DEPARTMENT OF CIVIL ENGINEERING

PSC SPECIAL STRUCTURES

Instructor:

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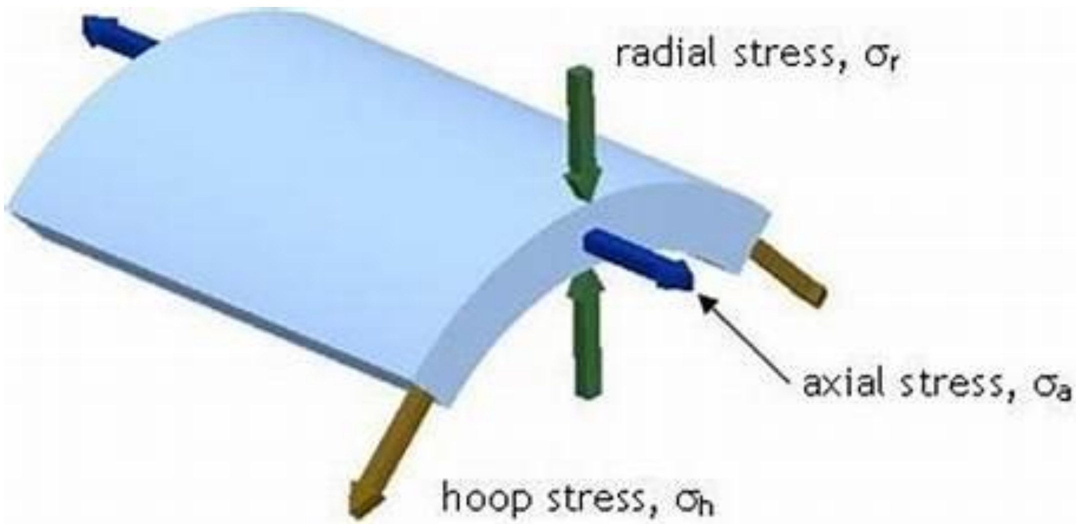
CIRCULAR PRESTRESS

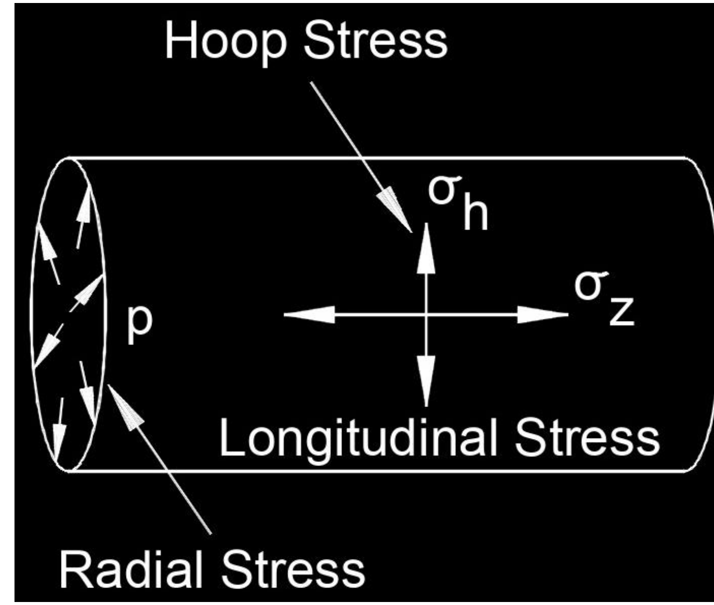
➢ Design procedure for tanks and pipes

CIRCULAR PRESTRESSING : When the prestressed members are curved in the direction of prestressing, the prestressing is called circular prestressing. For example, circumferential prestressing in pipes, tanks, silos, containment structures and similar structures is a type of circular prestressing

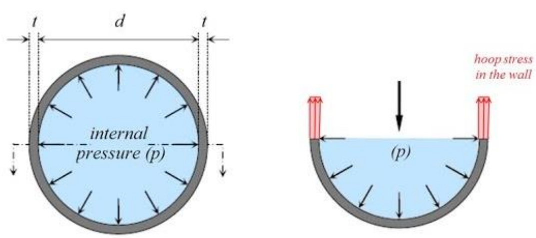
What are the design criteria for prestressed concrete tanks?

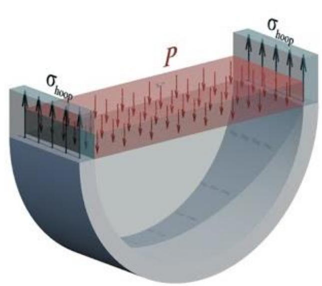
- It is to resist the hoop tension and moments developed are based on the considerations of desirable load factors against cracking and collapse.
- It is desirable to have at least a minimum load factor of 1.2 against cracking and 2 against ultimate collapse as per IS code.
- It is desirable to have at least a minimum load factor of 1.25 against cracking and 2.5 against ultimate collapse as per BS code.
- The principal compressive stress in concrete should not exceed one-third of the characteristic cube strength.
- When the tank is full, there should be a residual compressive stress of at least 0.7 N/mm2.

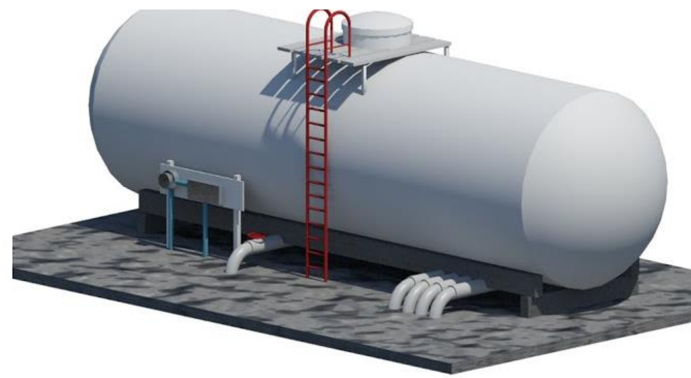


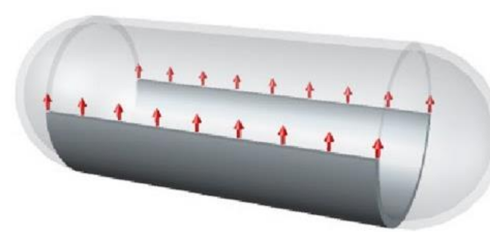


Part 1- Normal stress analysis









When the tank is empty, the allowable tensile stress at any point is limited to 1 N/mm2.

- ❖ The maximum flexural stress in the tank walls should be assumed to be numerically equal to 0.3 times the hoop compression.

What are the design criteria for prestressed concrete pipes?

- ❖ Circumferential prestressing, winding with or without longitudinal prestressing.
- ❖ Handling stresses with or without longitudinal prestressing.
- ❖ Condition in which a pipe is supported by saddles at extreme points with full water load but zero hydrostatic pressure. "The pressure exerted by a fluid at equilibrium at any point of time due to the force of gravity)
- ❖ Full working pressure conforming to the limit state of serviceability.
- ❖ The first crack stage corresponding to the limit state of local damage.

How are the tanks classified based on the joint?

- ❖ Tank wall with hinged base.
- ❖ Tank wall with fixed base
- ❖ Tank wall with sliding base.

Define two stage constructions.

In the first the concrete is cast over a tensioned longitudinal reinforcement.

In the second stage the concrete pipes after curing are circumferentially stressed by means of a spiral wire wound under tension and protected by a coat of mortar.

Write any two general failures of prestressed concrete tanks.

- Deformation of the pre-cast concrete units during construction.
- Manufacturing inaccuracies led to out of tolerance units being delivered to the site under investigation.
- It May have affected the ability to achieve a good seal.

What is the stress induced in concrete due to circular prestressing?

The circumferential hoop compression stress is induced in concrete by prestressing counter balances the hoop tension developed due to the internal fluid pressure.

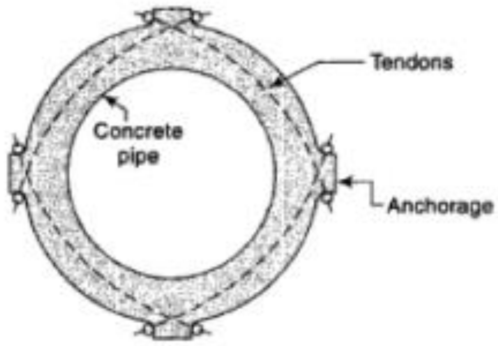
What are the advantages of prestressing water tanks?

- Water storage tanks of large capacity are invariably made of prestressed concrete.
- Square tanks are used for storage in congested urban and industrial sites where land space is a major constraint.
- This shape is considerable reduction in the thickness of concrete shell.
- The efficiency of the shell action of the concrete is combined with the prestressing at the edges.

