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AN EXPERIMENTAL INVESTIGATION INTO SHEAR CAPACITY OF HIGH STRENGTH CONCRETE BEAMS

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ABSTRACT

The shear capacity of the concrete beams having stirrups is assumed as the sum of individual contributions of both the concrete and shear reinforcement. Different international building codes have suggested empirical relations for both of these contributions.
In this research seventy beams with five values of longitudinal reinforcement and seven values of shear span to depth (a/d) ratios were tested in two sets of thirty five beams each, without and with shear reinforcement to study the contribution of the stirrups in resisting the shear. The beams were tested under the concentrated load at the mid span. The test results were analyzed for the contribution of stirrups, the effect of longitudinal steel and shear span to depth a/d ratios. It has been shown by the results that the assumption of summing the individual contribution of steel and concrete for the shear strength of reinforced beams is not proved.

Keywords: Shear, stirrups, reinforcement, shear span, beam, slender

1. INTRODUCTION

Extensive research has been made in last 20 years to understand the shear properties of reinforced concrete beams. The reinforced concrete beams are presently designed with the help of certain provisions of different international building codes, but the latest research [1-3] has shown that most of these are un-conservative for beams with large sizes and lower values of longitudinal reinforcement. It has also been observed that the stirrups contribution has also been adversely affected in large beams [4].

The shear strength of concrete beams mainly depends on the following variables:

- Depth of member or size effect [5]
- Shear span to effective depth a/d or moment to shear ratio [6]
- Longitudinal Reinforcement or dowel action, [7]

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- Axial Force,
- The tensile Strength of concrete,
- Crushing strength of the Beam web, [9]
- Yielding of stirrups, [10]
- The aggregates sizes leading to aggregate interlocking. [11]
- Failure of Tension chord**.** [12]
- Failure of Stirrups anchorage: [13]
- Serviceability failure due to excessive crack width at Service load. [14]
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The latest research [15,16] has revealed that reduction in the shear capacity of all beams occur when the longitudinal reinforcement ratio is 1% or less for all sizes of beams and the provisions of different international building codes for the shear design are also not conservative for slender beams with a/d ratio $\geq$ 3.0.

The shear strength contribution due to aggregates interlocking in high strength concrete is less than that of normal strength concrete as the strength of mortar matrix is more than the aggregates itself. Thus the aggregates crush before the cracking of high strength concrete and the aggregates interlocking is playing relatively little role. In this research, the effect of shear span to depth a/d ratio, the longitudinal reinforcement ρ, and transverse steel ratio $\rho_{V,}$ on the shear properties of high strength concrete has been studied. Seventy beams have been tested in this research in two sets of 35 beams each. The test results and beam failure mechanism for both of beams has also been observed. The contribution of stirrups has also been investigated and is compared with the provision of ACI-318.[8]

2. RESEARCH OBJECTIVES AND SIGNIFICANCE:

The research objectives can be summarized as follows;

- To investigate the effect of longitudinal reinforcement, shear span to effective depth “a/d” ratio and contribution of stirrups on the shear capacity of concrete slender beams.
- To check the whether the assumption of summin the individual concrete and stirrups contribution for the combined shear capacity of reinforced concrete beams with transverse reinforcement is experimentally proved or not?
- To investigate the failure mechanism of high strength concrete beams.

3. MATERIAL

Reinforcing Steel: Deformed steel of 60 grade (410 M Pa) of nominal sizes # 3 (9.5 mm), #4 (12.70mm) , 6 (19 mm) and #7 (22mm) have been used as the main reinforcement and for transverse steel, 40 grade (276 M Pa) steel plain bars of #2 (6.35 mm) @ 6 in (15 cm) c/c were used.

Concrete.

All beams were cast from the same mix design. The coarse aggregates of lime stone source were used with ¾ in (19 mm) and below sizes. The fine aggregates with modulus of fineness as 2.67 were used in the concrete. The High Range water Reducers Conforming to ASTM C-494 type F standards was used at 1.70 % by weight of cement to control the water cement ratio. The design strength of 7500 psi (51.71 M Pa) was used, however the average concrete strength was achieved as 8200 psi (56.54 M Pa). The details of Mix design of Concrete are given in table No.1.

