Module 6

Shear, Bond, Anchorage, Development Length and Torsion

Lesson 14

Limit State of Collapse in Shear – Numerical Problems

Instructional Objectives:

At the end of this lesson, the student should be able to:

- solve specific numerical problems of rectangular and *T*-beams for the complete design of shear reinforcement as per the stipulations of IS 456.

6.14.1 Introduction

Lesson 13 explains the three failure modes due to shear force in beams and defines different shear stresses needed to design the beams for shear. The critical sections for shear and the minimum shear reinforcement to be provided in beams are mentioned as per IS 456. In this lesson, the design of shear reinforcement has been illustrated through several numerical problems including the curtailment of tension reinforcement in flexural members.

6.14.2 Numerical Problems

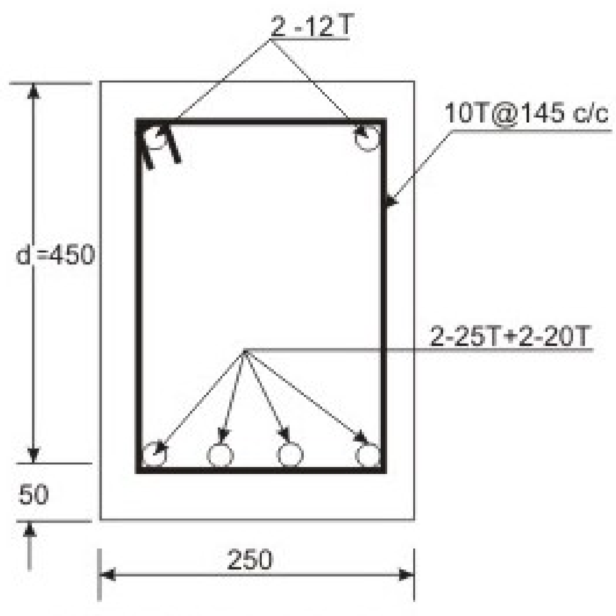

Fig. 6.14.1: Problem 1

Problem 1:

Determine the shear reinforcement of the simply supported beam of effective span 8 m whose cross-section is shown in Fig. 6.14.1. Factored shear force is 250 kN. Use M 20 and Fe 415.

Solution 1:

Here, A_{st} = 2-25T + 2-20T gives the percentage of tensile reinforcement

$$p = \frac{100\,(1609)}{250\,(450)} = 1.43$$

From Table 6.1 of Lesson 13, τ_c = 0.67 + 0.036 = 0.706 N/mm^2 (by linear interpolation).

Employing Eq. 6.1 of Lesson 13,

$\tau_v = \dfrac{V_u}{b\,d} = \dfrac{250\,(10^3)}{250\,(450)} = 2.22 \text{ N/mm}^2$ and τ_{cmax} = 2.8 N/mm^2 (from Table 6.2 of Lesson 13).

Hence, $\tau_c < \tau_v < \tau_{cmax}$. So, shear reinforcement is needed for the shear force (Eq. 6.4 of Lesson 13).

$$V_{us} = V_u - \tau_c\, b\, d = 250 - 0.706\,(250)\,(450)\,(10^{-3}) = 170.575 \text{ kN}$$

Providing 8 mm, 2 legged vertical stirrups, we have

$$A_{sv} = 2\,(50) = 100 \text{ mm}^2$$

Hence, spacing of the stirrups as obtained from Eq. 6.5 of Lesson 13:

$$s_v = \frac{0.87\, f_y\, A_{sv}\, d}{V_{us}} = \frac{0.87\,(415)\,(100)\,(450)}{170575} = 95.25 \text{ mm, say } 95 \text{ mm.}$$

For 10 mm, 2 legged vertical stirrups, (A_{sv} = 157 mm^2), spacing

$$s_v = \frac{0.87\,(415)\,(157)\,(450)}{170575} = 149.54 \text{ mm}$$

According to cl. 26.5.1.5 of IS 456, the maximum spacing of the stirrups = 0.75 d = 0.75 (450) = 337.5 mm = 300 mm (say).

Minimum shear reinforcement (cl. 26.5.1.6 of IS 456) is obtained from (Eq.6.3 of sec. 6.13.7 of Lesson 13):

$$\frac{A_{sv}}{(b)\,s_v} \geq \frac{0.4}{0.87\,(f_y)}$$

From the above, $A_{sv(minimum)}$ = $\dfrac{0.4\,b\,s_v}{0.87\;f_y} = \dfrac{0.4\,(250)\,(145)}{0.87\,(415)} = 40.16\;\text{mm}^2$.

So, we select 10 mm, 2 legged stirrups @ 145 mm c/c.

