CIRCULAR PRESTRESSING

INTRODUCTION

- 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.

- In these structures, there can be prestressing in the longitudinal direction (parallel to axis) as well. Circular prestressing is also applied in domes, shells and folded plates.

- The circumferential prestressing resists the hoop tension generated due to the internal pressure.

- The prestressing is done by wires or tendons placed spirally, or over sectors of the circumference of the member.

- The wires or tendons lay outside the concrete core. Hence, the centre of the prestressing steel (CGS) is outside the core concrete section.

- The Hoop compression generated is considered to be uniform across the thickness of a thin shell. Hence, the pressure line (or C-line) lies at the centre of the core concrete section (CGC).

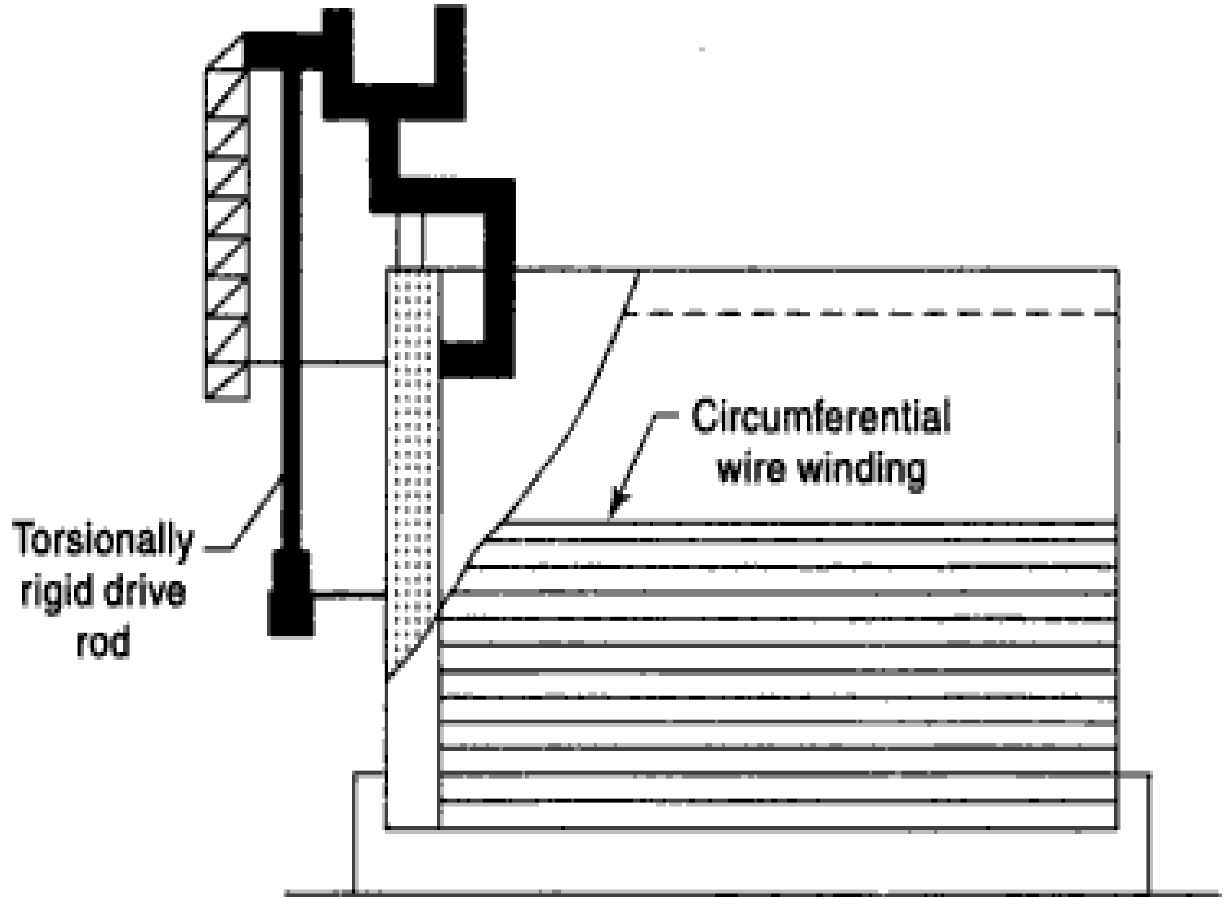


Fig. 16.12 *Wire Winding Machine for Circular Cylindrical Tanks*

Circumferential prestressing

Shotcrete operation

DESIGN OF PRESTRESSED CONCRETE TANKS

16.6.2 Design Procedure for 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/mm^2
t = thickness of the tank wall, mm
f_c = compressive stress in concrete, N/mm^2

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

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

$$\therefore \quad w_t = \frac{2 f_s A_s}{sD}$$

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

also $$N_t = tf_c$$

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

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

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

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

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.

EXAMPLE 16.5 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 diameter 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 diameter 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 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,

