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Research paper



Influence of stirrup spacing on shear resistance and deformation of reinforced concrete beams

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Abstract

An experimental investigation was carried out to study shear carrying capacity and ultimate flexural moment of reinforced cement concrete beam. Two series of simply supported beams were prepared by varying diameter and spacing of shear and flexural reinforcement. Beams of cross section 230 mm X 300 mm and length of 2000 mm. During testing, maximum load, first crack load, deflection of beams were recorded. Test results indicated that decreasing shear spacing and decreasing its diameter resulted in decrease in deflection of beam and increase in bending moment and shear force of beam.

Keywords: *Deflection; Flexural; Moment, Shear; Stirrups.*

1. Introduction

Strengthened Reinforced Cement Concrete (RCC) beams and columns are most regular basic individuals in structural building structures. The primary target of the basic plan is that the structure must fulfill as far as possible states. Structures planned by utmost condition of fall must be checked for deflection and width of cracks. The cracks in the concrete happen when the rigidity of the concrete is lesser than the nominal tensile stress in concrete. Inordinate cracking of cement and deflection genuinely influences the appearance and toughness of the structure.. The both flexure and shear failure happens when the beam achieved its maximum load. The inclined shear cracks may form before or after the flexural cracks development in the beam.

Various examinations were done on shear performance of concrete. But still at the same time shear cracking systems of concrete beams are not completely caught on. Shear reinforcement are important to enhance the shear resisting capacity of the beams if the permissible shear stress is lesser than the real shear stress. Since the inclining strain of the flexural part is bigger than the longitudinal strain the width of shear crack is generally broad than flexural cracks. In Reinforced Concrete (RC) beams inclined cracks are the sign shear failure. These cracks more extensive than the flexural cracks and happened in the shear zone which is closer to the supports. The shear cracks increase quickly and the beam fails all of a sudden. Giving shear reinforcement lessened this sudden failure and also boosts the ductility of the beam. Until the inclined crack develop, it was accepted that the concrete alone oppose the total shear. After the inclined crack develop, debonding and redistribution of stress happens in concrete and both stirrups and concrete shared the shear stress. In RCC shafts the stirrup proportion impacted the inclined width of the crack. The width of the inclined crack was additionally impacted by the bond between the concrete and the stirrups. By decreasing the stirrups spacing the bond amongst concrete and stirrups was expanded. The width of the shear cracks will be minor in decreased stirrups spacing beams than in conventional shear reinforced beams. The RC structure must have least shear reinforcement to resist shear and significant shear crack load is contributed by total interlocking force.

2. Research significance

Shear failure of reinforced concrete is difficult to predict accurately. Notwithstanding many decades of experimental research and the use of highly sophisticated analytical tools, an accurate mathematical model to represent shear in concrete structures is still elusive, consequently shear design of beams remains empirical. But continuing research is refining proportioning and detailing of structural concrete members for shear, which is still a preoccupation of many researchers. Research on simpler, more convenient and effective stirrup detailing than the conventional closed stirrups has been meager to date, Behra and Rajagopalan [3] pioneered notable research in this area. In three beams, in place of conventional closed stirrups, two piece stirrups were tried. Lap in one beam was provided in the top but adequate development length was not there, with the wrong assumption that maximum stress occurred only at stirrup mid height; failure was at 95% of its rated shear. In another beam, lap was provided on the side faces and a lap was provided on the side faces and a lap length of 171mm for 6mm stirrups was not adequate; it was reported to fail at 89%of total strength in the two piece stirrup could be taken care of by more effective lap length.

In large beams installation of closed links is problematic and time consuming, particularly in large structural concrete members such as pile caps. To eliminate this problems, an alternative stirrup detailing system, comprising a stirrup in two pieces with free ends meeting in the top and bottom faces, which satisfies the development length requirements of IS456:2000 [5] and ACI 318-2008 [1] was tried by Murty and Papa Rao [13]. This two- piece stirrup unit was found satisfactory, in comparison with conventional closed stirrups, relative to strength and deformational behavior. In the tests performed earlier by Anderson and Ramirez [2] it was

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confirmed that lapped closed stirrup unit exceeded under high shear stress, the capacity of closed two legs stirrup units. In wide beams, with several longitudinal bars in a layer, a lack of well distributed stirrup legs across the web of a member could lead to concentration of diagonal compression stress at the joint of the stirrup leg and outside the longitudinal bar. This system could results in premature failure due to crushing at these nodal zones and inefficient use of longitudinal reinforcement. Only a small number of studies have directly examined the influence of stirrup spacing across the beam width on one-way shear capacity. The required vertical stirrup leg spacing cross the beam width has been suggested variously by different investigation. In this context, beams were divided into two groups, one subjected to low shear force and the other to high shear force. Without specific experimental validation presented, Leonardthand Walther [10] reasonably suggested shear reinforcement spacing limit in the width direction of effective depth for low shear stresses, but noted the spacing limit should decrease as a function of the shear stress. For members with high shear stresses, a transverse spacing of 200mm was proposed. Euro code 2 [7] suggested spacing limits of 0.75d (where d is effective depth) or 600mm in the width direction. No other codes provide spacing limits across the width of beams. Anderson and Ramirez [2] in their wide beam tests, subjected to high shear stresses exceeding 6 fc adopted a maximum transverse leg spacing of 200mm, which was same as the value suggested by Leanhardt and Walther [10] Lubell AS [11] in their wide beam tests suggested stirrup spacing of d/2 or 300mm in beams under high shear stresses. BS 8110 1 [6] in section 3.4.5.5 specifies the horizontal spacing of links should be such that no longitudinal bar is more than 150mm from a vertical leg; this spacing should in any case not exceeded.

