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Modified Strut & Tie Method and Truss Reinforcement for Shear Strengthening of Reinforced Concrete Deep Beams

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Abstract. The aim of this study was to evaluate and test the limitations of the Indian Standard code 456-2000 related to deep beams, given that the code does not have any provisions regarding the use of the strut and tie method (STM)of design. This study validates the use of truss reinforcement and STM-shaped reinforcements as alternatives to STM design. We conclude that horizontal web reinforcement has a greater impact than vertical shear reinforcement. Deep beams with truss reinforcement and STM-based reinforcement were shown to have the highest shear strength capacity of all the deep beams. In the present study, 21 deep beams were cast and used to analyze their shear and flexural behavior. The specimens were divided into four groups based on length, width and depth, percentage of tension reinforcement, and percentage of horizontal and vertical shear reinforcement. The results revealed that truss-type reinforcement configuration is stronger than vertical shear reinforcement, as the former can resist 20% more load than the latter.

Keywords: Deep beams; Shear reinforcement; Shear span depth ratio; Shear strength; Web reinforcement

1. Introduction

Indian Standard (I.S) (2000) code 456-2000 defines a deep beam as a beam whose length to depth ratio is less than 2.0 for simply supported beams and less than 2.5 for continuous beams. Deep beams are used in a variety of engineering applications, such as bridges covering long spans, open rooms or halls of a building with no intermediate column, a side wall in reinforced concrete water tanks, foundation pile caps, transfer girders used to transfer loads safely if the soil bearing capacity is inadequate, and in bunkers and silos used to store toxic materials. Deep beams have two-dimensional action, unlike normal beams where the assumption plane section continues to be plane after bending is not applicable here. The deformation behavior of the normal beam is similar to that of the deep beam, except that shear plays a key role in the deep beam (Niken et al., 2017).

The factors that decrease catastrophic behavior and deflection are shear span to depth ratio, effective length to depth ratio, concrete compressive strength and vertical and

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horizontal reinforcement, effective beam depth, web reinforcement, type of loading, support conditions, and crack pattern. An increase in concrete strength leads to a significant increase in the fracture energy value (Siregar, 2017). When the deflection of the beam is less than 2.5 times the thickness, the experimental and analytical curves are about 1% using the average global stresses method (Benbouras et al., 2017). In 1909, (Talbot, 1909) declared that shear stress is a characteristic of the length, longitudinal reinforcement, and stiffness of a beam. He investigated on beams without web reinforcement and found that the shear strength of the concrete should also be considered in the design.

Many theories have been developed to describe shear behavior and the shear capability of beams. Most experimental and field research supports the theoretical studies predicts that a change in applied moment along a beam's length causes shear force. Studies have also found shear span to depth ratio to have a significant influence on deep beams, with an effective span to depth ratio having a qualitative influence on the failure mode, and diagonal cracking strength was found to have a marginal influence on deep beams(Tan et al., 1996). Aguilar et al. (2002) examined four RC deep beams under monotonic loading to study their behavior and strength. Specimens were designed in accordance with the American Concrete Institute (ACI, 2014) 318-99 code clauses 10.7 and 11.8 and the strut and tie method (STM) of the ACI 318-02 code, as shown in Appendix A. The load-carrying mechanism at failure in beams using STM is intended to minimize the vertical and horizontal reinforcement, however, the ACI 318-99 code's reinforcement provision no longer replicates the behavior. The percentage loss of flexural capacity of a beam without compressive pressure was found to be higher than that of a beam with compressive pressure when different bending moments were considered (Antonius et al., 2019). Here, the test load obtained was twice that was calculated, leading to the conclusion that the current ACI code must be improved. For a shear span of 1.0 to 2.5, the shear failure of a deep beam beneath single-point or two-point loading is due to the crushing of concrete in a compression zone (Zararis, 2003). Arabzadeh et al. (2011) investigated RC deep beams using two independent resistance measurements according to ACI 318-05 and Canadian Standard Association (CSA). These codes appear to be the most accurate and both have low variant and standard deviation. The study found the angle of strut is inversely proportional to the shear span to depth ratio and directly proportional to the horizontal web reinforcement. An exact analysis of concrete deep beams is a complicated problem, and a numerical method of analysis is required to predict the shear strength(Enem et al., 2012). Khan and Ahmed (2013) conducted an experimental evaluation to discover the ultimate shear strength of deep beams using the STM in accordance with ACI 318-05. The study found that Web reinforcement can be used to determine the shear strength of a deep beam. To identify the contribution of the steel to a beam's failure, a softening coefficient is introduced. Using this method, several conclusions have been drawn, such as an increase in the vertical reinforcement increases the shear strength, ultimate shear stress will increase with an increase in the horizontal shear reinforcement, and the softening coefficient of the concrete decreases with an increase in compressive strength.

Reineck and Todisco (2014)performed shear tests on non-slender beams without stirrups under point load and concluded that STMs are appropriate for RC deep beams at low slenderness ratios. With the increase of shear span, Swami et al. (2015) found a significant reduction in the preliminary cracking and failure, whereas the crack width increased with the increase of load.