Problem 2:

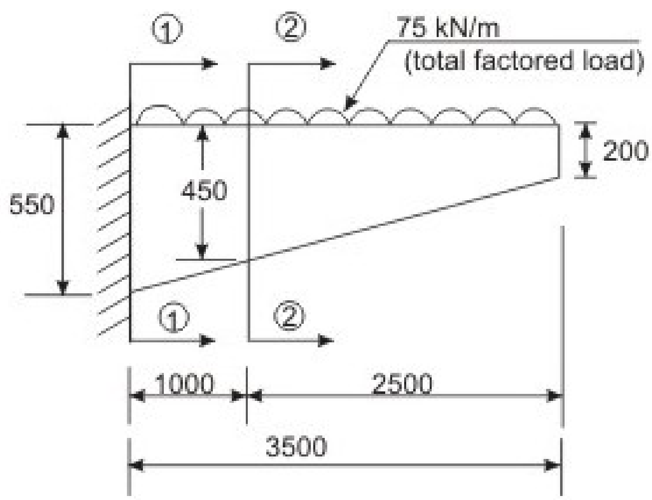

Fig 6.14.2: Problem 2

Design the bending and shear reinforcement of the tapered cantilever beam of width *b* = 300 mm and as shown in Fig. 6.14.2 using M 20 and Fe 415 (i) without any curtailment of bending reinforcement and (ii) redesign the bending and shear reinforcement if some of the bars are curtailed at section 2-2 of the beam. Use SP-16 for the design of bending reinforcement.

Solution 2:

$$M_u \text{ at section 1-1} = \frac{75\,(3.5)\,(3.5)}{2} = 459.375\;\text{kNm}$$

$$\frac{M_u}{b\,d^2} = \frac{459.375\,(10^6)}{300\,(500)\,(500)} = 6.125\;\text{N/mm}^2$$

Solution 1:

Here, A_{st} = 2-25T + 2-20T gives the percentage of tensile reinforcement

$$p = \frac{100\,(1609)}{250\,(450)} = 1.43$$

From Table 6.1 of Lesson 13, τ_c = 0.67 + 0.036 = 0.706 N/mm^2 (by linear interpolation).

Employing Eq. 6.1 of Lesson 13,

$\tau_v = \frac{V_u}{b\,d} = \frac{250\,(10^3)}{250\,(450)} = 2.22\ \text{N/mm}^2$ and τ_{cmax} = 2.8 N/mm^2 (from Table 6.2 of Lesson 13).

Hence, $\tau_c < \tau_v < \tau_{cmax}$. So, shear reinforcement is needed for the shear force (Eq. 6.4 of Lesson 13).

$$V_{us} = V_u - \tau_c\, b\, d = 250 - 0.706\ (250)\ (450)\ (10^{-3}) = 170.575\ \text{kN}$$

Providing 8 mm, 2 legged vertical stirrups, we have

$$A_{sv} = 2\ (50) = 100\ \text{mm}^2$$

Hence, spacing of the stirrups as obtained from Eq. 6.5 of Lesson 13:

$$s_v = \frac{0.87\ f_y\ A_{sv}\ d}{V_{us}} = \frac{0.87\,(415)\,(100)\,(450)}{170575} = 95.25\ \text{mm, say } 95\ \text{mm.}$$

For 10 mm, 2 legged vertical stirrups, (A_{sv} = 157 mm^2), spacing

$$s_v = \frac{0.87\,(415)\,(157)\,(450)}{170575} = 149.54\ \text{mm}$$

According to cl. 26.5.1.5 of IS 456, the maximum spacing of the stirrups = 0.75 d = 0.75 (450) = 337.5 mm = 300 mm (say).

Minimum shear reinforcement (cl. 26.5.1.6 of IS 456) is obtained from (Eq.6.3 of sec. 6.13.7 of Lesson 13):

Reinforcing bars of 3-28T + 1-16T give 2048 mm^2.

A_{sc} at section 2-2 = (0.686) (400) (300)/100 = 823.2 mm^2.

Reinforcing bars of 2-20T + 2-12T give 854 mm^2.

Though it is better to use 4-28T as A_{st} and 2-20T + 2-16 as A_{sc} with proper curtailment from the practical aspects of construction, here the bars are selected to have areas close to the requirements for the academic interest only.

Figure 6.14.4 shows the reinforcement at sec. 2-2.

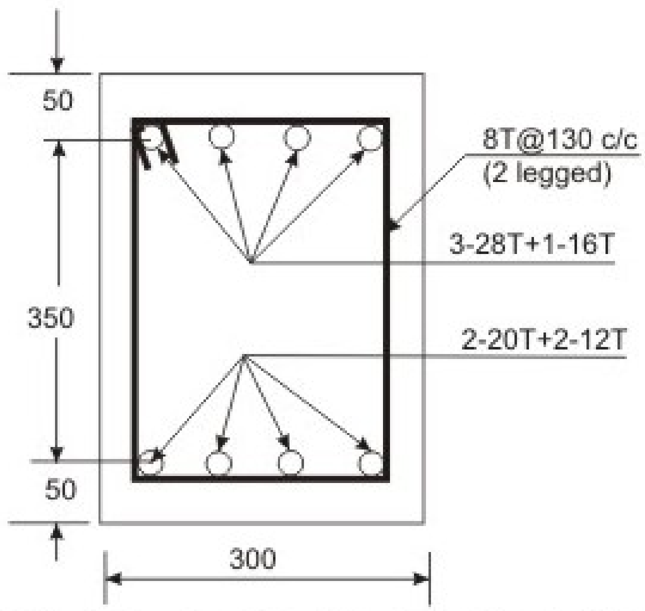

Fig. 6.14.4: Section 2-2 of Prob.2 (Fig. 6.14.2), with curtailment of bars (condition i)

