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EFFICIENCY OF CORNER REINFORCEMENT DETAILING NEAR SMALL OPENINGS IN RC DEEP BEAMS

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Abstract: This study deals with mitigation of concentration effects due to small opening corners in RC deep beams with different reinforcement detailing. Six different reinforcement details in six RC deep beams with small utility openings were tested under three-point loading. The deformations at peak load, strains in rebars at critical locations, load-carrying capacity, load vs. deflection response, crack pattern, strut deformations and energy dissipation have been described. The test results show that the design and detailing of reinforcement influence on deformations, strain concentrations, and strain distributions in rebars. Higher quantity of horizontal reinforcement near the openings performed better with reduced deformations and enhanced load-carrying capacity, while vertical-web reinforcement near openings enhances stiffness and reduces deflections, with significant structural stability under loading. The reinforced concrete deep beams with small openings underlines the role of reinforcement detailing for better performance with ductility up to the brink of ultimate failure.

1 INTRODUCTION

Non-slender deep beams are encountered in reinforced concrete structures, near supports with significant loads acting, result in a shear-span-to-depth ratio of less than 2.5. ACI code [1] defines a deep beam as a structural member whose span-depth ratio is 5.0 or less. CEB-FIP [2] defines a beam as deep beam if the span-to-depth ratio is less than 2.0 for simply supported and 2.5 for continuous beams respectively. The deep beams possess high shear strength that is much greater than the prediction by equations. As a/d ratio diminishes from 2.5 to 0.5, vertical web reinforcement normal to longitudinal axis becomes ineffective. Distributed reinforcement parallel to longitudinal axis amplifies the shear capacity. Approaching an a/d ratio of zero, this reinforcement effectively counters the shear through shear-friction. Diagonal reinforcement proves to be efficient in resisting shear. In deep beams, inclined cracking may extend the entire length of the shear span.

Utility openings are provided in certain RC girders for various utilities, which influence their strength and behaviour. Such utility openings in a deep beam changes the load path within the beam. The load to be carried by the material in the load path is now removed in the opening area, that needs load to be redistributed to the surrounding regions, causing localized stresses, resulting in overstressing due to stress concentration in the corners of the opening. Shear stresses are typically higher around openings due to the abrupt changes in geometry and the concentration of load paths, causing cracking in the vicinity of the opening due to stress concentration. Based on the size and location of the opening, special reinforcement detailing may be required to maintain the structural integrity and distribute loads effectively. Openings can also affect the serviceability of the structure with excessive deflection or vibration near the opening, impacting on its functionality and safety.

2. REVIEW OF LITERATURE

The deep beams can fail in diagonal compression by developing an inclined crack along a line joining the load point and the support point. The ultimate failure occurs due to crushing of concrete between diagonal cracks, that acts as a strut between the load and support point; diagonal tension failure occurs by a diagonal crack along the line joining either support with the nearest loading point. Anchorage failure results from the very high-tension stresses in the main longitudinal reinforcement in the region near the supports. Special anchorage provisions, such as hooking the bars, can prevent this mode of failure. Bearing failure is common in all deep beams, due to localized stress at the load points and at the reaction points. It can be avoided by providing bearing plates of adequate size.

PCA [3] proposed a design procedure applicable to reinforced concrete deep beams with different depth-to-length ratio. The area of steel is distributed within the whole of the tension zone, by spreading half of the area of steel uniformly throughout the tension zone and the other half should have a progressively linear distribution with increasing distance from the neutral axis.

Uhlman [4] recommended for the design of reinforcement in deep beams. Under a combination of loading, superposition of the reinforcement calculated for each case is advised. *Ramakrishnan* and *Ananthanarayana* [5] reported that shear failure in a deep beam is essentially a diagonal tension failure. The ultimate shear strength of the beam is taken as the load producing a diagonal tension failure. Therefore, developed equations to calculate the ultimate shear strength based on the splitting strength of concrete. Prakash [6] proposed a method for determining the ultimate shear strength for beams with $\frac{a}{d} < 1.0$. The shear failure of the beam was due to splitting. In beam with web reinforcement, it was assumed that at the time of splitting, the strain of concrete and steel perpendicular to the crack are equal.