Faroque and Kumar (2015) investigated deep beams using the Construction Industry Research and Information Association code, the ACI code, and the IS code. The beams were designed in three lengths, from 4.5 m to 5.5m. The results concluded that IS code was found to offer the maximum reinforcement for all loading conditions and sizes.

Mihaylov et al. (2015) validated the results of 129 published tests of continuous deep beams using the three-degrees-of-freedom kinematic model and local and global deformations with a number of settlements. Their results were comparable to those using the nonlinear finite element model with thousands of degrees of freedom. de DiosGaray-Moran and Lubell (2016) tested the failure of eight large-scale specimens longitudinally reinforced with deformed A1035 steel bars under stress ranging from 695 MPa to 988 MPa. After the formation of diagonal cracks, the bars without web reinforcement failed in a brittle manner. Bars containing effective shear span to depth ratio, longitudinal reinforcement, and web reinforcement were determined to have more influence on the failure mode. Failure in ductility was more likely to occur with an increase in shear span to depth ratio and a decrease in longitudinal reinforcement.

Yavuz (2016) took a different approach to investigating STM by calculating the shear strength of an RC deep beam with artificial neural networks (ANNs). Using different parameters affecting shear taken from experimental statistics and the literature database, they concluded that the ANN approach is better for predicting shear strength when compared to STM. Ismail et al. (2017) performed an experimental analysis of 24 beams to determine the parameters affecting their shear capacity, such as shear span to depth ratio, web reinforcement ratio, effective beam depth, and compressive strength of concrete, using various international codes, such as ACI 318-14, American Association of State Highway Transport Officials using Load and Resistant Factor Design (AASHTO LRFD), Euro Code 2 (EC2), and Model Code 2010. They concluded that the compressive strength and shear span to depth ratio have more influence than other stress parameters on the shear strength of deep beams. The major failure in deep beams is diagonal cracking failure, and the crack increases with the increase in span to depth ratio. The remaining portions, i.e., uncracked depths, resist the shear stress. The presence of shear reinforcement in the middle region of the shear span will improve the strength of a deep beam (Harsha and Poluraju, 2019). Beams created according to the ACI code have been found to be satisfactory for normal concrete but not for high-strength concrete, and those created according to AASHTO LRFD are less efficient because of the less shear span to depth ratio and those created following the EC2 and the Model Code 2010 are stable overall, but the stability decreases as the concrete strength increases. Many studies have concluded that STM is the best method, as the struts are placed in the path of the shear crack propagation such that the shear effect will be reduced in that region. Since, I.S. has no provisions related to the strut-and-tie design of deep beams, the present study uses vertical web reinforcement area obtained in a normal deep beam design arranged in the form of truss reinforcement to compare it with the regular arrangement of reinforcement.

2. Research Significance

The project evaluated and tested the limitations of the IS 456-2000 [IS 456] code related to deep beam specifications, given that the code does not make provisions for the use of an STM design. This study validates the use of truss reinforcement and STM-shaped reinforcements as an alternative to STM design.

3. Experimental Study

The experimental study consisted of 21 specimens divided into four groups based on the cross-section and percentage of reinforcement. Group I consisted of six beams of 150 mm width and 500 mm depth for a span of 900 mm with varying percentages of horizontal and shear reinforcement. The specimens were flexurally reinforced with three 16-mm diameter bars of high yield strength deformed (HYSD) 500 in a single layer and a tension region depth of 90 mm. Group II consisted of six beams of 200 mm width and 600 mm depth for a span of 1.2m with varying percentages of horizontal and shear reinforcement, as shown in Figure 1. The specimens were flexurally reinforced with four 16-mm diameter bars of HYSD 500 distributed equally in two layers and with a tension zone depth of 100 mm. Group III consisted of six beams of 250 mm width and 800 mm depth for a span of 1.5 m with varying percentages of horizontal and shear reinforcement, as shown in Figure2. The specimens were flexurally reinforced with five 16-mm diameter bars of HYSD 500 distributed between two layers (three in the bottom layer and two in the next consecutive layer) and a tension zone depth of 135 mm. Group IV consisted of three beams of 250-mm width and 800-mm depth for a span of 1.5m. The first beam in this group was a composite deep beam consisting of rolled I-section conforming to IS. The second beam had the arrangement of shear reinforcement shown in Figure3 at an angle of 45° in the form of a truss. This method of arranging the reinforcement was chosen since shear failure begins at the supports and penetrates towards the point of application of load in an inclined manner. The third beam consisted of shear reinforcement arranged in the form of a strut and tie, as shown in Figure4, which was adopted as an alternative to STM because the IS code does not have any provisions related to STM. All three specimens were geometrically similar, with a constant shear span to depth ratio of 0.9375. The flexural reinforcement in all the beams extended up to the top with a standard 90° hook to prevent bond failure through proper anchorage.