Prestressed pipes & tanks

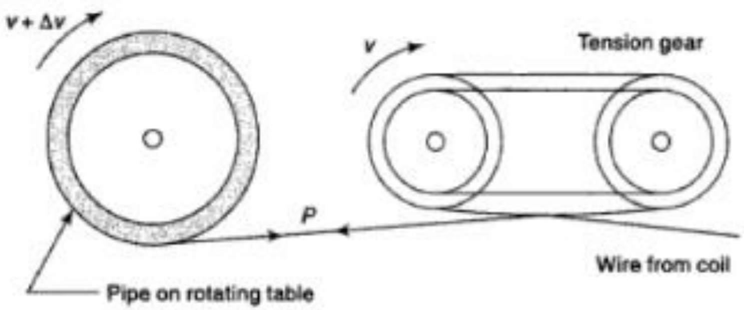
- Liquid retaining structures, such as circular pipes , tanks ad pressure vessels are admirably suited for circular prestressing.
- The circumferential hoop compression induced in concrete by prestressing counterbalances the hoop tension developed due to the internal fluid pressure.
- A reinforced concrete pressure pipe requires a large amount of reinforcement to ensure low-tensile stresses resulting in a crack free structure.
- Advantages in using circular prestressing are
  - Eliminates cracks
  - Economical use of materials
  - Safeguards against shrinkage cracks

Pipes



(a)

Overlapping of tendons within the ducts to minimize frictional loss



(b)

Wrap the high tensile wires under tension around precast cylindrical members.

Methods

- Monotype construction
  - A single type of operation is carried out and the pipe is cast
  - Developed by freyssinett in 1930
- Two-stage construction
  - The pipe is cast first, and prestressing is done after concrete hardens.
- Pre-cast construction
  - The segments are precast and the prestressing technique is used to connect the number of segments into a pipe.

Design of Non-cylinder pipe

- The tensioning of the prestressing steel induces a circumferential compression, f_c in the pipe and should not exceed the permissible compressive stress at transfer.
- The working pressure, p should not be less than f_{min} . Thus the permissible range of stress is ($\eta f_{c-} f_{min}$).
- The circumferential stress is given by the following equation:

Where

- D=inside diameter
- T= hoop tension=pD/2
- f_{ct} = allowable stress in concrete
- η = loss ratio
- f_{min} = permissible stress in concrete under working pressure=0 as per IS 784
- t= thickness of wall in mm
- f_c = compressive stress in concrete in N/mm^2

$$\frac{pD}{2t} < \left(\eta f_{ct} - f_{\min}\right)$$

$$t > \frac{\left(pD/2\right)}{\left(\eta f_{ct} - f_{\min}\right)}$$

$$t > \frac{T}{\left(\eta f_{ct} - f_{\min}\right)}$$

$$\eta f_{ct} - f_{\min} = \frac{T}{t}$$

$$f_{ct} = \frac{T}{\eta t} + \frac{f_{\min}}{\eta}$$

Where $T = N_d = pD/2$

The prestressing force is P per metre length

Where, t= thickness of wall in mm

f_c = compressive stress in concrete in N/mm²

$$P = 2000 t f_c$$

Referring to Figure

Where,

N=number of turns

d= diameter of wire

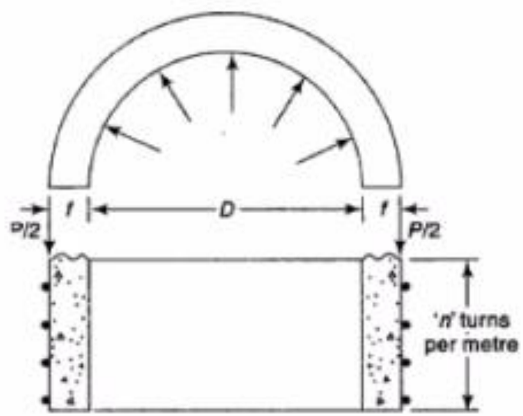
A_s = Area of steel

f_s = Stress in steel

$$P = A_s f_s \Rightarrow P = 2\left(\frac{\pi d^2}{4}\right) n f_s$$

Water pressure after winding

$$P_w = \frac{2t}{D}\left(f_c - f_{\min}\right)$$



Using force equilibrium condition

$$2000 t f_c = 2\left(\frac{\pi d^2}{4}\right) n f_s$$

$$n = \frac{4000 t f_c}{\pi d^2 f_s}$$

Loss of prestress due to elastic shortening

- There will be contraction in the pipe due to the application of circumferential tension in the wire wounds. Also when the adjacent length is wound, there will be further contraction of the diameter of the pipe.
- The loss due to elastic shortening is calculated as follows.

