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Effect of depth and distribution of horizontal shear reinforcement on shear strength and ductility of RC deep beams

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ABSTRACT: Some experimental investigations on the behavior of reinforced concrete (RC) deep beams have been reported. The effect of distribution of horizontal shear reinforcement and the size effect on shear strength and ductility were studied. Twelve RC deep beams were tested by varying the depth i.e. 300mm, 600mm and 1200mm, two different percentages, 0.2% and 0.3%, and two types of distribution of reinforcement; (i). uniformly distributed over the total depth and (ii). uniformly distributed only over the middle 0.3d of the beam. All the beams were provided with 1.5% flexural reinforcement. The shear span-to-depth ratio was 0.75. The mode of failure alters from ductile in small size beams to brittle in large size beams. The uniform distribution of reinforcement over middle 0.3d has been observed to improve the shear strength and ductility significantly. Very strong size effect has been observed in RC deep beams on the shear strength. When the beam depth increased from 600mm to 1200mm about 20-25% of the diagonal strength was found to decrease, while the decrease in shear strength is about 35-55% when the depth increases from 300mm to 1200mm

1 INSTRUCTION

The behavior of RC deep beams is complex. The assumption of "*plane sections remain plane in bending*" is not applicable in deep beams. The important characteristic of the deep beam is its high shear strength due to internal arch action, which thrusts the load directly on to the end support through concrete struts. As per ACI code (ACI 318), the beams are classified as deep beams when their shear span-to-depth ratio is less than or equal to two. If the quantity of flexural reinforcement is high without shear reinforcement, such deep beams fail in shear (Yang et al. 2003). In larger size deep beams, the crack propagates fast causing sudden failure (Bakir & Boduroglu, 2005).

The ACI-318 (ACI 318-2008) and IS code (IS 456-2000) consider the strength of concrete, percentage of longitudinal and transverse reinforcement and shear span-to-depth ratio as major parameters influencing the shear strength of deep beams. ACI 318 and IS code do not consider the size effect on the prediction of shear strength in deep beams. In deep beams, with shear span-to-depth ratio less than or equal to 2.5, there exists significant reserve strength beyond the peak load, resulting in relatively less brittle failure (Khaldoun & Khaled, 2004).

2 REVIEW OF LITERATURE

In deep beams, the shear reinforcement in the horizontal direction is found to be effective than the vertical shear reinforcement, on the load carrying capacity (Ashour & Morley, 1996). The shear strength of concrete based on strut-and tie model has been reported (Tang & Tan, 2004). An explicit expression for the shear strength deep beams based on the strut-and tie model has been reported (Russo et al. 2005). Tests have been carried out on 52 RC deep beams to study the effect of shear span-to-depth (a/d) ratio, and vertical and horizontal shear reinforcement on the ultimate shear strength and crack width (Smith & Vantsiotis, 1982). The web reinforcement does not affect the formation of diagonal cracking; however, it affects the ultimate shear strength. The vertical reinforcement improves the ultimate shear strength, while the horizontal shear reinforcement does not have any influence on the ultimate strength.

Some studies on RC beams under uniformly distributed loading with beam depth varying between 100 mm and 3000 mm without shear reinforcement has revealed that as the effective depth of beam increases the shear strength decreases asymptotically (Iguro et al. 1984). In large size lightly reinforced beams the reduction of shear strength was correlated with the vertical spacing of longitudinal bars rather than on the overall depth of the beam (Collins & Kuchma, 1999). Alternative shear strength, at both the ultimate and the cracking stages of RC members without web reinforcement has been estimated (Karim, 1999).

Comparison of test results on 24 beams, with and without shear reinforcement, showed that the shear strength of HSC beams estimated according to the current code provisions and the safety margins were found to be reduced (Raghu & Priyan, 2000). Tests on 21 RC beams in shear by (Anngelakos et al. 2001) showed that the shear strength decreases substantially as the beam size increases, and also as the longitudinal reinforcement ratio decreases. Studies on RC deep beams reported that the shear design procedures laid down in ACI 318 provisions are conservative (Aguilar et al. 2001). At small shear span-to-depth ratio, the large size beams failed in brittle manner with wide shear cracks and at high energy release rate due to the size effect (Yang et al. (2003). The failure of RC deep beams was found to be due to crushing of concrete in compression with reduced section at the end of the critical diagonal crack (Zararis, 2003), due to reduction of the contribution of the flexural reinforcement as the horizontal splitting of concrete impairs its contribution. A study on shear failure of large size wide beams has been reported (Lubell et al. 2004). Experimental studies on 11 RC beams made of 65 MPa concrete, reinforced with transverse and longitudinal reinforcement have been reported (Khaldoun and Khaled, 2004). Reduction of crack width was observed at high quantity of longitudinal reinforcement.