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

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

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

Referring to Tables 16.2 and 16.3, the maximum ring tension and moments in tank walls for the fixed base condition are:

$$N_d = (0.64 \times 10 \times 7.5 \times 15) = 720 \text{ kN/m} = 720 \text{ N/mm}$$

$$M_w = (0.01 \times 10 \times 7.5^3) = 42.5 \text{ kN m/m}$$

$$= 42500 \text{ N mm/mm}$$

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

$$(150 - 30) = 120 \text{ mm}$$

Required circumferential prestress is,

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

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

Spacings of circumferential wire winding at base is,

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

$$= 11.4 \text{ mm}$$

$\therefore$ 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,

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

Maximum vertical moment due to prestress is,

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

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

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,

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

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,

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

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

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

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

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

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

$$= 564 \text{ kN}$$

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

$$= 2610 \text{ kN}$$

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

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

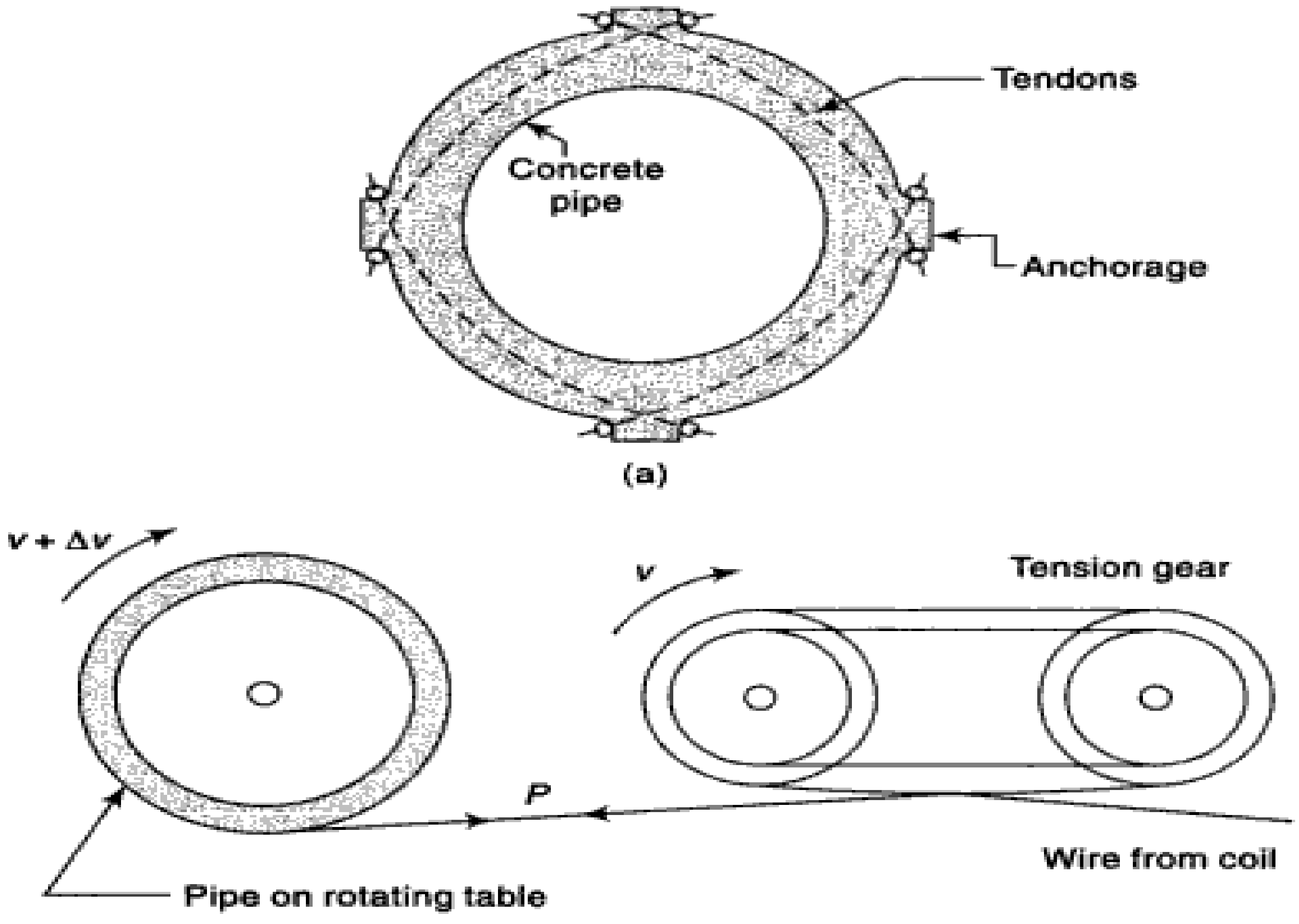
$$\text{Cracking load} = (1000 \times 200)\frac{(0.75 \times 9.4 + 1.7)}{(1000)} = 1760\ \text{kN}$$

