CHAPTER 7

EFFECT OF DISTRIBUTION OF REINFORCEMENT ON SHEAR STRENGTH

7.1. Introduction

The assumption of “plane sections before bending remain plane after bending” in simple bending theory cannot be applicable to deep beams due to complex redistribution of stresses upon cracking of concrete in the shear span. When adequate anchorage of beam tension reinforcement is ensured, the formation of internal arch enhances the shear capacity of the deep beams. In deep beams, the shear span-to-depth ratio is less than or equal to 2.0 (ACI 318, 2008). If the quantity of the flexural reinforcement is large enough, without shear reinforcement, such deep beams can fail due to shear (Yang et al. 2003). The cracks propagate catastrophically in deep beams causing brittle failures (Bakir and Boduroglu, 2005). The current American code (ACI 318, 2008) and also the Indian code (IS 456, 2000) consider the shear strength of deep beam varying with the compressive strength of concrete, the percentage longitudinal and transverse reinforcement and the shear span-to-depth ratio. In these codes, the size effect is not recognized for predicting the shear strength of deep beams. In deep beams with the shear span-to-depth ratio less than or equal to 2.5, significant reserve strength has been reported after the ultimate load,
which is accompanied by relatively less brittle failure (Khaldoun and Khaled, 2004).

7.2. Research Significance

RC deep beams exhibit complex cracking behavior due to several influencing parameters including the shear span-to-depth ratio, compressive strength of concrete, anchorage of reinforcement, depth of beam, percentage of the flexural and the shear reinforcement. The distribution of horizontal shear reinforcement influences the behavior and strength of RC beams. In general the failure of RC deep beams is catastrophic, the brittleness increases in large size deep beams made of high strength concrete. There is a lack of consensus in the literature on the cracking strength and ductility of RC deep beams vis-à-vis the size effect and distribution of the shear reinforcement. Hence, the objective of the study is to investigate the influence of the beam depth, the percentage and type of distribution of the horizontal shear reinforcement on the shear strength and cracking behavior of RC deep beams. The experimental programme is discussed in Chapter 5 (Part 2).

7.3. Results and Discussion

7.3.1. Effect of Beam Depth on Cracking Strength

7.3.1.1. Small Size Beams (D = 300mm)

The quantity of steel reinforcement required in small size beams of 300mm depth is relatively small corresponding to 0.2% and 0.3% of
the cross-section. When the nearest size of the diameter of the bar is identified, the number of reinforcing bars provided is the same in both the cases. Due to this, the number of bars required for these shear reinforcement ratios has resulted in only two; the horizontal reinforcement was distributed across the beam depth depending up on the type of distribution. The nominal stress is determined by dividing the load corresponding to cracking and/or ultimate load by the effective cross-sectional area of the beam. In small size beams of 300mm depth, the first diagonal crack was formed at a stress equal to 4.76 MPa. The cracks were observed along the diagonal joining the support and the load point. Further, with increase in the load, the diagonal cracks have been found to widen. When the nominal stress was greater than 11.38 MPa, several such diagonal cracks were observed, which were distributed over a band of diagonal cracks joining the support and the load point. The crack band width was relatively wider in the tension zone, while near the load point in the compression face, the width of the crack band was confined over a small band width. In small size beams, the distribution of cracking was uniform at closer spacing. Further, the ductility of the beams was found to be relatively large. Eventually, with adequate anchorage of the flexural reinforcement, a well defined diagonal splitting cracks in concrete was observed, which joined the support and the load point at a nominal stress of 12.00 MPa.
7.3.1.2. Medium Size Beams ($D = 600mm$)

In the medium size, 600mm depth, beams with 0.2% horizontal shear reinforcement, which was distributed uniformly over the whole depth, the first diagonal crack was observed at a nominal stress of 4.87 MPa. As the load is further increased, the diagonal crack was found to widen from 0.075mm at a nominal stress of 4.87 MPa to 0.625mm at a stress of 10.0 MPa. Eventually, the beam exhibited a high diagonal cracking at a nominal stress of 11.0 MPa. Further increase in the load increases the crack distribution along the diagonal.

When the quantity of the horizontal shear reinforcement is 0.2% with uniform distribution only over the middle third of the depth i.e. 0.3d, the first diagonal crack had appeared at a nominal stress of 4.74 MPa. It appeared that the formation of diagonal cracking was not affected by the distribution of the horizontal shear reinforcement. When the nominal stress reached a value of 9.5 MPa, the diagonal crack started to widen. Eventually, the failure in the beam was due to shear followed by crushing of the concrete under the point load at a nominal stress of 9.61 MPa.

