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BEHAVIOUR OF REINFORCED CONCRETE DEEP BEAM UNDER UNIFORM LOADING

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ABSTRACT : The results of fourteen reinforced concrete deep beams tested under four-point loading condition simulating approximately the uniformly distributed load, are reported. The test beams were simply supported and were made with brick aggregate concrete. The variables were flexural reinforcement, horizontal web reinforcement, and span to depth ratio of beam. The test beams were divided into two series according to their span to depth ratios (L/D = 1 and 2). The nominal cross section of the first series was 6" × 21" (152 mm × 533mm) and that of the second series was 6" × 12" (152mm × 305mm). The effective span lengths for the two series of beams were 21" (533mm) and 24" (610mm) respectively. The first beam of each series was designed and detailed as per the recommendations of the ACI Building Code 318-89 (ACI, 1989). In the remaining six beams of each series, the amount of either the flexural reinforcement or, the horizontal web reinforcement or, both were increased in relation to that of first beam of the corresponding series.

KEY WORDS: Reinforced Concrete, Deep Beams, Shear Strength, Brick Aggregates, Uniform Loading, Cracking Load, Ultimate Load, Crack Pattern.

INTRODUCTION

Deep beam can be defined as a beam having a ratio of span to depth of about 5 or less, or having a shear span less than about twice the depth and which are loaded at the top or compression face only (ACI, 1989). They are encountered in transfer girder, pile cap, foundation wall, raft beam, wall of rectangular tank, hopper, floor diaphragm and shear wall. Because of their proportions deep beams are likely to have strength controlled by shear rather than flexure. On the other hand, their shear strength is expected to be significantly greater than predicted by the usual equations, because of a special capacity to redistribute internal forces before failure and to develop mechanisms of force transfer quite different form beams of common proportions (Winter and Nilson, 1987).

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Brick aggregate is widely used in deep beams like other structural members in Bangladesh. But almost all of the Codes of Practices adopted in different countries are based on concrete made with stone chips as coarse aggregates. The behavior of brick aggregate reinforced concrete deep beam is expected to differ from those beams made with stone aggregates. Hence it is generally felt that studies are needed to understand the behavior of deep beam made with brick aggregate concrete under different conditions of loading.

REVIEW

Many of the complex behaviors of reinforced cement concrete under shear and flexure are yet to be identified to employ this material advantageously and economically. ASCE-ACI Shear Committee Report (1973) gave a selective list of about 200 papers on shear which indicates clearly the intensive research effort in this regard during two decades. Yet, the progress in the understanding and quantitative assessment of the behavior of members subjected to flexure and shear has been less spectacular. This is acknowledged by the ACI-ASCE Committee 426 (1962) in their concluding remarks as "It has been emphasized that the design procedures proposed are empirical because the fundamental nature of shear and diagonal tension strength is not yet clearly understood. Further basic research should be encouraged to determine the mechanism which results in shear failures of reinforced concrete members".

Among the several available methods for computing the ultimate load capacity of deep beam, the ACI method (ACI, 1989) and the Singh and Ray (1980) method consider the component shear of concrete, flexural steel, horizontal web steel and vertical web steel separately. But the Ramkrishnan and Ananthanarayana (1968) method and the Selvam and Thomas (1987) method consider the contribution of concrete only. On the other hand, the Mau and Hsu (1989) method consider the combined action of concrete and reinforcements (both flexural and web) but the contribution of each component cannot be separated. Siao (1993, 1995) included the effect of both horizontal and vertical web reinforcements in predicting the ultimate shear strength of deep beams but ignored the contribution of flexural steel.

A review of literature reveals that a very few number of studies [Kabir (1982), and Ali (1984)] were performed on deep beams having brick chips (khoa) as coarse aggregates. Moreover these two studies were done on single span simply supported deep beams by varying the web reinforcements (vertical and/or horizontal) only. No change in flexural reinforcements was done. The findings and suggestions of these studies should have been substantiated by further studies but nothing is available in literature.

EXPERIMENTAL INVESTIGATIONS

The test beams having span to depth ratio 1 and 2 were designated as DB-P series and DB-Q series respectively and each series consisted of seven beams.