3 RESEARCH SIGNIFICANCE

The prediction of shear strength of deep beams is complex due to the redistribution of internal stresses. Several parameters affect the shear strength of RC deep beams such as shear span-to-depth ratio, concrete strength, anchorage of reinforcement, size of beam, amount and distribution of flexural and shear reinforcement. The failure of RC deep beam should be accompanied by sufficient ductility. The reduction of shear strength of deep beams and alteration of its behavior from ductile to brittle with increasing depth needs to be understood. Therefore, an attempt has been undertaken to study the behavior and design strength of deep beams based on shear ductility.

4 EXPERIMENTAL PROGRAM

The objective of the study is to investigate the size effect on shear strength and shear ductility of RC deep beams. The scope of this study is limited to RC deep beams with shear span-to-depth ratio 0.75, with 2.0% longitudinal reinforcement and 0.2 and 0.3% horizontal shear reinforcement.

4.1 *Materials and preparation of test beams*

Ordinary Portland cement was used. Natural river sand with specific gravity 2.73 and fineness modulus 2.84 was used. 20mm size coarse aggregate with specific gravity 2.70 and fineness modulus 6.93 was used. Potable water was used for both concreting and curing of specimens. The water-cement ratio was 0.32. The concrete mix proportions were: 1: 1.5:2.9 (cement content = 474 kg/m^3, fine aggregate = 710 kg/m^3, coarse aggregate = 1373 kg/m^3). Well seasoned wooden beam moulds were fabricated to cast the beams of 300mm, 600mm and 1200mm depth and 150mm width. Flowable concrete used in this study was produced using superplasticizer. Along with RC deep beams, six standard concrete cubes of 150x150x150mm for determining the compressive strength and six standard cylindrical specimens of 150mm diameter and 300mm height, for determining the split tensile strength of concrete were cast. After 24hours of casting, the beams were demolded and cured for 28 days. The compressive strength of concrete ranges between 52.15 and 61.93 MPa and its tensile strength ranges between 4.77 to 6.04 MPa.

4.2 *Beam dimensions*

The beams are grouped in to four; Series I (BS-300-0.2-UN, BM-600-0.2-UN, BL-1200-0.2-UN), Series II (BS-300-0.2-CN, BM-600-0.2-CN, BL-1200-0.2-CN); Series III (BS-300-0.3-UN, BM-600-0.3-UN, BL-1200-0.3-UN); and Series IV (BS-300-0.2-CN, BM-600-0.2-CN, BL-1200-0.2-CN). The letter; S indicates-small, M-medium and L-large). The number 300/600/1200 indicates the overall depth of the beam in mm. All the beams were rectangular in cross-section with 150mm width. The overall depths of the three beams were; 300mm, 600mm and 1200mm and their effective depths were 252mm, 534mm and 1105mm respectively. The shear span-to-depth ratio was 0.75. The effective span-to-depth ratio was 1.5.

The overall length (L) of the beam was 1.5(overall depth, D, mm) + 2(150mm). The effective cover to the reinforcement was 40mm with a clear cover of 25mm in all the beams. The horizontal shear reinforcement was 0.2 and 0.3%, distributed uniformly over the total depth (UN) and uniformly distributed over 0.3d (CN). The beam designations and their dimensions are shown in Table 1.

Table 1. Beam Designation and Dimensions.

S. No	Beam Designation	D mm	d mm	a mm	L mm	l mm
1	BS-300-0.2-UN	300	252	225	750	450
2	BM-600-0.2-UN	600	534	450	1200	900
3	BL-1200-0.2-UN	1200	1105	900	2100	1800
4	BS-300-0.2-CN	300	252	225	750	450
5	BM-600-0.2-CN	600	534	450	1200	900
6	BL-1200-0.2-CN	1200	1105	900	2100	1800
7	BS-300-0.3-UN	300	252	225	750	450
8	BM-600-0.3-UN	600	534	450	1200	900
9	BL-1200-0.3-UN	1200	1105	900	2100	1800
10	BS-300-0.3-CN	300	252	225	750	450
11	BM-600-0.3-CN	600	534	450	1200	900
12	BL-1200-0.3-CN	1200	1105	900	2100	1800

4.3 *Beam Flexural and Shear Reinforcement*

All the beams were provided with 1.5% flexural reinforcement. The flexural reinforcement was extended or bent up at the supports to ensure adequate anchorage length. 6mm diameter mild steel bars were used as corner reinforcement. The vertical shear reinforcement was 6mm diameter two-legged stirrups (equal to 0.15% of the cross-section), which corresponds to the minimum shear reinforcement as per IS code. The spacing of the stirrups was 250mm c/c. In addition to the minimum vertical shear reinforcement, the horizontal reinforcement was also provided.

