Module
14
Tension Members

Lesson 36

Structural Requirements, Code Stipulations and Governing Equations

Instructional Objectives:

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

- state the need to design the tension structures using reinforced concrete though concrete is very weak in tension,
- justify the use of working stress method for designing reinforced concrete tension members,
- name the two essential requirements for the design of reinforced concrete tension structures,
- explain why some amount of cracking may be allowed in such structures,
- explain why porous aggregates are not allowed in the reinforced concrete tension structures,
- state the basis of design of reinforced concrete tension members,
- state the different cases of reinforced concrete tension members, and
- establish the governing equations for all the cases of tension members to determine the stresses of concrete and steel following the working stress method of design.

14.36.1 Introduction

Reinforced concrete is used in the design of several practical members of tension structures though it is not a potential material due to very inadequate tensile strength of concrete compared to its compression strength. In such cases, reinforced concrete develops tensile stresses either due to direct tension force or combined with bending. Tie members of trusses and arches, walls of rectangular tanks and bunkers, suspended roofs, cylindrical pipes, walls of liquid retaining structures are some of the examples where tension stresses also develop. Traditional elastic approach (working stress method) and the limit state method can be applied for the design of such structures. Based on elastic theory, the working stress method is simpler in concept and applications, while the limit state method, based on cracking behaviour of concrete, is not fully developed yet.

Some of the structures or members mentioned above may not be in direct contact with any liquid. On the other hand, some may be in direct contact with liquid. Though control of cracking is important for all types of structures, it is an essential requirement for liquid retaining structures. Impermeability of structure is not only for preventing leakage but also for improving durability, resistance to leaching, chemical action, erosion, frost damage and protecting the reinforcement from corrosion.

IS 456 gives due considerations for compression either direct or associated with bending and shear when limit state method is employed. However, it is almost silent on tension members. IS 3370, dealing with liquid retaining structures, is still adopting working stress method. Thus, the applications of limit state method for the design of tension members are still in the development stage. Accordingly, the working stress method shall be employed in this lesson to explain the design of such members.

14.36.2 Resistance to Cracking and Strength

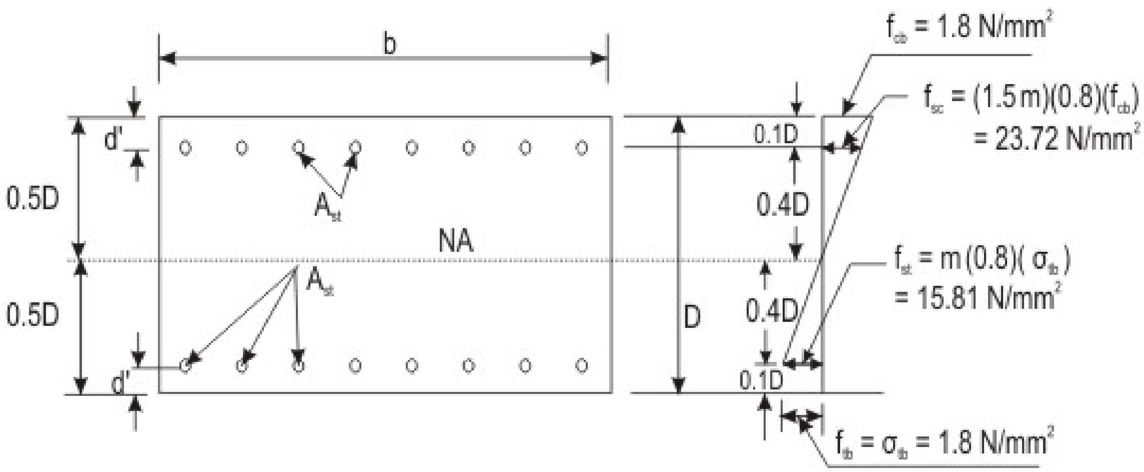

Fig. 14.36.1(a): Rectangular section

Fig. 14.36.1(b): Stress distribution for M25 (m = 10.98)

Fig. 14.36.1: Rectangular section under flexure

Figures 14.36.1a and b show one rectangular section under flexural tension and the distribution of stresses, respectively. The symmetric section of depth D is having the neutral axis at a depth of 0.5 D. Assuming that the actual tension stress of M 25 concrete (say) in bending f_{tb} reaches the permissible value of σ_{tb} = 1.8 N/mm^2 for resistance to cracking (see Table 14.1), the tensile stress of steel f_{st} at the level of steel shall be modular ratio times 0.8 σ_{tb} or 15.81 N/mm^2 {(10.98) (0.8) (1.8) N/mm^2, where modular ratio of M 25 concrete m = 93.33 / 8.5 = 10.98 and d' = 0.1 D}. The value of f_{st} is very low when compared with the values of the permissible tension stress of steel (115 N/mm^2 for Fe 250 and 150 N/mm^2 for Fe 415 as given in Table 14.2. Therefore, some amount of cracking may be permitted when the structure is not in contact with any liquid at all. Moreover, the remote face of the liquid retaining structures, which is not in contact with the liquid, also is a possible place of allowing minor cracks. However, it is also important to note that sufficient depth is available to prevent the corrosion of the reinforcement.