(i) Casting of Beams :

The test beams were cast using Portland Cement (ASTM Type-1), ordinary Sylhet sand (F. M. = 2.72) as fine aggregate and brick khoa [0.75" (19mm) down graded] as coarse aggregate. The flexural reinforcements used in the test beams were mild steel plain bars of 0.625" (16mm) through 1.0" (25mm) diameters. Both vertical and horizontal web reinforcements were 0.25" (6.3mm) diameter plain mild steel rods. Physical properties of all reinforcements used are tabulated in Table 1.

Table 1. Physical properties of reinforcements used in test beams

Bar size	Nominal diameter (in)	Actual diameter (in.)	Average area (sq. in.)	Average yield strength (ksi)	Average ultimate strength (ksi)	Average % elongation (8" gauge length)
#8	1.00	0.9485	0.707	38.70	60.00	18%
#7	0.875	0.8441	0.560	43.40	63.00	29%
#6	0.750	0.700	0.385	42.50	58.00	17%
#5	0.625	0.6117	0.294	51.00	78.00	19%
#2	0.250	0.2613	0.054	33.00	53.00	18%

Note : 1 inch = 25.4 mm, 1 sq. in. = 64f5 sq. mm, 1 ksi = 6.9 MPa.

The water-cement ratio of concrete mix was 0.50 and the concrete mix ratio was :- Cement : Sand : Khoa = 1 : 2.2 : 2.7 (by weight).

Two 0.5" (12.7 mm) thick and 3" x 6" (76m x 152mm) mild steel plates were welded to either end of the flexural bars to prevent premature bond failure (Fig. 1).

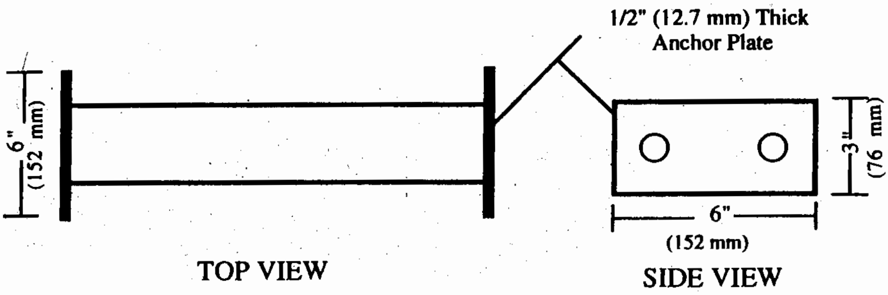

Fig 1. Flexural steel assembly with anchor plates.

On completion of the reinforcement assembly, some electrical resistance strain gauges were installed on certain selective locations on the surface of reinforcements. Details of reinforcement arrangement along with strain gauge locations for two beams (DB-P1 and DB-Q1) are shown in figs. 2 and 3. Two beams one from each series (e.g. DB-P1 and DB-Q1, DB-P2 and DB-Q2 etc.) were cast on the same day and a set of six control cylinders were also prepared. The physical properties of all the test beams are given in Table 2.

(ii) Testing of Beams :

The test beams were subjected to uniformly distributed load applied at the top (compression) surface of beams in a 400-kip capacity Universal Testing Machine (hydraulic type) of the Structures Laboratory in the department of Civil Engineering, BUET, Dhaka. Two series of steel I-joists with rollers, steel plates, and rubber pads were employed as load transfer devices for the two series of beams. This system transferred the concentrated load from the machine into a uniformly distributed load system upon the surface of the test beam. Details of the test set-up are shown in Figs. 4 and 5. Beam surfaces were white washed on all sides to facilitate visual observation of the propagation of cracks.

Four deflectometers having the smallest division of 0.01 mm were employed to measure the mid-span deflections of test beams at each load increment. Two of these were set at mid-span and other two at the ends for recording support settlements. The cracking and ultimate loads and the observed central deflections of test beams are given in Table 3 and Table 4 respectively. The observed crack patterns of test beams DB-P1 and DB-Q1 are shown in Fig. 6 and Fig. 7 respectively.