Case (i): No curtailment (all bars of bending reinforcement are continued):

Bending moment M_u at section 2-2 = 234.375 kNm

Shear force V_u at section 2-2 = 187.5 kN

Effective depth d at section 2-2 = 450 – 50 = 400 mm, and

Width b = 300 mm

tanβ = (550 – 200)/3500 = 0.1

Clause 40.1.1 of IS 456 gives (Eq.6.2 of sec. 6.13.3 of Lesson 13):

$$\tau_v = \frac{V_u - \frac{M_u}{d}\tan\beta}{b\,d} = \frac{(10^3)\{187.5 - 234.375\,(0.1)/0.4\}}{(300)\,(400)} = 1.074\ \text{N/mm}^2$$

(Here, the negative sign is used as the bending moment increases numerically in the same direction as the effective depth increases.)

Continuing 4-28T and 3-16T bars (= 3066 mm^2), we get

p = 3066 (100)/300 (400) = 2.555 %

Table 6.1 of Lesson 13 gives τ_c = 0.82 N/mm^2 < τ_v (= 1.074 N/mm^2). Hence, shear reinforcement is needed for shear force obtained from Eq. 6.4 of Lesson 13:

V_{us} = V_u - $\tau_v\, b\, d$ = 1.875 – 0.82 (300) (400) (10^{-3}) kN = 89.1 kN

From cl.40.4 of IS 456, we have (Eq.6.5 of sec. 6.13.8 of Lesson 13),

$$V_{us} = \frac{0.87\, f_y\, A_{sv}\, d}{s_v}$$

where A_{sv} = 100 mm^2 for 8 mm, 2 legged vertical stirrups. This gives s_v = 162.087 mm (f_y = 415 N/mm^2). IS 456, cl. 26.5.1.6 gives the spacing considering minimum shear reinforcement (Eq.6.3 of sec. 6.13.7 of Lesson 13):

$$s_v \le \frac{0.87\, f_y\, A_{sv}}{0.4\, b}$$

or $s_v \le$ 300.875 mm

Hence, provide 8 mm, 2 legged vertical stirrups @ 150 mm c/c, as shown in Fig. 6.14.3.

Case (ii): With curtailment of bars:

Clause 26.2.3.2 of IS 456 stipulates that any one of the three conditions is to be satisfied for the termination of flexural reinforcement in tension zone (see sec. 6.13.10 of Lesson 13). Here, two of the conditions are discussed.

(a) Condition (i):

$\tau_v \le \frac{2}{3}(\tau_c + \frac{V_{us}}{b\,d})$, which gives Eq. 6.9 of Lesson 13 as

$V_{us} \geq (1.5\, \tau_v - \tau_c)\, b\, d$

After the curtailment, at section 2-2 A_{st} = 2048 mm^2 (3-28T + 1-16T bars), gives p = 2048 (100)/300 (400) ≅ 1.71 %. Table 6.1 of Lesson 13 gives τ_c = 0.7452 N/mm^2 when p = 1.71% (making liner interpolation). Now from Eq. 6.2 of Lesson 13:

$$\tau_v = \frac{V_u - \dfrac{M_u}{d}\tan\beta}{b\,d} = \frac{(10^3)\{187.5 - 234.375\,(0.1)/0.4\}}{(300)\,(400)} = 1.074 \text{ N/mm}^2$$

So, V_{us} = {1.5 (1.074) – 0.7452} (300) (400) (10^{-3}) kN = 103.896 kN

which gives the spacing of stirrups (Eq. 6.5):

$$s_v \leq \frac{0.87\, f_y\, A_{sv}\, d}{V_{us}}$$

Using 8 mm, 2 legged vertical stirrups (A_{sv} = 100 mm^2), we have:

s_v = 0.87 (415) (100) (400)/(103.896) (10^3) = 139.005 mm

Hence, provide 8 mm, 2 legged vertical stirrups @ 130 mm c/c, as shown in Fig. 6.14.4.