De Pavia and Siess [7] conducted an experimental inquiry into the shear strength and behavior of moderately reinforced concrete deep beams. The primary factors under consideration in this experimental investigation included quantity of tension reinforcement, concrete strength, quantity of web reinforcement and Span-depth ratio. The findings indicated that reinforced concrete deep beams lacking web reinforcement exhibited a notable capacity for cracking beyond diagonal cracking. Furthermore, the introduction of vertical stirrups and inclined bars had minimal impact on the ultimate strength. Leonhardt and Walther [8] conducted tests on deep beams subjected to both top and bottom loading. The specimens, supported in a simply supported manner, exhibited a height/span ratio of 1.5. They determined that the optimal approach for providing main reinforcement involved well-anchored bars originating from the support, with horizontal hooks deemed suitable for anchorage. Furthermore, they advocated for the distribution of main reinforcement over the lower 20% of the beam's height. The recommendation included extending stirrups to a height equal to the span, and closely spaced stirrups (spacing < 400 mm) were advised to mitigate crack widths. Vertical stirrups were also suggested to extend the full height of the beam. Kong and Robins [9] made tests on simply supported lightweight concrete deep beams, and developed equations that calculate ultimate load for normal weight concrete, which was found not to be suitable for lightweight concrete. Kong and Robins [10] have also reported on lightweight concrete deep beams, they revised their previous formula in two factors. The $\frac{le}{d}$ ratio explicitly allowed for and used concrete cylinder splitting tensile strength as has been thought that the concrete contribution to the ultimate shear strength is more directly related to tensile strength than cylinder compressive strength. The $\frac{ln}{h}$; had a greater effect on cracking and ultimate loads than $\frac{l}{h}$. Prakash [11] suggested a method for determining the shear strength for span/effective depth ratio less than 1.0. The proposed formula considered the splitting strength of concrete and influence of any steel crossing the failure crack. It was stated that failure of deep beams with small value of a/d ratio is analogous to the splitting of cylinder along its length. The ultimate shear strength calculated by the proposed formula was found to be comparable with test results. Besser and Cusens [12] had tested seven simply supported models of reinforced concrete wall panels with depth/span ratio in the range of one to four. A beam panel with depth/span equal to 1.0 failed in shear with diagonal fracture line joining the load and support points. When the depth-span ratio is larger than 1.0, it failed by crushing of the bearing zones.

Smith and Vantsiotis [13] carried out a test on fifty-two simply support reinforced concrete deep beams under symmetrical point load. Considerable increase in load carrying capacity was observed with increasing concrete strength and decreasing shear span to effective depth ratio. The increase in ultimate shear strength and diagonal cracking load was attributed to arch action for specimens with shear span/depth ratio less than 2.5. It was also found that vertical stirrups became more effective with greater shear span to depth ratio. Horizontal web reinforcement was more efficient in beams with shear span/depth ratio less than 1.0, and the effect of concrete strength was greater on beams for controlling diagonal cracking load. Subedi [14] carried out tests on 13 simply supported reinforced concrete deep beams with different span/depth ratios. The modes of failure of deep beams have been demonstrated that failures were Diagonal splitting.

The present study determines the efficiency of different web reinforcement configurations on structural response of deep beam with square openings in shear span and to provide practical detailing deep beams with openings under point loads. The reinforcement and beam dimensions are shown in figure 1.

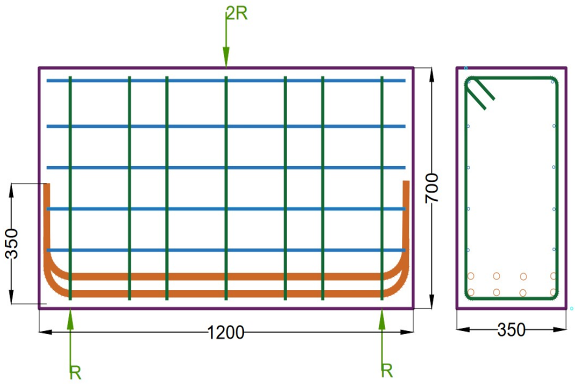

Figure 1: Typical reinforcement and beam dimensions.