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

Nominal reinforcements of 0.2 per cent of the cross-sectional area are to be provided in the circumferential and longitudinal directions. This requirement will be fulfilled by providing 8 mm diameter mild steel bars at 300 mm spacing on both faces at a cover of 20 mm.

PRESTRESSED CONCRETE PIPES

circular prestressing of pipes



Design of non cylinder pipes

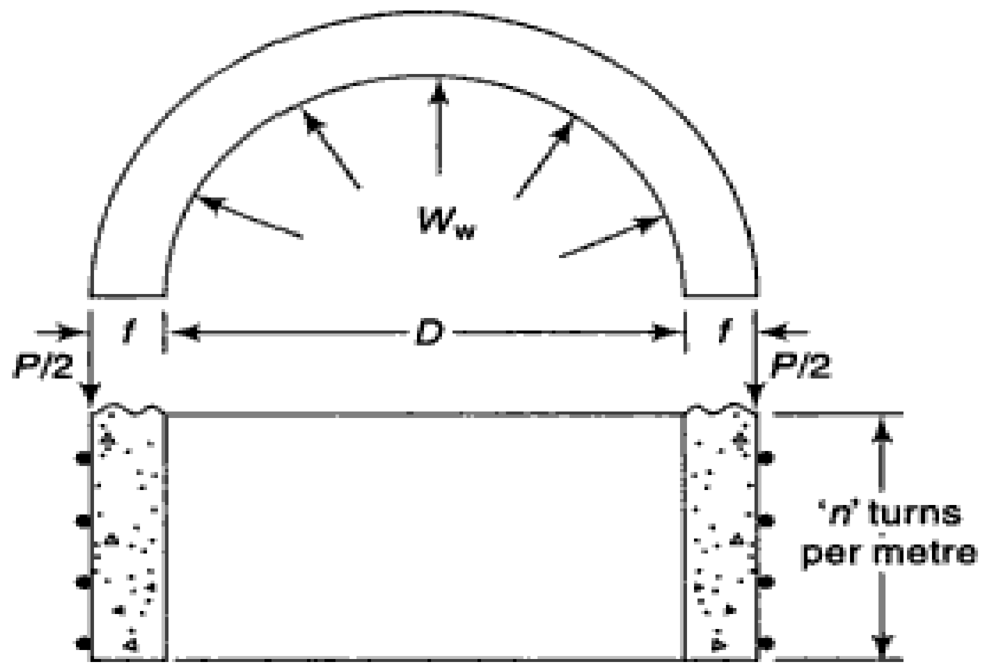


Fig. 16.5 *Circumferential Winding in Prestressed Pipes*

Circumferential Wire Winding The design principles outlined in Sec. 12.2.1 for members subjected to axial tension, is used for determining the minimum thickness of concrete required and the pitch of circumferential wire winding on the pipe.

If N_d = hoop tension developed under working pressure

t = thickness of concrete pipe

D = diameter of the pipe

W_w = hydrostatic pressure

f_{ct} = permissible compressive stress in concrete at transfer

$f_{min,w}$ = permissible stress in concrete under working pressure

then, considering the equilibrium of the pipe shown in Fig. 16.5, we have,

$$\frac{W_w D}{2t} < \eta f_{ct} - f_{min.w}$$

$$\therefore \quad t > \left[\frac{W_w D/2}{\eta f_{ct} - f_{min.w}}\right] > \left[\frac{N_d}{\eta f_{ct} - f_{min.w}}\right] \qquad (16.1)$$

If f_c = actual compressive stress in concrete

then
$$f_c = \frac{N_d}{\eta t} + \frac{f_{min.w}}{\eta} \tag{16.2}$$

At transfer, the prestressing force P per metre length of the pipe is given by,

$$P = 1000 \times 2t \times f_c$$

where t is in mm and f_c is in N/mm^2.

If A_s = cross-sectional area of wire/m length of pipe

f_s = stress in wire at transfer

n = number of turns of circumferential wire winding/m length of pipe

d = diameter of wire

then
$$A_s = \frac{2\pi d^2 n}{4} = \frac{2000 t f_c}{f_s}$$