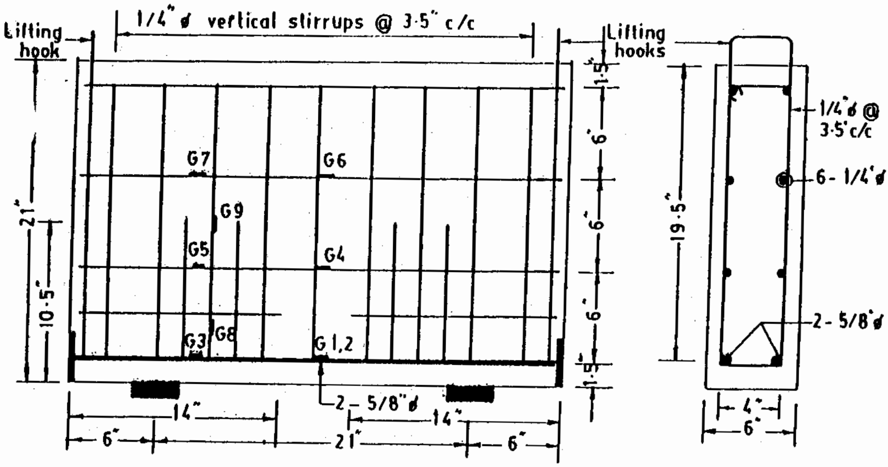

Fig 2. Reinforcement arrangement of beam DB-P1

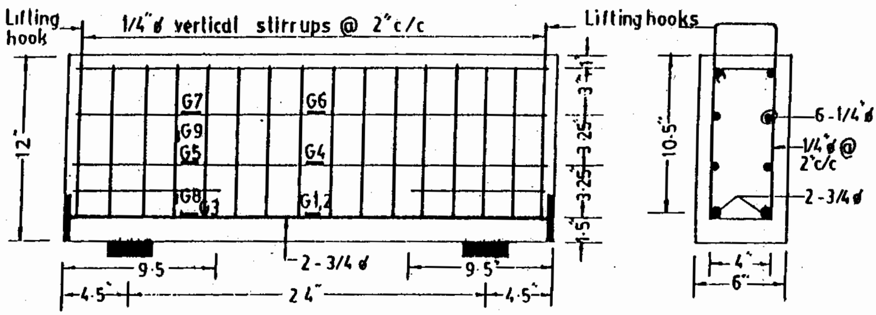

Fig 3. Reinforcement arrangement of beam DB-Q1

DISCUSSION OF TEST RESULTS

A brief discussion on some of the important aspects of deep beam behaviour observed are presented here.

(i) Cracking Load capacity :

The flexural and diagonal cracking loads are tabulated in Table 3 for the two series of beams. The variation of cracking and ultimate loads of test beams with change in the amount of reinforcements are shown in Table 5. In DB-P series of beams the diagonal cracks developed before the flexural cracks (except DB-P6) while the reverse was observed in case of DB-Q series of beams (except DB-Q7). From Table 5, it is seen that the mean ratios of diagonal cracking load to ultimate load are 0.469 for beams of DB-P series and 0.359 for beams for DB-Q series.