3. EXPERIMENTAL PROGRAMME

The diemsnions of the beams are 350mm X 700 mm X 1200 mm, which are same for all beams with a shear span-to-depth ratio (a/h) of 0.8. The flexural tensile steel reinforcement consists of 8-20 mm diameter HYSD bars at an effective depth of 630 mm. Total six beams were tested. One is controlled beam without openings and other five beams are provided with square openings of 100mmx100mm at the centre of the shear span at the mid-depth with different reinforcement detailing. Solid beam is used as reference beam and the other five beams including a openign in each shear span.

M25 grade concrete and Fe550D grade steel were used. The properties of concrete were determined from compression test on standard cubes of 150mmx150mmx150mm at the time of testing of each beams. All six beams have been securely encased, and reinforcement details are shown in figure 1.

The moulds for casting of six RC deep beams were fabricated using stell plates with required intermediate stiffeners. Steel plates of length 2600mm, breadth 380mm, and depth (overall) 700mm were cut and assembled using nuts and bolt system to achieve the two beams of dimensions of 1200mm x 350mm x 700mm at a time. The steel plates were cut to size using appropriate cutting tools as shown in Figure4.2.The steel plates were then welded together along their edges to form two separate moulds, each matching the dimensions of the deep beams. Care was taken during welding to ensure strong and secure joints. Following the welding process, the integrity of the welds was inspected to ensure structural stability. Finally, the formwork dimensions were verified to match the design specifications, and any necessary adjustments were made to achieve precise dimensions. The concrete mix Proportions are 1: 2.32: 2.184 with a cement content of 152 kg/m^3 at a water-cement ratio of 0.55. Once the mould was ready, unifomly mixed concrete was poured in to the beam moulds keeping in mind the initial setting time of OPC (30 minutes) into each section of the frame, Using a vibrator to remove air bubbles and ensuring the concrete was compacted evenly. The concrete was cured according to the manufacturer's instructions before removing the beams from the template. Curing was started immediately after 24 hours of casting and finishing to prevent moisture loss and ensure proper hydration of the concrete. According to IS 456:2000, beams should be cured for a minimum period of 7 days under normal curing conditions.

3.1. Testing of RC deep beams

All six beams were tested in a 600 tons compression testing mechine. The beams were tested using a staically determinate supporting system. One hinge and one rollers supports were provided and the load was transferred at the cenyter as single point load. Testing simply supported deep beams under a point load in the center involves controlled loading rate to assess their structural behavior and load-carrying capacity. In a load-controlled set-up, the load was gradually increased at 0.5 kN per second, to simulate realistic loading scenarios and observe the response of the beams.

The deep beams, supported at both ends and subjected to a concentrated load at the mid-span, represent a critical structural element in many engineering applications. The testing aims to evaluate deflection, strain distribution, and ultimate load carrying capacity, providing valuable insights into the beam's performance. During testing, deflections and strains were recorded at regular intervals as the load is incrementally applied. This data allows to analyze the beam's stiffness, deformation characteristics, and potential failure modes. Overall, testing simply supported deep beams under a point load in a load-controlled set-up with a gradual increase in load at 0.5 kN per second provides crucial experimental data for validating theoretical predictions, improving design practices, and ensuring the structural safety and reliability of deep beam structures in engineering applications.

3.2.Test set-up

The test set-up for a simply supported deep beam under a single point load is in figure 2. The deep beam is securely connected at both ends to support allowing rotational movement, simulating the conditions of simple support. A single point load was applied at the midpoint of the beam's span. Strain gauges and displacement sensors were strategically placed along the beam's length to monitor its response to the applied load accurately.

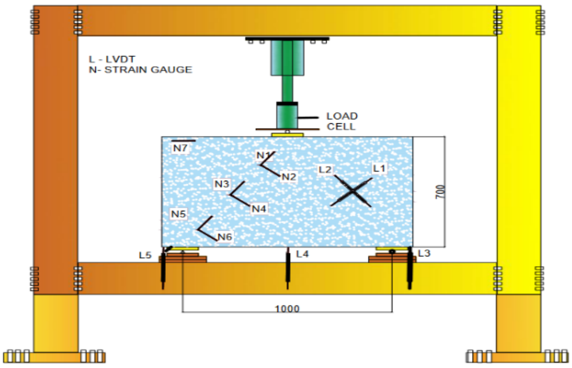

Figure 2: Simply supported beam test set-up.