When the medium size, 600mm depth, beams were provided with 0.3% horizontal shear reinforcement and distributed uniformly over the total depth of the beam, the diagonal cracks were observed when the nominal stress reached a value of 5.37 MPa. The crushing of concrete occurred when the nominal stress was 10.5 MPa. In RC beams
with 0.3% horizontal shear reinforcement, which was distributed over the middle third of the beam depth i.e. 0.3d, the diagonal cracking was formed when the nominal stress reached a value of 5.24 MPa. The crushing of concrete was occurred at a stress of 9.5 MPa, which was followed by cracking of concrete along the horizontal reinforcement. The crushing and spalling of concrete progressed further with the increase in the nominal stress level and continued up to a stress of 10.74 MPa. When the nominal stress reached 11.24 MPa, the medium size beams failed due to the crushing of concrete under the point load.

In the beams with 0.3% horizontal shear reinforcement, distributed uniformly only over the middle third of the beam depth i.e. 0.3d, improvement in the shear strength as well as the ductility of the beams were observed. The ultimate shear strength of the beam at failure was 11.24 MPa. It has been observed that the horizontal shear reinforcement distributed uniformly only over the middle third of the depth had improved the shear strength and beam ductility. The formation of the diagonal cracking at the middle depth of the beam was effectively confined by the horizontal shear reinforcement in the middle zone. By providing the adequate anchorage length of the tension reinforcement, the beam designed with 0.3% horizontal shear reinforcement exhibited smaller crack widths and uniform distribution of cracking with improvement of the shear strength.
7.3.1.3. Large Size Beam (D = 1200mm)

In large size beams, 1200mm depth, with 0.2% horizontal shear reinforcement and with uniform distribution over the total depth, the diagonal cracking was observed at a nominal stress level of 3.5 MPa. The inclination of the diagonal crack was observed to be at an angle of 60°, which is greater than that observed in the conventional beams, where the inclination of the cracking is about 45°. This is an important observation need to be recognized for designing effective shear reinforcement in deep beams. As the nominal stress increased further up to 3.98 MPa, the additional parallel cracks were also observed. The beams exhibited brittle failure in shear near the support at an ultimate stress of 5.1 MPa. As the horizontal shear reinforcement was uniformly distributed only over the middle-third of the depth i.e. over 0.3d, the diagonal cracks formed at a nominal stress of 3.61 MPa. It is clear from the observations on the large size beams that there has been an improvement in the diagonal strength with 0.2% horizontal shear reinforcement distributed uniformly only over the middle-third portion of the depth. As the load increased further, the beam sustained up to a maximum nominal stress of 5.13 MPa. Eventually, the beam exhibited catastrophic failure without warning.

In the large size, 1200mm depth, beams, provided with 0.3% horizontal shear reinforcement and uniformly distributed over the total depth, the diagonal cracking strength was observed to be 4.22 MPa. As the stress increased further, already formed cracks started widen-
ing further without any indication of new crack formation. This shows that in large size beams, only one major crack was formed and it further widened with increase in the stress. The ultimate failure of the beam was observed to be mainly due to the crushing of concrete over the support at a stress of 7.72 MPa. It was also observed that as the load carrying capacity of the beam increased, the beam also exhibited increase in the brittleness resulting in sudden failure.

When 0.3% of horizontal shear reinforcement was distributed only over the middle-third of the beam depth i.e. 0.3d, the diagonal cracking strength was observed to be 4.31 MPa. As the load was increased further, the initially formed diagonal crack was widened. Very few secondary diagonal cracks were also formed in and around the major diagonal crack. More and more secondary cracks were observed as the stress increased up to 6.52 MPa. At a nominal stress of 8.93 MPa, the diagonal crack was found to widen followed by several new parallel cracks. This revealed that relatively uniform distribution of cracks along the diagonal crack band has been observed. The process of crack growth was delayed, indicating that the increase in the percentage of the horizontal shear reinforcement increases the shear strength and ductility of the beams. The cracking behavior showed that 0.3% horizontal shear reinforcement distributed uniformly only over the middle-third of the depth is effective compared to the uniform distribution over the entire depth.
7.3.2. Size Effect on Diagonal Cracking Strength

The comparison of the diagonal cracking strength of deep beams with different beam depths and two different percentages of horizontal shear reinforcement is shown in Fig. 7.1.