Since $A_s f_s = P$

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

$$\therefore \quad n = \frac{4000 t f_c}{\pi d^2 f_s} \tag{16.3}$$

Losses of Prestress Due to the elastic deformation of concrete during circumferential wire winding, there is a loss of prestress which depends upon the modular ratio α_e and the reinforcement ratio ρ.

If f_{si} = initial stress in steel

f_{se} = effective stress in steel after winding for compatibility of strains

then
$$\frac{f_{si} - f_{se}}{E_s} = \frac{f_c}{E_c} = \left(\frac{A_s\, f_{se}}{2000t}\right)\frac{1}{E_c}$$

If
$$\frac{A_s}{2000t} = \rho = \frac{f_c}{f_s} \text{ and } \frac{E_s}{E_c} = \alpha_e$$

then
$$f_{si} = (1 + \alpha_e \rho) f_{se} \tag{16.4}$$

Example 16.1 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 $E_s = 210$ 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, ($\eta = 1$)

From Eq. 16.2,

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

$$\therefore \quad W_w = \frac{2t}{D}(f_c - f_{min,w}) = \frac{2 \times 30}{600}[14 - (-0.7)] = 1.47 \text{ N/mm}^2$$

If f_{si} = winding stress in steel,

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

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

$$\therefore \quad f_{si} = (1 + 6 \times 0.014)1000 = 1084 \text{ N/mm}^2$$

EXAMPLE 16.2 A non-cylinder prestressed concrete pipe of 1.6 m diameter with a core thickness of 100 mm is required to withstand a working pressure of 1 N/mm^2. Determine the pitch of a 5 mm-diameter wire winding if the high-tensile initial stress in the wire is limited to 1000 N/mm^2. The permissible maximum and minimum stresses in concrete are 12 N/mm^2 (compression) and zero (tension). The loss ratio is 0.8. If the direct tensile strength of concrete is 2 N/mm^2, estimate the load factor against cracking.