4. RESULTS AND DISCUSSION

4.1.Crack width and propagation

Considering the structural characteristics of deep beams with a clear span-to-depth ratio of 1.4 and a shear span-to-depth ratio of 0.71, these crack patterns provide valuable insights. The detailed data highlight critical load points where crack initiation and propagation occur in each beam. Beam without opening, DB-WO-H20-V12 provided with conventional web reinforcement, the first shear crack was observed at a load of 640 kN, and first flexural crack at 1100 kN. Crack width increases gradually with increasing load, showing a linear trend in both shear and flexural cracks. This behavior is obvious since as the load increases, concrete undergoes significant deformation leading to wider cracks.

In deep beam DB-OO-H20-V12 with opening with conventional reinforcement, the first shear crack was observed at a load of 447 kN, and first flexural crack at 620 kN. Crack width linearly increases with load. The opening accelerates the crack initiation and progression than the beam without opening. The opening creates stress concentration, leading to earlier crack initiation and wider cracks at lower loads. While investigating the deep beam with openings, DB- OO-H20-V34, with additional vertical reinforcement, the first shear crack formed at a load of 420 kN, and first flexural crack at 600 kN. The vertical reinforcement near the opening controls crack width, than the beam without this reinforcement. The crack width increases with increasing the load but with slightly reduced values with additional vertical reinforcement.

In deep beam with openings, DB-OO-H36-V12, provided with additional horizontal reinforcement, the first shear crack was observed at a load of 406 kN, and first flexural crack at 520 kN. The horizontal reinforcement near the opening has a significant impact on reducing crack widths, especially on flexural cracks. Crack widths are smaller compared to beams without horizontal reinforcement.

For the deep beam with opening, vertical, and inclined reinforcement, DB-OO-H0-V12-I4, the first shear crack was observed at a load of 400 kN, and first flexural crack at 460 kN. The combination of vertical and inclined reinforcement along the struts improves crack control, with smaller crack widths across all load levels, are significantly lower than beams without this combined reinforcement. Deep beam with opening, DB-OO-H0-V12-I6, with vertical, and higher Inclined reinforcement, the First shear crack was observed at 454 kN, and first flexural crack at 600 kN. As observed in the previous beam, the combination of vertical and higher inclined reinforcement is an excellent crack controller, with smallest crack width among all configurations. The crack width increase is minimal, indicating superior reinforcement effectiveness in limiting crack propagation.

Beams with additional reinforcement near the openings (vertical, horizontal, inclined) exhibit smaller crack widths compared to beams without these reinforcements. Horizontal reinforcement has a pronounced effect on reducing crack widths, especially in flexural cracks. Vertical and inclined reinforcements also contribute significantly to crack control, with higher inclined reinforcement providing better performance. The reflects the influence of reinforcement pattern on crack initiation and propagation, emphasising the importance of reinforcement detailing in controlling crack widths and improving structural performance under loading conditions.

4.2. Deformation along strut

In contrast, beam DB-OO-H20-V12, featuring 300mmx300mm central openings without additional reinforcement, experienced a notable increase in peak deformation of 1.1mm. This outcome resonates the vulnerability of structural elements to deformations and stress concentrations when openings are not appropriately reinforced. The introduction of vertical reinforcement near the openings in beam DB-OO-H20-V34 enhanced the stiffness. However, the reduction in peak deformation was relatively modest and was found to be 1.0mm, that vertical reinforcement alone may not fully mitigate the effects of openings on structural performance. Beam DB-OO-H36-V12, incorporating horizontal reinforcement near the openings, demonstrated improved performance with reduced deformation of 0.6mm. Beam DB-OO-H36-V12 with horizontal reinforcement near the openings, demonstrated improved performance with a reduced deformation of 0.6mm.