Table 2. Properties of test beams

Beam mark	Measured overall depth D, in.	Measured beam width b, in	Actual L/D	Flexural reinf. ratio P_f	% Change of flexural reinf. over 1st. beam (ACI beam)	Web steel ratio		% Change of vert. web reinf. over 1st. beam	% Change of horz. web reinf. over 1st. beam	f'_c (psi)	f'_{sp} (psi)
						Vertical P_v	Horizontal P_h				
Series DB-P Nominal L/D=1, Span Length = 21" (533mm)											
DB-P1	21.0	6.00	1.0	0.0050	-	0.0051	0.0030	-	-	2.510	240
DB-P2	21.0	6.06	1.0	0.0065	+ 30.0%	0.0051	0.0040	0.0%	+ 33.3%	2870	310
DB-P3	21.0	6.06	1.0	0.0095	+ 90.0%	0.0051	0.0060	0.0%	+ 100.0%	2930	325
DB-P4	21.0	6.19	1.0	0.0049	* - 2.0%	0.0050	0.0058	* - 2.0%	+ 93.3%	2920	395
DB-P5	21.0	6.13	1.0	0.0094	+ 88.0%	0.0050	0.0029	* - 2.0%	* - 3.3%	2930	338
DB-P6	21.0	6.13	1.0	0.0049	* - 2.0%	0.0050	0.0039	* - 2.0%	+ 30.0%	2890	350
DB-P7	21.0	6.13	1.0	0.0065	+ 30.0%	0.0050	0.0029	* - 2.0%	* - 3.3%	2730	320
Series DB-Q Nominal L/D=2, Span Length = 24" (610mm)											
DB-Q1	12.18	6.13	1.97	0.0120	-	0.0088	0.0054	-	-	2510	240
DB-Q2	12.18	6.06	1.97	0.00176	+ 46.7%	0.0089	0.0071	* + 1.1%	+ 31.5%	2870	310
DB-Q3	12.06	6.06	1.99	0.0222	+ 85.0%	0.0089	0.0089	* + 1.1%	+ 64.8%	2930	325
DB-Q4	12.30	6.13	1.95	0.0120	0.0%	0.0089	0.0089	0.0%	+ 64.8%	2920	395
DB-Q5	12.30	6.06	1.95	0.0222	+ 85.0%	0.0089	0.0055	* + 1.1%	* + 1.9%	2930	338
DB-Q6	12.24	6.19	1.96	0.0119	* - 0.8%	0.0087	0.0070	* - 1.1%	+ 29.6%	2890	350
DB-Q7	12.37	6.00	1.94	0.0178	+ 48.3%	0.0090	0.0055	* + 2.3%	* + 1.9%	2730	320

f'_c = Compressive strength of concrete; f'_{sp} = Splitting tensile strength of concrete. (1 psi = 6.9 × 10^{-3} MPa)

* The change was considered as zero but this small amount of change appears due to unintentional change in beam dimensions during casting.