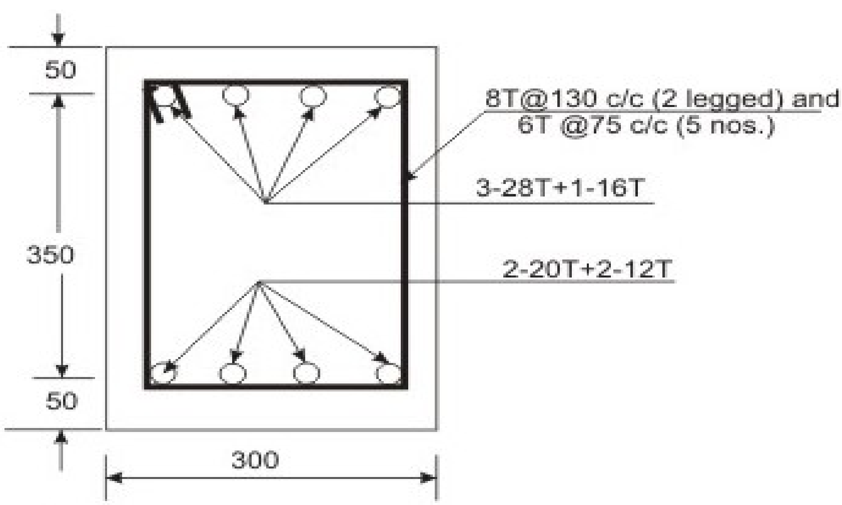

Fig. 6.14.5: Section 2-2 of Prob.2 (Fig. 6.14.2), with curtailment of bars (condition ii)

(b) Condition (ii):

Additional stirrup area for a distance of 0.75 d {= 0.75 (400) = 300 mm} = 0.4 $b\ s/f_y$, where spacing s is not greater than ($d/8\beta_b$), where β_b = cut off bar area/total bar area = 2048/3066 = 0.67. Since, additional stirrups are of lower diameter, mild steel bars are preferred with f_y = 250 N/mm^2. Maximum spacing s = $d/8\beta_b$ = 400/8 (0.67) = 75 mm. Excess area = 0.4 $b\ s/f_y$ = 0.4 (300) (75)/250 = 36 mm^2.

Provide 6 mm, 2 legged mild steel vertical stirrups (56 mm^2) @ 75 mm c/c for a distance of 300 mm, i.e., five numbers of stirrups (additional), as shown in Fig. 6.14.5.

Problem 3:

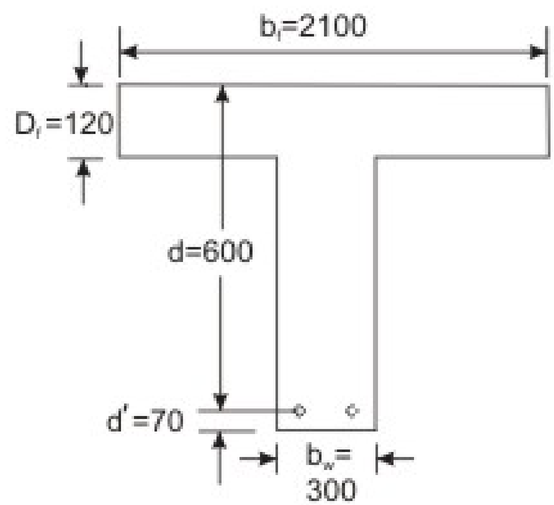

Fig. 6.14.6: Problem 3

Design the flexural and shear reinforcement of the simply supported T-beam (Fig. 6.14.6) of effective span 8 m placed @ 4.2 m c/c and subjected to a total factored load of 150 kN/m. Use M 30, Fe 415 and SP-16 tables for the design of flexural reinforcement.

Solution 3:

Design of flexural reinforcement with SP-16:

Effective width of flange $b_f = l_o/6 + b_w + 6\ D_f$ = 8000/6 + 300 + 6(120) = 2353 mm > 2100 mm (breadth of the web plus half the sum of the clear distance to the adjacent beams on either side).

So, b_f = 2100 mm.

$(M_u)_{\text{factored}}$ = 150 (8) (8)/(8) = 1200 kNm, at the mid-span.

$(V_u)_{\text{factored}}$ = 150 (8)/(2) = 600 kN, at the support.