Truss models are very useful for detailing of stirrup reinforcement for shear as per Anderson and Ramirez [2]. The concept of truss models in reinforcement members was first introduced at the turn of nineteenth century by Ritter [14] and Morsch [12]. This pioneering work was later refined by several renowned researches. Rausch [15], Kupfer (1964) and Leonhardt [9]. Lampert and Thurliman [8] and several others have provided a foundation for truss model by means of the theory of plasticity. The truss model approach was extended to overall structures in the form of strut and tie systems by Schlaich [16]. The truss model of reinforced concrete beam under bending and shear illustrates the function of vertical stirrups. The stirrups form the vertical tension ties of a truss and the bottom flexural reinforcement constitutes the bottom tension chord of the truss. Under the truss assumption that forces can be equilibrated at the joints, stirrups must be capable of developing the required force over the entire height. Hooks are preferred for stirrup anchorage. Anchorage of stirrup hooks in the flexural tension zone is questionable because of the reduced confinement provided by the cracked concrete. Continuation of stirrup leg would seem to be the only feasible alternative stirrup anchorage in the flexural tension region. Adequate stirrup spacing is also critical; large spacing in the longitudinal direction of the beam creates a concentration of diagonal compression stresses at the truss joints. This practice results in overloading of the nodal zones or the diagonal struts themselves leading to premature failures due to concrete crushing. Spacing of stirrup legs in the transverse direction can also be a critical factor in wide beams when the legs are concentrated around the outer longitudinal bars. The diagonal compression truss members are equilibrated at the truss joint formed by the stirrup and the longitudinal reinforcement. The horizontal component of the diagonals is balanced by the longitudinal reinforcement. The vertical force component is equilibrated by the stirrup reinforcement. In the wide beams with several layer, the lack of well distributed stirrup legs across the web of the member could lead to a concentration of diagonal compression stresses at the joint of the stirrup leg outside longitudinal bar. This situation could result in premature failure due to concrete crushing in these nodal zones and inefficient use of interior longitudinal reinforcement. To correct this situation, interior stirrup leg can be placed to furnish the necessary vertical equilibrium resultants, thus creating additional interior truss joints.

To eliminate shear failure, before the attainment of full moment capacity, web reinforcement is provided in the form of small sized bars, vertical stirrups. Various national codes specify placement limits for the web reinforcement as vertical stirrups placed perpendicular to the axis of the member. Stirrup spacing is limited to 0.5d or 24in (60.96cm) by ACI 318-2008 [1]; to 0.75d or 300mm by IS 456:2000 [5], where d is effective depth of beam in all cases. Although maximum permissible spacing limit is specified in the codes, they are silent regarding the influence of placement of stirrups at a lesser spacing than their maximum permitted limits. For example, shear occurring in a beam of 410mm effective depth as per IS456:2000, design allows placement of 12mm diameter stirrups at 300mm or 10mm dia at 200mm intervals, or 8mm dia at 130mm center to center. In all cases, tensile force in the stirrups in beam length/1mm remains the same or nearly the same. In the absence of code guidance and work done on the aspect a designer will fail to comprehend which of these alternative options, the amount of web reinforcement per unit length of beam remains the same. The present study undertaken fills the gap and shows the forward method to follow. Although the use of stirrups of smaller diameter at smaller spacing involves marginally higher labour, time and cost of steel cage fabrication, the disadvantage is more than offset by the resulting benefits. Stirrups intended to resist shear force directly in a beam, contribute additional shear resistance in no less way from the presence of concrete, even in the cracked state. Concrete in the compression, owing to confining effects of the stirrups that prevent diagonal crack propagation, provides the beam extra shear capacity. Another source of additional shear strength mobilization is the support given to the flexural reinforcement by the stirrups, and also the prevention of longitudinal splitting by the stirrups; this strength enhancement is likely to be proportional to the decrease in stirrups spacing.

3. Methodology

To arrive at the objectives, the methodology included basic test on materials, casting of beams, curing and testing, and comparison of results.

A) Dimension of beams

Experimental investigations were carried out on eight simply supported reinforced concrete beams to study the behavior of various beams of first series and second series. Both series of beams has dimension of 230mm wide, 300mm depth and 2000mm long on a simply supported span of 1800mm, but vary in flexural, compressive and shear reinforcement.

Fig. 1 shows first series of beams with cross section 230 mm x 230mm. Beam FB1 indicates beams wit tension reinforced of 3 numbers of 16 mm diameter steel rods and compressive reinforcement of 2 numbers of 16mm diameter. Shear reinforcement of 10mm diameter of two legged stirrups are placed at equal interval of 265mm center-to-center along the length of the span. In B2 and B3, tension and compressive reinforcement are same in both the beams as of B1 but shear reinforcement of 8mm diameter of two legged stirrups placed at 170 mm center-to-center and 6mm diameter of two legged stirrups placed at 65 mm center-to-center respectively.