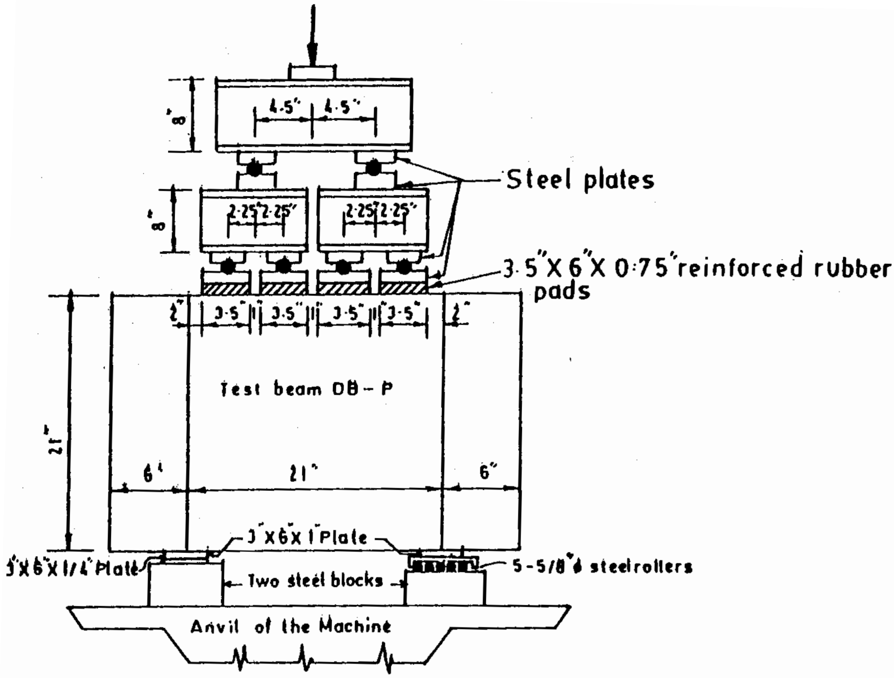

Fig 4. Test set-up for loading of beam DB-P

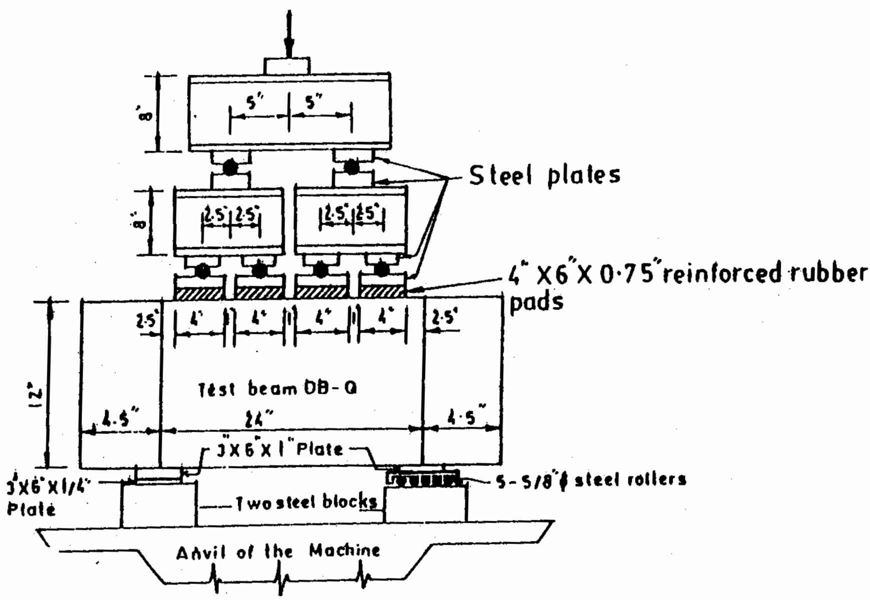

Fig 5. Test set-up for loading of beam DB-Q

Table 3. Observed cracking and ultimate loads of test beams

Beam mark	Concrete crushing strength f'_c, ksi	Flexural cracking load P_f, kip	Diagonal cracking load P_{cr}, kip	Ultimate load P_u, kip
Series DB-P : L/D= 1.0				
DB-P1	2.51	90	80	166
DB-P2	2.87	120	90	210
DB-P3	2.93	120	110	222
DB-P4	2.92	100	90	183
DB-P5	2.93	100	90	187
DB-P6	2.89	80	90	200
DB-P7	2.73	110	80	175
Series DB-Q : L/D = 2.0				
DB-Q1	2.51	40	55	118
DB-Q2	2.87	50	50	150
DB-Q3	2.93	50	50	170
DB-Q4	2.92	40	50	136
DB-Q5	2.93	50	80	135
DB-Q6	2.89	30	30	133
DB-Q7	2.73	40	30	130

[1 Kip = 4.45 kN, 1 ksi = 6.9 MPa]

Table 4. Observed maximum deflections (at mid-span) of test beams

Beam mark	Maximum Deflection (mm) of the Beam at the Applied Load of														
	0 kip	20 kip	40 kip	60 kip	80 kip	100 kip	110 kip	120 kip	130 kip	140 kip	150 kip	160 kip	170 kip	180 kip	190 kip
Series DB-P : L/D = 1.0															
DB-P1	0.0	0.09	0.17	0.26	0.36	0.54	0.65	0.74	0.85	0.97	1.16	1.47	2.0	--	--
DB-P2	0.0	0.09	0.08	0.12	0.15	0.23	0.28	0.33	0.37	0.43	0.48	0.56	0.64	0.72	0.83
DB-P3	0.0	0.27	0.34	0.42	0.49	0.56	0.59	0.66	0.69	0.76	0.80	0.84	0.93	1.02	1.09
DB-P4	0.0	0.43	0.62	0.74	0.85	1.01	1.06	1.14	1.22	1.28	1.44	1.57	1.78	2.29	2.73
DB-P5	0.0	0.33	0.47	0.59	0.70	0.87	0.95	1.01	1.10	1.23	1.33	1.48	1.66	2.01	2.64
DB-P6	0.0	0.27	0.31	0.37	0.43	0.51	0.59	0.67	0.75	0.83	0.91	1.03	1.15	1.27	1.34
DB-P7	0.0	0.43	0.60	0.69	0.78	0.90	0.98	1.07	1.16	1.26	1.42	1.73	2.23	2.65	--
Series DB-Q : L/D = 2.0															
DB-Q1	0.0	0.27	0.50	0.69	0.96	1.31	1.67	2.22	--	--	--	--	--	--	--
DB-Q2	0.0	0.13	0.18	0.25	0.35	0.51	0.64	0.78	1.05	2.11	--		--	--	--
DB-Q3	0.0	0.06	0.23	0.41	0.58	0.78	0.87	0.98	1.08	1.22	1.41	1.66	2.52	--	--
DB-Q4	0.0	0.09	0.04	0.19	0.40	0.65	0.84	1.09	1.56	1.96	--	--	--	--	--
DB-Q5	0.0	0.33	0.57	0.82	1.12	1.44	1.66	1.88	2.32	2.85	--	--	--	--	--
DB-Q6	0.0	0.27	0.61	0.94	1.26	1.60	1.80	2.07	2.71	3.41	--	--	--	--	--
DB-Q7	0.0	0.14	0.54	0.82	1.06	1.34	1.54	1.84	2.25	--	--	--	--	--	--