Allowing minor cracks in such cases means increasing the values of permissible stresses of concrete and steel reinforcement specifying the particular cases. IS 3370 Part II recommends the permissible stresses of concrete and reinforcement for different types of situations, which are given in Tables 14.1 and 14.2.

Hence, the design of tension members shall provide adequate control of cracking in addition to normal requirements of strength. There are many other issues involved in the design of tension structures. IS 3370 Parts I to IV deal with such issues in detail. The relevant important aspects are briefly mentioned in the following section.

14.36.3 IS Code Stipulations

(a) Porous aggregates – (cl.2.1.a of IS 3370, Part I)

Use of porous aggregates, such as burnt clay and broken bricks or tiles is not allowed for parts of structure either in contact with the liquids on any face or enclosing the space above the liquid.

(b) Concrete mix - (cl.3.1 a of IS 3370, Part I)

Concrete mix weaker than M 20 shall not be used except in thick sections (thickness > 450 mm) and parts of structure neither in contact with the liquid on any face nor enclosing the space above the liquid.

(c) Basis of design - (cl.3.2 of IS 3370, Part II)

(i) The parts of the structure not in contact with the liquid shall be designed in accordance with the requirements of IS 456.

(ii) Design of members other than those in (i) above shall be based on consideration of adequate resistance to cracking as well as adequate strength.

(iii) Calculation of stresses shall be based on the following assumptions in addition to the general assumptions given in IS 456.

1. The whole section of concrete including the cover together with the reinforcement shall be taken into account in calculating both flexure and direct tension (or combination of both) relating to resistance to cracking.

2. Total shear stress = $Q/(b\ jd)$, shall not exceed the permissible value given in Table 14.1, where Q, b and jd are the total shear, breadth and lever arm, respectively.

3. Concrete has no tensile strength in strength calculations.

(d) Permissible stresses in concrete - (cl.3.3 of IS 3370 Part II)

(i) For resistance to cracking

Table 14.1 furnishes the permissible stresses in tension σ_{td} and σ_{tb} (direct and due to bending) and shear τ_{sh} for calculations relating to the resistance of members to cracking. The permissible tensile stresses due to bending apply to the face of the member in contact with the liquid. In members less than 225 mm thick and in contact with the liquid on one side, these permissible stresses in bending apply also to the face remote from the liquid.

Table 14.1: Permissible stresses in concrete in calculations relating to resistance to cracking

Grade of concrete	Permissible stresses (N/mm^2)		
	Direct Tension, σ_{td}	Tension due to Bending σ_{tb}	Shear τ_{sh} ($Q / b\ jd$)
M 15	1.1	1.5	1.5
M 20	1.2	1.7	1.7
M 25	1.3	1.8	1.9
M 30	1.5	2.0	2.2
M 35	1.6	2.2	2.5
M 40	1.7	2.4	2.7

(ii) For strength calculations

In strength calculations, the permissible concrete stresses shall be in accordance with IS 456 (Table 13.1 of Lesson 34). Where the calculated shear stress in concrete alone exceeds the permissible value, reinforcement acting in conjunction with diagonal compression in the concrete shall be provided to take the whole of the shear.

(e) Permissible stresses in steel - (cl.3.4 of IS 3370, Part II)

(i) For resistance to cracking

When steel and concrete are assumed to act together for checking the tensile stress in concrete for avoidance of cracks, the tensile stress in the steel will be limited by the requirement that the permissible tensile stress in concrete is not exceeded, so that the tensile stress in steel shall be equal to the product of modular ratio of steel and concrete and the corresponding allowable tensile stress in concrete.

(ii) For strength calculations

For strength calculations the permissible stresses in steel reinforcement are given in Table 14.2.

Table 14.2: Permissible stresses in steel reinforcement for strength calculations

Sl. No	Types of stress in steel reinforcement	Permissible stresses σ_{st} N/mm^2	
		Fe 250	Fe 415
(i)	Tensile stress in members under direct tension	115	150
(ii)	Tensile stress in members in bending (a) On liquid retaining face of members (b) On face away from liquid for members less than 225 mm in thickness (c) On face away from liquid for members 225 mm or more in thickness	115 115 125	150 150 190
(iii)	Tensile stress in shear reinforcement: (a) For members less than 225 mm in thickness (b) For members 225 mm or more in thickness	115 125	150 175
(iv)	Compressive stress in columns subjected to direct load	125	175

Note: Stress limitations for liquid retaining faces shall also apply to the following:

a) Other faces within 225 mm of the liquid retaining face.
b) Outside or external faces of structures away from the liquid but placed in water logged soils up to the level of the highest subsoil water.