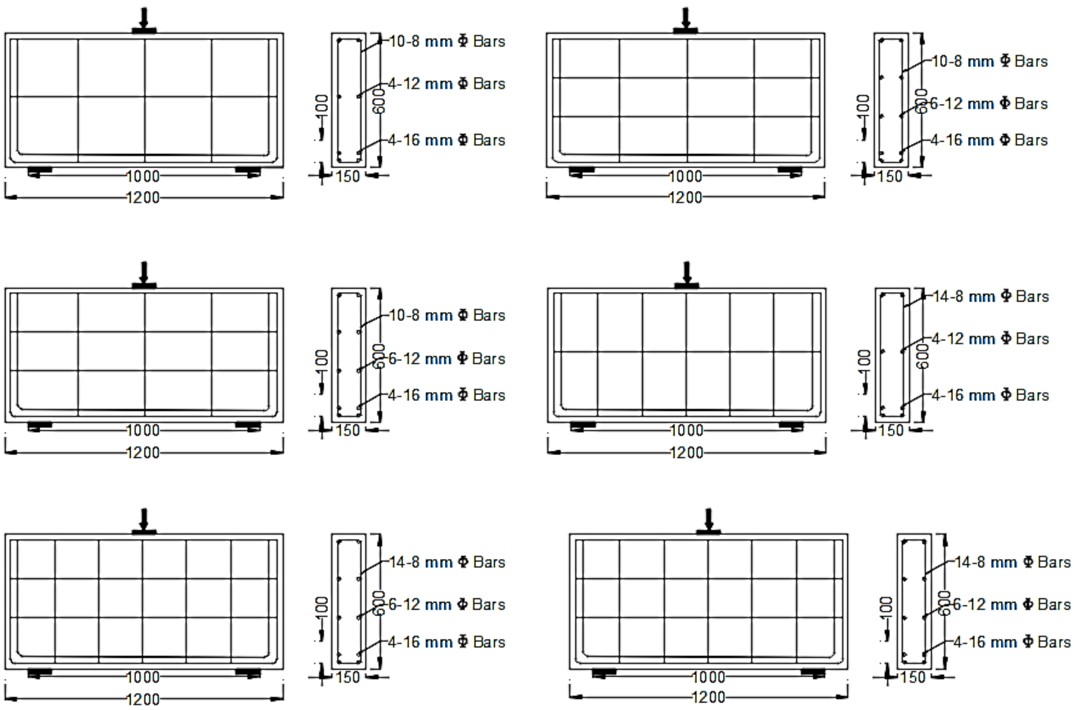


Figure 1 Cross-Section details of group II beams

Table 1 shows the values of the compressive strength of the concrete in all the groups. All specimens were cast using M 35 grade concrete to attain a target strength of 43.25 N/mm^2. The water–cement ratio was 0.45, conforming to IS 10262-2009. The quantity of cement content and fine aggregate content obtained was350.51 kg/m^3 and 651.47 kg/m^3, respectively. A mixture of 10 mm and 20 mm coarse aggregates in concrete was used for a smooth finishing of the specimens, and the quantity obtained for three cubes was 498.3

kg/m³ and 747.45 kg/m³. Standard cubes of size 150 mm × 150 mm were cast with the trial mix and tested for compressive strength. Table1 shows the compressive strength of the specimens after 7 days, 14 days, and 28 days, respectively. Deformed bars of grade Fe 500, 16 mm diameter, and high yield strength were used for flexural reinforcement, and 8 mm and 12 mm diameter bars of grade Fe 500 were used for shear reinforcement (both horizontal and vertical). Table 2 shows the yield strength and ultimate strength of the bars used.