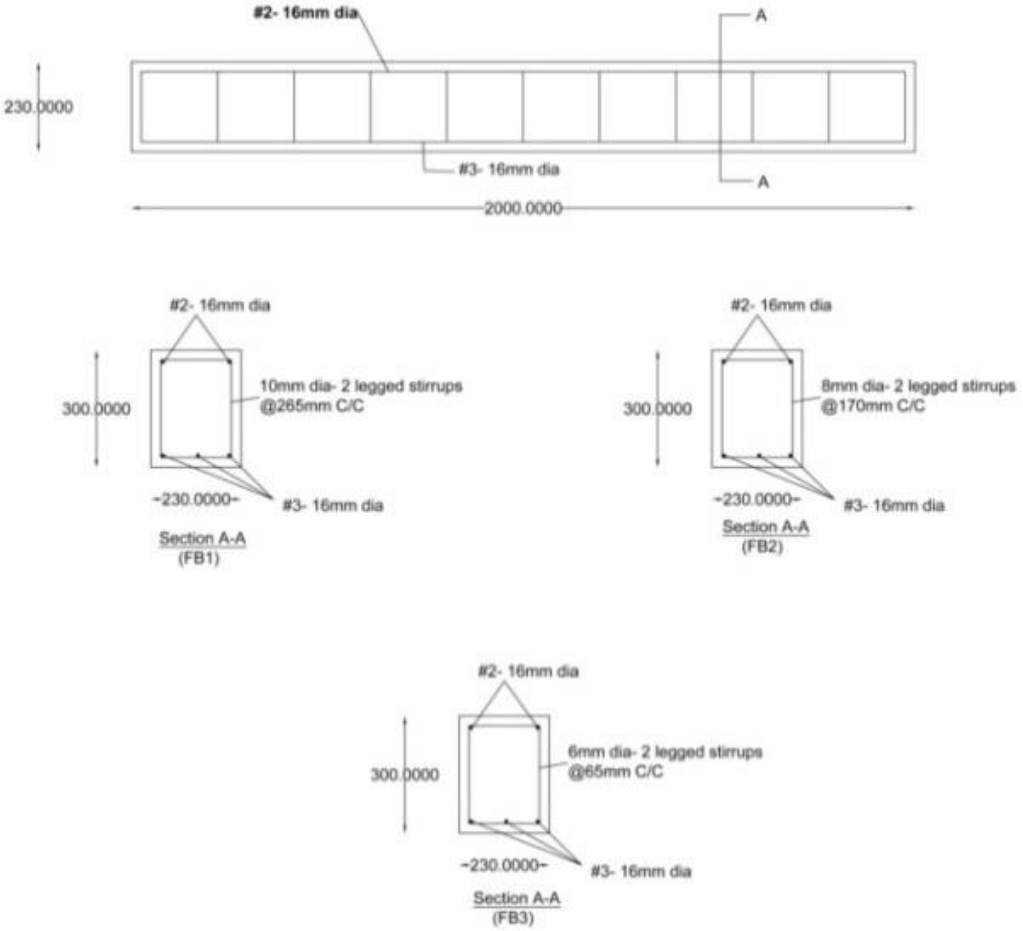


Fig. 1: Details of Test Specimens B1, B2, B3.

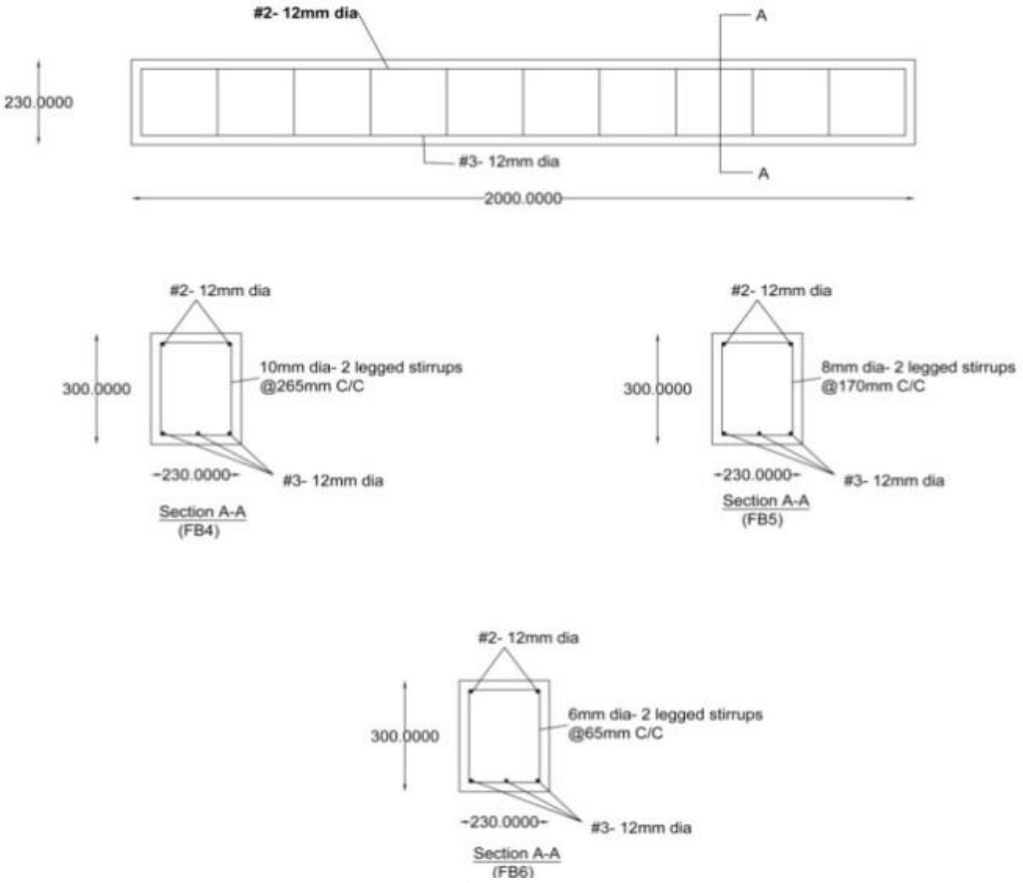


Fig. 2: Details of Test Specimens B4, B5, B6.