Table 1. Mix Proportioning/ Designing of High Strength Concrete .

Constituent	Proportion
Type- I Cement	1058 lbs/yd^3 (628 kg/m^3)
Fine aggregates	815 lbs/yd^3 (484 kg/m^3)
Coarse aggregates	1900 lbs/yd^3 (1128 kg/m^3)
HRWR @ 1.7 % by weight of cement	18 lbs/yd^3 (10.70 kg/m^3)
Water @ 0.25 w/c ratio	164.5 lbs/yd^3(97.65 kg/m^3)
Design Compressive strength (28 days)	7500 psi (51.71 M Pa)
Actual Average strength (28 days)	8200 psi) (56.54 M Pa)

4. EXPERIMENTAL INVESTIGATIONS

To study the behavior of high strength concrete beams in shear, seventy beams in two series of thirty five beams each of size 9″×12″ (23 cm×30 cm) were prepared. Seven values of shear span to depth (a/d) ratios were used (a/d = 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0). For each value of a/d, five types of longitudinal steel ratios were employed (ρ = 0.0033,0.0073,0.01, .015, 0.020) to study the effect of longitudinal steel ratios. For series-I, thirty five beams were used without transverse reinforcement where as in series-II, thirty five beams having shear reinforcement were used. The details of beams are shown in the Figure 1 and Figure 2.

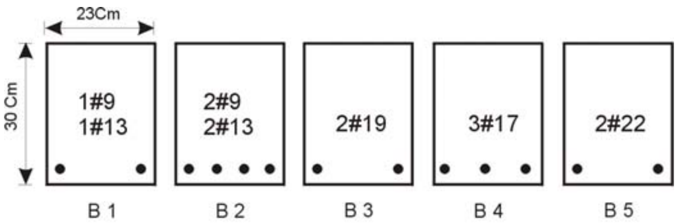

Figure 1. Detail of beams with no longitudinal steel

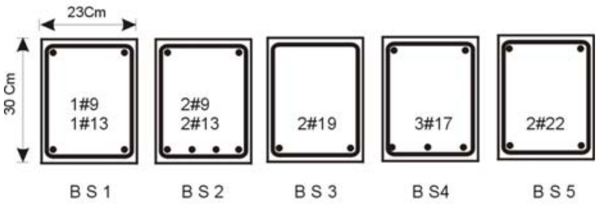

Figure 2. Detail of beams with longitudinal steel

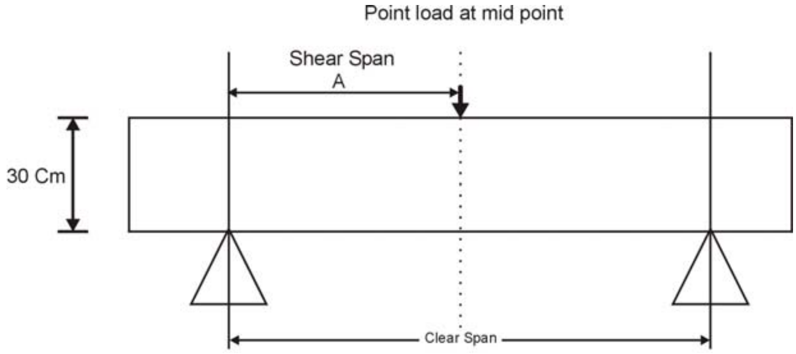

Figure 3. Loading arrangement

5. OBSERVATIONS AND STRUCTURAL BEHAVIOR OF BEAMS

When the load is applied and gradually increased, flexural cracks appear in the beams which are more or less vertical in nature. With further increase of load, inclined shear cracks develop in the beams which are sometimes called primary shear cracks. The typical cracking in the slender beams without transverse reinforcement, leading to the failure involves two branches. The first branch is slightly inclined shear crack and is typical of the height of the flexural crack. The second branch of the crack also called secondary shear crack[13] initiates from the tip of the first crack at relatively flatter angle, splitting the concrete in the compression zone. This crack further extends in the compression zone and finally meets the loading point leading to the collapse of the beam. The nominal shear stress at the diagonal tension cracking at the development of the second branch of inclined crack is taken as the shear capacity of the beams. The load deflection curve also shows an abrupt increase in the mid span deflection as the curve becomes relatively flatter and we observe substantial increase in the deflection with further increase in the load. These points of secondary shear formation have been marked on the individual load deflection curves (see figure). In beams without transverse reinforcement, the secondary shear crack is formed shortly after the development of primary shear crack.