14.36.4 Types of Tension Structures

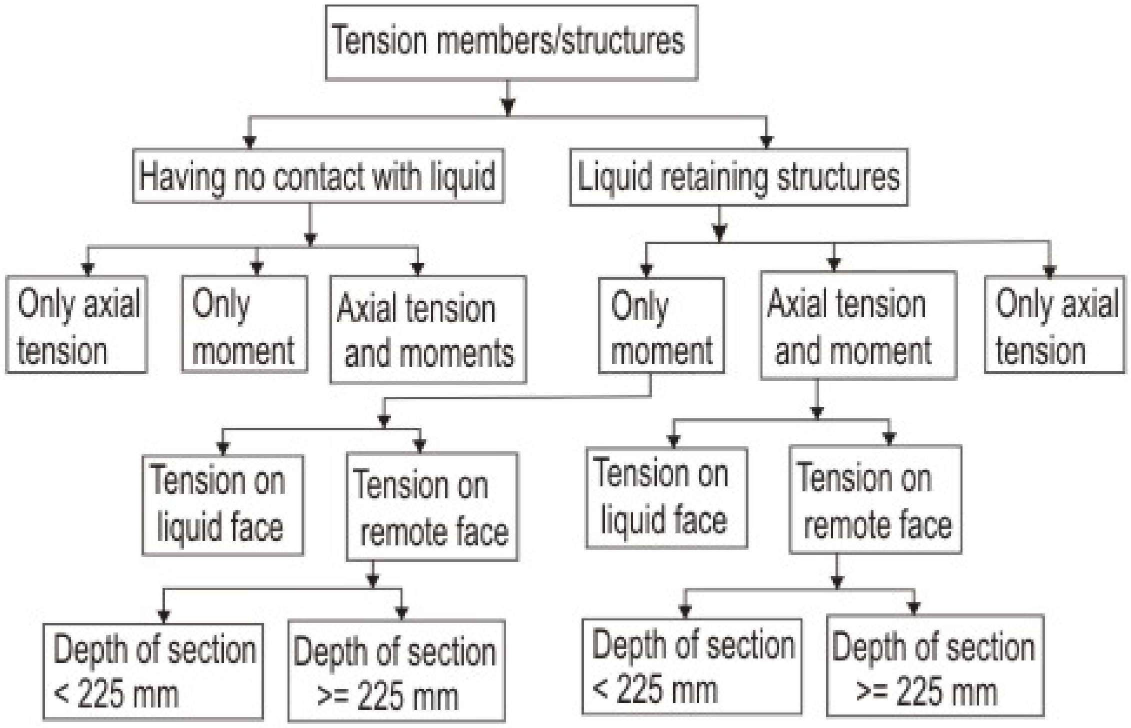

Fig. 14.36.2: Different cases of tension structures

Figure 14.36.2 summarises the two types of tension structures made of reinforced concrete indicating the different cases. The two types are (i) structures having no contact with the liquid and (ii) structures in direct contact with the liquid or liquid retaining structures. The different cases are first due to the three sources of tension stresses: (i) due to direct tension, (ii) pure flexure and (iii) direct tension associated with the flexure. Secondly, for the liquid retaining structures if the tension is on the (i) liquid face or (ii) on the remote face. Further two cases are there for the structures having tension on the remote face depending on, if the depth of section is (i) < 225 mm or (ii) ≥ 225 mm.

It is worth mentioning that understanding of the behaviour of tension structures and developing the governing equations of different cases are possible by taking up three main types: (i) when subjected to axial tension only, (ii) when subjected to bending moment only and (iii) when subjected to combined axial tension and bending moment. Accordingly, we take up these three main types in the following sections.

14.36.5 Members Subjected to Axial Tension only

Based on the discussion made so far, the criteria of design of such tension members are:

(i) Reinforcement alone shall take the full tension force.

(ii) The tension stress in steel shall not exceed the recommended permissible stress values given in Table 22 of IS 456 and Table 13.2 of Lesson 34.

(iii) The tensile stress of concrete shall be determined transforming the steel into equivalent concrete.

(iv) The tensile stress in the transformed section shall not exceed the stipulated permissible values given in cl. B-2.1.1 of IS 456 (Table 13.1 of Lesson 34). This will regulate the cracking of concrete.