Table 2. Mechanical properties of reinforcing bars.

S. No.	Diameter mm	Yield Strength fy , MPa	Ultimate Strength, MPa
1	6	425	600
2	16	607	657
3.	20	543	663

Two percentages of the horizontal shear reinforcement, 0.2% and 0.3%, were adopted to study the effect of their distribution. In one case, the "*horizontal shear reinforcement distributed uniformly over the total depth of the beam*", designated as UN, and in another case, the "*horizontal shear reinforcement distributed uniformly over the middle 0.3d of the beam*", designated as CN. The strength of reinforcement is given in Table 2.

4.4 *Experimental setup and testing of beams*

Twelve beams were tested up to failure under three-point loading with two simple supports as shown in Figure 1. The ends of the beams were 150mm beyond the support reactions. Bearing plates of size 150mmx100mmx20mm were provided above the roller supports and below the load point to avoid the crushing of concrete locally. All the beams were tested using 6000kN capacity load controlled system. Linear variable differentiable transducers (LVDT) were mounted to monitor the central deflection of the beams. At every load increment, the central displacement, crack width and diagonal strain in concrete were recorded.

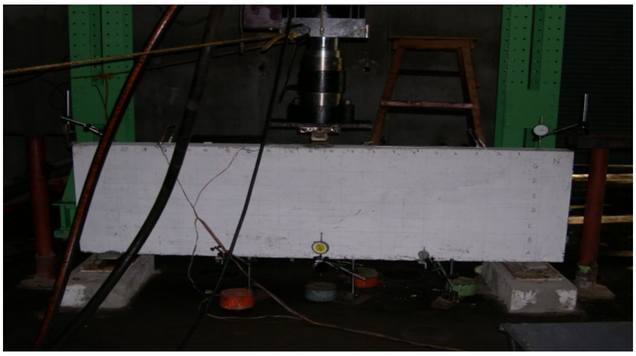

Figure 1. Beam experimental set up.

5 TEST RESULTS AND DISCUSSION

5.1 *Effect of beam depth on cracking*

The diagonal cracking strength and the ultimate shear strength of various sizes of beams are shown in Table 3.

Table 3. Cracking and ultimate shear strength of deep beams.

S. No.	Beam Designation	Dia. Cracking Strength, MPa	Ultimate Shear Strength, MPa
1	BS-300-0.2-UN	4.76	12.00
2	BM-600-0.2-UN	4.87	11.00
3	BL-1200-0.2-UN	3.5	5.07
4	BS-300-0.2-CN	4.76	12.00
5	BM-600-0.2-CN	4.75	9.61
6	BL-1200-0.2-CN	3.62	5.13
7	BS-300-0.3-UN	4.76	12.00
8	BM-600-0.3-UN	5.37	10.50
9	BL-1200-0.3-UN	4.22	7.72
10	BS-300-0.2-CN	4.76	12.00
11	BM-600-0.3-CN	5.24	11.12
12	BL-1200-0.3-CN	4.31	8.51

5.1.1 *Small size beams (D = 300mm)*

The stress is calculated using the effective beam dimensions. In beams of 300mm depth, the first diagonal crack was formed at a stress equal to 4.76 MPa. The crack was appeared diagonally from the support to the load point. Further increase in the loading the diagonal cracks were widened. At the stress in excess of 11.38 MPa, several diagonal cracks were formed showing distribution of damage. In small size beams, such a distributed damage leads to more ductile failures. Eventually, the diagonal splitting occurred along a line from support and the load point at a stress equal to 12.00 MPa.