[Note : 1 kip = 4.45 kN]

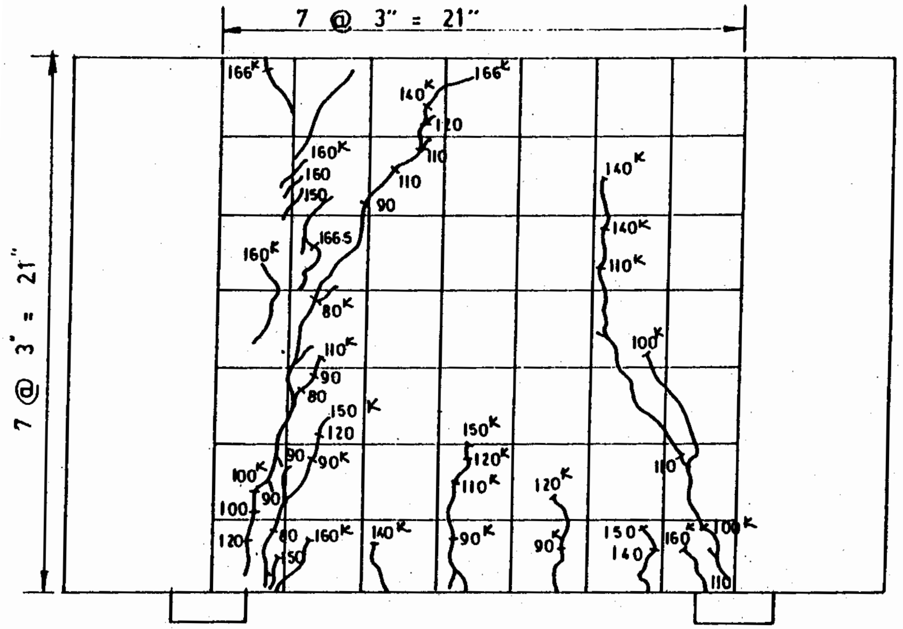

Fig 6. Crack pattern of beam DB-P1

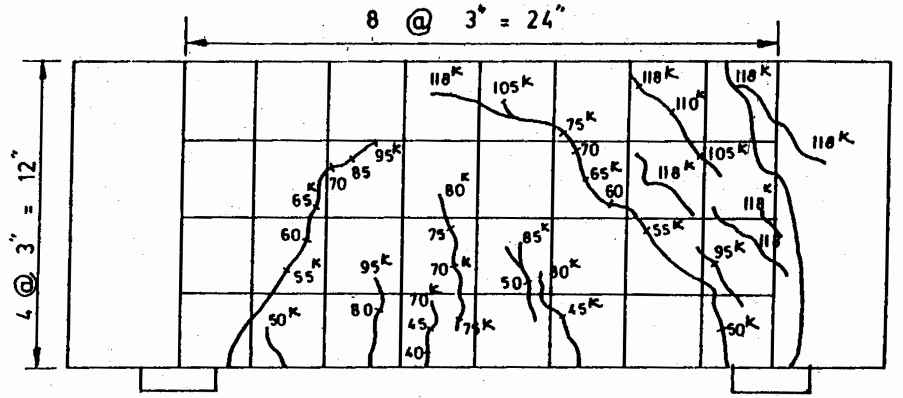

Fig 7. Crack pattern of beam DB-Q1

(ii) Ultimate Load capacity :

The observed ultimate load capacity of different test beams are also given in Table 3. It is evident that the variations of the ultimate load capacity of beams (Table 2 and Table 3) are due to the variations of their concrete strengths and the amount of horizontal (both flexural and web) reinforcements in a particular series of beams.