Therefore, we can determine the actual tensile stress of steel f_{st} and concrete f_{td} from the following equations:

$$f_{st} = F_t / A_{st} \tag{14.1}$$

and

$$f_{td} = F_t /(A_c + m\, A_{st}) \tag{14.2}$$

where

F_t = total tension force on the member minus pretension in steel, if any, before concreting,

A_{st} = cross-sectional area of reinforcing steel in tension,

A_c = cross-sectional area of concrete excluding any finishing material and reinforcing steel, and

m = modular ratio

14.36.6 Members Subjected to Pure Flexure

For this, we will consider two cases: (i) when the section is uncracked and (ii) when the section is cracked. The first case is applicable when either the tension is on the liquid face or when the reinforcement is away from the liquid by a distance less than 225 mm. The second case is applicable when there is no direct contact of the structure with the liquid. The two cases are explained below.

(A) Uncracked Section

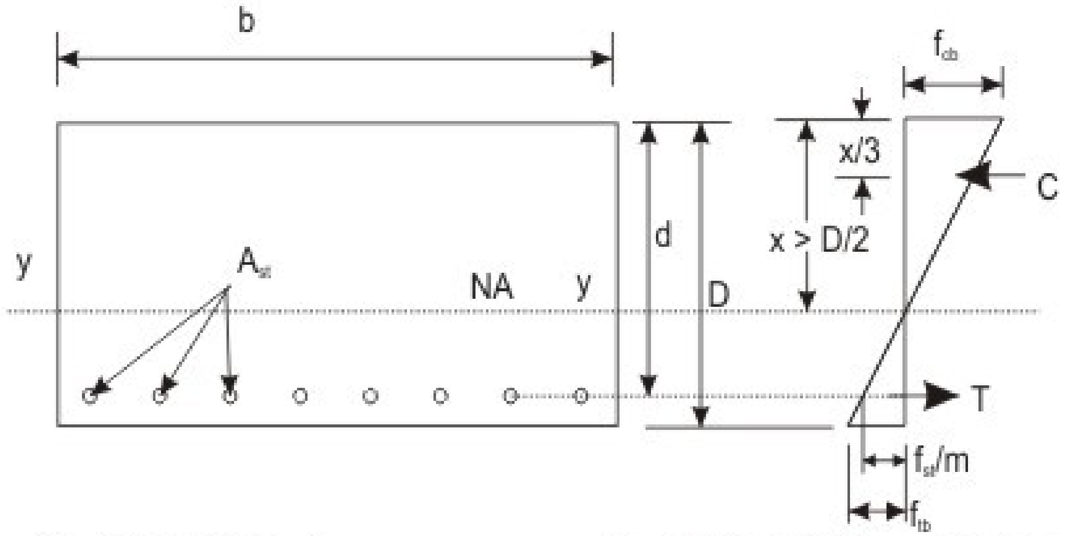

Fig. 14.36.3(a): Section   Fig. 14.36.3(b): Stress distribution

Fig. 14.36.3: Uncracked rectangular section under flexure

Figures 14.36.3a and b show the uncracked section and the stress distribution of such section subjected to bending moment alone. The maximum bending stresses in compression or tension are given by the expression.

$$f_{cb} = M\,x \,/\, I_{yy} \tag{14.3}$$

and

$$f_{tb} = M\,(D-x) \,/\, I_{yy} \tag{14.4}$$

where M = Applied moment on the member

x and $(D - x)$ = maximum distances of the compression and tension fibres from the neutral axis, x is also the depth of the neutral axis.

I_{yy} = moment of inertia of the uncracked section about the neutral axis of the section transforming area of steel into equivalent concrete.

The depth of the neutral axis x is obtained by taking moment of the transformed section about the top face, which gives: $bD^2/2 + (m\text{-}1)\,p_t\,b\,Dd/100 = \{bD + (m\text{-}1)\,p_t\,bD\,/\,100\}x$

or

$$x = \{b\,D^2/2 + (m - 1)\,p_t\,b\,Dd/100\} \,/\, \{bD + (m\text{-}1)\,p_t\,bD\,/\,100\} \tag{14.5}$$

The moment of inertia of the transformed section about the neutral axis is obtained from:

:

$$I_{yy} = b\,x^3/3 + b\,(D-x)^3/3 + (m-1)\,p_t\,bD\,(D\text{-}x)^2/100 \qquad (14.6)$$

The values of f_{cb} and f_{tb} are then obtained from Eqs. 14.3 and 14.4, respectively.