![Graph showing diagonal cracking strength vs. Depth.](image)

Fig. 7.1. Diagonal cracking strength vs. Depth.

When the horizontal shear reinforcement was 0.2%, distributed uniformly over the total depth of the beam, the diagonal cracking strengths were found to be 4.76, 4.87 and 3.5MPa in the beams of depth 300mm, 600mm and 1200mm respectively. The diagonal cracking strength was observed to decrease with the increase in the beam depth from 600mm to 1200mm. In the beams with 0.2% horizontal shear reinforcement and distributed uniformly only over the middle-third of the depth i.e. 0.3d, the cracking strengths were observed to be 4.76, 4.75 and 3.62 MPa in beams of depths of 300mm, 600mm and
1200mm respectively. As the beam depth increased from 600mm to 1200mm, the diagonal cracking strength was found to decrease. As shown in Fig. 7.1, there exists a nonnegligible size effect on the diagonal cracking strength of RC beams when the beam depth is greater than 600mm.

Table 7.1. Experimental results on shear strength of Part 2 Beams.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Beam Designation</th>
<th>$V_{cr}$, (kN)</th>
<th>$V_u$, (kN)</th>
<th>$\tau_{cr}$, (MPa)</th>
<th>$\tau_v$, (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>BS-300-0.2-UN</td>
<td>180</td>
<td>450</td>
<td>4.76</td>
<td>12.00</td>
</tr>
<tr>
<td>2.</td>
<td>BM-600-0.2-UN</td>
<td>390</td>
<td>880</td>
<td>4.87</td>
<td>11.00</td>
</tr>
<tr>
<td>3.</td>
<td>BL-1200-0.2-UN</td>
<td>580</td>
<td>840</td>
<td>3.50</td>
<td>5.10</td>
</tr>
<tr>
<td>4.</td>
<td>BS-300-0.2-CN</td>
<td>180</td>
<td>450</td>
<td>4.76</td>
<td>12.00</td>
</tr>
<tr>
<td>5.</td>
<td>BM-600-0.2-CN</td>
<td>380</td>
<td>770</td>
<td>4.74</td>
<td>9.61</td>
</tr>
<tr>
<td>6.</td>
<td>BL-1200-0.2-CN</td>
<td>600</td>
<td>850</td>
<td>3.61</td>
<td>5.13</td>
</tr>
<tr>
<td>7.</td>
<td>BS-300-0.3-UN</td>
<td>180</td>
<td>450</td>
<td>4.76</td>
<td>12.00</td>
</tr>
<tr>
<td>8.</td>
<td>BM-600-0.3-UN</td>
<td>430</td>
<td>840</td>
<td>5.37</td>
<td>10.50</td>
</tr>
<tr>
<td>9.</td>
<td>BL-1200-0.3-UN</td>
<td>700</td>
<td>1280</td>
<td>4.22</td>
<td>7.72</td>
</tr>
<tr>
<td>10.</td>
<td>BS-300-0.3-CN</td>
<td>180</td>
<td>450</td>
<td>4.76</td>
<td>12.00</td>
</tr>
<tr>
<td>11.</td>
<td>BM-600-0.3-CN</td>
<td>420</td>
<td>900</td>
<td>5.24</td>
<td>11.24</td>
</tr>
<tr>
<td>12.</td>
<td>BL-1200-0.3-CN</td>
<td>710</td>
<td>1480</td>
<td>4.31</td>
<td>8.93</td>
</tr>
</tbody>
</table>

The diagonal cracking strengths of beams with 0.3% horizontal shear reinforcement and distributed uniformly only over the total depth are found to be 4.76, 5.37 and 4.22 MPa respectively in beams of 300mm, 600mm and 1200mm depth. The diagonal cracking
strengths were observed to be 4.76, 5.24 and 4.31 MPa in beams, with 0.3% horizontal shear reinforcement and distributed uniformly only over the middle third of the depth i.e. 0.3d. At this reinforcement, a non negligible size effect has been observed on the diagonal cracking strength of the beams. As shown in Fig. 7.1, there is an increase in the diagonal cracking strength of RC deep beams with increase in the horizontal shear reinforcement. To observe the nonnegligible size effect, the minimum depth of the beam should be at least 600mm, as has been observed from the experimental observations. The decrease in the diagonal cracking strength with the increase in the beam depth ranges between 18.0% and 25%.