5.1.2 *Medium size beams (D = 600mm)*

In beams with 0.2% horizontal shear reinforcement distributed uniformly over the total depth; the first diagonal crack was appeared at 4.87 MPa stress. As the stress increased to 10.0 MPa, the diagonal crack was widened from 0.075mm to 0.625mm. Eventually, the beam failed along the diagonal at a stress of

11.0MPa, which was followed by several diagonal cracks. At the same horizontal reinforcement with uniform distribution over the middle 0.3d, the first diagonal crack appeared at a stress 4.74MPa. At the stress equal to 9.5 MPa, the diagonal crack was widened. Eventually, the beam failed due to shear and crushing of concrete under the load at a stress of 9.61 MPa.

When the horizontal reinforcement was 0.3%, distributed uniformly over the total depth, the diagonal crack appeared at a stress of 5.37 MPa. Crushing of concrete was observed at a stress of 10.5 MPa. When 0.3% horizontal shear reinforcement was distributed over the middle 0.3d of the beam, the diagonal crack was formed at a stress of 5.24 MPa. Initiation of crushing was occurred at a stress of 9.5 MPa, which was accompanied by spalling of concrete. The process of crushing and spalling of concrete was continued up to a stress of 10.74 MPa. At a stress of 11.24 MPa, the beam failed due to crushing of concrete under the load point. 0.3% horizontal shear reinforcement distributed over the middle 0.3d of the beam appears to enhance the shear strength and also to improve the ductility. The ultimate strength of the beam was 11.24 MPa, which is greater than 10.5MPa on same size beam but the reinforcement was distributed uniformly over the total depth.

5.1.3 *Large size beam (D = 1200mm)*

In beams with 0.2% horizontal shear reinforcement, uniformly distributed over the total depth; the diagonal cracking strength was 3.5 MPa. The diagonal crack was inclined at an angle of 60^0 with the horizontal. As the diagonal stress was increased to 3.98 MPa, another parallel crack was formed. The beam failed due to shear near the support at an ultimate strength of 5.1 MPa in brittle mode. As the horizontal shear reinforcement was uniformly distributed over the middle 0.3d of the beam, a diagonal crack was formed at a stress of 3.61 MPa. As the load increased further, the beam sustained a maximum shear stress of 5.13 MPa. At this stress, the beam failure was sudden without warning.

When the horizontal shear reinforcement was 0.3%, uniformly distributed over the depth, the diagonal cracking strength was 4.22 MPa. As the stress increased further, the existing cracks widened further, leading to crushing of concrete at the support. The ultimate strength was 7.72 MPa. The ultimate strength was found to increase with brittle failure. When the reinforcement was distributed over the middle 0.3d, the diagonal cracking strength was 4.31 MPa. As the load was increased further, already the formed cracks were widened, but the initially formed diagonal crack was widened. More cracks were formed as the stress exceeded 6.52 MPa. At a stress of 8.93 MPa, the diagonal crack was widened followed by several parallel cracks. The process of crack propagation was prolonged, revealing that the increase in the percentage of horizontal shear reinforcement increases the shear strength and ductility of the beams.

5.2 *Size effect on diagonal cracking strength*

The diagonal cracking strength of deep beams with different beam depths and different percentages of horizontal shear reinforcement is shown in Table 3. When the horizontal shear reinforcement was 0.2%, with uniform distribution over the total depth of the beam, the diagonal cracking strengths were 4.76, 4.87 and 3.5MPa in beams with 300mm, 600mm and 1200mm depth respectively. The diagonal cracking strength decreases as the beam depth increases from 300mm to 600mm. In beams reinforced with 0.2% horizontal shear reinforcement distributed uniformly over the middle 0.3d of the beam, the diagonal cracking strengths were 4.76, 4.75 and 3.62 MPa in the beams with depths 300mm, 600mm and 1200mm respectively. The diagonal cracking strength decreases as the depth of the beam increases as shown in Figure 2.

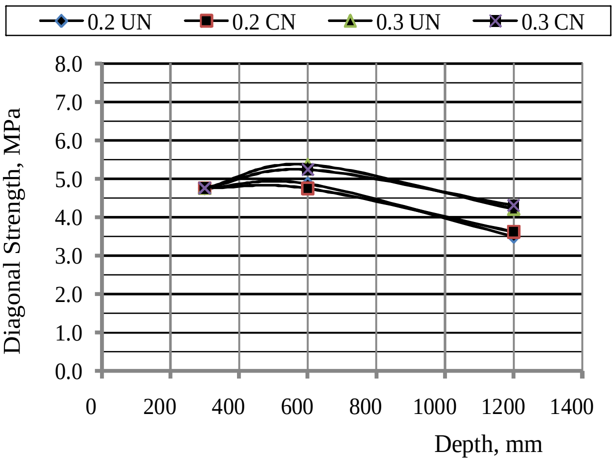

Figure 2. Diagonal cracking strength vs. Depth.