Minimum thickness of pipe required,

$$t > \frac{1.0(1600/2)}{0.8 \times 12 - 0} > 84 \text{ mm}$$

Thickness provided = 100 mm

$$\therefore \qquad f_c = \frac{1 \times 1600}{2 \times 0.8 \times 100} = 10 \text{ N/mm}^2$$

$$\text{No. of wires/m}, n = \frac{4000 \times 100 \times 10}{\pi 5^2 \times 1000} = 51 \text{ turns/m}$$

$$\text{Pitch of winding} = \frac{1000}{51} = 19.6 \text{ mm}$$

Hoop tension due to fluid to pressure = $\frac{1\times1600}{2\times100}$ = 8 N/mm^2

Hoop compression due to prestress = 10 N/mm^2

∴ Resultant compressive stress in concrete = 10 – 8 = 2 N/min^2

Tensile strength of concrete = 2 N/mm^2

Additional fluid pressure required to develop a tensile stress of 4 N/mm^2 in concrete is given by,

$$= \frac{2\times100\times4}{1600} = 0.5\ \text{N/mm}^2$$

∴ Cracking fluid pressure = 1 + 0.5 = 1.5 N/mm^2

Working pressure = 1 N/mm^2

Load factor against cracking = 1.5/1 = 1.5

EXAMPLE 16.3 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.

(a) Design the circumferential wire winding using 5 mm-diameter wires stressed to 1000 N/mm^2.

(b) Design the longitudinal prestressing using 7 mm wires tensioned to 10.00 N/mm^2. The maximum permissible tensile stress under the critical transient loading (wire wrapping at spigot end) should not exceed $0.8\sqrt{f_{ci}}$ where f_{ci} is the cube strength of concrete at transfer = 40 N/mm^2.

$D = 1000$ mm $f_{ct} = 15$ N/mm^2

$W_w = 1.5$ N/mm^2 $f_{min,w} = 2$ N/mm^2

$t = 75$ mm $f_s = 1000$ N/mm^2

$L = 6$ m

(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 $= 0.6 \times$ 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

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

Using 7 mm wires stressed to $1000\ \text{N/mm}^2$,

Force in each wire = 38.5 kN

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

Design of cylindrical pipes

16.3.3 Design of Cylinder Pipes

The design principles of cylinder pipes are similar to those of the non-cylinder pipes, except that the required thickness of concrete is computed by considering the equivalent area of the light gauge steel pipe embedded in the concrete.

If

$$t_s = \text{thickness of steel pipe}$$

$$\alpha_e = \text{modular ratio} = \frac{E_s}{E_c}$$

The thickness of concrete pipe required is given by

$$t = \frac{N_d}{\eta f_{ct} - f_{min.w}} - \alpha_e t_s \qquad (16.5)$$

The prestress required in the concrete at transfer is

$$f_c = \frac{N_d}{\eta(t + \alpha_e t_s)} + \frac{f_{min.w}}{\eta} \qquad (16.6)$$

The number of turns of circumferential wire winding per metre length of pipe is

$$N = \frac{4000(t + \alpha_e t_s) f_c}{\pi d^2 f_s} \qquad (16.7)$$

The bursting fluid pressure is estimated by the expression,

$$P_u = \frac{f_{pu} A_s + f_y A_{cs}}{D}$$

Since $A_{ps} = \frac{\pi d^2}{2} n = 1.57\, d^2 n$ mm²/m

$= 0.00157\, d^2 n$ mm²/mm

and $A_{cs} = 2t_s$

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

where p_u = bursting pressure, N/mm²

d = diameter of wire winding, mm

n = number of turns per metre length of pipe

f_{pu} = tensile strength of wire winding, N/mm²

f_y = yield stress of steel cylinder, N/mm²

t_s = thickness of steel cylinder, mm

D = diameter of steel cylinder, mm

EXAMPLE 16.4 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,

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

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

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

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

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