In second series of beams B4, B5 and B6, the tensile and compressive reinforcement of 12mm diameter was used and other reinforcement details remain same as first series beams (Fig. 2).

B) Test on cement, fine and coarse aggregate

Ordinary Portland cement of 43 grade was taken for all beams and the Fine aggregate was river sand conforming to ZONE-2 as per IS 383-1970. The coarse aggregate was locally available crushed granite stone sieved to 20mm maximum size, also satisfying the requirement of IS 383:1970 [4]; 20mm and 10mm aggregate sizes were used. The mix proportion by weight for cement, sand and coarse aggregate was respectively, 1: 1.5: 3 (M20, IS: 10262-2009) with water to cement ratio of 0.56 by weight.

C) Test on concrete

To calculate the strength of concrete we have conducted compression strength and split tensile strength test and they were carried out as per IS: 516-1959.

D) Reinforcement details

The flexural reinforcement will be same in all the three beams of first series (16mm diameter bar). Similarly all the beams in the second series had same flexural reinforcement (12mm diameter bar).The shear reinforcement configuration in the test specimens designated as B1, B2 and B3 was 10mm two legged stirrups at 265mm, 8mm 2 legged stirrups at 170mm, and 6mm two legged stirrups of 65mm respectively. Table 1 describes the yield stress of 16mm diameter, 12mm diameter, 10mm diameter, 8mm diameter and 6mm diameter bar with details of ultimate tensile stress and percentage elongation. The above beams were designed (230mm x 300mm) to take maximum load of 300 kN. Table 2 gives details of reinforcement for beams B1, B2, B3, B4, B5, and B6with compressive and split strength of M20 concrete.

Table 1: Properties of Steel Reinforcement Used in Beams

Nominal Diameter (mm)	Area (mm^2)	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)	Percentage Elongation
16	201.06	500	650	20
12	113.14	545.8	595.9	22
10	78.57	564.7	631.0	18
8	50.29	566.4	676.3	19
6	28.29	282.6	441.3	30

Table 2: Properties of Test Specimen

Specimen label	Dimensions of the Speimens in'mm'	Flexural reinforcement @ bottom	@ top	Shear reinforcement spacing	Cube compresive strength at 28 days (MPa)	Split tensile strength at 28 days (MPa)
B1	Width=230, Overall Depth= 300, Effective Depth= 270, Effective Span= 1800, Shear span/ effective depth= 3.33 (a/d)	3# 16 mm dia	2#16 mm dia	2Lvertical stps 10mm dia@265mm c/c	32.89	3.21
B2		3#16 mm dia	2#16 mm dia	2Lvertical stps 8mm dia@170mm c/c	32.89	3.21
B3		3#16 mm dia	2# 16 mm dia	2Lvertical stps 6mm dia @65mm c/c	32.89	3.21
B4		3# 12 mm dia	2#12 mm dia	2Lvertical stps 10mm dia@265mm c/c	32.89	3.21
B5		3#12 mm dia	2#12 mm dia	2Lvertical stps 8mm dia@170mm c/c	32.89	3.21
B6		3# 12 mm dia	2# 12 mm dia	2Lvertical stps 6mm dia @65mm c/c	32.89	3.21

E) Test procedure

The cast reinforced concrete beams were tested using loading frame (100 tons capacity). Before testing, the beams were marked with center point and supports points were marked 100mm away from the edge on both side. The beam were placed on the loading frame using hand pumping crane, then the set-up of beam should be done as shown in Fig 3 . Both series of beams were of 230mm wide, 300mm depth and 2000mm long on a simply supported span of 1800mm. The applied load on each specimen was 3- point loading, in this loading system as beam with rectangular cross-area is set on two parallel simple support. The load is applied at the middle of the beam through loading cell. The working load for design of all the beams in two series was 200 kN. As applying of load start at the center of specimen at very slow rate (2.3 KN per second), simultaneously load taken by specimens were recorded in excel sheet in system. Deflection of the beam will also recorded together by means of Linear Variable Deformable Transformer (LVDT) in the system. When testing is completed the crack patterns were marked and measured through scale. The photographs have been taken for ever testing of beam as shown Fig. 12.

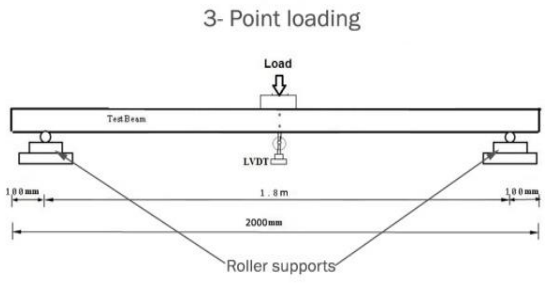


Fig. 3: Details of Test Set Up For 3- Point Loading.

4. Results and discussion

Beams were tested using three point loads to study the behavior of beams for varying reinforcement in flexure and shear. The calculated moment resistance of the beam (experimental will be more than theoretical moment, generally) was more than the bending moment exhibited in the test at shear failure. The fore mentioned points established shear failure, but not bending failure. Table III tabulates complete testing details of initial crack load, service load

and ultimate loads of beams and calculated bending moment and shear stress. The Load versus Deflection curve for First series of beams B1, B2 and B3 is shown in Fig. 4. At service load level 132.8 kN, 140.3 kN and 151 kN and the deflection were 14.41 mm, 13.36 mm and 11.78 mm for beams B1, B2 and B3 respectively. From observation of graph, the deflection of the beams is decreased as stirrups spacing decreased in the beams.