Beam DB-OO-H36-V12, incorporating horizontal reinforcement near the openings, demonstrated improved performance with a reduced deformation of 0.6mm. This is in accordance with the principles outlined in

ACI 318, highlighting the effectiveness of horizontal reinforcement in distributing stresses and enhancing structural stability. On the other hand, beam DB-OO-H0-V12-I4, which integrated both vertical and inclined reinforcement, showed higher peak deformation of 2mm. This outcome, indicates that complex reinforcement arrangements and load paths can introduce complexities that lead to increased deformations, despite attempts to enhance stiffness through multiple reinforcement types. Similarly, beam DB-OO-H0-V12-I6, featuring an increased inclined reinforcement, exhibited elevated deformation of 1.5mm.

4.3. Transverse deformation of strut

In the experiment with six deep beams of varying configurations, the peak deformations normal to the diagonal strut were measured. Beam DB-WO-H20-V12 is a solid deep beam. The ultimate deformation normal to the diagonal strut in beam DB-WO-H20-V12 has been observed to be 0.32mm. This beam was provided with conventional reinforcement, exhibited the lowest peak deformation normal to the diagonal strut. The absence of openings reduces stress concentration and potential weak points in the beam's structure, leading to minimal deformation. This behaviour aligns with general principles of beam design where fewer discontinuities result in better structural performance. Beam DB-OO-H20-V12 with the Peak deformation of 2.25mm, introducing an opening at the Centre of shear span without additional reinforcement led to a significant increase in peak deformation normal to the diagonal strut. Openings created stress concentrations and reduced the beam's effective cross-sectional area, thereby increasing deformations under the point load. Beam DB-OO-H20-V34 with Peak deformation of 2.2mm, adding vertical reinforcement near the openings slightly reduced the peak deformation compared to the beam DB-OO-H20-V12. This reinforcement configuration helps distribute stresses more effectively, especially around the openings, leading to improved performance. Beam DB-OO-H36-V12With the Peak deformation of 1.2mm, including horizontal reinforcement near the openings further decreased the peak deformation compared to the beam DB-OO-H20-V34. Horizontal reinforcement improves the beam's resistance to lateral forces and helps control deflections more effectively. Beam DB-OO-H00-V12-I4 with the Peak deformation of 2.2mm, this beam, with vertical and inclined reinforcements but no horizontal reinforcement, exhibited a peak deformation similar to the beam DB-OO-H20-V12. Inclined reinforcements alone might not significantly affect deformations normal to the diagonal strut in this configuration.

Beam DB-OO-H0-V12 I6with the Peak deformation of 2.1mm, increasing the amount of inclined reinforcement slightly reduced the peak deformation compared to the beam DB-OO-H0-V12-I4. This suggests that higher amounts of inclined reinforcement can contribute to reducing deformations, although the effect may be less pronounced than horizontal reinforcements. The *ACI 318 Code,* acknowledges the beneficial effects of inclined reinforcements in reducing crack widths and improving overall beam performance, especially when combined with adequate horizontal and vertical reinforcements.

4.3. Ductility energy index

The energy absorption can be found by calculating the area under the curve (AUC) of the Load deformation (load–deflection curve), which is calculated utilizing Simpson's rule (Eq. 1) for all beams. Where μ_E,$E_{ULTIMATE}$, $E_{@75\%\ OF\ ULTIMATE}$ are the ductility energy index, total energy absorption up to the failure load, and energy absorption up to 75% of the ultimate load respectively (15). Table 1 shows the energy absorption capacities up to ultimate load and 75% of the ultimate load for all the beams. Figure 3 shows the load vs. deflection for calculating the energy.

$$A = \left(\frac{F_{i+1}+F_i}{2}\right) \times (\Delta_{i+1} - \Delta_i) \qquad (1)$$

$$\mu_E = \frac{E_{ULTIMATE}}{E_{@75\%\ OF\ ULTIMATE}} \tag{2}$$

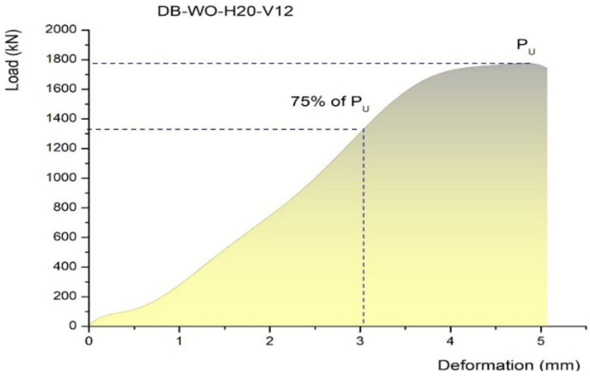

Figure 3: Energy absorption capacity at ultimate load and 75% of ultimate load for DB-WO-H20-V12.