The first branch of shear cracking of the beams with transverse reinforcement is typically same in nature as that of beams without transverse reinforcement. The shear crack in this case also involves two branches. The formation of the second crack and the corresponding load may be assumed to be the same, however after the formation of the secondary crack the stirrups are brought into action and with further opening of crack, the stirrups also starts yielding leading to the failure of the beam.

The nominal shear capacity Vn of the beam with transverse reinforcement is the sum of the contribution of concrete Vcr and that of the stirrups Vs .i.e.

$$Vn = Vcr + Vs$$

The test results showing the shear stresses for $\rho \leq 1$ % for both types of beams with and without transverse reinforcement are shown in Table No.2 & Table No.4 whereas for $\rho > 1$ %, these are given in table No.2 & table No.5 respectively. The comparison of the same is given in table No. 6 and table No.7

Table 2. Test results of series-I beams without transverse reinforcement–21 beams (for $\rho < 1\%$)

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
B1-1	0.33	150	3.0	0.95
B1-2	0.33	178	3.5	0.88
B1-3	0.33	203	4.0	0.7
B1-4	0.33	227	4.5	0.56
B1-5	0.33	254	5.0	0.48
B1-6	0.33	280	5.5	0.41
B1-7	0.33	305	6.0	0.25
B2-1	0.73	150	3.0	0.95
B2-2	0.73	178	3.5	0.88
B2-3	0.73	203	4.0	0.8
B2-4	0.73	227	4.5	0.73
B2-5	0.73	254	5.0	0.65
B2-6	0.73	280	5.5	0.57
B2-7	0.73	305	6.0	0.41
B3-1	1	150	3.0	0.99
B3-2	1	178	3.5	0.96
B3-3	1	203	4.0	0.88
B3-4	1	227	4.5	0.81
B3-5	1	254	5.0	0.73

B3-6	1	280	5.5	0.66
B3-7	1	305	6.0	0.58

Table 3. Test results of series-I beams without transverse reinforcemnt-14 beams (for ρ> 1%)

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
B4-1	1.5	150	3.0	1.86
B4-2	1.5	178	3.5	1.68
B4-3	1.5	203	4.0	1.62
B4-4	1.5	227	4.5	1.39
B4-5	1.5	254	5.0	1.31
B4-6	1.5	280	5.5	1.17
B4-7	1.5	305	6.0	1.08
B5-1	2	150	3.0	1.68
B5-2	2	178	3.5	1.59
B5-3	2	203	4.0	1.55
B5-4	2	227	4.5	1.37
B5-5	2	254	5.0	1.23
B5-6	2	280	5.5	1.16
B5-7	2	305	6.0	1.08

Table 4. Test results of series-II beams with transverse reinforcement-21 beams (for ρ< 1%)

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
Bs1-1	0.33	150	3.0	0.99
Bs1-2	0.33	178	3.5	0.88
Bs1-3	0.33	203	4.0	0.8
Bs1-4	0.33	227	4.5	0.73
Bs1-5	0.33	254	5.0	0.57
Bs1-6	0.33	280	5.5	0.46
Bs1-7	0.33	305	6.0	0.41
Bs2-1	0.73	150	3.0	1.7
Bs2-2	0.73	178	3.5	1.38

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
Bs2-3	0.73	203	4.0	1.22
Bs2-4	0.73	227	4.5	1.06
Bs2-5	0.73	254	5.0	0.98
Bs2-6	0.73	280	5.5	0.82
Bs2-7	0.73	305	6.0	0.75
Bs3-1	1	150	3.0	1.7
Bs3-2	1	178	3.5	1.54
Bs3-3	1	203	4.0	1.45
Bs3-4	1	227	4.5	1.39
Bs3-5	1	254	5.0	1.23
Bs3-6	1	280	5.5	1.07
Bs3-7	1	305	6.0	0.91

Table 5. Test results of series-I beams without transverse reinforcemnt-14 beams (for ρ> 1%)