$$f_{se} = \frac{f_s}{1+\alpha_e \rho}$$

Where,

f_s = initial stress in steel

f_{se} = Effective stress after winding

α_e = modular ratio $=E_s/E_c$

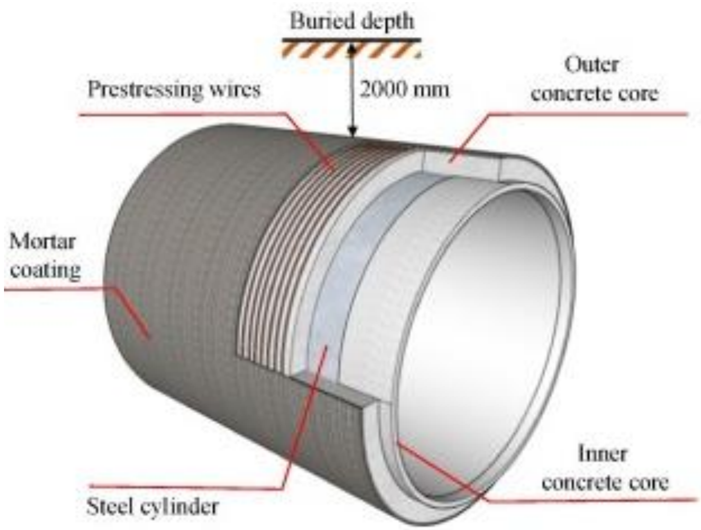
ρ= reinforcement ratio= f_c/f_s

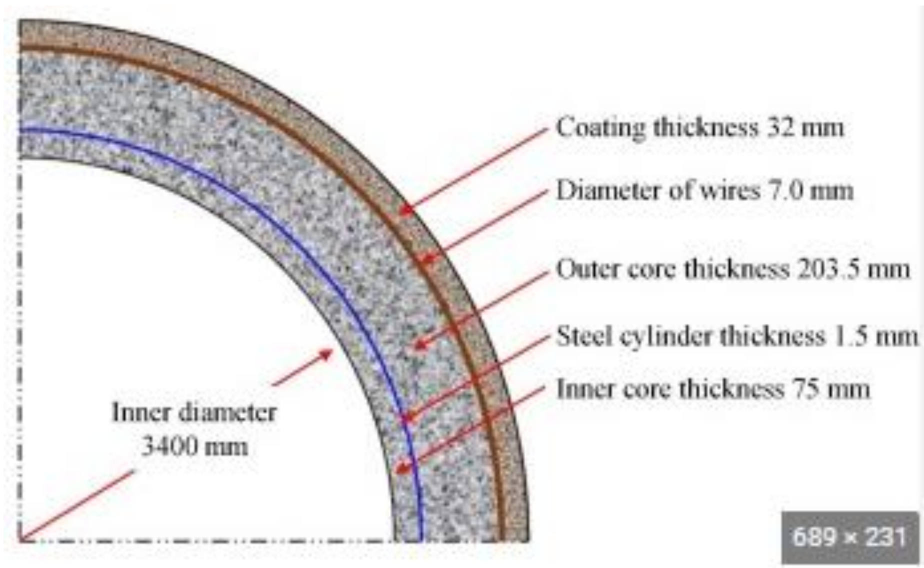
Guidelines

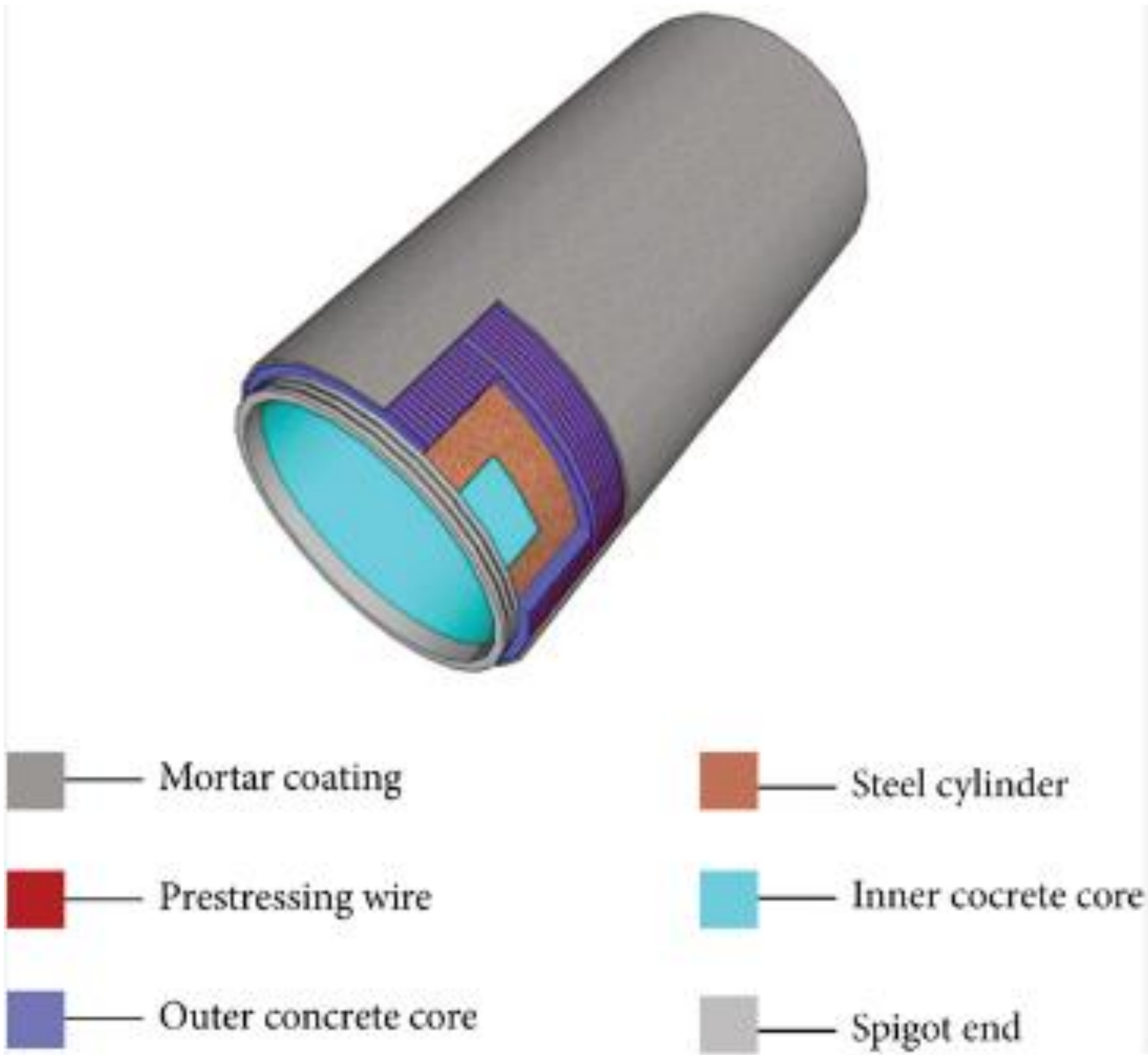
Percentage of reinforcement= 0.5 to 1 %

Modular ratio =5 to 6

Loss due to elastic shortening =3 to 6 %


Buried depth
2000 mm
Prestressing wires
Outer
concrete core
Mortar
coating
Inner
concrete core
Steel cylinder


Coating thickness 32 mm
Diameter of wires 7.0 mm
Outer core thickness 203.5 mm
Steel cylinder thickness 1.5 mm
Inner core thickness 75 mm
Inner diameter
3400 mm
689 × 231


Mortar coating
Steel cylinder
Prestressing wire
Inner cocrete core
Outer concrete core
Spigot end

Problem-1

Design a non - cylinder prestressed concrete pipe of 600 mm internal diameter to withstand a working hydrostatic pressure of 1.05 N/mm^2, using a 2.5 mm high - tensile wire stressed to 1000 N/mm^2 at transfer. Permissible maximum and minimum stresses in concrete at transfer and service loads are 14 and 0.7 N/mm^2. The loss ratio is 0.8. calculate also the test pressure required to produce a tensile stress of 0.7 N/mm^2 in concrete when applied immediately after tensioning and also the winding stress in steel if E_S = 28 kN/mm^2 and E_C = 35 kN/mm^2.

$$t > \frac{N_d}{\eta f_{ct} - f_{min.w}} > \frac{1.05(600/2)}{0.8 \times 14 - 0.7} > 30 \text{ mm}$$

For a 30 mm thick concrete pipe, the actual compressive stress in concrete $f_c = 14$ N/mm^2.

The number of turns of the 2.5 mm wire stressed to 1000 N/mm^2 per metre length of the pipe is given by,

$$n = \frac{4000 t f_c}{\pi d^2 f_s} = \frac{4000 \times 30 \times 14}{\pi \times 2.5^2 \times 1000} = 86 \text{ turns/m}$$

$$\text{Pitch of circumferential wire winding} = \frac{1000}{86} = 11.6 \text{ mm}$$

If W_w = test pressure required immediately after winding, ($\eta = 1$)

$$f_c = \frac{W_w D}{2\eta t} + \frac{f_{min.w}}{\eta}$$

$$W_w = \frac{2t}{D}(f_c - f_{min.w})$$

$$= \frac{2 \times 30}{600}[14 - (-0.7)] = 1.47 \text{ N/mm}^2$$

If f_{si} = winding stress in steel,

$$f_{si} = (1 + \alpha_e \rho) f_{se}$$

$$\alpha_e = 6 \text{ and } \rho = \frac{f_c}{f_s} = \frac{14}{1000} = 0.014$$

$$f_{si} = (1 + 6 \times 0.014)1000$$

$$= 1084 \text{ N/mm}^2$$

Problem-2

A non - cylinder prestressed concrete pipe of internal diameter 1000 mm and thickness of concrete shell 75 mm is required to convey water at a working pressure of 1.5 N/mm^2. The length of each pipe is 6 m. the maximum direct compressive stresses in concrete are 15 and 2 N/mm^2. The loss ratio is 0.8. i. Design the circumferential wire winding using 5 mm diameter wires stressed to 1000 N/mm^2. ii. Design the longitudinal prestressing using 7 mm wires tensioned to 1000 N/mm^2. The maximum permissible tensile stress under the critical transient loading (wire wrapping at spigot end) should not exceed 0.8 root fci , where fci is the cube strength of concrete at transfer = 40 N/mm^2. iii. Check for safety against longitudinal stresses that develop, considering the pipe as a hollow circular beam as per IS: 784 provisions.

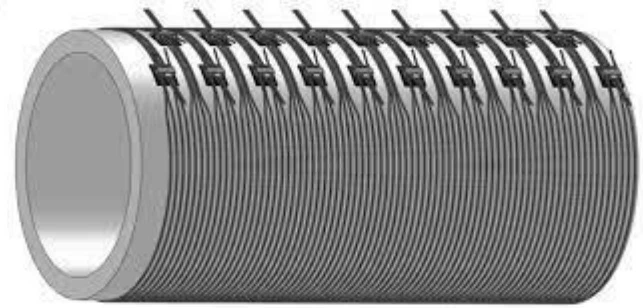
$D = 1000$ mm
$W_w = 1.5$ N/mm^2
$t = 75$ mm
$L = 6$ m

$f_{ct} = 15$ N/mm^2
$f_{min,w} = 2$ N/mm^2
$f_s = 1000$ N/mm^2

(a) Circumferential wire winding

Compressive stress in concrete,

$$f_c = \frac{N_d}{\eta t} + \frac{f_{min.w}}{\eta} = \frac{1.5(1000/2)}{0.8 \times 75} + \frac{2}{0.8} = 15 \text{ N/mm}^2$$



Number of turns,

$$n = \frac{4000 t f_c}{\pi d^2 f_s} = \frac{4000 \times 75 \times 15}{\pi \times 5^2 \times 1000} = 57 \text{ turns/m}$$

$$\text{Pitch of winding} = \frac{1000}{57} = 17.5 \text{ mm}$$

(b) Longitudinal prestressing

Critical transient stress at spigot end $= 0.6 \times \text{hoop stress} = 0.6 \times 15$
$= 9 \text{ N/mm}^2$

Maximum permissible tensile stress $= 0.8\sqrt{f_{ci}} = 0.8\sqrt{40} = 5 \text{ N/mm}^2$

Hence the tensile stress of $9 - 5 = 4 \text{ N/mm}^2$ should be counterbalanced by longitudinal prestressing. Cross-sectional area of the pipe

$$= (\pi \times 1.075 \times 0.075) \text{ m}^2$$

If P is the longitudinal prestressing force required, then

$$P = \frac{\pi \times 1.075 \times 0.075 \times 10^6 \times 4}{10^3} = 1013 \text{ kN}$$

Using 7 mm wires stressed to 1000 N/mm^2,

Force in each wire = 38.5 kN

$$\therefore \quad \text{Number of wires} = \frac{1013}{38.5} = 27$$

(c) Check for flexural stresses as per IS: 784

Considering the pipe as a beam of hollow cicular section over a span of 6 m.