The moment of resistance of the section is determined from Eq.14.4 as f_{tb} is the governing stress of the section. This gives

$$M = f_{tb}\,I_{yy}/(D-x) \qquad (14.7)$$

(B) Cracked Section

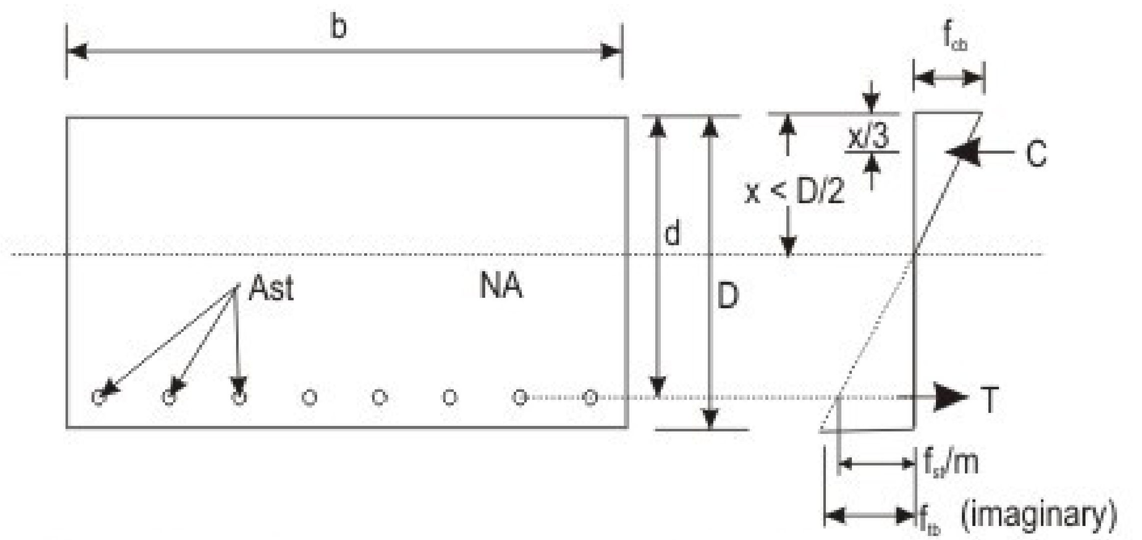

Fig. 14.36.4(a): Section

Fig. 14.36.4(b): Stress distribution

Fig. 14.36.4: Cracked rectangular section under flexure

Figures 14.36.4a and b show the section and stress distribution of the cracked section when subjected to moment alone. This particular case has been discussed in secs. 13.34.8 and 13.34.9 when the section is balanced and under-reinforced, respectively. Therefore, the equations are not derived here and only the final equations are given for the balanced and under-reinforced sections separately. The only difference is the notation of compressive stress of concrete in bending compression, which is f_{cbc} in secs. 13.34.8 and 9, while the same is denoted by f_{cb} here.

(i) Equations for the under-reinforced sections

The depth of the neutral axis is determined from $x = kd$, where

$$k = -\,(p_t\,m/100) + \{(p_t m/100)^2 + (p_t\,m/50)\}^{1/2} \qquad (13.16)$$

The compressive and tensile forces C and T are obtained from:

$C = (1/2)\, f_{cb}\, b\, kd$
(13.20)

$T = f_{st}\, A_{st}$
(13.6)

The moment of resistance with respect to steel is obtained from:

$M = A_{st}\, f_{st}\, d(1 - k/3)$
(13.24)

$M = (p_t /100) f_{st}\, (1 - k/3)\, bd^2$
(13.19)

(ii) Equations for the balanced section are as follows:

The depth of the balanced neutral axis is determined from: $x_b = k_b\, d,$ where

$k_b = 93.33 / (\sigma_{st} + 93.33)$ (13.3)

The expressions of compressive and tensile forces C and T are:

$C = (1/2)\, (\sigma_{cb})\, b\, k_b\, d$ (13.5)

$T = A_{st}\, \sigma_{st}$ (13.6)

The expressions of the balanced moment of resistance with respect to concrete and steel are:

$M_b = (1/2)\, \sigma_{cb}\, k_b\, j_b\, (b\, d^{\,2})$ (13.7)

$M_b = (p_{t,\, bal} / 100)\, \sigma_{st}\, j_b\, (b\, d^2)$
(13.8)

14.36.7 Members Subjected to Combined Axial Tension and Moment.

Here also, we will consider two cases: (i) when the section is uncracked and (ii) when the section is cracked.

(A) Uncracked Section

If tension is there on the liquid face, the tensile stress actually developed, i.e., f_{td} and f_{tb} in direct tension and bending tension, respectively should satisfy the following condition:

$$(f_{td} / \sigma_{td}) + (f_{tb} / \sigma_{tb}) \leq 1.0 \tag{14.8}$$

where σ_{td} and σ_{tb} are the permissible stresses of concrete in direct tension and bending tension, respectively and are to be taken from Table 14.1, and f_{td} and f_{tb} are the actual stresses of concrete in direct tension and bending tension, respectively and are determined from Eqs.14.2 and 14.4, respectively.