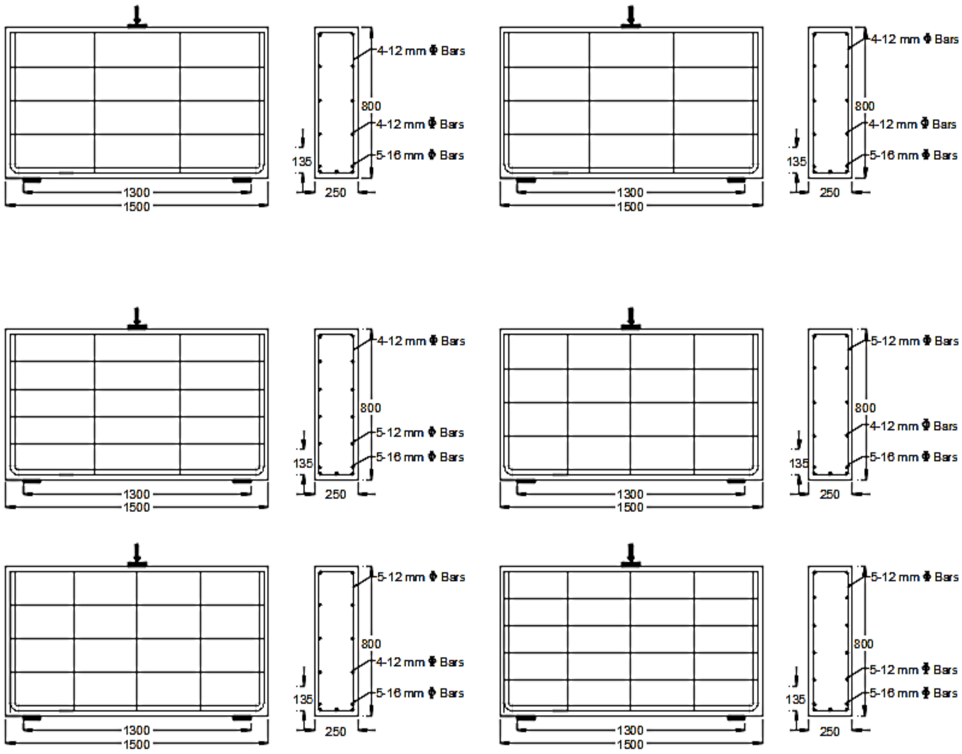


Figure 2 Cross-section details of group III beams

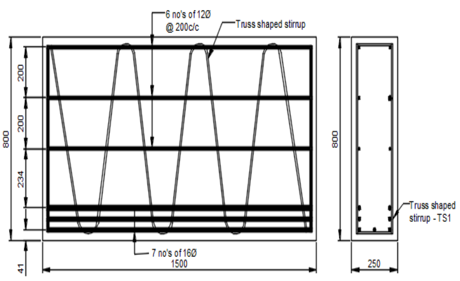


Figure 3 Cross-section details of truss configuration in group IV beams

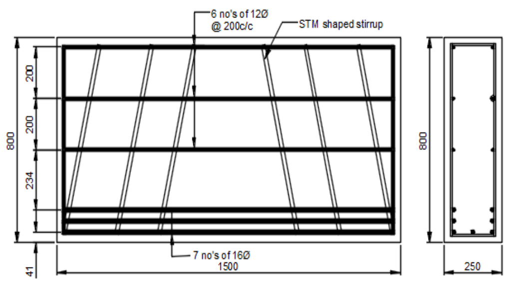


Figure 4 Cross-section details of STM reinforcement in group IV specimens

Table 1 Average compressive strength of concrete

S. No	Age of Specimen (days)	Group I Mix Load (kN)	Group II Mix Load (kN)	Group III Mix Load (kN)	Group IV Mix Load (kN)
1	7	870	860	880	920
2	14	890	900	910	940
3	28	930	920	930	1040
Compressive Strength (N/mm^2)		39.90	39.71	40.29	42.96

Table 2 Mechanical properties of steel reinforcement

S. No	Bar diameter (mm)	Area (mm^2)	Yield Strength (MPa)	Ultimate Strength (MPa)
1	8	50.24	540.45	631.3
2	12	113.1	569.8	637.1
3	16	201	564.3	652.8

3.1. Test Setup

All the specimens were tested under three-point bending with simply supported conditions using a loading frame capacity of 2000 kN. Surface strain gauges were used to calculate the strains, and a linear variable displacement transducer was used to monitor deflections. Crack width was measured using a micrometer with an accuracy of 0.01 mm. Table 3 shows the span to depth ratio, shear span to depth ratio, percentage of horizontal shear reinforcement, percentage of vertical shear reinforcement, and flexural reinforcement. Keeping the compressive strength constant, horizontal reinforcement varied from 0.45% to 0.6%, and vertical shear reinforcement varied from 0.45% to 0.6%.

Table 3 Properties of deep beam specimens

S. No	Group	Beam Id	L (mm)	B (mm)	D (mm)	l/d	a/d	ρ_h%	ρ_v%
1	I	1D500	900	150	500	1.8	0.9	0.45	0.4
2		2D500	900	150	500	1.8	0.9	0.5	
3		3D500	900	150	500	1.8	0.9	0.55	
4		4D500	900	150	500	1.8	0.9	0.45	0.6
5		5D500	900	150	500	1.8	0.9	0.5	
6		6D500	900	150	500	1.8	0.9	0.55	
7	II	1D600	1200	200	600	2	1	0.45	0.4
8		2D600	1200	200	600	2	1	0.5	
9		3D600	1200	200	600	2	1	0.55	
10		4D600	1200	200	600	2	1	0.45	0.6
11		5D600	1200	200	600	2	1	0.5	
12		6D600	1200	200	600	2	1	0.55	
13	III	1D800	1500	250	800	1.875	0.9375	0.45	0.4
14		2D800	1500	250	800	1.875	0.9375	0.5	
15		3D800	1500	250	800	1.875	0.9375	0.55	
16		4D800	1500	250	800	1.875	0.9375	0.45	0.6
17		5D800	1500	250	800	1.875	0.9375	0.5	
18		6D800	1500	250	800	1.875	0.9375	0.55	
19	IV	I-Section	1500	250	800	1.875	0.9375	-	-
20		Truss	1500	250	800	1.875	0.9375	0.5	0.4
21		STM	1500	250	800	1.875	0.9375	0.55	0.6

4. Results and Discussion

The load was applied gradually from zero until the failure of the specimen. Cracks and deflections were noted for further investigation. Table 4 shows the first cracking, ultimate failure load and its respective deflection, and mode of failure. Later, shear strength at initial cracking and failure was determined. A significant amount of fracture energy was released in the small-sized beams due to softening of the concrete. However, in the medium- and large-sized beams, because they had more shear reinforcement, the specimens only failed due to crushing of concrete in the compression zone. Table 5 shows the shear strength at cracking load, shear strength at ultimate load, and the ratio of shear strength at ultimate load to crack load. Figures 5–8 show the applied load and respective mid-span deflection of all 21 specimens.