The diagonal cracking strengths in beams with 0.3% horizontal shear reinforcement distributed uniformly over the total depth were 4.76, 5.37 and 4.22 MPa in beams with 300mm, 600mm and 1200mm depths respectively. The diagonal cracking strengths were 4.76, 5.24 and 4.31 MPa in beams with 0.3% horizontal shear reinforcement distributed uniformly over the middle 0.3d of the beam. It shows that there exists a nonnegligible size effect on the diagonal cracking strength of beams. Further, it is also apparent from the experimental observations that the diagonal cracking strength looks constant in beams with depth varying between 300mm and 600 mm. The decrease in the diagonal cracking strength of deep beams with the increase in the beam depth ranges between 18.0% and 25%.

5.3 *Size effect on ultimate shear strength*

The ultimate shear strengths of deep beams with different beam depths and with different percentages of the horizontal shear reinforcements are shown in Table 3. When the horizontal shear reinforcement was 0.2%, with uniform distribution over the total depth of the beam the ultimate shear strengths were 12.00, 11.00 and 5.07 MPa respectively in beams of 300mm, 600mm and 1200mm depth respectively. In beams reinforced with 0.2% horizontal shear reinforcement distributed over the middle 0.3d, the ultimate shear strengths were 12.00, 9.61 and 5.13 MPa respectively in the beams with depths of 300mm, 600mm and 1200mm. The ultimate shear strengths in beams with 0.3% horizontal shear reinforcement distributed uniformly over the total depth were 12.00, 10.49 and 7.72 MPa respectively in beams of 300mm, 600mm and 1200mm depths. The ultimate shear strengths were 12.00, 11.12 and 8.51 MPa respectively in beams of 300mm, 600mm and 1200mm depth with 0.3% horizontal shear reinforcement distributed over the middle 0.3d.

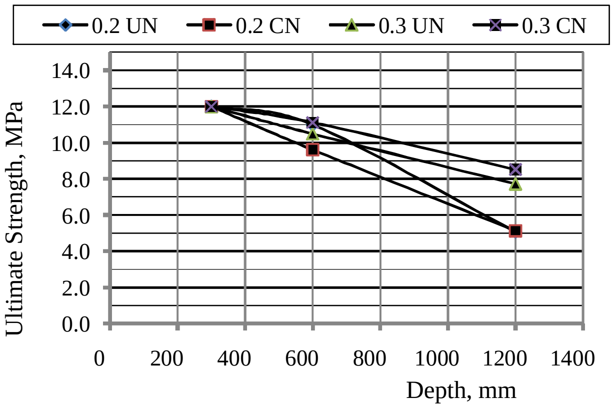

Figure 3. Ultimate shear strength vs. Depth.

As shown in Figure 3, it has been observed that the ultimate shear strength decreases as the depth of the beam increases, showing that there exists a strong size effect on the ultimate shear strength RC deep beams. For the design of RC beams in practice it is assumed that the ultimate shear strength is constant. The decrease in the ultimate shear strength of deep beams is about 20-25% when the depth increases from 300mm to 600mm, while the decrease in the shear strength is about 40-60% when the depth increases from 300mm to 1200mm. The decrease in the shear strength is about 20-23% when the depth increases from 600mm to 1200mm with 0.3% horizontal shear reinforcement uniformly distributed over the middle 0.3d of the beam. The decrease in the shear strength is about 35-55% in beams with 0.3% horizontal shear reinforcement distributed uniformly over the total depth of the beam when the depth increases from 600mm to 1200mm.

6 CONCLUSIONS

As the depth of the beam increases from 600mm to 1200mm, the diagonal cracking strength decreases with increasing the beam depth. Small size beams exhibited improved shear ductility. As the depth of the beam increases, the beams exhibit relatively brittle failure. As the quantity of horizontal shear reinforcement increases, the shear strength and the shear ductility of deep beam increase. The distribution of horizontal shear reinforcement has significant effect on the shear strength and the ductility of the beams. The uniform distribution of horizontal shear reinforcement over the middle 0.3d of the beam increases the shear strength and ductility very significantly. About 20-25% decrease in the diagonal cracking strength was observed when the beam depth increases from 600mm to 1200mm. Very strong size effect has been observed in RC deep beams on the shear strength. About 35-55% decrease in the shear strength was found when the beam depth increased from 300mm to 1200mm.

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