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
B4-1	1.5	150	3.0	1.86
B4-2	1.5	178	3.5	1.68
B4-3	1.5	203	4.0	1.62
B4-4	1.5	227	4.5	1.39
B4-5	1.5	254	5.0	1.31
B4-6	1.5	280	5.5	1.17
B4-7	1.5	305	6.0	1.08
B5-1	2	150	3.0	1.68
B5-2	2	178	3.5	1.59
B5-3	2	203	4.0	1.55
B5-4	2	227	4.5	1.37
B5-5	2	254	5.0	1.23
B5-6	2	280	5.5	1.16

B5-7	2	305	6.0	1.08

Table 6. Test results of series-II beams with transverse reinforcemnt-14 beams (for ρ> 1%)

Beam Title	Steel ratio (ρ%)	Span (cm)	a/d	Shear stress (Mpa)
Bs4-1	1.5	150	3.0	1.86
Bs4-2	1.5	178	3.5	1.8
Bs4-3	1.5	203	4.0	1.71
Bs4-4	1.5	227	4.5	1.6
Bs4-5	1.5	254	5.0	1.56
Bs4-6	1.5	280	5.5	1.24
Bs4-7	1.5	305	6.0	1.08
Bs5-1	2	150	3.0	2.19
Bs5-2	2	178	3.5	1.94
Bs5-3	2	203	4.0	1.88
Bs5-4	2	227	4.5	1.8
Bs5-5	2	254	5.0	1.73
Bs5-6	2	280	5.5	1.57
Bs5-7	2	305	6.0	1.24

Table 7. Comparison of Shear capacity of beams with and without shear reinforcement for same values of longitudinal steel and a/d ratio (for ρ< 1%)

Steel ratio (ρ%)	a/d	Shear stress	
		Beam without stirrups	Beam with stirrups
		Stress (MPa)	Stress (MPa)
0.33	3.0	0.95	0.99
0.33	3.5	0.88	0.88
0.33	4.0	0.7	0.8
0.33	4.5	0.56	0.73
0.33	5.0	0.48	0.57
0.33	5.5	0.41	0.46
0.33	6.0	0.25	0.41
0.73	3.0	0.95	1.7

Steel ratio (ρ%)	a/d	Shear stress	
		Beam without stirrups	Beam with stirrups
		Stress (MPa)	Stress (MPa)
0.73	3.5	0.88	1.38
0.73	4.0	0.8	1.22
0.73	4.5	0.73	1.06
0.73	5.0	0.65	0.98
0.73	5.5	0.57	0.82
0.73	6.0	0.41	0.75
1	3.0	0.99	1.7
1	3.5	0.96	1.54
1	4.0	0.88	1.45
1	4.5	0.81	1.39
1	5.0	0.73	1.23
1	5.5	0.66	1.07
1	6.0	0.58	0.91

Table 8. Comparison of Shear capacity of beams with and without shear reinforcement for same values of longitudinal steel and a/d ratio- (ρ>1%)

Steel ratio (ρ%)	a/d	Shear stress	
		Beam without stirrups	Beam with stirrups
		Stress (MPa)	Stress (MPa)
1.5	3.0	1.86	1.86
1.5	3.5	1.68	1.8
1.5	4.0	1.62	1.71
1.5	4.5	1.39	1.6
1.5	5.0	1.31	1.56
1.5	5.5	1.17	1.24
1.5	6.0	1.08	1.08
2	3.0	1.68	2.19
2	3.5	1.59	1.94
2	4.0	1.55	1.88
2	4.5	1.37	1.8

2	5.0	1.23	1.73
2	5.5	1.16	1.57
2	6.0	1.08	1.24

6. DISCUSSION OF TESTS RESULTS

When the longitudinal steel increases, the shear capacity of the beams also increases for all values of a/d ratios. However for same value of longitudinal steel, the shear capacity decreases with the increase of a/d ratio.

For lower values of longitudinal steel .i.e. for $\rho \leq 1\%$, the failure is mainly due flexural cracks which are mostly vertical in nature and the angles of failure is greater than 60^0. The typical flexural failure of the beam has been shown in Figure 4 & 5 . The stirrups contribution in such cases is very minimal as the longitudinal steel starts yielding before yielding of the stirrups as shown in Table 7.