(B) Cracked Section

This case is classified under two groups: (i) when the eccentricity e of the tension force F_t is small; i.e., tensile force is large and (ii) when the eccentricity e of the tension force is large, i.e., tension force is small. We are explaining them separately.

(i) When the eccentricity is small, i.e., F_t is large

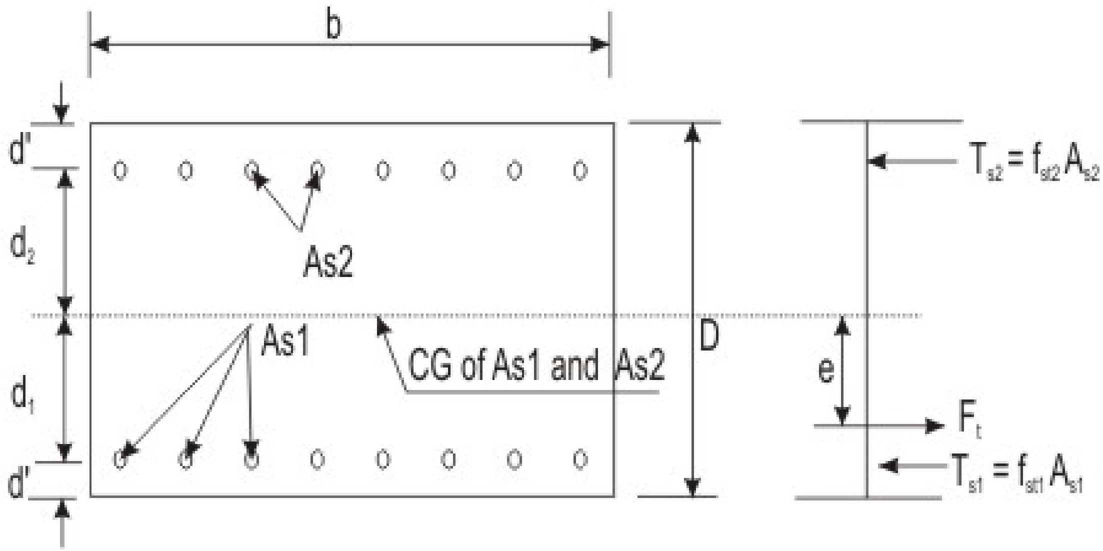

Fig. 14.36.5(a): Section

Fig. 14.36.5(b): Forces

Fig. 14.36.5: Cracked rectangular section under eccentric tension (e is small)

Figures 14.36.5a and b show the cracked section subjected to tension force at a small eccentricity e within the depth of the section. As the eccentricity is small, measured from the center of gravity of the two areas of steel, A_{s1} and A_{s2}, the whole section is in tension and hence the entire concrete is ineffective.

We have two equations of equilibrium: (i) equilibrium of forces and (ii) equilibrium of moments. They are expressed as follows:

$$F_t = T_{s1} + T_{s2} = f_{st1} A_{s1} + f_{st2} A_{s2} \tag{14.9}$$

Moment of the forces about the bottom steel gives: $F_t (d_1 - e) - T_{s2} (d_1 + d_2) = 0$

or $F_t (d_1 - e) - f_{st2} A_{s2} (d_1 + d_2) = 0$ (14.10)

Substituting the expression of F_t from Eq.14.9 into Eq.14.10, f_{st2} can be computed. The value of f_{st1} can then be computed from Eq.14.9.