Three times self-weight $= 3\pi \times 1.075 \times 0.075 \times 24 = 18.30$ kN/m

Weight of water $= (\pi \times 1^2 \times 10)/4 = 7.90$ kN/m

Total u.d.l on pipe $= 26.20$ kN/m

$$\text{Maximum bending moment} = \frac{26.2 \times 6^2}{8} = 118 \text{ kN m}$$

$$\text{Second moment of area, } I = \frac{\pi(1.15^4 - 1^4)}{64} = 0.0365 \text{ m}^4$$

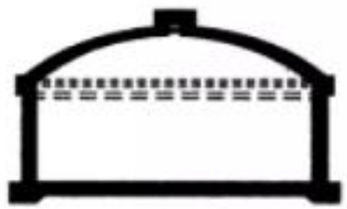
$$\text{Flexural tensile stress} = \frac{118 \times 10^6 \times 575}{0.0365 \times 10^{12}} = 1.88 \text{ N/mm}^2 \text{ (tension)}$$

Longitudinal prestress $= 4$ N/mm^2

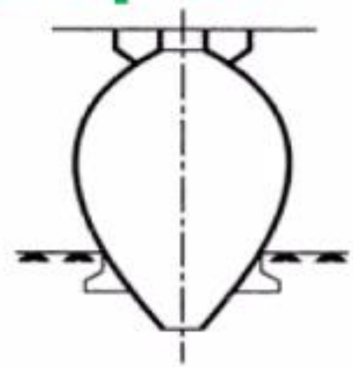
$\therefore$ Resultant stress in concrete $= 4 - 1.88 = 2.12$ N/mm^2 (compression)

The resultant stress being compressive, the pipe is safe against cracking.

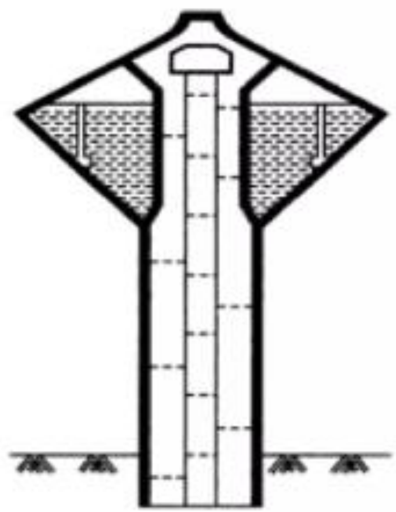
Tanks-Shapes



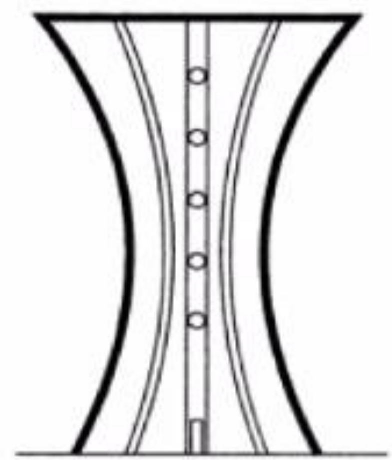
Circular cylindrical tank
(a)



Conical tank
(b)



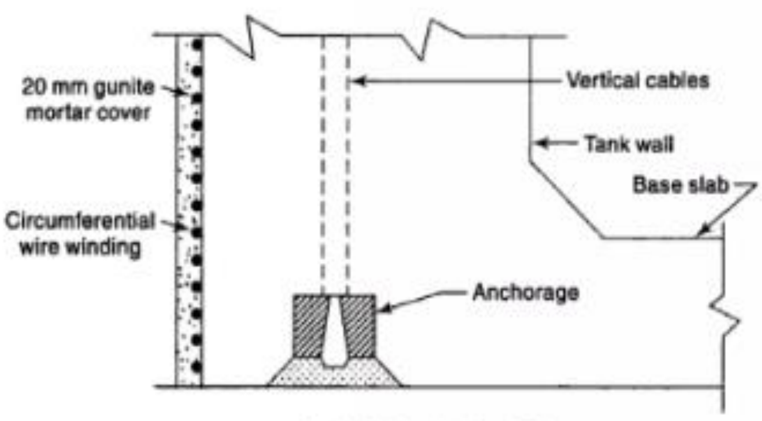
Water tower with conical tank
(c)



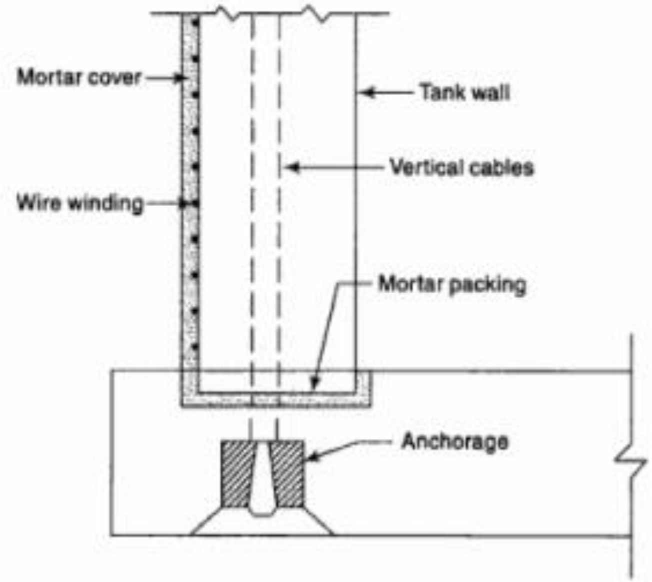
Water tower of doubly curved shell
(d)

Shapes of Prestressed Concrete Tanks

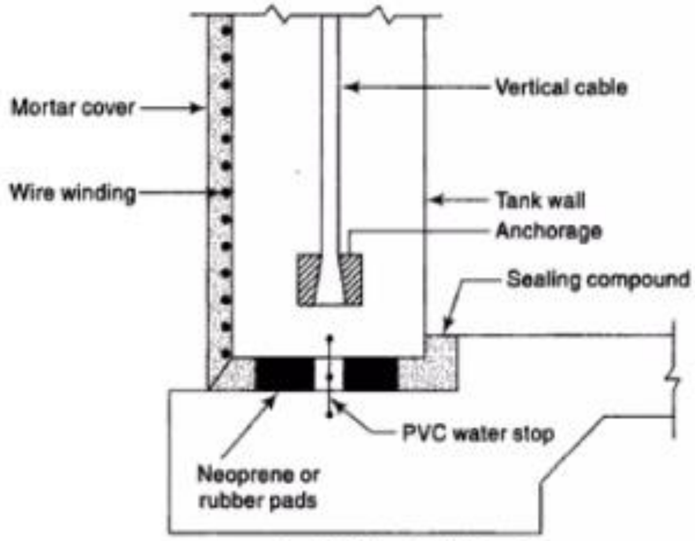
Tank with different base



Tank Wall with Fixed Base



Tank Wall with Hinged Base



Tank Wall with Sliding Base

Design Procedure for circular tanks Computations

1. Minimum wall thickness

2. Circumferential Prestress

3. Vertical Prestress.

Estimate

1) Maximum, ring tension Nd

2) Bending Moment Mw

3) Minimum wall thickness = $\frac{Nd}{\eta fct - fmin.w}$

Minimum cover 35mm

4) Circumferential Prestress

$fc = \frac{Nd}{\eta t} + \frac{fmin.w}{\eta}$ N/mm^2

5) Spacing of wires

As = Cross sectional area of wire coinding, mm^2

Wt = average radial Pressure of wires at transfer at a given section N/mm^2

D = Diameter of the tank, mm

S = Spacing of wires at the given section mm

fs – Stress in wires at transfer, N/mm^2

t – Thickness of the tank wall, mm

fc – compressive stress in concrete, N/mm^2

Hoop compression due toprestressing

$= \frac{wt \cdot D}{2}$

Equating $\frac{wt. D}{2} = \frac{fs\ As}{S1}$

$Wt = \frac{2\ fs\ As}{sD}$

Nd – hoop tension due to hydrostatic working pressure, Ww

Nt – hoop compression due to radial pressure of wires, wt

Then $Nt = Nd\left(\frac{wt}{Ww}\right)$

Also $N_t = t\, f_c$

Spacing of the wire winding

$$S = \frac{2\,N_d}{W_w} \cdot \frac{f_s.\,A_s}{f_c.\,D_t} \quad \text{mm}$$

$$M_t = M_w\left(\frac{w_t}{W_w}\right)$$

Where Mt = Vertical moment due to the prestress at transfer.

Mw = Vertical moment due to hydrostatic pressure.

The compressive prestress required

$$F_c = \frac{f_{min}.\,W}{\eta} + \frac{M_w}{\eta z}$$

When the tank is empty

$$f_c = \frac{f_{min}.\,W}{\eta} + \frac{M_t}{Z}$$

Vertical prestressing force is required

$$P = f_c.\,A_c$$

(Note: Vertical Prestressing force = 30% of hoop compression.]