In Table 6, the measured ultimate load along with the ratios of different horizontal reinforcements of each test beam are shown. The first beam of each series are provided with minimum requirements of horizontal (both flexural and web) reinforcements as per ACI Code [1]. The horizontal reinforcements in the rest six beams of each series are increased above that of minimum requirements.

It may be mentioned here that the ultimate crushing strength (f'_c) of concrete are not same for all the beams of a series. To find out the exclusive effect of horizontal reinforcements on the ultimate load capacity, the observed load values are modified to eliminate the effect of variation of f'_c. The modifications are done by multiplying the observed load value of the concerned beam by the ratio β obtained by the following relation :

$$\beta = \frac{\sqrt{f'_{cl}}}{\sqrt{f'_{cb}}} \qquad (1)$$

Where, f'_{cl} = Crushing strength of concrete of first beam.

f'_{cb} = Crushing strength of concrete of beam concerned.

The flexural reinforcements of the 7th and 5th beams of each series were increased over that of the 1st beam while the horizontal web reinforcements were kept constant. But it is seen that the ultimate load capacities of DB-P1, DB-P7, and DB-P5 are 166^k (739 kN), 167.8^k (747 kN), and 173.1^k (770 kN) respectively and that of beams DB-Q1, DB-Q7, DB-Q5 are 118^k (525 kN), 124.7^k (555 kN), 125^k (556 kN) respectively. It is therefore, seen that the increase in ultimate load capacity due to the increase in flexural reinforcement alone is negligible.

On the other hand, the horizontal web reinforcements of 6th and 4th beams were increased over that of the 1st beam of each series keeping the flexural reinforcements constant. But the increase in their ultimate load capacities (See Col. 4 and Col. 7 of Table 6) are also negligible.

The 2nd and the 3rd beams of each series faced the increase in both the flexural and the horizontal web reinforcements over that of the 1st beam of that series. The ultimate load capacities of beams DB-P1, DB-P2, and DB-P3 are 166^k (739 kN), 196.4^k(874 kN), 205.5^k (914.5 kN) respectively and that of the beams DB-Q1, DB-Q2, and DB-Q3 are 118^k (525 kN), 140.3^k (624 kN), 157.3^k (700 kN) respectively (See Tables 2 and 6). In this case the increase in ultimate load capacities for both the series of test beams are of considerable amount.

Table 5. Observed cracking and ultimate loads for various amount of flexural and horizontal shear reinforcement.

Beam mark	Concrete crushing strength f'_c, ksi	Flexural steel ratio $P_f=A_s/bd$	% Change of flexural reinf. over first beam (ACI beam)	Horizontal web steel ratio $P_h=A_{vh}/bs_2$	% Change of horizontal web reinf. over first beam (ACI beam)	Flexural cracking load P_f (kip)	Diagonal cracking load P_{cr} (kip)	Ultimate load P_u, (kip)	Ratio P_f/P_u	Ratio P_{cr}/P_u
Series DB-P : L/D=1.0										
DB-P1	2.51	0.0050	--	0.003	--	90	80	166	0.542	0.482
DB-P2	2.87	0.0065	+ 30.0	0.004	+ 33.3	120	90	210	0.571	0.429
DB-P3	2.93	0.0095	+ 90.0	0.006	+ 100.0	120	110	222	0.541	0.495
DB-P4	2.92	0.0050	0.0	0.006	+ 100.0	100	90	183	0.456	0.492
DB-P5	2.93	0.0095	+ 90.0	0.003	0.0	100	90	187	0.535	0.481
DB-P6	2.89	0.0050	0.0	0.004	+ 33.3	80	90	200	0.400	0.450
DB-P7	2.73	0.0065	+ 30.0	0.003	0.0	110	80	175	0.629	0.457
								Mean	0.538	0.469
								C*	11.9%	4.9%
Series DB-Q : L/D=2.0										
DB-Q1	2.51	0.0120	--	0.0054	--	40	55	118	0.339	0.466
DB-Q2	2.87	0.0176	+ 46.7	0.0071	+ 31.5	50	50	150	0.333	0.333
DB-Q3	2.93	0.0222	+ 85.0	0.0089	+ 64.8	50	50	170	0.294	0.294
DB-Q4	2.92	0.0120	0.0	0.0089	+ 64.8	40	50	136	0.294	0.368
DB-Q5	2.93	0.0222	+ 85.0	0.0054	0.0	50	80	135	0.370	0.593
DB-Q6	2.89	0.0119	0.0	0.0070	+ 31.5	30	30	133	0.226	0.226
DB-Q7	2.73	0.0178	+ 48.3	0.0054	0.0	40	30	130	0.308	0.231
								Mean	0.309	0.359
								C*	13.7%	34.2%