Table 4 Initial crack load and failure load of deep beams

S. No	Group	Beam Id	Initial Crack Load (V_{cr}, kN)	Failure Load (V_u, kN)	Mid-Span Deflection at Failure (mm)	Mode of Failure
1	I	1D500	215.3	586.8	3.89	Compression
2		2D500	210.1	553.8	4.87	Compression
3		3D500	221.4	556.8	5.23	Diagonal Tension
4	1	4D500	228.7	565.9	4.12	Diagonal Tension
5		5D500	238.6	613.7	4.38	Shear Compression
6		6D500	266.8	626.7	4.23	Shear Compression
7	II	1D600	284.5	740.3	4.26	Compression
8		2D600	306.1	746.8	5.26	Compression
9		3D600	324.3	778.2	5.43	Diagonal Tension
10		4D600	368.7	766	5.69	Diagonal Tension
11		5D600	365.1	785.3	4.23	Shear Compression
12		6D600	371.4	800.4	4.08	Shear Compression
13	III	1D800	380.8	861.7	7.5	Diagonal Tension
14		2D800	387.9	878.4	4.8	Diagonal Tension
15		3D800	398.2	934	6	Shear Compression
16		4D800	406.4	905	6.5	Shear Compression
17		5D800	413.2	966.3	6.6	Diagonal Tension
18		6D800	421.8	978	8.1	Diagonal Tension
19	IV	I-Section	437.1	1120.7	6.48	Shear Compression
20		Truss	442.8	1084.3	5.48	Shear Compression
21		STM	461.8	1110.6	5.64	Compression

Table 5 Shear strength of deep beams

S. No	Group	Beam Id	V_{cr} (kN)	V_u (kN)	τ_{cr} (N/mm^2)	τ_v (N/mm^2)	τ_v/τ_{cr}
1	I	1D500	215.3	586.8	2.871	7.824	2.73
2		2D500	210.1	553.8	2.801	7.384	2.64
3		3D500	221.4	556.8	2.952	7.424	2.51
4		4D500	228.7	565.9	3.049	7.545	2.47
5		5D500	238.6	613.7	3.181	8.183	2.57
6		6D500	266.8	626.7	3.557	8.356	2.35
7	II	1D600	284.5	740.3	2.371	6.169	2.60
8		2D600	306.1	746.8	2.551	6.223	2.44
9		3D600	324.3	778.2	2.703	6.485	2.40
10		4D600	368.7	766	3.073	6.383	2.08
11		5D600	365.1	785.3	3.043	6.544	2.15
12		6D600	371.4	800.4	3.095	6.670	2.16
13	III	1D800	380.8	861.7	1.904	4.309	2.26
14		2D800	387.9	878.4	1.940	4.392	2.26
15		3D800	398.2	934	1.991	4.670	2.35
16		4D800	406.4	905	2.032	4.525	2.23
17		5D800	413.2	966.3	2.066	4.832	2.34
18		6D800	421.8	978	2.109	4.890	2.32
19	IV	I-Section	437.1	1120.7	2.186	5.604	2.56
20		Truss	442.8	1084.3	2.214	5.422	2.45
21		STM	461.8	1110.6	2.309	5.553	2.40