Table 3: Principal Test Results

Spcimen label		Central load (kN)	Moment (kNm)	Shear force (kN)	Shear stress (MPa)	Deflection under the load (mm)	Crack width (mm)
B1		52.80	23.79	26.40	0.38	2.61	-
B2		66.20	29.79	33. 10	0.48	2.84	-
B3	At Intial Crack	95.60	43.02	47.80	0.69	4.62	-
B4		34.20	15.39	17.10	0.24	1.22	-
B5		45.80	20.61	22.90	0.33	1.35	-
B6		82.10	36.95	41.05	0.59	3.89	-
B1		132.40	59.58	66.20	0.95	14.41	1.0
B2		140.30	63.09	70.10	1.05	13.36	0.8
B3	At service load	151.00	67.95	75.50	1.09	11.78	0.5
B4		88.50	39.82	44.20	0.64	12.50	2.0
B5		101.70	45.76	50.80	0.73	9.18	1.5
B6		140.70	63.31	70.30	1.01	8.16	1.3
B1		137.10	61.69	68.55	0.99	18.29	1.5
B2		144.60	65.07	72.30	1.04	17.45	1.0
B3	At Ultimate Load	173.50	78.07	86.75	1.25	16.20	0.8
B4		94.70	42.61	47.30	0.68	14.52	3.0
B5		115.50	51.97	57.75	0.83	13.32	2.5
B6		171.10	76.99	85.55	1.23	14.21	2.0

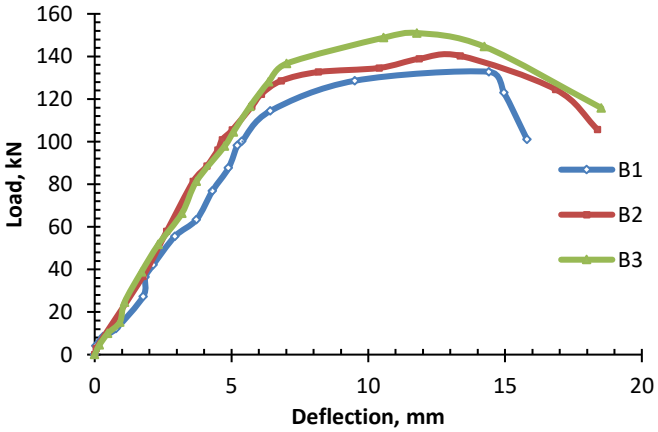


Fig. 4: Plot of Load versus Deflection.

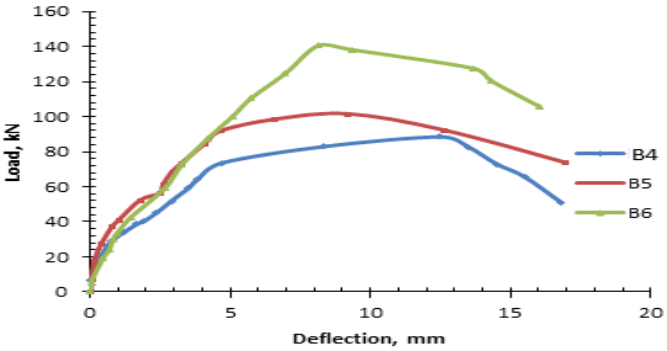


Fig. 5: Plot of Load versus Deflection.

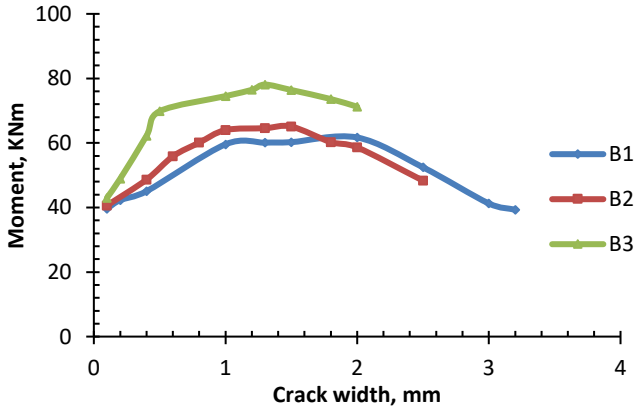


Fig. 6: Moment VS Crack Width for B1, B2 & B3 Beams.

The Load versus Deflection curve for Second series of beams B4, B5 and B6 is shown in above Fig. 5. At service load level 88.5 kN, 101.7 kN and 140.7 kN and the deflection were 12.5 mm, 9.18 mm and 8.16 mm for beams B4, B5 and B6 respectively. Fig. 5 shows that the deflection of the beams is decreased as stirrups spacing decreased in the beams.

Moment versus Crack width for first series beams is shown in above Fig. 6. In the beam B1, the initial crack developed was flexural at moment 23.76 kN-m, at the bottom of side face which was 38% of its ultimate moment 61.69 kN-m, with slight shear compression distress on top face. In beam B2, two or three initial flexural cracks originated at the bottom on the side face, near the center of span at moment 29.76 kN-m which was 46% of its ultimate moment 65.07 kN-m. The beam B3 with stirrups at closer spacing than the companion two beams developed three or four initial flexural cracks, near the center of the span at the bottom of the side face at moment 43.02 kN-m, which was 55% of its ultimate moment 78.07kN-m. From the observation of the graph shows, that the number of cracks and crack width increases with stirrups spacing increases in the beam.

