة تلك الابحاث التى استخدمت فيها خرسانة بمقاومة انضغاط (Compressive Strength) (40MPa) او اقل ، لذلك السبب ، استخدام تلك المعادلات لتخمين قوة القص للعتبات الخرسانية ذات مقاومة انضغاط عالية ادت الى اسئلة كثيرة لدى الباحثين ، لأن أى زيادة فى مقاومة الأنضغاط لا يؤدى الى زيادة واضحة فى مقاومة القص (وفى معظم الأحيان تقل) مقارنة مع الزيادة التى نجدها فى العتبات ذات مقاومة انضغاط اقل . بالأضافة الى وجود عوامل كثيرة تؤثر على قوة القص وقلة الأبحاث التى أجريت على العتبات الخرسانية المسلحة عالية القاومة ، كل هذه الأمور ادت الى جدل كثير بين الباحثين وهذا ادى الى ضرورة استمرار الابحاث . هذا البحث محاولة جديدة لدراسة مقاومة القص ومعرفة سلوك العتبات الخرسانية المسلحة عالية المقاومة بدون (Stirrups) ، ومقارنة النتائج ببعض المعادلات الموجودة و ايجاد معادلة عملية لتخمين مقاومة القص . ولهذا الغرض تم صب واختبار 12 عتبة خرسانية مسلحة عالية المقاومة بدون (Stirrups) بأبعاد 200ملم *400ملم وبأطوال مختلفة وبأخذ (a/d) (نسبة مسافة القص الى العمق الفعال للعتبات) و مقاومة انضغاط (Compressive Strength) كمتغيرين اساسيين . علما ان (a/d) تضمنت القيم الاتية (2.43,2.86,3.29,3.71) و مقاومة انضغاط تضمنت هذه القيم (MPa, 67.72MPa, 74.58MPa63.98) . وقد تم اختبار جميع العتبات بوضع حمل فى وسط كل عتبة وقرأة الانحراف فى وسط العتبة (Mid Span Deflection) ثم قراءة سمك الشقوق فى الاسطح الخارجية للعتبة (Web Shear Crack Width) . وقد اضهرت النتائج ان تأثير (a/d) اكثر انتظاما و فاعلية على مقدار الانحراف فى وسط العتبات وعلى مقدار القوة اللازمة لضهور الشقوق الاولية (First Flexural Crack Load) مقارنة بتأثير مقاومة ا انضغاط . وقد اضهرت النتائج ايضا ان بزيادة مقاومة انضغاط و (a/d) ،القوة اللازمة للانهيار (Failure Load) ومقاومة القص (Shear Strength) تقل او لا تزيد بنسبة واضحة . وبعد مقارنة نتائج الاختبار بالمعادلات الموجودة تبين ان المعادلة (ACI 318M -11) تعطى نتائج اعلى من نتائج الاختبار لبعض من النماذج وهذا يعنى انها معادلة غير امنة بينما معادلة (Sudheer et al) تعطى نتائج اقل بكثير من نتائج الاختبار بصورة مبالغ فيها لكل النماذج . لكن معادلة (Modified Zsutty) تعطى نتائج اقل من نتائج الاختبار لكل العتبات بفارق مقبول وهذه اشارة الى انها افضل معادلة لتخمين مقاومة القص للعتبات مقارنة بمعادلات اخرى . واخيرا ،تم استحداث معادلة جديدة بأستخدام نتائج الفحوص وبعد مقارنة هذه المعادلة الجديدة بالمعادلات الاخرى باستخدام نتائج النماذج الحالية ونتائج ابحاث سابقة تبين ان المعادلة الجديدة موثوقة وامنة مقارنة بالمعادلات اخرى لتخمين مقاومة القص للعتبات الخرسانية المسلحة عالية المقاومة بدون (Stirrups) .

الكلمات المفتاحيه: مقاومة القص ،مقاومة عالية ،قفائص .