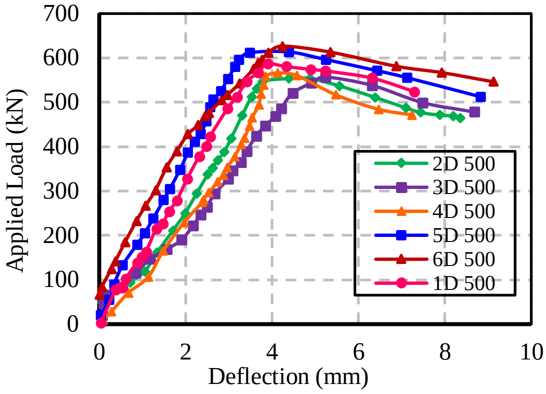


Figure5 Applied load *vs.* deflection response of group I beams

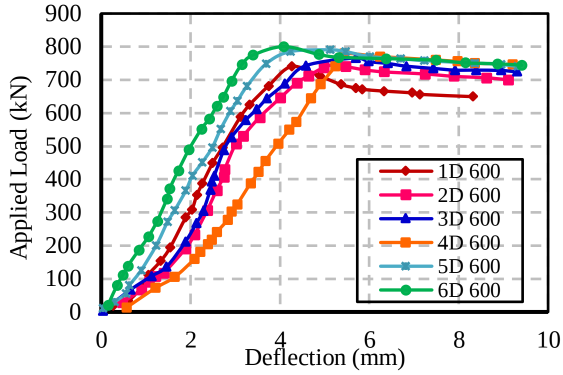


Figure6 Applied load *vs.* deflection response of group II beams

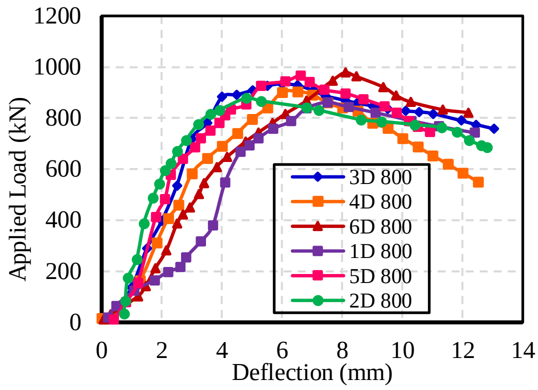


Figure7 Applied load *vs.* deflection response of group III beams

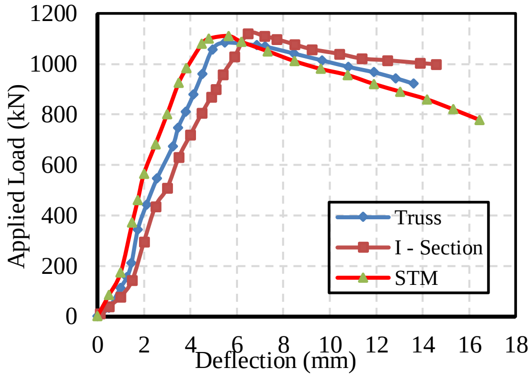


Figure8 Applied load *vs.* deflection response of group IV beams

4.1. Crack Pattern and Mode of Failure

All 21 beams were tested under three-point loading up to failure, as shown in Figure9. The first six beams in Group I were not provided with sufficient anchorage length, so showed anchorage failure along with shear failure. The initial flexural crack appeared at 20–25% of the applied load, and a diagonal shear crack started appearing at 40% of the applied load. All the specimens showed an inclination of nearly 52°. The first two beams in Group II underwent compression failure with minute or fewer cracks. Beams 3D600 and 4D600 had a wide diagonal crack starting at the supports and reaching the application of load. This type of failure mode is called diagonal tension failure. Due to heavy compression at the edges, the concrete was crushed in 5D600 and 6D600, a mode of failure known as shear compression failure. Thus, based on the data from all six beams in Group II, it can be concluded that, as the horizontal web reinforcement percentage increases, the mode of failure is shifted from shear tension to shear compression. The beams 1D800 and 2D800 from Group III exhibited diagonal tension failure, and 3D800 and 4D800 showed shear compression failure. In beams 5D800 and 6D800, flexural cracks developed that then spread into the shear region. With further increase of the load, diagonal cracks started to appear at the mid-depth of the shear span. In these beams, horizontal shear reinforcement had been placed near the tension zone, which protected the tension zone from flexural cracking. Thus, diagonal tension was not only restricted by the tensile nature of the concrete, but also the horizontal reinforcement. The first beam in Group IV—a deep beam with an I-section—did not fail since the entire reinforcement was replaced with a rolled I-section. Because the concrete was crushed only at that point of application of load and only minor cracks were observed, it can be concluded that no flexural or shear failure occurred in this case. The second beam—i.e., deep beam with truss reinforcement—took more load before failure, this case was similar to that of the beam with the I-section, and the concrete was crushed at the applied load with no flexure or shear failure. In the third beam—a deep beam with STM reinforcement—only diagonal shear failure occurred.