Moment versus Crack width for second series beams is shown in above Fig. 7. In the second series, beam B4 had first flexural crack at moment 15.39 kN-m at the bottom of the side face; the cracking moment was 36% of its ultimate moment 42.61kN-m with shear compression distress near the load. Beam B5 showed initial one or two flexural cracks at bottom of side face at moment 20.61kN-m, which was 40% of its ultimate moment of 51.97kN-m; compression distress was visible in the top face near the load. Beam B6 with least stirrup spacing showed initial crack at moment 36.945 kN-m which was 48% of its ultimate moment 76.99 kN-m, compression distress was visible under load. Even photos of beams B4, B5, and B6 show reduction in crack width as stirrup spacing decreased.

Shear force versus Stirrups spacing for first series beams is shown in above Fig. 8. The shear reinforcement for B1 was 10mm two legged stirrups at 265mm, for B2 was 8mm 2 legged stirrups at 170mm, and for B3 was 6mm two legged stirrups of 65mm, therefore for this stirrup spacing the shear force were 68.55 kN, 72.3 kN and 86.75 kN respectively. The above graph is showing that the shear force is increasing as stirrups spacing of beam decreasing. The maximum shear force was obtained for B3 beam; hence the B2 beams have reduced 16.65% than B3 beam. B1 beam also decreased 20.96% then B3 beam.

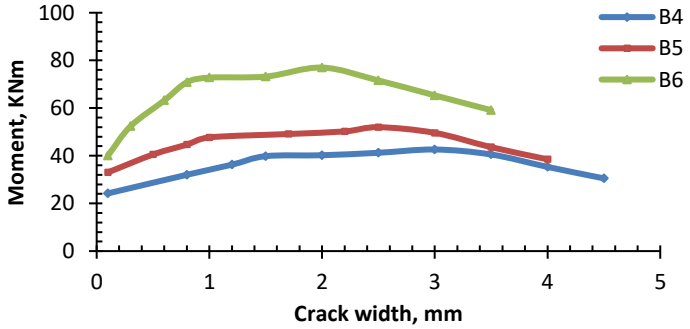


Fig. 7: Moment VS Crack Width for B4, B5 & B6 Beams.

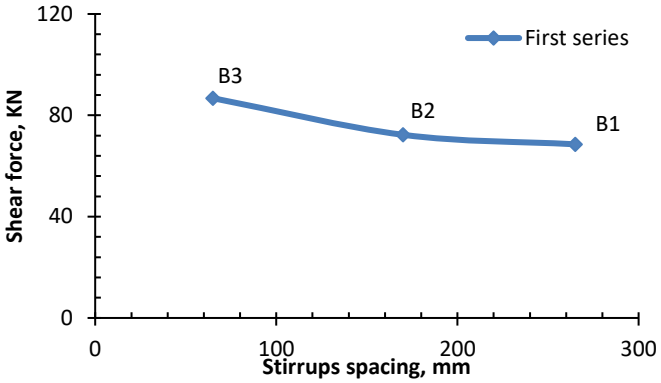


Fig. 8: Shear Force VS Stirrups Spacing for B1, B2 & B3 Beams.

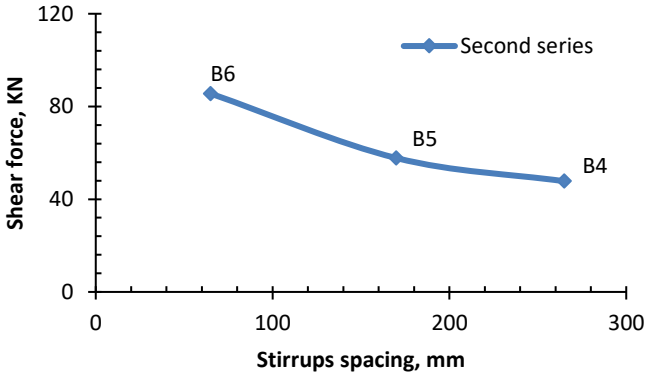


Fig. 9: Shear Force VS Stirrups Spacing for B4, B5 & B6 Beams.

Shear force versus Stirrups spacing for second series beams is shown in above Fig. 9. The shear reinforcement for B4 was 10mm two legged stirrups at 265mm, for B5 was 8mm 2 legged stirrups at 170mm, and for B6 was 6mm two legged stirrups of 65mm, therefore for this stirrup spacing the shear force were 47.75 kN, 57.75 kN and 85.55 kN respectively. The above graph is showing that the shear force is increasing as stirrups spacing of beam decreasing. The maximum shear force was obtained for B6 beam, hence the B5 beams have reduced 32.49% than B6 beam. B4 beam also decreased 44.18% than B6 beam.

Moment versus Stirrups spacing for first series beams is shown in above Fig. 10. The shear reinforcement for B1 was 10mm two legged stirrups at 265mm, for B2 was 8mm 2 legged stirrups at 170mm, and for B3 was 6mm two legged stirrups of 65mm, therefore for this stirrup spacing the moment were 61.695 kN-m, 65.07 kN-m and 78.075 kN-m respectively. The above graph is showing that the moment is increasing as stirrups spacing of beam decreasing. The maximum moment was obtained for B3 beam; hence the B2 beams have reduced 16.65% than B3 beam. B1 beam also decreased 20.96% than B3 beam.