Table 1 : Series Classifications and Details

Series ID	Beam ID	(a/d)	f_c'(MPa)
S1	B1S1	2.43	74.58
	B2S1	2.86	
	B3S1	3.29	
	B4S1	3.71	
S2	B1S2	2.43	67.72
	B2S2	2.86	
	B3S2	3.29	
	B4S2	3.71	
	B1S3	2.43	
	B2S3	2.86	
	B3S3	3.29	
	B4S3	3.71	

Table 2 : Mix Proportions and Properties

Mix No.	Cement kg/m^3	Silica Fume Kg/m^3	Sand kg/m^3	Gravel kg/m^3	(HRWA) Lit/(100kg cement)	Water kg/m^3	W/cm* ratio	f_c' (MPa)
1	525	25 (4.7%)	840	945	0.95	140	0.25	74.58
2	510	42.84 (8.4%)	685	1080	3	143.73	0.26	67.72
3	450	22.5 (5%)	700	1100	1.1	151.2	0.32	63.98

W/cm = water cementitious material ratio

Table 3 : Properties and details of tested beams

Series ID	Beam ID	Total length mm	Effective length mm	b mm	H mm	d mm	a mm	a/h*	a/d	ρ **	f_c' MPa
S1	B1S1	2000	1700	200	400	350	850	2.13	2.43	0.013464	74.58
	B2S1	2400	2000				1000	2.50	2.86	0.013464	74.58
	B3S1	2800	2300				1150	2.88	3.29	0.013464	74.58
	B4S1	2800	2600				1300	3.25	3.71	0.013464	74.58
S2	B1S2	2000	1700				850	2.13	2.43	0.013464	67.72
	B2S2	2400	2000				1000	2.50	2.86	0.013464	67.72
	B3S2	2800	2300				1150	2.88	3.29	0.013464	67.72
	B4S2	2800	2600				1300	3.25	3.71	0.013464	67.72
S3	B1S3	2000	1700				850	2.13	2.43	0.013464	63.98
	B2S3	2400	2000				1000	2.50	2.86	0.013464	63.98
	B3S3	2800	2300				1150	2.88	3.29	0.013464	63.98
	B4S3	2800	2600				1300	3.25	3.71	0.013464	63.98

* All values of this column are greater than 2 which confirms that all beams are out of limits of deep beams as described in ACI 318[6].

** All values of this column are within the maximum and minimum limits as described in ACI318[6].

Table 4 : Summary of Statistical Parameters of the Selected Equations Based on Test Results.

Series	Beam	f_c' MPa	a/d	$V_{(predict)}$ / $V_{(test)}$ ACI	Modified Zsutty	Sudheer
1	B1S1	74.58	2.43	0.59	0.57	0.58
	B2S1		2.86	0.81	0.74	0.69
	B3S1		3.29	1.08	0.96	0.84
	B4S1		3.71	1.11	0.94	0.77
			Mean	0.8955	0.8018	0.7205
			Standard Deviation	0.2468	0.1807	0.1118
			Coefficient of Variation %	27.5634	22.5366	15.5132
2	B1S2	67.72	2.43	0.47	0.46	0.45
	B2S2		2.86	0.80	0.74	0.67
	B3S2		3.29	0.97	0.86	0.73
	B4S2		3.71	0.86	0.73	0.59
			Mean	0.7726	0.6993	0.6102
			Standard Deviation	0.2134	0.1680	0.1200
			Coefficient of Variation %	27.6236	24.0245	19.6720
3	B1S3	63.98	2.43	0.44	0.43	0.43
	B2S3		2.86	0.61	0.57	0.52
	B3S3		3.29	0.69	0.62	0.54
	B4S3		3.71	0.96	0.83	0.67
			Mean	0.6746	0.6117	0.5414
			Standard Deviation	0.2185	0.1634	0.1006
			Coefficient of Variation %	32.3913	26.7164	18.5760

Table 5 : Test and Predicted Shear Results Based on the Proposed Eq.(4)

Series	Beam	f_{sp}' MPa	f_c' MPa	ρ	d mm	b_w mm	a/d	V_c (prop.) Eq. (5-4)	V_c (Test)	V_c(prop.)/V_c (Test)
1	B1S1	4.21	74.58	0.013464	350	200	2.43	214.17	192	1.12
	B2S1						2.86	169.87	140	1.21
	B3S1						3.29	139.27	104	1.34
	B4S1						3.71	117.49	102	1.15
2	B1S2	3.89	67.72				2.43	192.23	230	0.84
	B2S2						2.86	152.42	136	1.12
	B3S2						3.29	124.93	112	1.12
	B4S2						3.71	105.38	126	0.84
3	B1S3	3.89	63.98				2.43	191.87	242	0.79
	B2S3						2.86	152.18	174	0.87
	B3S3						3.29	124.76	152	0.82
	B4S3						3.71	105.25	110	0.96
									Mean	1.0144
									Standard Deviation	0.1831
									Coefficient of Variation %	18.0476