A cylindrical prestressed concrete water tank of internal diameter 30m is required to store water over a depth of 7.5m. The permissible compressive stress in concrete at transfer is 13 N/mm^2 and the minimum compressive stress under working presuure is 1 N/mm^2. The loss ratio is 0.75. Wires of 5mm diameter with an initial stress of 1000N/mm^2 are available for circumferential winding and freyssinet cables made up of 12 wires of 8mm diameter stressed to 1200N/mm^2 are to be used for vertical prestressing. Design the tank walls assuming the base as fixed. The cube strength of concrete is 40N/mm^2.

Solution:

From table 16.1

Assume t = 150mm

$$\frac{H^2}{Dt} = \frac{7.5^2}{30 \times 0.15} = 12.5$$

$$Ww = wH = 10 \times 7.5 = 75kN/m^2 = 0.075N/mm^2$$

From table 16.2 & 16.3

Maximum ring tension Nd = (coefficient) wHR kN/m

$= 0.64 \times 10 \times 7.5 \times 15$

$= 720kN/m = 720N/mm.$

Moment in tank wall for the fixed base condition = (coefficient) Wh^3 kNm/m

$= 0.01 \times 10 \times 7.5^3$

$= 42.5$ kNm/m

$= 42500$ Nmm/mm

Minimum wall thickness $= t = \dfrac{Nd}{\eta f_{ct} - f_{min.w}}$

$= \dfrac{720}{0.75 \times 13 - 1} = 82.3\text{mm}$

Net thickness available (allowing for vertical cables of diameter 30mm) is (150 − 30) = 120mm

$$f_c = \frac{Nd}{\eta t} + \frac{f_{min.w}}{\eta}$$

$$= \frac{720}{0.75 \times 120} + \frac{1}{0.75} = 9.42\text{N/mm}^2$$

Spacing of circumferential wire winding at base.

$$S = \frac{2\ Nd\ fs.\ As}{Ww\ \ fc.\ Dt}$$

$$= \frac{2 \times 720 \times 1000 \times \pi/4)(5)^2}{0.075 \times 9.4 \times 30 \times 10^3 \times 120}$$

= 11.4mm

Number of wires / metre = 87

Ring tension Nd at 0.1 H (0.75m) from top

Nd = (coeff) wHR kN/m

= 0.097 X 10 X 7.5 X 15 = 109 kN/m = 109N/mm

$$fs = \frac{2 \times 109 \times 1000 \times 20}{0.075 \times 2.5 \times 30 \times 10^3 \times 120}$$

= 64mm

Number of wires / metre t the top of tank = 16

$$\text{Vertical moment} = Mw\left(\frac{wt}{Ww}\right)$$

$$Wt = \frac{2\ fs\ As}{Sd} = \frac{2 \times 1000 \times 20}{11.4 \times 30 \times 10^3} = 0.117\ N/mm^2$$

$$Mt = 42500\left(\frac{0.117}{0.075}\right) = 67{,}000\ Nmm / mm = 67 \times 10^6\ Nmm / m.$$

Considering one metre length of tank

Along the circumferential

$$Z = \frac{100 \times 150^2}{6} = 375 \times 10^4 mm^3$$

$$fc = \frac{fmin.\ w}{\eta} + \frac{Mt}{Z}$$

$$= \frac{1}{0.75} + \frac{67X\ 10^6}{375\ X\ 10^4} = 19.20N/mm^2$$

Since this stress exceeds the permissible value of fct = 13N/mm², increased to 200mm. the thickness of the tank wall of base is

increased to 200mm.

$$Z = \frac{1000 \times 100^2}{6} = 666 \times 10^4 \text{ mm}^3$$

$$fc = \frac{1}{0.75} + \frac{67 \times 10^6}{666 \times 10^4} = 12 \text{N/mm}^2$$

$$\text{Vertical Prestressing force} = fc = A = \frac{12 \times 1000 \times 200}{1000}$$

$$= 2400 \text{kN}$$

Using 8mm diameter (12Nos.) Freyssinet cables

$$\text{Force / cable} = \frac{\pi/4 \times 8^2 \times 12 \times 1200}{1000} = 720 \text{kN}$$

$$\text{Spacing} = \frac{1000 \times 720}{2400} = 800 \text{mm}$$

App. Vertical Prestress = 0.3 fc

$$= 0.3 \times 9.4 = 2.82 \text{ N/mm}^2$$

$$\text{Vertical prestressing force} = \frac{2.82 \times 1000 \times 200}{1000}$$

$$= 564 \text{kN}$$

$$\text{Ultimate tensile force} = \frac{87 \times 20 \times 1500}{1000} = 2610 \text{kN}$$

Load factor = 2610 / 720 = 3.6

Direct tensile strength of concrete $= 0.267 \sqrt{40}$

$$= 1.7 \text{N/mm}^2$$

$$\text{Cracking load} = 1000 \times 200 \left(\frac{0.75 \times 9.4 + 1.7}{1000} \right)$$

$$= 1760 \text{Kn}$$

F.S against cracking = 1760 / 720 = 2.45

Nominal reinft. 0.2 percent circumferential & longitudinal directions

8mm ϕ @ 300mm spacing on both faces at a cover of 20mm.

A cylindrical prestressed concrete water tank of internal diameter 30 m is required to store water over a depth of 7.5 m. The permissible compressive stress in concrete at transfer is 13 N/mm^2 and the minimum compressive stress under working pressure is 1 N/mm^2, the loss ratio is 0.75, Wires of 5 mm dia with an initial stress of 1000 N/mm^2 are available for circumferential winding and freyssinet cables made up of 12 wires of 8 mm dia stressed to 1200 N/mm^2 are to be used for vertical prestressing. Design the tank walls assuming the base as fixed. The cube strength of concrete is 40 N/mm^2. For the thickness of wall is 150 mm.

For the required depth of storage of 7.5 m and diameter 30 m, an average wall thickness of 150 mm is tentatively assumed based on Table 16.1.

$D = 30$ m, $H = 7.5$ m and $t = 150$ mm, $\eta = 0.75$

$$\frac{H^2}{Dt} = \frac{7.5^2}{30 \times 0.15} = 12.5$$

$$w_w = wH = (10 \times 7.5)\ \text{kN/m}^2 = 0.075\ \text{N/mm}^2$$

maximum ring tension $N_d = (0.64 \times 10 \times 7.5 \times 15) = 720$ kN/m $= 720$ N/mm

maximum moments $M_w = (0.01 \times 10 \times 7.5^3) = 42.5$ kN m/m $= 42500$ N mm/mm

Minimum wall thickness

$$t = \frac{N_d}{\eta f_{ct} - f_{min.w}} = \frac{720}{(0.75 \times 13) - (1)} = 82.3\ \text{mm}$$

Net thickness available (allowing for vertical cables of diameter 30 mm) is = $(150 - 30) = 120$ mm

Required circumferential prestress is,

$$f_c = \frac{N_d}{\eta t} + \frac{f_{min.w}}{\eta}$$

$$f_c = \frac{720}{0.75 \times 120} + \frac{1}{0.75} = 9.4\ \text{N/mm}^2$$

Spacings of circumferential wire winding at base is,

$$s = \frac{2N_d}{w_w}\frac{f_s A_s}{f_c D t} = \frac{2 \times 720}{0.075} \times \frac{1000 \times 20}{9.4 \times 30 \times 10^3 \times 120} = 11.4\ \text{mm}$$

Number of wires/metre = 87

Ring tension N_d at 0.1 H(0.75 m) from top is

$$N_d = (0.097 \times 10 \times 7.5 \times 15) = 109 \text{ kN/m} = 109 \text{ N/mm}$$

$$f_c = \frac{109}{0.75 \times 120} + \frac{1}{0.75} = 2.5 \text{ N/mm}^2$$

$$s = \frac{2 \times 109}{0.075} \times \frac{1000 \times 20}{2.5 \times 30 \times 10^3 \times 120} = 64 \text{ mm}$$

Number of wires/metre at the top of tank = 16

Maximum radial pressure due to prestress is,

$$w_s = \frac{2 f_s A_s}{sD} = \frac{2 \times 1000 \times 20}{11.4 \times 30 \times 10^3} = 0.117 \text{ N/mm}^2$$

Maximum vertical moment due to prestress is,

$$M_s = M_w \left(\frac{w_s}{w_w}\right) = 42500\left(\frac{0.117}{0.075}\right) = 67{,}000 \text{ N mm/mm}$$

$$= 67 \times 10^6 \text{ Nmm/m}$$

Considering one metre length of tank along the circumference, the section modulus is,

$$Z = \frac{1000 \times 150^2}{6} = 375 \times 10 \text{ mm}^3$$

Vertical prestress required is,

$$f_c = \frac{f_{min.w}}{\eta} + \frac{M_s}{Z} = \frac{1}{0.75} + \frac{67 \times 10^6}{375 \times 10^4} = 19.2 \text{ N/mm}^2$$