7.3.3. **Size Effect on Ultimate Shear Strength**

The ultimate shear strengths of deep beams with different beam depths and with different percentages of horizontal shear reinforcements are shown in Fig. 7.2. When the horizontal shear reinforcement was 0.2% distributed uniformly over the total depth, the ultimate shear strengths were found to be 12.00, 11.00 and 5.07 MPa respectively in the beams of 300mm, 600mm and 1200mm depth respectively. In the beams reinforced with 0.2% horizontal shear reinforcement distributed uniformly only over the middle third of the depth i.e. over 0.3d, the ultimate shear strengths were found to be 12.00, 9.61 and 5.13 MPa respectively in beams of 300mm, 600mm and 1200mm depth respectively. 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 the beams of 300mm, 600mm and 1200mm depth. The ultimate shear strengths were observed to be 12.00, 11.12 and 8.51 MPa respectively in the beams of 300mm, 600mm and 1200mm depth with 0.3% horizontal shear reinforcement distributed uniformly only over the middle third of the depth i.e. over 0.3d.

Fig. 7.2. Ultimate shear strength vs. Depth.

Fig. 7.2 demonstrates that the ultimate shear strength decreases as the depth of the beam increases. There exists a strong size effect on the ultimate shear strength of RC deep beams. The effect of beam size on the shear strength of RC beams is not accounted for in the design codes of practice. In the codes of practice, the ultimate shear strength of RC beams is assumed to be constant with any depth of the beam. The decrease in the ultimate shear strength ranges between 20% and 25% when the beam depth increases from 300mm to 600mm. When
the beam depth increases from 300mm to 1200mm, the decrease in the shear strength ranges between 40% and 60%.

The decrease in the shear strength is about 20-23% when the depth is increased from 600mm to 1200mm with 0.3% horizontal shear reinforcement distributed uniformly only over the middle third of the depth i.e. over 0.3d. The decrease in the shear strength is about 35-55% in the beams with 0.3% horizontal shear reinforcement distributed uniformly over the total depth when the depth is increased from 600mm to 1200mm. Further, with the increase in the percentage of the horizontal shear reinforcement, the ultimate shear strength has been found to increase significantly. It can be understood that the horizontal shear reinforcement is effective in improving the shear strength of RC deep beams. However, the horizontal shear reinforcement distributed uniformly only over the middle third of the beam depth is effective in controlling the diagonal cracking as well as increasing the ultimate shear strength.

Further, as shown in Fig. 7.2, the ultimate strength of beams with 300mm depth was the same, since the horizontal reinforcement in the beam is practically the same. In the beams of 600mm depth, 0.3% horizontal shear reinforcement achieved the highest shear strength when distributed over the middle third of the depth. The strength of the beams with 0.2% horizontal shear reinforcement is always lesser than that of the 0.3% reinforcement. The influence of the quantity of horizontal shear reinforcement and its distribution has
been observed to be significant on the large size, 1200mm deep, beams. As shown in Fig. 7.2, the shear strength decreases with increase in the beam depth at the given quantity of horizontal shear reinforcement. There has been a significant enhancement of shear strength when the reinforcement increased from 0.2% to 0.3%, as shown in Fig. 7.2. The important reason for the effective performance of 1200mm beams with 0.3% horizontal shear reinforcement distributed uniformly only over the middle third of the depth is that once the diagonal crack is formed, with adequate anchorage of the tension reinforcement, strong concrete strut was formed between the diagonal cracks. The reinforcement at the middle third of the depth confined the crack growth with further increase in the loading. Further, the reinforcement at the middle third of the depth also acts as a lateral reinforcement for the short concrete column between the support and the load point. Therefore, it looks very positive that strut-and-tie approach in deep beams looks advantageous in view of the complex stress redistribution.

### 7.4. Conclusions

1. There has been a nonnegligible size effect on the diagonal cracking strength of RC deep beams, in which as the beam depth increases from 600mm to 1200mm, the diagonal cracking strength has been found to decrease.

2. In small size beams, the cracking distribution is uniform with improved ductility.
3. About 20-25% decrease in the diagonal cracking strength was observed when the beam depth was increased from 600mm to 1200mm.

4. As the beam depth is increased, RC deep beams exhibited relatively brittle failure forming only one major diagonal crack.

5. As the quantity of the horizontal shear reinforcement increased, the shear strength and the ductility of the beams were found to increase.

6. The uniform distribution of the horizontal shear reinforcement only over the middle third of the beam depth increases the shear strength with significant ductility.

7. Very strong size effect has been observed in RC deep beams on the ultimate shear strength.

8. About 35-55% decrease in the shear strength was observed when the beam depth was increased from 300mm to 1200mm.