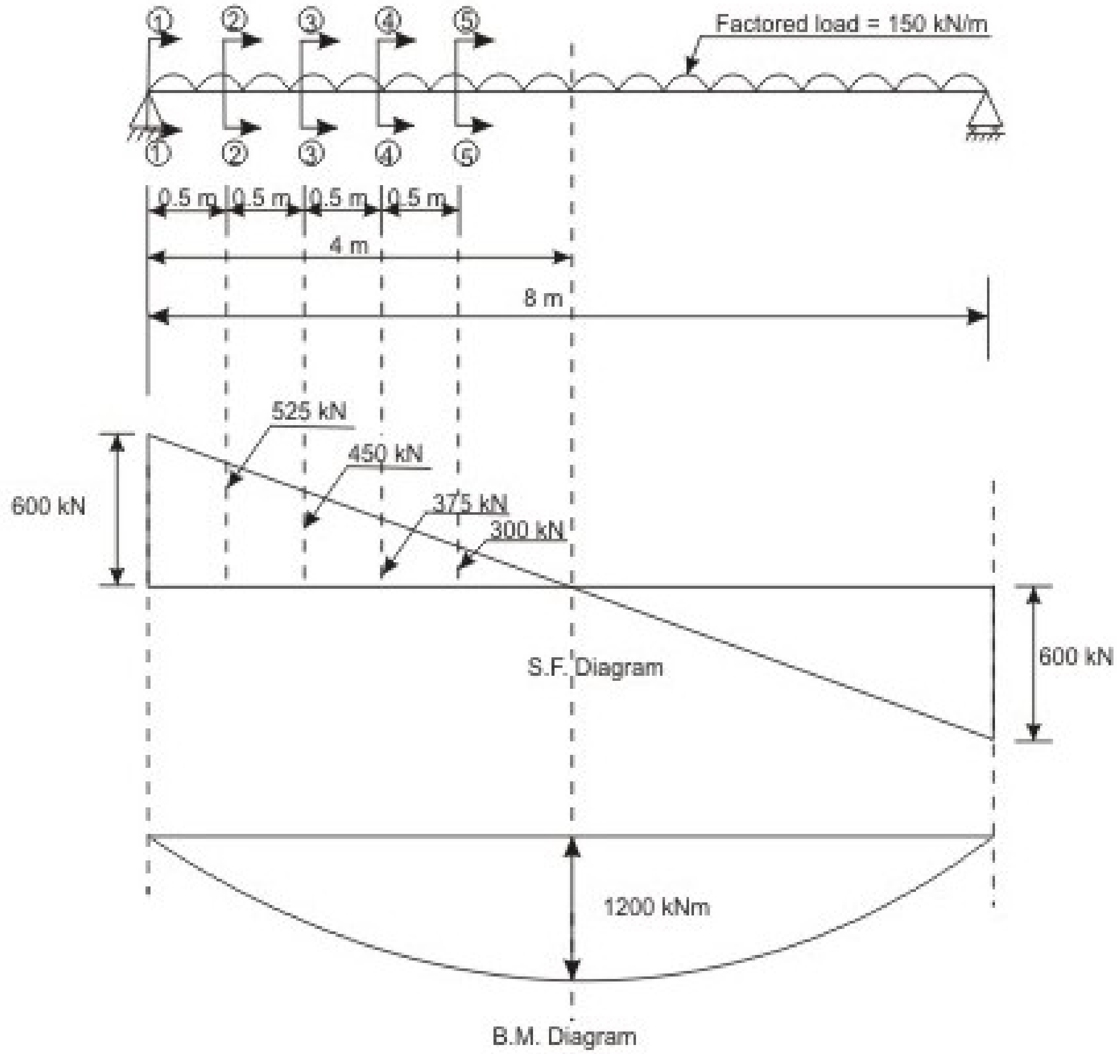

Fig. 6.14.7: B.M. & S.F. diagrams of Problem 3

The bending moment and shear force diagrams are shown in Fig. 6.14.7. At the mid-span

$$\frac{M_u}{b_w\, d^2\, f_{ck}} = \frac{1200\ (10^6\ )}{300\ (600)\ (600)\ (30)} = 0.37$$

D_f/d = 120/600 = 0.2 and b_f/b_w = 2100/300 = 7

Table 58 of SP-16 (f_y = 415 N/mm^2) gives:

$$\frac{M_{u,\lim}}{b\,d^2\,f_{ck}} = 0.62$$ (when b_f/b_w = 7.0 and D_f/d = 0.2) > 0.37 in this case.

Hence, o.k.

$$A_{st} = \frac{M_u}{0.87\,f_y\,(d - d_f/2)} = \frac{1200\,(10^6)}{0.87\,(415)\,(540)} = 6155 \text{ mm}^2$$

Provide 7-32T + 1-28T (= 6245 mm^2) bars at mid-span and up to section 5-5 (Fig. 6.14.8, sec. 5-5). The flexural reinforcement is cranked up and the reinforcement diagrams are shown at five sections in Fig. 6.14.8.