Since this stress exceeds the permissible value of $f_{ct} = 13$ N/mm^2, the thickness of the tank wall at base is increased to 200 mm. Thus,

$$Z = \frac{1000 \times 200^2}{6} = 666 \times 10^4 \text{ mm}^3$$

$$f_c = \frac{1}{0.75} + \frac{67 \times 10^6}{666 \times 10^4} = 12 \text{ N/mm}^2$$

Vertical prestressing force = $f_c A = \frac{(12 \times 1000 \times 200)}{(1000)} = 2400$ kN

Using 8 mm diameter (12 nos.) Freyssinet cables

$$\text{Force/cable} = \frac{(50 \times 12 \times 1200)}{(1000)} = 720 \text{ kN}$$

$$\therefore \quad \text{Spacings of vertical cables} = \frac{1000 \times 720}{2400} = 300 \text{ mm}$$

The approximate vertical prestress required to counteract winding stresses as per IS code is

$$= 0.3 f_c = (0.3 \times 9.4) = 2.82 \text{ N/mm}^2$$

$$\text{Vertical prestressing force required} = \frac{(2.82 \times 1000 \times 200)}{(1000)} = 564 \text{ kN}$$

$$\text{Ultimate tensile force in wires at base of tank} = \frac{(87 \times 20 \times 1500)}{(1000)} = 2610 \text{ kN}$$

$$\text{Load factor against collapse} = \frac{(2610)}{(720)} = 3.6$$

$$\text{Direct tensile strength of conerete} = 0.267\sqrt{40} = 1.7 \text{ N/mm}^2$$

$$\text{Cracking load} = (1000 \times 200)\frac{(0.75 \times 9.4 + 1.7)}{(1000)} = 1760 \text{ kN}$$

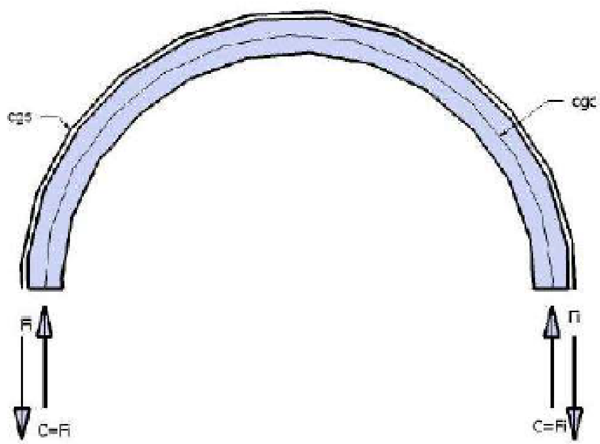
$$\therefore \quad \text{Factor of safety against cracking} = \frac{(1760)}{(720)} = 2.45$$

Circular pre-stressing

Circumferential pre-stress

Circumferential pre-stressing is done to resist hoop tension in circular structures, like water-tanks and pipes. Essentially each horizontal slice of the wall forma a ring subjected to uniform internal pressure. This ring may be considered as a pre-stresses concrete member under tension.

Considering one half of a thin cylindrical slice of a tank as a free-body: under the action of pre-stress F_i in steel, the total compression C in the concrete equals F_i. The C-line coincides with the cgs line, which is a concordant cable linearly transformed.

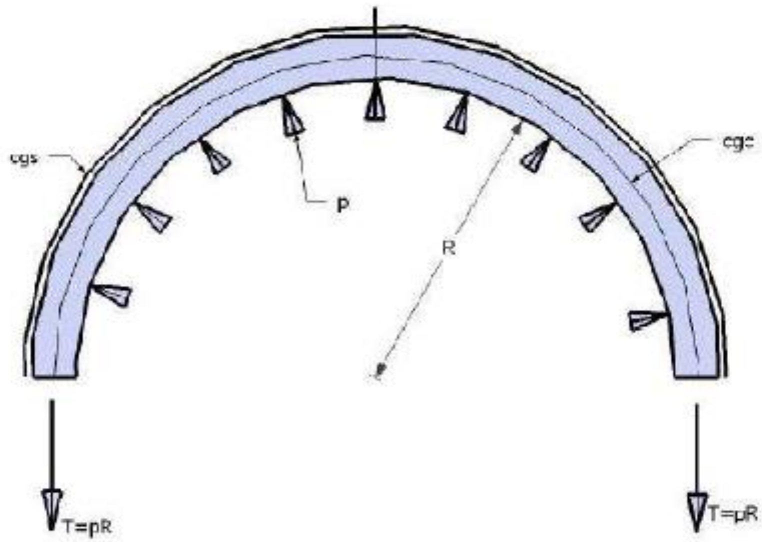


Due to pre-stress, initially after transfer of pre-stress,

$$f_c = -\frac{F_i}{A_c},$$ A_c = Area of concrete

which after losses in pre-stress reduces to

$$f_c = -\frac{F_e}{A_c}$$



When internal liquid pressure is acting at working load stage, the internal pressure intensity,

$$f_c = \frac{pR}{A_T}$$ where

p = internal pressure intensity

R = internal radius of the vessel

A_T = transformed area = $A_c + nA_p$

A_p = area of steel

The resultant stress in concrete at working load due to internal pressure 'p' and pre-stress F_e is

$$f_c = -\frac{F_e}{A_c} + \frac{pR}{A_T} \; \Lambda(1)$$

In Eq.1, if it is assumed that hoop tension is entirely carried by the effective pre-stress, $F_e = pR$.

And since $A_t \rangle A_c$, f_c is always negative, implying that there is always a residual compressive stress in concrete.

Design method 1

A_p = area of steel

A_c = area of concrete

f_{ct} = permissible stress at transfer in concrete

f_{cw} = permissible stress at working load in concrete

F_i = initial pre-stress

F_e = effective pre-stress after losses

m = factor of safety

$$n = \frac{E_s}{E_c}$$

$$F_i = A_p f_i$$

$$F_e = A_p f_e$$

At transfer

$$A_c = -\frac{F_i}{f_{ct}} \Lambda(2)$$

At working load

$$-\frac{F_e}{A_c} + \frac{pR}{A_T} = f_{cw} \Lambda(3) \text{ where } A_t = A_c + nA_p$$

Assuming that hoop tension is entirely carried by the effective pre-stress, $F_e = pR$,

$$A_p = \frac{pR}{f_e}$$

$$F_i = A_p f_i$$

$$A_c = -\frac{F_i}{f_{ct}} \text{ from Eq.2}$$

$$f_{cw} = -\frac{F_e}{A_c} + \frac{pR}{A_T} \text{ from Eq.3}$$

Design method 2

If both f_{ct} and f_{cw} are to be kept in concrete, which may be the case when a tensile stress f_{cw} = cracking stress, may be allowed, and if a factor of safety 'm' is required, then Eq.2 and Eq.3 can be combined together into the following from.

A_p = area of steel

A_c = area of concrete

f_{ct} = permissible stress at transfer in concrete

f_{cw} = permissible stress at working load in concrete

F_i = initial pre-stress

F_e = effective pre-stress after losses

m = factor of safety

$$n = \frac{E_s}{E_c}$$

$$F_i = A_p f_i$$

$$F_e = A_p f_e$$

At transfer

$$A_c = -\frac{F_i}{f_{ct}} = -\frac{f_i A_p}{f_{ct}}$$

$$A_t = A_c + nA_p = A_p\left(n - \frac{f_i}{f_{ct}}\right)$$

At working load

$$-\frac{F_e}{A_c} + \frac{mpR}{A_T} = f_{cw}$$

$$-\frac{f_e A_p}{-A_p \dfrac{f_i}{f_{ct}}} + \frac{mpR}{A_p\left(n - \dfrac{f_i}{f_{ct}}\right)} = f_{cw}$$

$$A_p\left(f_{ct}\frac{f_e}{f_i}-f_{cw}\right)=-\frac{mpR}{nf_{ct}-f_i}f_{ct}$$

$$A_p\left(\frac{f_e f_{ct}-f_i f_{cw}}{f_i}\right)=-\frac{mpR}{nf_{ct}-f_i}f_{ct}$$

$$\begin{aligned}A_p&=-\frac{mpR}{(nf_{ct}-f_i)(f_e f_{ct}-f_i f_{cw})}f_{ct}f_i\\&=-\frac{mpR}{f_i\left(n\frac{f_{ct}}{f_i}-1\right)f_{ct}\left(f_e-f_i\frac{f_{cw}}{f_{ct}}\right)}f_{ct}f_i\\&=\frac{mpR}{\left(f_e-f_i\frac{f_{cw}}{f_{ct}}\right)\left(1-n\frac{f_{ct}}{f_i}\right)}\end{aligned}$$

Design of pipes

Pre-stressed concrete pipes are suitable when the internal pressure is within 0.5 to 2.0

Mpa. There are two types of pre-stressed concrete pipes:

1. Cylinder type which has a steel cylinder core, over which the concrete is cast and pre-stressed.
2. Non-cylinder type which is made of pre-stressed concrete only.