For larger values of longitudinal steel, the angle of failure crack is relative shallower and is in the range of 40^0 to 50^0**.** However the stirrups contribution is more prominent, when the longitudinal steel increases as shown in Figure 6. The effect of a/d on the shear capacity is shown in Figure 7 and 8 for both sets of beams. The effect of longitudinal steel on the shear capacity of both sets of beams is shown in Figure 9&10 respectively

Figure 4. Typical flexural failure mode of the beam at minimum longitudinal steel and no web reinforcement. (ρ = 0.33 % , a/d = 3.00 , span=152cm)

Figure5. Typical flexural failure mode of the beam at longitudinal steel $\rho \leq 1\%$ and no web reinforcement. (ρ = 0.73 % , a/d = 5.5 , span=321cm

Figure 6. Typical shear failure of slender beam without web reinforcement at ρ > 1% (ρ = 1.5 % a/d = 5.5 , Span = 203cm

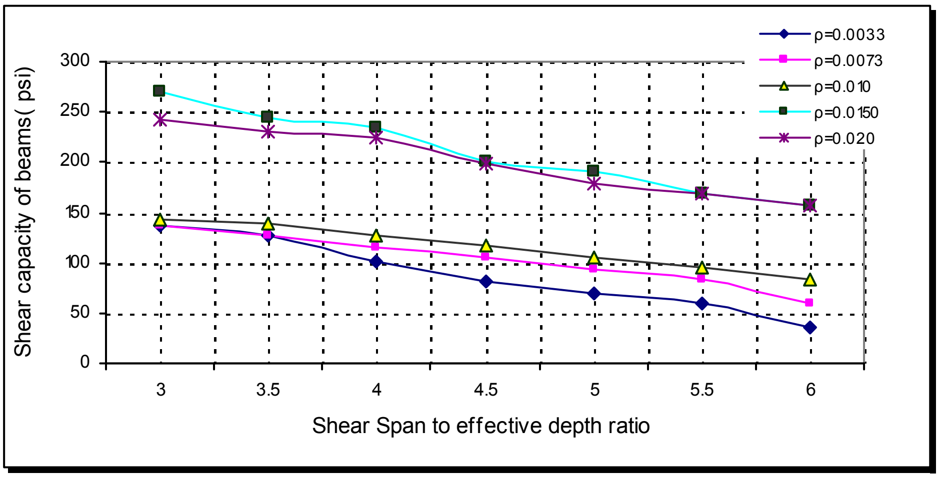

Figure 7. Effect of Shear span to depth (a/d) ratio on the shear capacity of beams without transverse reinforcement

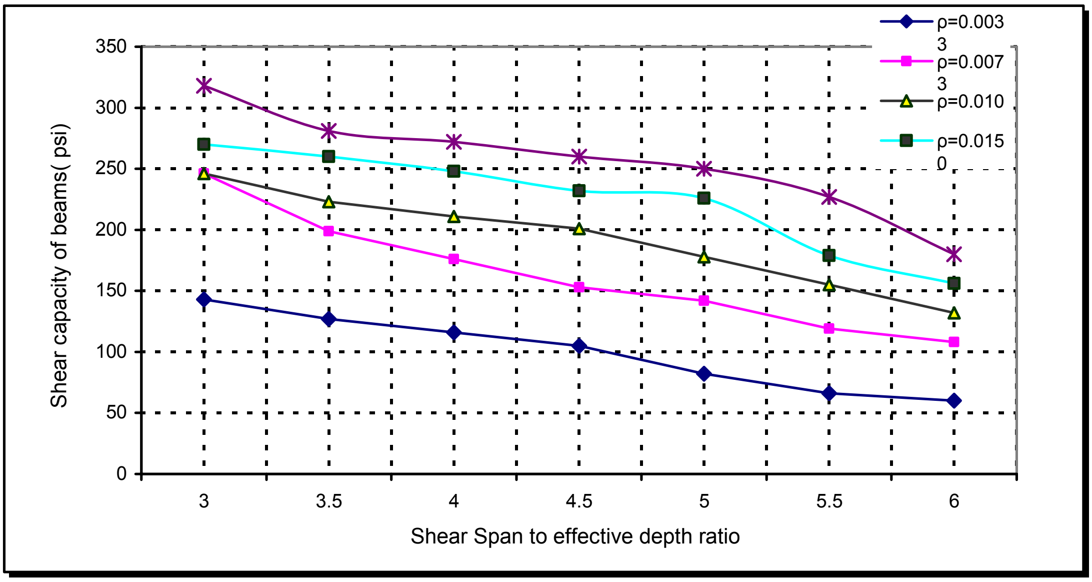

Figure 8. Effect of Shear span to depth (a/d) ratio on the shear capacity of beams with transverse reinforcement for different values steel ratios (ρ)