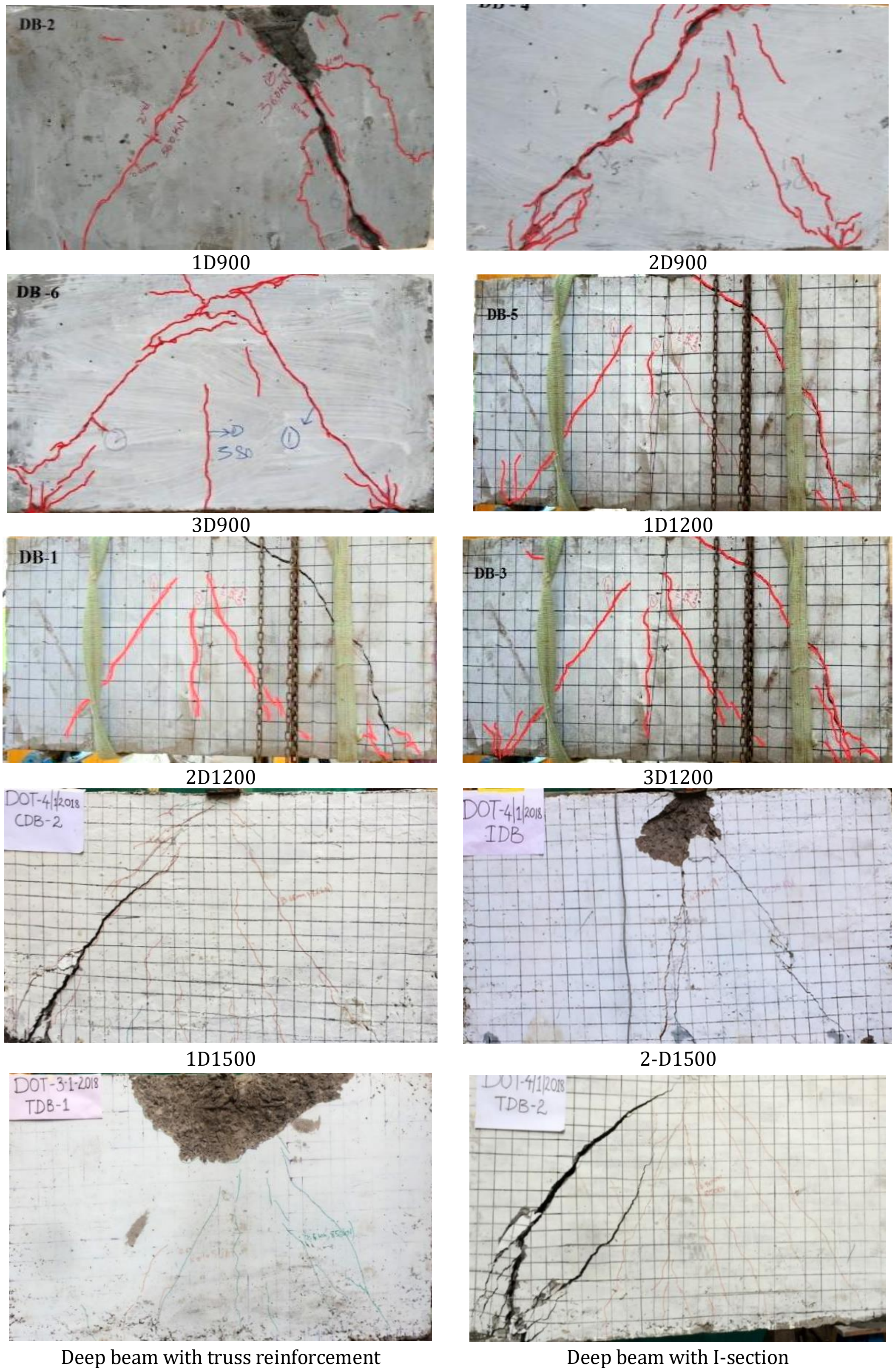
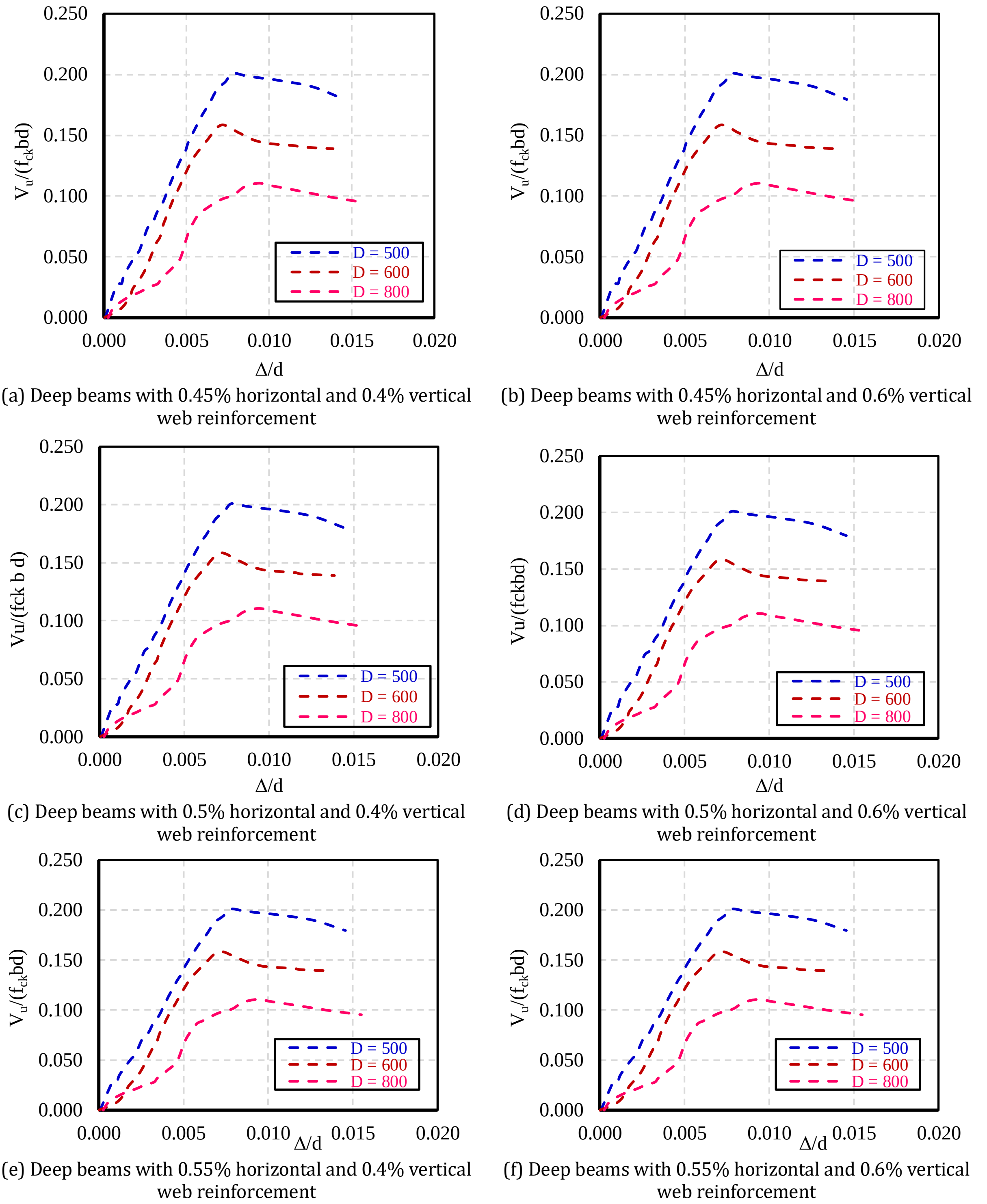