C* = Co-efficient of Variation.
[1 Kip = 4.45 kN]

Table 6. Variation of ultimate load capacity with the variation of horizontal reinforcement

Beam Mark	Concrete crushing strength f'_c, ksi	Flexural reinf. ratio $p_f = A_s/bd$	Horizontal web reinf. ratio $p_h = A_{vh}/bs_2$	Total horizontal reinf. ratio $p_t = p_f + p_h$	Observed ultimate load P_u, kip	Ultimate load correspond -ing to f'_c = 2.51 ksi P'_u, kip
Series DB-P : L/D = 1.0						
DB-P1	2.51	0.0050	0.0030	0.0080	166	166.00
DB-P2	2.87	0.0065	0.0040	0.0105	210	196.4
DB-P3	2.93	0.0095	0.0060	0.0155	222	205.5
DB-P4	2.92	0.0050	0.0058	0.0108	183	169.7
DB-P5	2.93	0.0095	0.0029	0.0124	187	173.1
DB-P6	2.89	0.0050	0.0039	0.0089	200	186.4
DB-P7	2.73	0.0065	0.0029	0.0094	175	167.80
Series DB-Q : L/D = 2.0						
DB-Q1	2.51	0.0120	0.0054	0.0174	118	118.00
DB-Q2	2.87	0.0176	0.0071	0.0247	150	140.3
DB-Q3	2.93	0.0222	0.0089	0.0311	170	157.34
DB-Q4	2.92	0.0120	0.0089	0.0209	136	126.1
DB-Q5	2.93	0.0222	0.0055	0.0277	135	125.0
DB-Q6	2.89	0.0119	0.0070	0.0189	133	124.0
DB-Q7	2.73	0.0178	0.0055	0.0233	130	124.7

[1 kip = 4.45 kN, 1 ksi = 6.9 MPa]

(iii) Cracking Pattern :

In all the beams it was observed that diagonal cracks developed first in the beams of DB-P series while flexural cracks developed first in the other series. It was also observed that diagonal cracks propagated initially at higher rate but this rate of propagation decreases with the increase of load applied. The average values of flexural crack penetrations are 0.24D and 0.47D for beams of DB-P series and DB-Q series respectively, where D is the overall depth of the beam.

(iv) Mode of Failure :

All of the beams of DB-P series failed due to diagonal tension. Here concrete splitting occurred along the line of propagation of main inclined cracks. DB-Q series beams also failed in diagonal tension. Although flexural cracks developed first in almost all of these beams but flexural failure was not the final mode of failure in any of the test beams.

CONCLUDING REMARKS

In summary, following conclusions can be drawn from the various observations and analysis performed in this study :

(i) Diagonal cracks develop first in relatively deeper beams and flexural cracks develop first in the shallower beams provided the beams have sufficient reinforcements.

(ii) The mean ratios of both the diagonal cracking load to ultimate load and the flexural cracking load to ultimate load of deeper beams are greater than those of shallower beams.

(iii) The increase in ultimate load capacity of deep beams depend upon the increase in both the flexural and the horizontal web reinforcements.

(iv) The mean ratio of the depth of flexural crack to overall depth of deeper beam is smaller than that of shallower beam and even at ultimate load level the flexural cracks remain within the lower mid-depth.

(v) The principal mode of failure in deep beams having adequate reinforcements is diagonal tension cracking.

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