IS:784-2001 Pre-stressed Concrete Pipes (Including Specials), provides guidelines for the design of pre-stressed concrete pipes with the internal diameter ranging from 200 mm to 2500 mm. The pipes are designed to withstand the combined effect of internal pressure and external loads. The minimum grade of concrete in the core should be M40 for non-cylinder type pipes.

The pipes are manufactured either by,

1. Centrifugal method: In the centrifugal method the mould is subjected to spinning till the concrete is compacted to a uniform thickness throughout the length of the pipe.
2. Vertical casting method: In the vertical casting method, concrete is poured in layers up to a specified height.

After adequate curing of concrete, first the longitudinal wires are pre-stressed. Subsequently, the circumferential pre-stressing is done by the wire wound around the core in a helical form. The wire is wound using a counter weight or a die. Finally a coat of concrete or rich cement mortar is applied over the wire to prevent from corrosion. For cylinder type pipes, first the steel cylinder is fabricated and tested. Then the concrete is cast around it.

Example 1 – non-cylinder

Design a non-cylinder pre-stressed pipe for the following specifications: R = 300 mm, p = 1.05 MPa, f_i = 1000 MPa, f_e = 800 MPa, f_{ct} = -14 MPa, f_{cw} =-0.7 MPa, $E_s = 2.1\times10^5$ MPa, $E_c = 0.35 \times 10^5$ MPa and 2.5 mm wires are used. And what would be the internal pressure 'p' required to balance the pre-stress at transfer before losses to maintain a stress of -0.7 in concrete?

Method 1:

Assuming that hoop tension is entirely carried by the effective pre-stress, $F_e = pR$,

$$A_p = \frac{pR}{f_e}$$

$$A_p = \frac{1.05\times10^3\times300}{800} = 394 \text{ mm}^2$$

$$F_i = A_p f_i$$

$$F_i = 394\times1000 = 394 \text{ kN}$$

$$A_c = -\frac{F_i}{f_{ct}}$$

$$A_c = \frac{394\times10^3}{14} = 28143 \text{ mm}^2$$

Taking a 1000 mm height of the pipe

$$t = \frac{28142}{1000} = 29 \text{ mm}$$

$$\approx 30 \text{ mm}$$

$$A_c = 30\times1000 = 30000 \text{ mm}^2$$

Checking for final stress

$$A_t = A_c + nA_p$$

$$A_t = 30000 + 6\times394 = 32364 \text{ mm}^2$$

$$f_{cw} = -\frac{F_e}{A_c} + \frac{pR}{A_T}$$

$$f_{cw} = -\frac{394 \times 800}{30000} + \frac{1.05 \times 10^3 \times 300}{32364} = -0.77 \text{ MPa}$$

Since f_{cw} is slightly more than specified -0.7 MPa, another trail could be made in the design.

$$A_w = \frac{\pi \times 2.5^2}{4} = 4.91 \text{ mm}^2$$

No of wires $= \frac{A_p}{A_w}$

$$= \frac{394}{4.91} \approx 81 \text{ wires}$$

Spacing $= \frac{1000}{81}$ = 12 mm

Method 2:

$$A_p = \frac{mpR}{\left(f_e - f_i \frac{f_{cw}}{f_{ct}}\right)\left(1 - n\frac{f_{ct}}{f_i}\right)}$$

$$A_p = \frac{1.05 \times 10^3 \times 300}{\left(800 - 1000\frac{-0.7}{-14}\right)\left(1 - 6\frac{-14}{1000}\right)} = 388 \text{ mm}^2$$

$$F_i = 388 \times 1000 = 388 \text{ kN}$$

$$A_c = \frac{388 \times 10^3}{14} = 27715 \text{ mm}^2$$

$$t = \frac{27715}{1000} = 28 \text{ mm}$$

$$A_c = 28 \times 1000 = 30000 \text{ mm}^2$$

Checking for final stress

A_t $= 28000 + 6\times388$ = 30328 mm^2

f_{cw} $= -\dfrac{388\times800}{28000} + \dfrac{1.05\times10^3\times300}{30328}$ = -0.70 MPa

At transfer before losses,

f_{cw} $= -\dfrac{388\times1000}{28000} + \dfrac{p\times10^3\times300}{30328}$ = -0.7 MPa

p = 1.33 MPa

Example 2 – non-cylinder

Design a non-cylinder pre-stressed pipe for the following specifications: R = 800 mm, p = 1 MPa, f_i = 1000 MPa, f_e = 800 MPa, f_{ct} = -12 MPa, f_{cw} = 0, E_s = 2.1x10^5 MPa, E_c = 0.35 x 10^5 MPa and 5 mm wires are used. If cracking stress is +2 MPa, what is the F.S against cracking?

$$A_p = \frac{mpR}{\left(f_e - f_i\dfrac{f_{cw}}{f_{ct}}\right)\left(1 - n\dfrac{f_{ct}}{f_i}\right)}$$

A_p $= \dfrac{1\times10^3\times800}{\left(800-1000\dfrac{-0}{-12}\right)\left(1-6\dfrac{-12}{1000}\right)}$ = 933 mm^2

F_i $= 933\times1000$ = 933 kN

A_c $= \dfrac{933\times10^3}{12}$ = 77750 mm^2

t $= \dfrac{77750}{1000}$ = 78 mm

Checking for stresses

A_c $= 78\times1000$ = 78000 mm^2

A_t $= 78000 + 6\times933$ = 83598 mm^2

$$f_{cw} = -\frac{933\times800}{78000}+\frac{1\times10^3\times800}{83598} = 0$$

If cracking stress is allowed, f_{cw} = 2 MPa

$$A_p = \frac{mpR}{\left(f_e - f_i\frac{f_{cw}}{f_{ct}}\right)\left(1-n\frac{f_{ct}}{f_i}\right)}$$

$$933 = \frac{m\times1\times10^3\times800}{\left(800-1000\frac{2}{-12}\right)\left(1-6\frac{-12}{1000}\right)}$$

$$m = 1.2$$

Design of circular water tanks

Concrete liquid retaining structures must be impervious. Hence, their design is based on no in cracking in concrete. Circular pre-stressed liquid retaining structures, are stressed to avoid tension in concrete.

Pre-stressed concrete liquid retaining structures require low maintenance and resist seismic forces satisfactory.

Circular pre-stressed concrete tanks are used in water treatment, water distribution, storm water management, large industrial tanks, bulk storage tanks and for storing liquefied natural gas (LNG). The construction of the circular tanks is in the following sequence. First, the concrete core is cast and cured. The surface is prepared by sand or hydro blasting. Next, the

circumferential pre-stressing is applied by strand wrapping machine. Shotcrete is

applied to provide a coat of concrete over the pre-stressing strands.

IS:3370-1967 (1-4) Code of Practice for Concrete Structures for the Storage of Liquids provides guidelines for the analysis and design of liquid storage tanks. The four sections of the code are titled as follows:

Part 1: General Requirement.

Part 2: Reinforced Concrete Structures.

Part 3: Pre-stressed Concrete Structures.

In IS:3370-1967 (3), the design requirements for pre-stressed tanks are mentioned. A few of them are:

1. The computed stress in the concrete and steel, during transfer, handling and construction, and under working loads, should be within the permissible values as specified in IS:1343-1980.
2. The liquid retaining face should be checked against cracking with a load factor of 1.2.
3. The ultimate load at failure should not be less than twice the working load.
4. When the tank is full, there should be compression in the concrete at all points of at least 0.7 N/mm2. When the tank is empty, there should not be tensile stress greater than 1.0 N/mm2. Thus, the tank should be analyzed both for the full and empty conditions.
5. There should be provisions to allow for elastic distortion of the structure during pre-stressing. Any restraint that may lead to the reduction of the pre-stressing force should be considered.
6. The cover requirement is as follows. The minimum cover to the pre-stressing wires should be 35 mm on the liquid face. For faces away from the liquid, the cover requirements are as per IS:1343-1980.

The general equations from Eq 1 to Eq 3, would serve well for the design of circular pre-stressed liquid retaining structure.

Example 1

Determine the area of steel required per meter height of a circular pre-stressed water tank with an inside diameter of 18 m and a height of 6 m water pressure. Compute the thickness of concrete required.

f_i = 1034 MPa, f_e = 827 MPa, f_{ct} = -5.17, MPa and n = 10.

Design for the following two cases:

1. Assume that the entire hoop-tension is carried by the effective pre-stress.
2. For a load factor of 1.25, producing zero stress in concrete. f_{ct} = -5.17, f_{cw} =0.