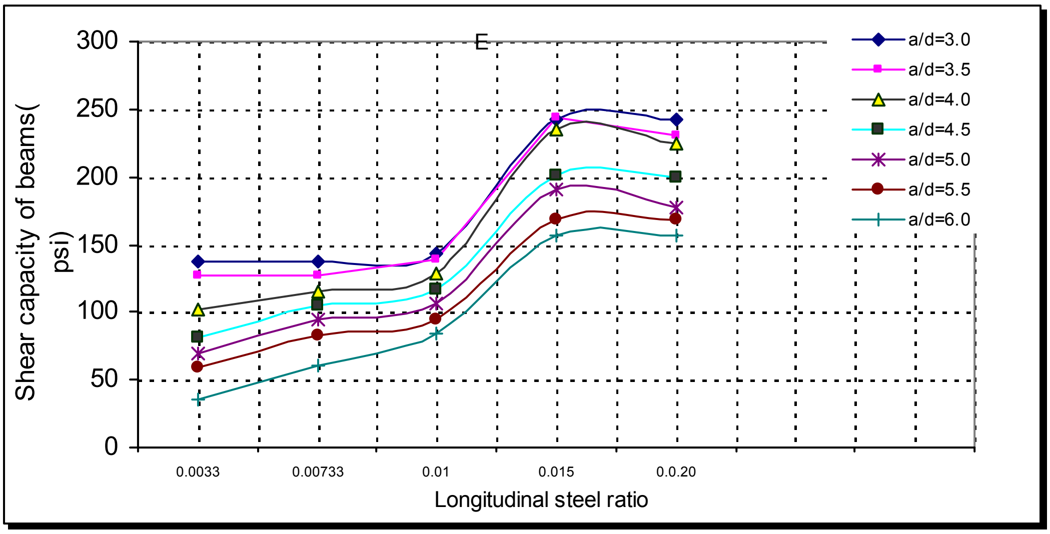

Figure 9. Effect of longitudinal steel ratio on the shear capacity of beams without transverse reinforcement for constant value of a/d ratio.

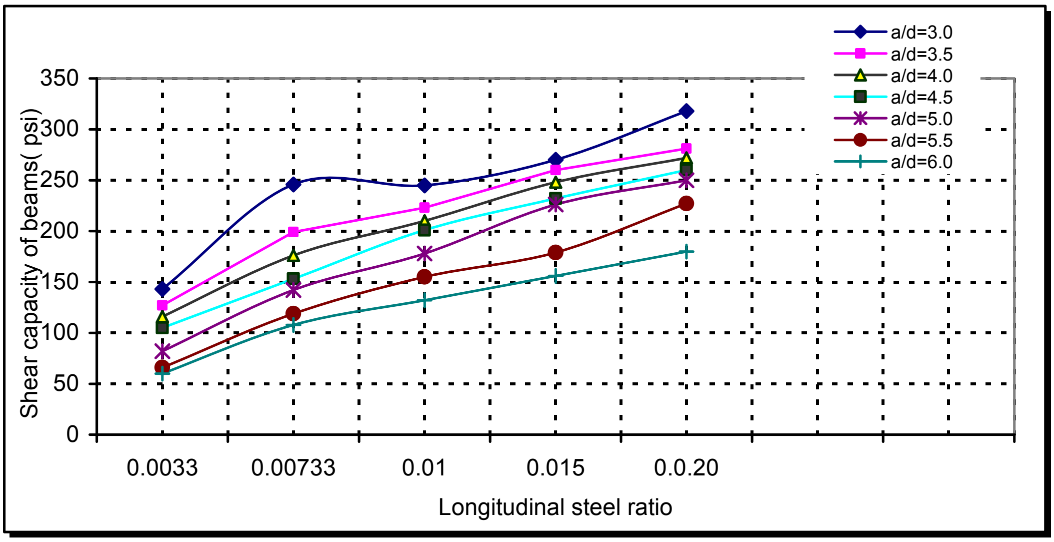

Figure 10. Effect of longitudinal steel ratio on the shear capacity of beams with transverse reinforcement for constant value of a/d ratio