(ii) When the eccentricity is large, i.e., F_t is small

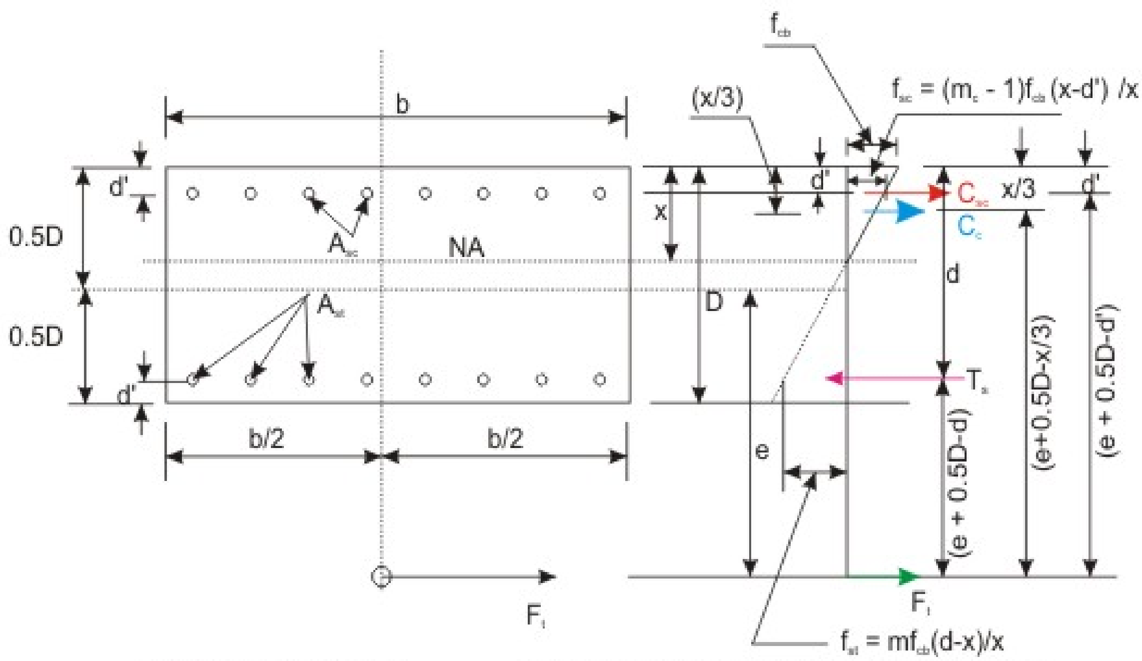

Fig. 14.36.6(a): Section Fig. 14.36.6(b): Forces and stress distribution

Fig. 14.36.6: Cracked rectangular section under eccentric tension (e is large)

Figure 14.36.6a and b show the section and stress distribution of cracked section subjected to tension force F_t having large value of the eccentricity e measured from the mid-depth of the section. The line of action of F_t is outside the section. The areas of compression and tension steel are denoted by A_{sc} and A_{st}, respectively. Due to large eccentricity, the direct and bending stresses are equally dominant. The forces of compression and tension steel are represented by C_{sc} and T_s, respectively, while the force of compressive concrete is represented by C_c. The distance of the neutral axis is x.

The expressions of these three forces are:

$$C_{sc} = f_{sc} A_{sc}$$
(14.11)

$$T_s = f_{st} A_{st}$$
(14.12)

$$C_c = 0.5 f_{cb} bx$$
(14.13)

The expressions of f_{sc} and f_{st}, obtained from the stress distribution of Fig. 14.36.6 b, are:

$$f_{sc} = (m_c - 1) f_{cb} (x - d')/x$$
(14.14)

$$f_{st} = m f_{cb} (d - x) / x$$
(14.15)

Using the expression of f_{sc} and f_{st} from Eqs. 14.14 and 14.15 in Eqs. 14.11 and 14.12, we have:

$$C_{sc} = (m_c - 1) A_{sc} f_{cb} (x - d') / x$$
(14.16)

$$T_s = m A_{st} f_{cb} (d - x) / x$$
(14.17)

The equation of the equilibrium of forces is:

$$F_t - T_{s\,+} C_c + C_{se} = 0$$
(14.18)

Taking moment of all forces about the line of action of F_t, the equation of equilibrium of moment is:

$$T_s (e + 0.5D - d) - C_c (e + 0.5D - x/3) - C_{sc} (e + 0.5D - d') = 0$$
(14.19)

Substituting the expressions of C_c, C_{sc} and T_s from Eqs. 14.13, 14.16 and 14.17, respectively into Eqs. 14.18 and 14.19, we have:

$$F_t = f_{cb} \{m A_{st} (d - x) / x - 0.5 bx - (m_c - 1)A_{sc} (x - d') / x\}$$
(14.20)

$$m\,A_{st}\,(d - x)\,(e + 0.5D - d)\,/\,x = 0.5\,bx\,(e + 0.5D - x/3) + (m_c - 1)\,A_{sc}\,(x - d')\,(e + 0.5D - d')\,/\,x \tag{14.21}$$

Equations 14.20 and 14.21 have seven unknowns $b, d, D, x, f_{cb}, A_{st}$ and A_{sc} of which b, d and D are assumed or taken from the preliminary dimensions. So, we have four unknowns x, f_{cb}, A_{st} and A_{sc} to be determined from two equations (Eqs. 14.20 and 14.21). Therefore, trial and error method has to be used.

As a particular case, when $A_{sc} = 0$, Eqs. 14.20 and 14.21 are reduced to:

$$F_t = f_{cb}\,\{m\,A_{st}\,(d - x)\,/\,x - 0.5\,bx\} \tag{14.22}$$

and $$m\,A_{st}\,(d - x)\,(e + 0.5\,D - d)\,/\,x = 0.5\,bx\,(e + 0.5\,D - x/3) \tag{14.23}$$

Here also the three unknowns x, f_{cb} and A_{st} are determined from Eqs. 14.22 and 14.23 by trial and error.