Table 6 : Summary of Statistical Parameters for the Proposed and other Equations Based on the Current Test and other Researchers' Test Results

Equation	No.of Beams	Mean $V_{predict}$ / V_{Test}	Standard Deviation	Coeffficient of Variation %	Note
Proposed Equation(5.4)	133	0.8497	0.2773	32.6360	Overestimates for 40 beams
ACI 318M-11		1.0118	0.2504	24.7535	Overestimates for 74 beams
Modified Zsutty		0.8840	0.1893	21.4189	Overestimates for 35 beams
Sudheer Reddy.L et al.		0.8308	0.3343	40.2453	Overestimates for 43 beams

Fig.1 : Deflection digital dial gauge at mid-span of beams.

Fig.2 : LVDT Instruments and their location

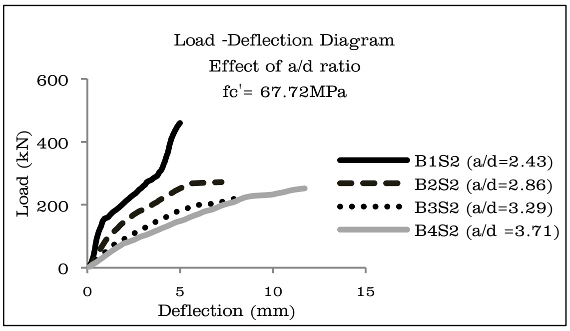

Fig.3 : Load-Deflection relationship (Series 2)

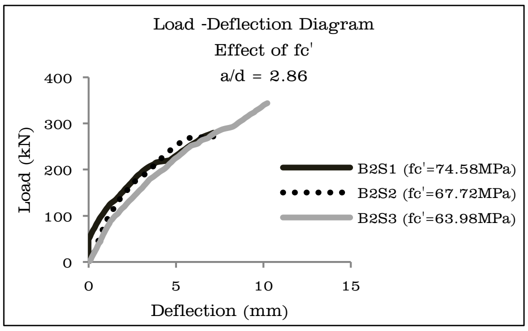

Fig.4 : Load-Deflection relationship (B2S1, B2S2, B2S3)

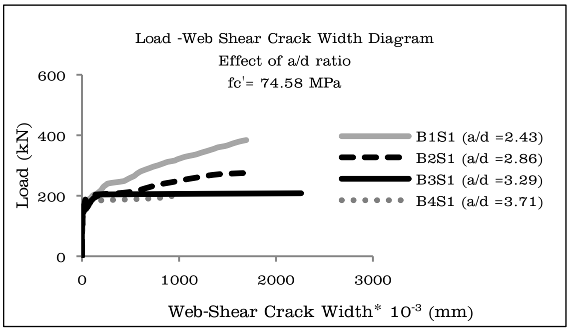

Fig.6 : Load versus web-shear crack width diagram (Series 1)

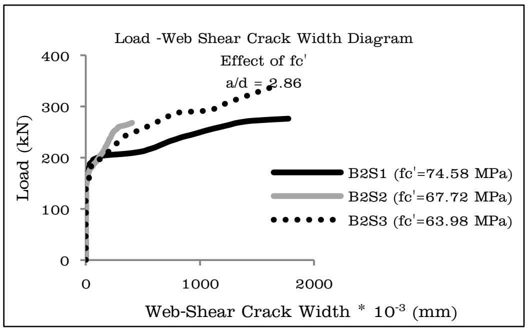

Fig.7 : Load versus web-shear crack width diagram (B2S1,B2S2,B2S3)