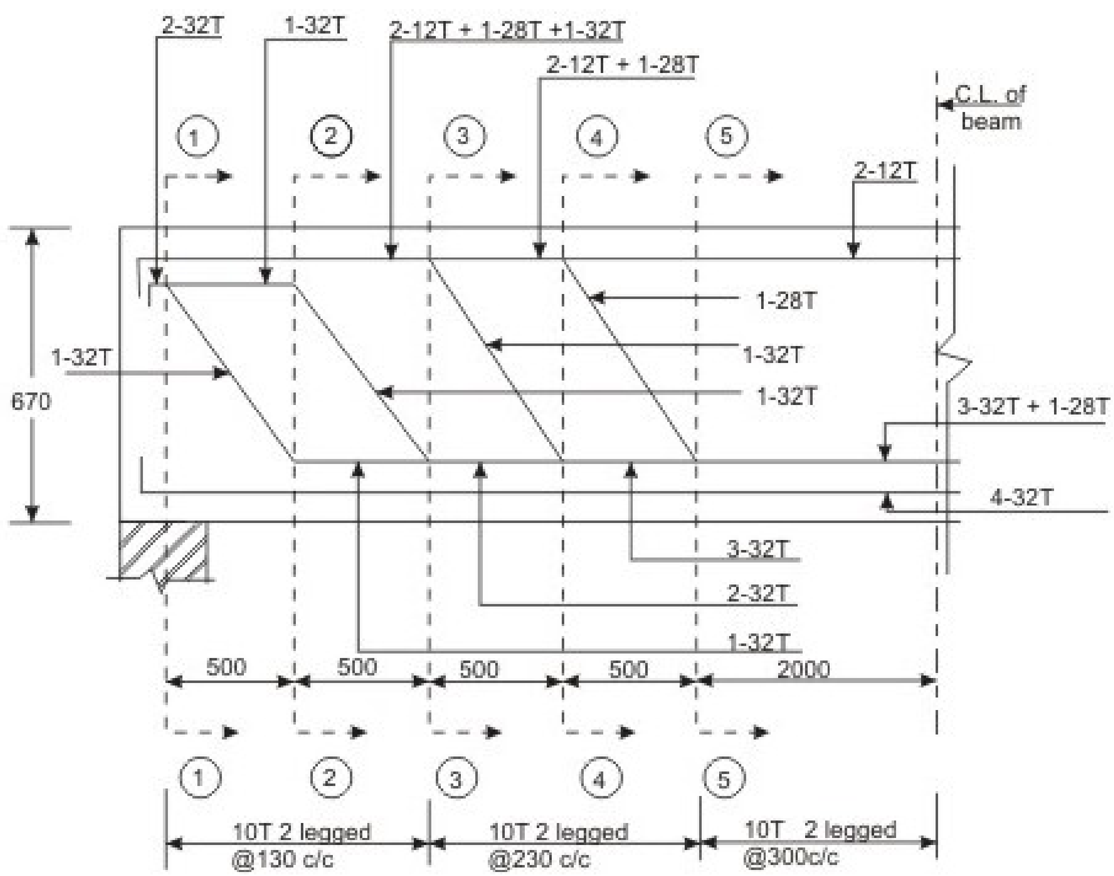

Fig. 6.14.8: Reinforcement of Prob. 3

Design of shear reinforcement:

The details of calculations are shown below for the section 1-1 in six steps. Results of all four sections are presented in Table 6.3.

Step 1:

A_{st} at section 1-1 is determined (= 3217 mm^2 = 4-32T) from Fig. 6.14.7 to calculate $p = A_{st}$ (100)/b_w d = 3217 (100)/300 (600) = 1.79%. From Table 6.1 of Lesson 13, τ_c is determined for p = 1.79% as 0.81 N/mm^2. Table 6.2 of Lesson 13 gives $\tau_{c,max}$ for M 30 = 3.5 N/mm^2.

Step 2:

V_u is 600 kN at section 1-1 from Fig.6.14.7 to get τ_v from Eq.6.1 of Lesson 13 as:

$$\tau_v = \frac{V_u}{b_w\, d} = \frac{(600)\,(10^3)}{(300)\,(600)} = 3.33 \text{ N/mm}^2$$

Here, τ_v is less than τ_{cmax}.

Step 3:

The magnitude of shear force for which shear reinforcement is needed (say, $V_{reinf.}$) is determined from Fig. 6.14.7. For section 1-1, from Eq. 6.4 of Lesson 13, $V_{reinf} = V_u - \tau_c\, b\, d$ = 600 – 0.81 (300) (600) = 454.2 kN.

The magnitude of shear force taken by bent up bar(s) is obtained from Eq. 6.7 of Lesson 13, $V_{bent} = 0.87\, f_y\, A_{sv}\, sin\alpha$ = 0.87 (415) (804) (1/√2) (10^{-3}) = 206.5 kN. This force should not be greater than 0.5 (V_{reinf}), which, at this section, is 227.1 kN (vide sec. 6.13.8 of Lesson 13).

The magnitude of the shear force for the design of vertical stirrup = V_{us} = $V_{reinf} - V_{bent}$ = 454.2 – 206.5 = 247.7 kN.

Step 4:

Assume the diameter of vertical stirrup bars as 10 mm, 2 legged (A_{sv} = 157 mm^2). The spacing of vertical stirrups $s_v = 0.87\, f_y\, A_{sv}\, d/V_{us}$ = 0.87 (415) (157) (600)/247.7 (10^3) = 137.3 mm c/c. Please refer to Eq.6.5 of Lesson 13.

Step 5:

Check s_v considering minimum shear reinforcement from cl. 26.5.1.6 of IS 456 as (see Eq.6.3 of Lesson 13):

$$s_v \le 0.87 f_y A_{sv} /0.4\, b_w \le 0.87\,(415)\,(157)\,/0.4\,(300) \le 472 \text{ mm}$$

Further, cl. 26.5.1.5 stipulates the maximum spacing = 0.75 *d* on 300 mm. Here, the maximum spacing = 300 mm.

Step 6:

So, provide 10 mm, 2 legged stirrups @ 135 mm c/c.