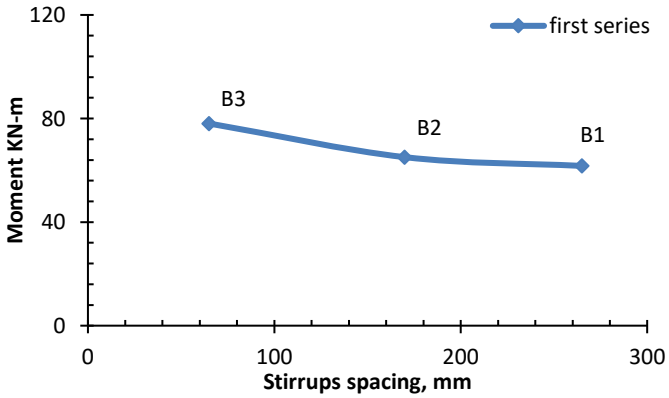


Fig. 10: Moment VS Stirrups Spacing for B1, B2 & B3 Beams.

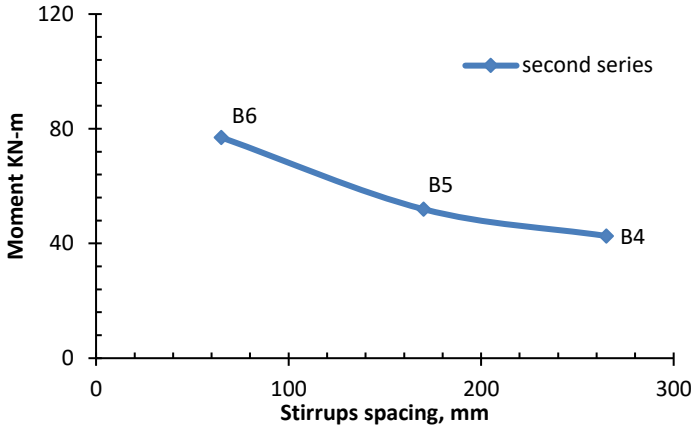


Fig. 11: Moment versus Stirrups Spacing for B4, B5 & B6 Beams.

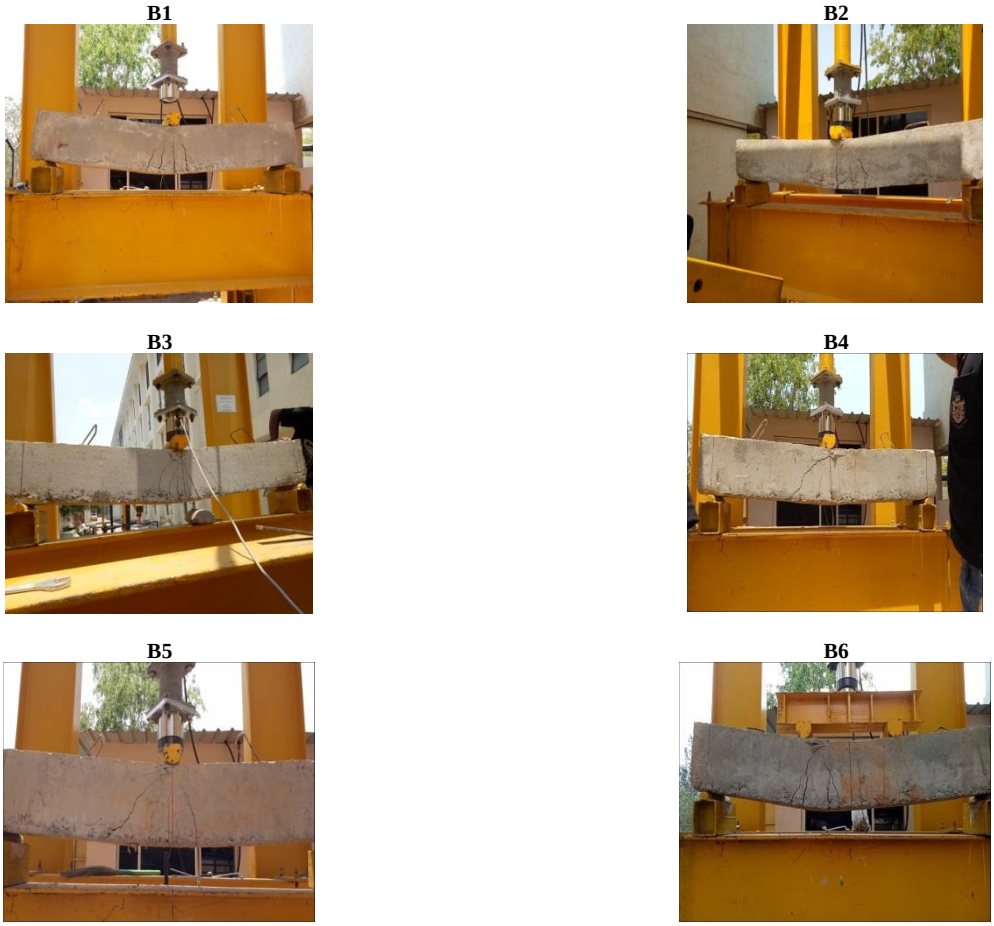


Fig. 12: Photographs of Tested Specimens.