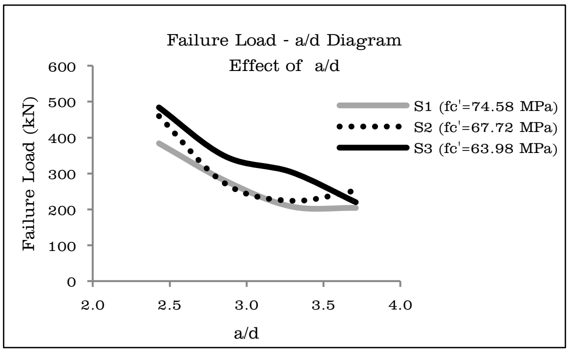

Fig.8 : Effect of (a/d) on failure load

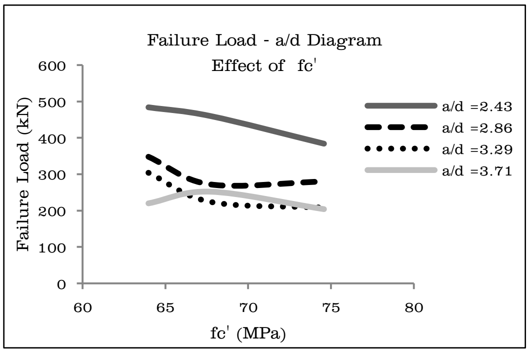

Fig.9 : Effect of (fc') on failure loads

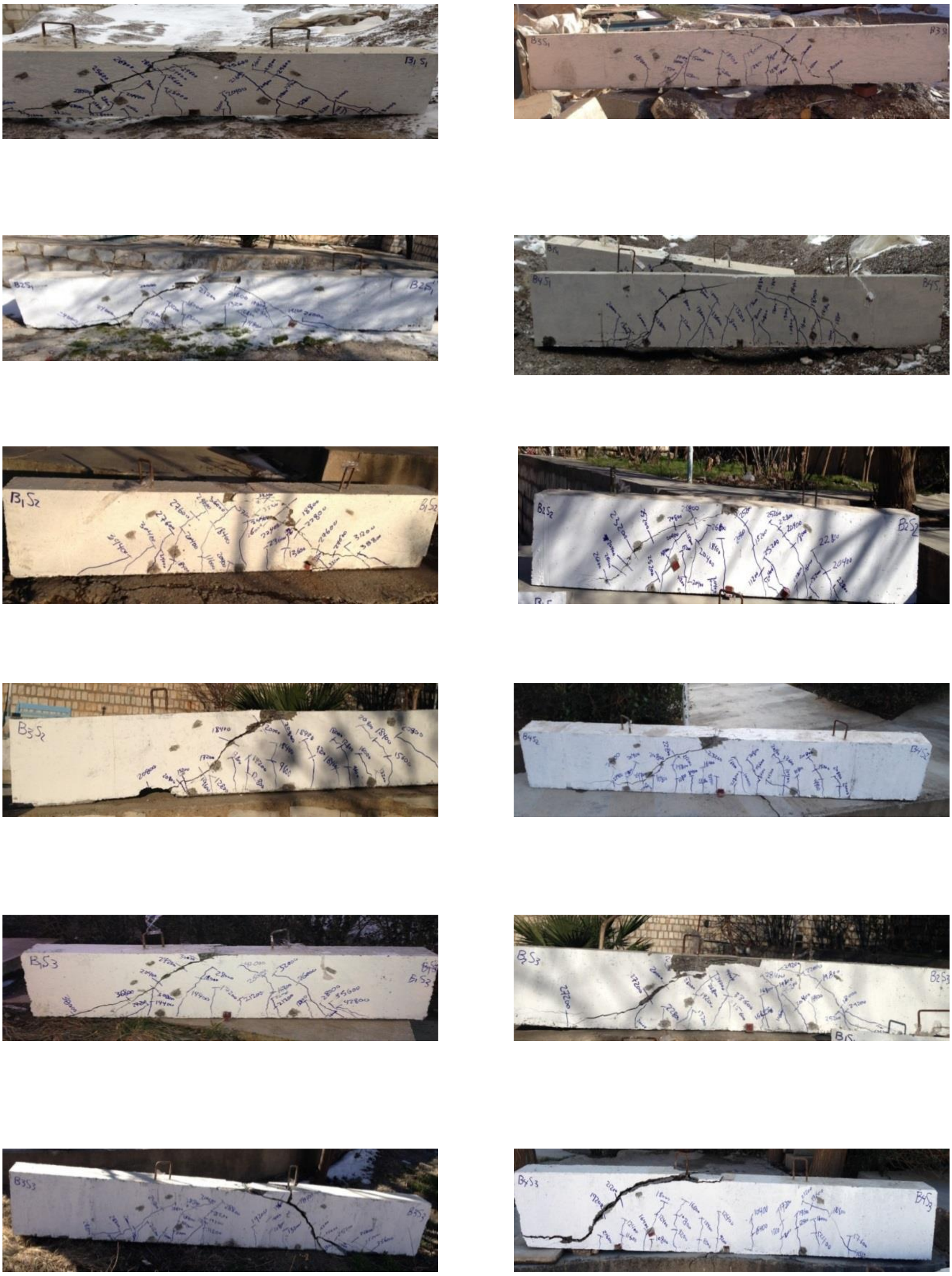

Fig.5 : Crack patterns of tested beams