The results of all the sections are given below:

Table 6.3 Design of stirrups using 10 mm 2 legged vertical stirrups, (τ_{cmax} = 3.5 N/mm^2)

Step	Values of	Sec. 1-1	Sec. 2-2	Sec. 3-3	Sec. 4-4
1	A_{st} (mm^2)	3,217	4,021	4,825	5,629
	p (%)	1.79	2.23	2.68	3.13
	τ_c (N/mm^2)	0.81	0.877	0.93	0.96
2	V_u (kN)	600	525	450	375
	τ_v (N/mm^2)	3.33	2.92	2.50	2.08
3	V_{reinf} (kN)	454.2	367.14	282.6	202.2
	V_{bent} (kN)	206.5* < 0.5 V_{reinf}	206.5 < 183.57	206.5 < 141.3	157.24** < 101.1
	V_{us} (kN)	247.7	183.57	141.3	101.1
4	s_v (mm)	137.3	185.27	240.7	336.4
5	Min s_v (mm)	≤ 300	≤ 300	≤ 300	≤ 300
6	Provide s_v (mm)	135	180	240	300

* diameter of bent up bar = 32 mm

** diameter of bent up bar = 28 mm

To avoid several spacings for the practical consideration, provide stirrups @ 130 mm c/c for first 1 m, @ 230 mm for next 1 m and then @ 300 mm up to the mid-span in a symmetric manner (Fig. 6.14.8, secs. 1-1 to 5-5).

6.14.3 Practice Questions and Problems with Answers

Q.1: Check if shear reinforcement is needed for the beam shown in Fig. 6.14.9. If so, design the shear reinforcement using M 20 and mild steel (Fe 250). The tensile reinforcement is of Fe 415. Factored shear force = 300 kN.

A.1:

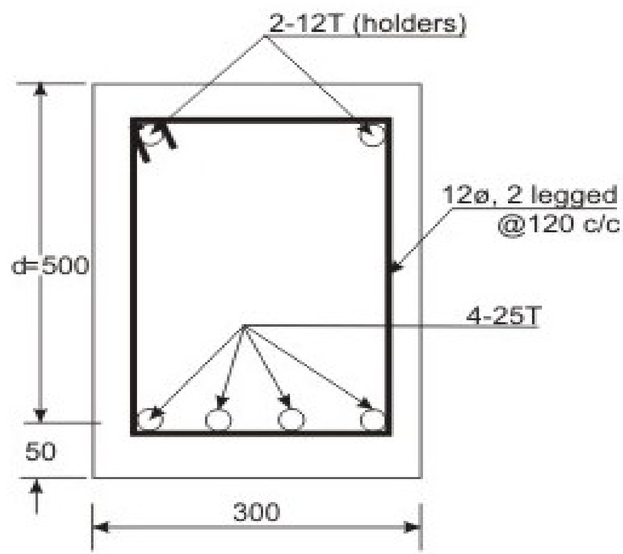

Fig. 6.14.9: Q. 1

A_{st} = 4-25T = 1963 mm^2

p = 1963/300(500) = 1.31%

τ_c from Table 6.1 of sec. 6.13.4.1 of Lesson 13 = 0.68 N/mm^2

From Table 6.2 of sec. 6.13.4.2 of Lesson 13 τ_{cmax} = 2.8 N/mm^2

$\tau_v = V_u/b\,d$ (Eq.6.1 of Lesson 13) = 300000/300(500) = 2.0 N/mm^2

Since $\tau_c < \tau_v < \tau_{cmax}$, shear reinforcement is needed. From Eq.6.4 of Lesson 13:

$$V_{us} = V_u - \tau_c\, b\, d = 300 - 0.68(300)(500)(10^{-3}) = 198 \text{ kN}$$

Alternative 1: Providing 10 mm, 2 legged stirrups (A_{sv} = 157 mm^2), the spacing s_v = 0.87(250)(157)(500)/198000 = 86.23 mm. Provide 10 mm, 2 legged stirrups @ 85 mm c/c. Please refer to Eq.6.5 of Lesson 13. The required area of stirrups spaced @ 85 mm c/c to satisfy the minimum shear reinforcement (cl.

26.5.1.6 of IS 456) is obtained from Eq. 6.3 of Lesson 13 as: A_{sv} = 0.4(300)(85)/0.87(250) = 46.89 mm^2 < 157 mm^2 .

Alternative 2: Providing 12 mm, 2 legged stirrups (A_{sv} = 226 mm^2), the spacing s_v = 0.87(250)(226)(500)/198000 = 124.13 mm. Provide 12 mm, 2 legged stirrups @ 120 mm c/c. The required area of stirrups spaced @ 120 mm c/c to satisfy the minimum shear reinforcement (cl. 26.5.1.6 of IS 456) is obtained from Eq. 6.3 of Lesson 13 as: A_{sv} = 0.4(300)(120)/0.87(250) = 66.21 mm^2 < 226 mm^2 .

Further, the maximum spacing (cl. 26.5.1.5 of IS 456 and sec. 6.13.7 of Lesson 13) = 0.75 d = 0.75(500) = 375 mm.