However, for such problems of singly-reinforced section, the initial value of A_{st} can be determined as explained below.

We use the equation of equilibrium of forces i.e., Eq. 14.24 as such and write the equation of equilibrium of moment by taking moment about T_s, which gives

$$C_c\,(jd) - F_t\,(e + 0.5D - d) = 0 \tag{14.24}$$

or $$C_c = F_t\,(e + 0.5\,D - d)/jd \tag{14.25}$$

Using the expression of C_c from Eq. 14.25 in Eq. 14.18, when $A_{sc} = 0$, we get:

$$F_t = T_s - C_c \quad = \; T_s - F_t\,(e + 0.5\,D - d)/\,jd$$

or $$T_s = F_t\,\{1 + (e + 0.5\,D - d)/\,jd\} \tag{14.26}$$

Assuming $T_s = A_{st}\ \sigma_{st}$ in Eq. 14.26, we have:

$$A_{st} = (F_t / \sigma_{st})\{1 + (e + 0.5\,D - d)/\,jd\} \qquad (14.27)$$

Equation 14.27 is used to get the starting value of A_{st} assuming j as 0.87 (say). This value of A_{st} now can be used in Eq. 14.23 to get the value of x. Using that value of x in Eq. 14.22, the value of f_{cb} can be determine. If $f_{cb} > \sigma_{cb}$, either the value of A_{st} shall be increased keeping D as the same or the value of D may be increased keeping A_{st} as the same. The third option is to increase both A_{st} and D, as appropriate.

Numerical problems are taken up in Lesson 37 for tension structures having no contact with liquid and for liquid retaining structures covering all the cases explained in Fig. 14.36.2.

14.36.8 Practice Questions and Problems with Answers

Q.1: Why is it needed to design the reinforced concrete tension structures when concrete is not good in tension?

A.1: Sec. 14.36.1, Paragraph 1.

Q.2: Name the two criteria of design of reinforced concrete tension structures.

A.2: Sec. 14.36.2

Q.3: State the basis of design of reinforced concrete tension structures.

A.3: Sec. 14.36.3, Part (c)

Q.4 Draw a schematic diagram of different cases of tension structures made of reinforced concrete.

A.4: Fig. 14.36.2

Q.5: Establish the equations to determine the tensile stresses of concrete and steel when the member is subjected to axial force F_t alone.

A.5: Sec. 14.36.5

Q.6: Establish the equations to determine the stresses in concrete due to applied moment only when the section is uncracked.

A.6: Sec. 14.36.6, Part A

Q.7: Answer Q.6, if the section is cracked.

A.7: Sec. 14.36.6, Part B

Q.8: Answer Q.6. if the section is uncracked and subjected to combined axial tension and moment.

A.8: Sec. 14.36.7, Part A

Q.9: Answer Q.6, if the section is cracked and subjected to combined axial tension and moment. Assume the eccentricity of the tension force F_t is small.

A.9: Sec. 14.36.7, Part B (i)

Q.10: Answer Q.6, if the section is cracked and subjected to combined axial tension and moment. Assume the eccentricity of the tension force F_t is large.

A.10: Sec. 14.36.7, Part B, (ii)

14.36.9 References

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14.36.10 Test 36 with Solutions

Maximum Marks = 50, Maximum Time = 30 minutes

Answer all questions.

TQ.1: Draw a schematic diagram of different cases of tension structures made of reinforced concrete.

(20 marks)

A.TQ.1: Fig. 14.36.2

TQ.2: Establish the equations to determine the stresses in concrete due to applied moment only when the section is uncracked.

(15 marks)

A.TQ.2: Sec. 14.36.6, Part A

TQ.3: Answer TQ.2, if the section is cracked and subjected to combined axial tension and moment. Assume the eccentricity of the tension force F_t is small.

(15 marks)

A.TQ.3: Sec. 14.36.7, Part B (i)

14.36.11 Summary of this Lesson

This lesson presents the analysis and design of tension structures following the working stress method as stipulated in IS 456 and IS 3370. The two requirements i.e., the resistance to cracking and strength must be considered for all types of tension structures whether they are in direct contact with the liquid or not. The respective permissible stresses of concrete in direct tension, bending tension, bending compression and shear are taken from the IS Codes for both cases: when no cracking is allowed and when some cracking may be allowed. The different cases of tension structures are classified depending on if they are in direct contact with the liquid or not, if the tension is on the liquid face or not and on the depth of the section. Understanding of the philosophy and concept of design and the different equations established for different cases will help to apply them in numerical problems. The numerical problems are taken up in Lesson 37.