Table 1. Ductility Energy index of RC deep beams.

S. No.	Beam	$E_{ultimate}$ (Nm)	$E_{@75\%}$ of ultimate, (Nm)	μ_E
1.	DB-WO-H20-V12	5100	1684	3.03
2.	DB-OO-H20-V12	3723	1653	2.25
3.	DB-OO-H20-V34	4078	582	7.01
4.	DB-OO-H36-V12	1224	773	1.58
5.	DB-OO-H00-V12-I4	692	371	1.87
6.	DB-OO-H00-V12-I6	4015	835	4.81

Comparing the six specimens tested for energy absorption capacity, ductility, and reinforcement effectiveness, several key observations emerge. Beam DB-WO-H20-V12 demonstrated a notable energy absorption capacity ($E_{ultimate}$ = 5100 Nm), indicating its ability to withstand substantial loads before reaching failure. However, its ductility energy index (μ_E = 3.03) suggests a moderate level of ductility. On the other hand, DB-OO-H20-V34 exhibited exceptional ductility energy index (μ_E = 7.00), showcasing its superior ability to dissipate energy and withstand deformation before failure, despite having openings.

Presence of openings in beams, as seen in DB-OO-H20-V12 and other configurations, generally led to reduced energy absorption capacities and ductility. This is attributed to the stress concentrations and structural weaknesses introduced by openings, which can hasten failure under load. Horizontal reinforcement played a significant role in influencing the performance of the specimens. For instance, DB-OO-H36-V12, with increased horizontal reinforcement (0.36%), showed a lower energy absorption capacity ($E_{ultimate}$ = 1224 Nm) but also exhibited lower ductility (μ_E = 1.58), indicating a trade-off between stiffness and ductility.

Overall, beams without openings tended to perform better in terms of energy absorption and ductility compared to beams with openings. Among the tested configurations, DB-OO-H20-V34 emerged as the superior choice due to its balanced performance, showcasing good energy absorption, high ductility, and effective reinforcement design. This configuration would be particularly suitable for applications where both strength and ductility are critical, such as in earthquake-prone regions or structures subjected to dynamic loads. DB-OO-H00-V12-I6 has the highest ultimate energy absorption (4015 Nm) among all beams, indicating its ability to withstand substantial loads. In terms of ductility energy index (μE), DB-OO-H20-V34 has the highest value (7.03), followed by DB-OO-H00-V12-I6 (4.81), indicating their superior ductility compared to other beams. DB-OO-H00-V12-I6 outperforms DB-OO-H00-V12-I4 in terms of energy absorption capacity and ductility.

5. CONCLUSIONS

The following conclusions have been drawn from the studies on RC deep beams with openings.

The beams with additional vertical-web reinforcement near openings reduces deflections with better stiffness compared to beams with nominal reinforcement. Conversely, increasing horizontal reinforcement decreases deflections with a decrease in load carrying capacity. Beams with additional vertical and higher inclined reinforcement show superior crack control with minimal crack widths and minimal increase with load.

Openings without additional reinforcement led to notable deformations along the strut due to stress concentration. Complex reinforcement arrangements such as inclined reinforcement increase strut deformations despite beam stiffness. Beams with added vertical and horizontal reinforcement near openings reduces deformations. Inclined reinforcement exhibited enhanced beam stiffness and reducing strut deformations.

Beams with additional vertical reinforcement near openings reduces strain in vertical rebar near opening compared to conventional reinforcement. Configurations with only vertical and inclined reinforcement slightly lowers strain in critical vertical rebars near openings. Higher inclined reinforcement lowers vertical strain. Horizontal reinforcement near openings lowers horizontal strain, indicating superior resistance to horizontal deformations. Beam with inclined web reinforcement showed better energy absorption and ductility.

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