8. CONCLUSIONS AND RECOMMENDATIONS

1. The shear capacity of beams both with and without web reinforcement has been increased with the increase of the longitudinal steel. This fact is well illustrated by ACI code.
2. The shear capacity of beams both with and without web reinforcement has been decreased with the increase in shear to depth (a/d) ratio but this decrease is not much pronounced in case of beams with web reinforcement.
3. The failure of the beams with lower values of longitudinal steel is mainly due to flexure cracks and the shear reinforcement plays no or very little role in improving the shear capacity or restricting the beam failure. Hence the longitudinal steel level may be selected between 1% and 2% to ensure that the stirrups can play active role in resisting the shear failure.
4. The ACI provisions for the stirrups contribution is less conservative for lower values of the longitudinal steel.
5. The traditional approach of summing up the individual concrete and steel contribution for determining the shear strength of the reinforced beams is also not proved by the experiments.

REFERENCES

1. Iguro, M., Shioya T., Nojiri, Y. and Akiyama, H., Experimental studies of shear strength of large reinforced concrete beams under uniformly distributed loads. Concrete Library of JSCE, No. 5, August 1985.
2. Thompson, E., Influence of beam size and stirrup effectiveness on the shear strength of reinforced concrete beams, Master thesis, Prude University, 2000.
3. Kani.M.W.; Huggins, M.W. and Wittkopp, R.R., Kani on shear of reinforced concrete" Department of Civil Engineering, University of Toronto, Canada, 1979.
4. Frosch R.J Behavior of Large scale reinforced concrete beams with minimum shear reinforcement. *ACI Structural Journal*, Nov-Dec. 2000. pp814-820
5. Shioya T; Iguru , M.Y Akioyama H and Okada T (1989) "Shear strength of large reinforced concrete beams , fracture mechanics applications to concrete SP-118 ACI Detroit.
6. Bazant, Z.P and Kim J.K (1984). The Size effect in shear failure of longitudinally reinforced beams. *ACI Structural Journal* Vol 81(5), pp. 456-468.
7. Collins, M.P., Mitchell, D., Adebar, P.E., and Vecchio, F.J. (1996). "A general shear design method". ACI Structural Journal, Vol. 93, No. 1, January-February 1996, pp. 36-45.
8. ACI- ASCE Committee 326(1962), Shear Diagonal Tension" ACI J; 59(1).
9. Adebar, P and Collins, M.P (1994), Shear Design of Concrete Offshore structures, ACI S. Journal May- June 1994.
10. Mac Gregor, J.G., Reinforced Concrete Mechanism and design, 3rd edition Prentice Hall, Eaglewood Calif, 1992.
11. Eric.J, Tompos and Frisch Robert. J., Influence of beam size, longitudinal reinforcement and stirrups on the concrete shear strength, *ACI Structural Journal*, Sept-Oct 2002.
12. Collins and Mitchell, Structural design considerations of High strength concrete ACI Concrete International 27-34.
13. Zararis, P.D., Aggregate interlock and steel shear forces in the analysis of RC membrane elements. *ACI Structural Journal* Mar-Apr, 1997.
14. ACI Committee 318-2002, Building Code Requirements for structural Concrete.
15. Vechio, F.J and Collins, M.P., The modified compression field theory for reinforced concrete elements subjected to shear, *ACI Structural Journal*, Mar 1989.
16. Ramirez, J.A and Breen, J.E., Evaluation of Modified truss model approach in shear" *ACI Structural Journal*, No. 5, **88**(1991)562-571.
17. Eurocode No.2, Design of Concrete Structures, Part 1: General Rules and Rules for buildings. Commission of European Communities ENV 1992-1-1 Dec. 1991.
18. Zararis P.D , Shear strength and minimum shear reinforcement of reinforced concrete slender beams. *ACI Structural Journal*, March-April 2003.