Hence, both are possible, though 12 mm @ 120 mm c/c is desirable since the other spacing of 85 mm c/c is very close (Fig. 6.14.9).

6.14.4 References:

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10. Textbook of R.C.C, by G.S.Birdie and J.S.Birdie, Wiley Eastern Limited, New Delhi, 1993.
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14. Reinforced Concrete Designer's Handbook, 10th Edition, by C.E.Reynolds and J.C.Steedman, E & FN SPON, London, 1997.
15. Indian Standard Plain and Reinforced Concrete – Code of Practice (4th Revision), IS 456: 2000, BIS, New Delhi.
16. Design Aids for Reinforced Concrete to IS: 456 – 1978, BIS, New Delhi.

6.14.5 Test 14 with Solutions

Maximum Marks = 50, Maximum Time = 30 minutes

Answer all questions.

TQ. 1: The *T*-beam of Fig. 6.14.10 has a factored shear force of 400 kN. Determine the diameter and spacing of vertical stirrups at a section where two 25 mm diameter bent up bears are also available for the shear resistance. Use M 20 and Fe 415.

(50 marks)

A.TQ. 1:

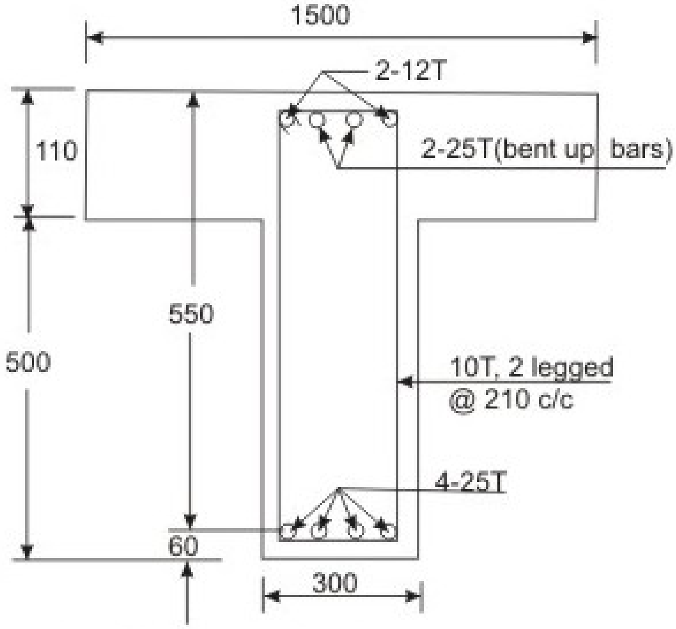

Fig. 6.14.10: TQ. 1

A_{st} = 4-25ϕ = 1963 mm^2

p = 1963(100)/300(550) = 1.19%

τ_c = 0.658 N/mm^2 (Table 6.1 of Lesson 13)

V_u = 400 kN

τ_v (Eq.6.1 of Lesson 13) = 400/165 = 2.43 N/mm^2 < τ_{cmax} of 2.8 N/mm^2.

Hence, o.k.

$V_{\text{reinf.}}$ = $V_u - \tau_c\, b\, d$ = 400 – 0.658(300)(0.55) = 291.43 kN (please refer to Eq.6.4 of Lesson 13)

V_{bent} (2-25 mm diameter) = $0.87\, f_y\, A_{sv}\, sin\alpha$ = 0.87(415)(981)(1/√2)

= 250.48 kN,

subjected to the maximum value of 0.5($V_{\text{reinf.}}$) = 145.71 kN (see sec. 6.13.8 of Lesson 13)

V_{us} = 145.72 kN

Using 10 mm, 2 legged vertical stirrups (A_{sv} = 157 mm^2), the spacing, obtained from Eq.6.5 of Lesson 13, $s_v = 0.87\, f_y\, A_{sv}\, d/V_{us}$ = 0.87 (415) (157) (550)/145720 = 213.95 mm c/c.

For the minimum shear of reinforcement as per cl. 26.5.1.6 of IS 456, using 10 mm, 2 legged vertical stirrups, the spacing as obtained from Eq.6.3 of Lesson 13:

$s_v \le 0.87\, f_y\, A_{sv}/0.4\, b_w \le$ 0.87 (415) (157) /0.4 (300) ≤ 472 mm

Again, cl. 26.5.1.5 of IS 456 stipulates the maximum spacing = 0.75 d = 0.75(550) = 412.5 mm (see sec. 6.13.7 of Lesson 13).

Hence, provide 10 mm, 2 legged vertical stirrups @ 210 mm c/c (Fig. 6.14.10).

6.14.6 Summary of this Lesson

Learning the different failure modes, the shear stresses and the design procedure of beams subjected to shear in Lesson 13, this lesson explains the design through several numerical problems with special reference to curtailment of tension reinforcement in flexural members. Solution of problems given in the practice problems and test, students will be thoroughly conversant with the design of rectangular and *T*-beams subjected to shear following the limit state of collapse.