Figure 9 Crack pattern and mode of failure

4.2. Effect of Web Reinforcement

Figure10 shows graphs representing the effect of web reinforcement on the shear strength of a deep beam. This clearly indicates that horizontal web reinforcement is more effective than vertical web reinforcement. The shear strength of the deep beam increased with an increase in the percentage of web reinforcement. However, the deep beam with truss reinforcement and STM-based reinforcement showed the highest shear strength capacity of all the deep beams.



(a) Deep beams with 0.45% horizontal and 0.4% vertical web reinforcement

(b) Deep beams with 0.45% horizontal and 0.6% vertical web reinforcement

(c) Deep beams with 0.5% horizontal and 0.4% vertical web reinforcement

(d) Deep beams with 0.5% horizontal and 0.6% vertical web reinforcement

(e) Deep beams with 0.55% horizontal and 0.4% vertical web reinforcement

(f) Deep beams with 0.55% horizontal and 0.6% vertical web reinforcement

Figure10 Effect of web reinforcement on shear strength of deep beam

4.3. Effect of Shear Span to Depth Ratio

All the results indicate that the failure behavior of a deep beam is dominated by the shear span to depth ratio. The capacity to resist shear increases as the shear span to depth ratio decreases. This is because of the direct transfer of load to the supports. The data on the strains in vertical and side face reinforcement indicate that tensile strain has developed in perpendicular to the reinforcement. Crack patterns were also affected by shear span to depth ratio, which can be seen in Table 4. Due to the shear span to depth ratio, the failure mode changed from diagonal tension to shear compression, and the cracks spread from the bottom of the beam to the total height of the beam.

4.4. Comparison of Codes

Table 6 gives the codes' predictions of shear strength compared to that of the experimental data. The approximate variation and standard deviation of experimental data compared to IS 456 were 0.85 and 0.04, respectively, whereas it was 0.91 and 0.05, respectively, when compared to ACI. The results give an indication of the anomalies in the behavior when the beam is designed using different design codes. When the load put on the beam and the length of the beam are constant as Length to Depth ratio (L/D) increases, flexural capacity of steel also increases. The IS code gives a moderate value of tensile reinforcement for a 1.5m length, while the ACI code gives a minimum value. The IS code gives maximum percentage of reinforcement in shear and in total reinforcement, while the total reinforcement in the ACI code is minimal as the load gradually increases, there is a huge variation in bending moment and shear.

Table 6 Code predictions of shear strength against experimental data

S. No	Beam Designation	V_u Calculated (IS 456)	V_u Calculated (ACI)	$V_{u,}$ (EXP)	$\frac{v_u^{IS\,456}}{v_u^{EXP}}$	$\frac{v_u^{ACI}}{v_u^{EXP}}$
1	1D500	450	480	587	0.77	0.82
2	2D500	464	492	554	0.84	0.89
3	3D500	488	513	557	0.88	0.92
4	4D500	512	548	566	0.90	0.97
5	5D500	549	563	614	0.89	0.92
6	6D500	563	594	627	0.90	0.95
7	1D600	604	611	740	0.82	0.83
8	2D600	623	642	747	0.83	0.86
9	3D600	641	684	778	0.82	0.88
10	4D600	666	712	766	0.87	0.93
11	5D600	678	748	785	0.86	0.95
12	6D600	692	776	800	0.86	0.97
13	1D800	741	811	862	0.86	0.94
14	2D800	768	836	878	0.87	0.95
15	3D800	796	871	934	0.85	0.93
16	4D800	814	890	905	0.90	0.98
17	5D800	829	923	966	0.86	0.96
18	6D800	842	948	978	0.86	0.97
19	I-Section	900	950	1121	0.80	0.85
20	Truss	900	950	1084	0.83	0.88
21	STM	900	950	1111	0.81	0.86
				Average	0.85	0.91
				Standard Deviation	0.04	0.05

5. Conclusions

Horizontal web reinforcement had more impact than vertical shear reinforcement in all the specimens, irrespective of size. After the observation of all failures, it was concluded that 0.5% horizontal web reinforcement is the optimum percentage in deep beams. The deflection of the beams increased with an increase in shear reinforcement, but load-carrying capacity also increased. The width of the cracks in the beam decreased with an increase in the percentage of shear reinforcement. Deep beams with truss reinforcement and STM-based reinforcement were shown to produce the highest shear strength capacity in deep beams with normal web reinforcement. Finally, truss-type reinforcement configuration was found to be more effective than vertical shear reinforcement, as it was able to endure 20% more load.

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