<u>Case 1</u>:

$$p = \frac{(6\times10)\times1000}{10^6} \text{ (on an area of 1m x 1m)} = 0.06 \text{ MPa}$$

Assuming that hoop tension is entirely carried by the effective pre-stress, $F_e = pR$,

$$A_p = \frac{pR}{f_e}$$

$$A_p = \frac{0.06\times10^3\times9000}{827} = 653\ \text{mm}^2$$

$$F_i = A_p f_i$$

$$F_i = 653\times1034 = 675\ \text{kN}$$

$$A_c = -\frac{F_i}{f_{ct}}$$

$$A_c = \frac{675\times10^3}{5.17} = 130600\ \text{mm}^2$$

Taking a 1000 mm height of the pipe

$$t = \frac{130600}{1000} = 130.60\ \text{mm}$$

$$\approx 140\ \text{mm}$$

$$A_c = 140\times1000 = 140000\ \text{mm}^2$$

Checking for final stress

$$A_t = A_c + nA_p$$

$$A_t = 140000 + 10\times653 = 146530\ \text{mm}^2$$

$$f_{cw} = -\frac{F_e}{A_c} + \frac{pR}{A_T}$$

$$f_{cw} = -\frac{653\times827}{140000} + \frac{0.06\times10^3\times9000}{146530} = -0.172\ \text{MPa}$$

Case 2:

$$A_p = \frac{mpR}{\left(f_e - f_i\frac{f_{cw}}{f_{ct}}\right)\left(1 - n\frac{f_{ct}}{f_i}\right)}$$

A_p = $\dfrac{1.25\times0.06\times10^3\times9000}{\left(827-1034\dfrac{0}{-5.17}\right)\left(1-10\dfrac{-5.17}{1034}\right)}$ = 778 mm^2

F_i = 778×1034 = 805 kN

A_c = $\dfrac{805\times10^3}{5.17}$ = 156 $x10^3$ mm^2

t = $\dfrac{156\times10^3}{1000}$ = 156 mm

$\approx$ 165 mm

A_c = 165×1000 = 165000 mm^2

Checking for final stress

A_t = $165000+10\times778$ = 172780 mm^2

f_{cw} = $-\dfrac{778\times827}{165000}+\dfrac{0.06\times10^3\times9000}{172780}$ = -0.77 MPa

If we had provided the actual

Design of cylinder pipe

- The design principles, in general , follow the design of non-cylinder pipe, and the thickness of concrete is found out by using equivalent area of concrete of light gauge steel cylinder.
- The thickness of concrete wall can be known by

$$t = \frac{T}{\eta f_{ct} - f_{\min}} - \alpha_e t_s$$

- The prestress required in concrete at transfer is given as follows

$$f_c = \frac{T}{\eta\left(t + \alpha_e t_s\right)} + \frac{f_{\min}}{\eta}$$

- The number of turns of wire per meter length of pipe is as follows

$$n = \frac{4000\left(t + \alpha_e t_s\right) f_s}{\pi d^2 f_s}$$

- In cylinder pipe, the failure occurs due to the yielding of the steel cylinder and followed by excessive elongation or fracture of hard drawn wires. The bursting fluid pressure is estimated as follows:

$$P_u = \frac{0.00157 d^2 n f_{pu} + 2 t_s f_y}{D}$$

Where

D = diameter of the pipe

ts = thickness of the cylinder

f_{ct} *= permissible compressive stress in concrete*

$f_{min,w}$ *= allowable tensile stress*

a_e *=* (E_S/E_C)*= Modular ratio*

P_u = Bursting pressure in N/mm²

d= diameter of wire winding in mm.

f_{pu}, f_y= ultimate and yield stress of prestressing steel

Design procedure of circular tanks

The procedure to be followed and the salient design equations for the computations of the minimum wall thickness, circumferential prestress, spacing of wires and vertical prestress required are as follows:

1. Estimate the maximum ring tension, N_d, and bending moment, M_w, in the walls of the tank using the IS code Tables 16.2 to 16.5.

2. Minimum wall thickness = $\dfrac{N_d}{\eta f_{ct} - f_{min.w}}$

   The thickness of the wall provided should be such tbat a minimum cover of 35 mm is available to the vertical prestressing cables. In practice, the walls are seldom less than 120 mm thick to ensure proper compaction of concrete.

3. The circumferential prestress required is given by

$$f_c = \frac{N_d}{\eta t} + \frac{f_{min.w}}{\eta} \text{ N/mm}^2$$

4. The spacing of wires required at any section is obtained by considerations of the hoop tension due to fluid pressure and hoop compression due to the circumferential wire winding, as follows:

   If A_s = cross-sectional area of wire winding, mm^2

   w_t = average radial pressure of wires at transfer at a given section, N/mm^2

   D = diameter of the tank, mm

   s = spacing of wires at the given section, mm

f_s = stress in wires at transfer, N/mm²
t = thickness of the tank wall, mm
f_c = compressive stress in concrete, N/mm²

∴ Hoop compression due to prestressing = $\dfrac{w_t D}{2}$

Equating $\dfrac{w_t D}{2} = \dfrac{f_s A_s}{s}$

∴
$$w_t = \frac{2 f_s A_s}{sD} \tag{16.8}$$

If N_d = hoop tension due to hydrostatic working pressure, w_w
N_t = hoop compression due to radial pressure of wires, w_t

then
$$N_t = N_d\left(\frac{w_t}{w_w}\right) \tag{16.9}$$

also
$$N_t = t f_c$$

From Eqs 16.9 and 16.10, the spacing of the wire winding

$$s = \frac{2N_d}{w_w} \times \frac{f_s A_s}{f_c D t} \text{ mm} \tag{16.10}$$

5. The vertical prestress required to resist the bending moments in the wall due to the circumferential wire winding and hydrostatic pressure as a consequence of end restraint is computed as follows:

If M_t = vertical moment due to the prestress at transfer,

and Mw = vertical moment due to hydrostatic pressure

then $$M_t = M_w\left(\frac{w_t}{w_w}\right)$$

The compressive prestress required in concrete is expressed as

$$f_c = \frac{f_{min.w}}{\eta} + \frac{M_w}{\eta Z}$$

where Z is the section modulus of a unit length of wall about an axis in the tangential direction and passing through the centroid.

When the tank is empty, the prestress required

$$f_c = \frac{f_{min.w}}{\eta} + \frac{M_t}{Z} \tag{16.11}$$

The vertical prestressing force required is given by,

$$P = f_c A_c$$

where A_c is the cross-sectional area of concrete per unit length along the circumference.

According to the Indian standard code, the vertical prestressing force is to be designed for 30 per cent of the hoop compression.

A prestressed cylinder pipe is to be designed using a steel cylinder of 1000 mm internal diameter and thickness 1.6 mm. The cucumferential wire winding consists of a 4 mm high tensile wire, initially tensioned to a stress of 1000 N/mm^2. Ultimate tensile strength of the wire = 1600 N/mm^2. Yield stress of the steel cylinder = 280 N/mm^2. The maximum permissible compressive stress in concrete at transfer is 14 N/mm^2 and no tensile stresses are permitted under working pressure of 0.8 N/mm^2. Determine the thickness of the concrete lining required, the number of turns of circumferential wire winding and the factor of safety against bursting. Assume modular ratio as 6.

$$t > \frac{N_d}{\eta f_{ct} - f_{min.w}} - \alpha_e t_s.$$

$$> \frac{0.8(1000/2)}{0.8 \times 14 - 0} - 6 \times 1.6 > 25.9 \text{ mm}$$

Using 26 mm thick concrete lining,

$$f_c = 14 \text{ N/mm}^2$$

$$n = \frac{4000(26 + 6 \times 1.6)14}{\pi \times 4^2 \times 1000} = 40 \text{ turns/metre}$$

$$\text{Bursting pressure, } p_u = \frac{(0.00157 \times 4^2 \times 40 \times 1600) + (2 \times 1.6 \times 280)}{1000}$$

$$= 2.516 \text{ N/mm}^2$$

$$\text{Factor of safety against bursting} = \frac{\text{bursting pressure}}{\text{working pressure}} = \frac{2.516}{0.08} = 3.14$$

General Considerations

- A PSC pole is essentially a vertical cantilever.
- The bending moment increases from zero at the top to the maximum at the base.
- consequently, the maximum moment of resistance and the maximum cross-sectional area is required at the base.
- Generally rectangular and square cross sections are used in PSC poles.
- The width of the pole is kept constant while the depth is tapered from top to bottom.
- Since the pole is subjected to reversible wind pressure, the prestress has to be uniform over the whole section.
- The eccentricity 'e' is taken as zero. Thus a PSC Pole is an axially prestressed member.
- It may be designed as a fully prestressed member or a partially prestressed member as per IS 1343.

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Thank You