Moment versus Stirrups spacing for second series beams is shown in above Fig. 11. The shear reinforcement for B4 was 10mm two legged stirrups at 265mm, for B5 was 8mm 2 legged stirrups at 170mm, and for B6 was 6mm two legged stirrups of 65mm, therefore for this stirrup spacing the moment were 42.615 kN-m, 51.975 kN-m and 76.99 kN-m respectively. The above graph is showing that the moment is increasing as stirrups spacing of beam decreasing. The maximum moment was obtained for B6 beam; hence the B5 beams have reduced 32.49% than B6 beam. B4 beam also decreased 44.64% than B-6 beam.

5. Conclusions

Useful ideas gleaned from the study under taken, are summed up in conclusions listed below. Tests were on two series of shear critical beams; beams B-1, B-2 and B-3 were in the first series and beams B-4, B-5 and B-6 in the second series. Beams in each series were identical in all respects, including geometrical dimensions, the amount of longitudinal and web reinforcement provided. In each series, each beam contained different stirrup diameter; this enabled to get same amount of web reinforcement per unit length of beam, in all the three beams in a series.

a) As stirrup spacing decreased cracking strength of beams increased. Cracking moments of B1, B2 and B3 were 38%, 46% and 55% of their ultimate moment capacities respectively in the first series. In the second series, cracking moments B4, B5 and B6 were 36%, 40% and 48% of their ultimate moment capacities respectively. In the post cracking stage, the integrity of cracked concrete was more effective as the stirrup spacing decreased, mobilizing additional shear strength.

b) Closer stirrup spacing resulted in marginally enhanced carrying capacity of beams at ultimate load. In the first series, beam B3 with the smallest stirrup spacing recorded 7% and 14% higher ultimate loads respectively than the companion beams B2 and B1 which had stirrup spacing larger than that of B3. In the second series, beam B6 with the smaller stirrup

spacing recorded 6% and 12% higher ultimate loads respectively than the companion beams B5 and B4 which had stirrup spacing larger than that of B6.

c) Deformational characteristics of the beams improved at serviceability load level, as stirrup spacing decreased. The deterioration of cracked concrete was more restrained with the presence of closer stirrup spacing. At service load level transverse deflections were 14.41mm, 13.36mm and 11.78mm and crack widths were 1mm, 0.8mm and 0.5mm for beams B1, B2 and B3 respectively, showing decreased deformations as stirrup spacing decreased, same trend was seen with beams of second series, B4, B5 and B6 at service load level; transverse deflections were 12.5mm, 9.18mm and 8.16mm and crack widths were 2mm, 1.5mm and 1.3mm respectively.

d) Significant increase of Shear capacity and Ultimate bending moment of the beam increased by reducing the stirrups spacing with diameter of the bar.

e) In proportioning reinforced concrete beams for shear, use of small size bars as stirrups at closer spacing is recommended in an empirical way, based on the findings of the current study. Such guidance is not available in any current national code.

f) Despite the slightly higher labour involved in steel cage fabrication, lower stirrup spacing imparts to the beam, the beneficial effects of marginally improved ultimate strength and beneficial deformational behavior, as revealed by the present investigations.

References

[1] ACI (American Concrete Institute). (2008) ACI 318: Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary, ACI, Farmington Hills, MI, USA, ACI Committee 318.

[2] Anderson NS, Ramirez JA (1989). Detailing of stirrup reinforcement. ACI Structural Journal, 86, (5): 507–515.

[3] Behra U, Rajagopalan KS (1969). Two-piece U-stirrups in reinforced concrete beams. ACI Structural Journal, 66, (7): 522–524.

[4] BIS (Bureau of Indian Standards). IS 383-1970: Specification for coarse and fine aggregates from natural sources for concrete, BIS, New Delhi, India.

[5] BIS. IS 456-2000: Plain and reinforced concrete – code of practice, BIS, New Delhi, India.

[6] BSI. BS 8110-1985: Structural use of concrete, Part 1, BSI, London, UK.

[7] BSI. BS EN 1992-1-1:2004: Eurocode 2: Design of concrete structures. General rules and rules for buildings, European Committee for Standardization, Brussels, Belgium.

[8] LampertP, Thurliman B (1971). Ultimate Strength and Design of Reinforced Concrete Beams in Torsion and Bending, International Association for Bridge and Structural Engineering (IABSE), Zurich, Switzerland, 107–131, Publication No. 31-I.

[9] LeonhardtF. Die Verminderte Schudeckung bei Stahlbetontragwerken. Der Baungenieur (Heidelberg) (1965), 40, (1): 1–15.

[10] LeonhardtF, Walther R. The Stuttgart Shear Tests (1964), Cement and Concrete Association, London, UK, 134, Translation No. 111, PP 134.

[11] LubellAS, Bentz EC, Collins MP (2009). Shear reinforcement spacing in wide members. ACI Structural Journal, 106, (2): 205–214.

[12] MorschE. Der Eisenbetonbau (1920) – Science Theorie und Anwendung, Vol. 1, 5th edn., Wittwev, Stuttgart, Germany, 112, Part 1 and Part 2.

[13] Murthy DSR, Papa Rao G (2011). New stirrup detailing schemes for shear demands in pile cap beams. Journal of Structural Engineering, India, 38, (4): 345–353.

[14] Ritter W. Die Bauweise Hennebique. SchweizerischeBauzeitung (1899), 33, (7): 59–61.

[15] Rausch E .Drillung, Schub und ScherenimStahlbetonbau, (1953), DeutscherIngenieurVerlag, Berlin, Germany: 168.

[16] SchlaichJ, Schafer K, Jennewein M (1987). Toward a consistent design of structural concrete. Journal of Prestressed Concrete Institute, 32, (3): 74–150. https://doi.org/10.15554/pcij.05011987.74.150.