Concrete Poles
Design & Manufacturing
Presentation 5.2

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ASCE MOP # 123

- Reference documents
  - ASCE- MOP 123, Prestressed Concrete Transmission Pole Structures, Recommended Practice for Design and Installation, American Society of Civil Engineers, Reston, Virginia
Design of Concrete Poles

- Prestressed concrete poles and structures shall be designed to meet or exceed the loading and structural performance requirements.
- The section properties of a pole change when bending forces applied to the cross section cause tensile forces on the face of the pole that exceed the compressive forces exerted on the prestressed steel.
Loading Considerations:

- Typically defined by the customer and should include the following information:
  - Specified loading conditions
  - Foundation behavior
  - Height & geometric configuration
  - Deflections limitations
  - Other limitations such as diameter restrictions and length and weight restrictions
  - Special material requirements affecting pole durability
Design of Concrete Poles

Design Criteria:

Ultimate Strength:

- Ultimate flexural strength of a pole is the point at which the pole will fail, usually by compressive failure of the concrete
- Poles shall be designed for ultimate strength at all sections of the pole to exceed the required strength calculated from the appropriate factored loads applied to the structure

Cracking Strength:

- Poles shall be designed for the cracking strength to exceed the moments calculated from serviceability requirements
Design of Concrete Poles

Design Criteria (Cont.):

First Cracking Strength:
- Pole capacity at which the first circumferential crack will occur
- Moment in the pole causes the tensile strength of the concrete to be exceeded on the tension face of the pole

Crack Reopen Strength:
- Pole capacity at which a crack that was previously created will open again
- An applied moment will not cause any tensile stress in the surfaces of the crack
Design of Concrete Poles

Design Criteria (Cont.):

Zero Tension Strength:

- Pole calculated capacity at which the extreme fiber of the concrete surface is subjected to zero stress due to the applied loads, including prestressing forces
- Control by the physical dimensions of the pole section and the prestress level, but it is not a function of concrete strength

Shear and Torsion:

- High shear and torsion loads can be developed from conductor or guy wire attachments or under broken wire conditions
Design of Concrete Poles

Design Criteria (Cont.):

Prestress Losses:

- Decrease in the prestressing forces with time is referred to as the prestress loss
- Depending upon materials used, 15 to 25 % for total losses are common design assumptions

Development Length:

- Bond development length should be checked to ensure adequate bond capacity when reinforcing steel is cut, such as by drilling holes
Design of Concrete Poles

Design Methodology:

- Ultimate moment capacity of a pole at any given cross section is a function of the strains in the prestressing steel and concrete.
- Factored design moment should not exceed the ultimate moment capacity.

Assumptions for ultimate moment capacity:

- Plane sections remain plane.
- Steel and concrete are adequately bonded.
- Steel and concrete are considered in the elastic and plastic ranges, respectively.
Assumptions for ultimate moment capacity (Cont.):

- Concrete compressive stress at failures is $0.85 f'_c$
- Tensile concrete strength is neglected in flexural computations
- Ultimate concrete strain is 0.003 in
- Conditions of compatibility and equilibrium are met
Design of Concrete Poles

Determination of ultimate moment capacity:

Equilibrium of Section

- Equal forces in the prestressing steel and concrete \( C_c = T_s \)
  
  Where \( C_c \) is the concrete compression and \( T_s \) is the strand tension force

- Concrete Compression: \( C_c = 0.85f'_c A_a \)
  
  Where \( A_a \) is the area of the annulus of the concrete in compression as defined by a rectangular stress block of depth \( \beta_c \).
Design of Concrete Poles

Determination of ultimate moment capacity (Cont.):

Where Parameter $\beta_1$

- $\beta_1 = 0.85 - (0.05) \times \{(f'_c - 4000)/1000\} \geq 0.65$
Design of Concrete Poles

Determination of ultimate moment capacity (Cont.):

- Steel Tension is expressed as

\[ T_s = \sum_{i=1}^{n} A_{psi} f_{sei} \]

Where \( A_{psi} \) and \( f_{sei} \) are the area and stress in the \( i^{th} \) strand, respectively

- Ultimate Moment Capacity Equation

\[ \phi M_n = \sum_{i=1}^{n} e_i A_{psi} f_{sei} + cC_c (1 - K) \]

Where \( e_1 = d_1 - c \) and \( \Phi = \) Capacity reduction factor \( c(1-K) = \) Distance of centroid of concrete area from neutral axis
Design of Concrete Poles

Determination of ultimate moment capacity (Cont.):

Cracking Moment: Cracking starts when the tensile stress in the extreme fiber of the concrete reaches its modulus of rupture

\[ M_{cr} = \frac{f_r I_g}{y_t} + \frac{P I_g}{A_g y_t} \]

Where \( f_r I_g / y_t \) is the resisting moment attributable to the modulus of rupture of concrete \( f_r \)

\[ P I_g / A_g y_t \] is the moment attributable to the direct compression to prestress

Modulus of rupture \( f_r = 7.5 \sqrt{f'_c} \)
Design of Concrete Poles

Determination of ultimate moment capacity:

- Zero Tension Moment:
  \[ M_o = \frac{P l g}{A_g y_t} \]

- Stress Distribution:
Design of Concrete Poles

Shear and Torsion:

- Shear: $V_u \leq \Phi \ V_n$

Where $V_u =$ factored shear force, $\Phi =$ Capacity reduction factor (0.75) and $V_n =$ nominal shear strength

$$V_n = V_c + V_s$$

Where $V_c =$ nominal shear strength provided and $V_s =$ nominal shear strength provided by the shear reinforcement
Design of Concrete Poles

Shear and Torsion (Cont.):

- For Circular Concrete Poles:

  For circular prestressed concrete members:

  $$V_c = \sqrt{\frac{F_t^2 + F_t f_{pc}}{Q}}$$

  where
  - $F_t$ = tensile strength of concrete taken as $4 \sqrt{f'_c}$
  - $f_{pc}$ = effective compressive stress in concrete due to prestress
  - $Q$ = moment of area above centroid
  - $I$ = moment of inertia of cross section
  - $t$ = wall thickness

  For the shear force $V_s$ contributed by the steel:

  $$V_s = \frac{A_v f_y d}{s}$$

  where $A_v$ is the area of the shear reinforcement within a distance $s$, $f_y$ is the yield strength of the steel, and $d$ is the distance from the compression force to the centroid of the prestressing steel, or 0.8 times the outside diameter of the section, whichever is greater.
Shear and Torsion (Cont.):

- **Torsion:** \( T_u \leq \Phi \ T_c \)

Where \( T_u = \) factored Torsional force, \( \Phi = \) Capacity reduction factor (0.75) and \( T_c = \) Torsional resistance of the prestressed concrete member

- **For Circular Concrete Poles:**

For circular cross sections:

\[
T_c = \frac{J}{r_o} \sqrt{F_i^2 + F_t f_{pc}}
\]

where \( J \) is the polar moment of inertia and \( r_o \) is the outside radius of the section.
Design of Concrete Poles

Combined Shear and Torsion:

For members subject to simultaneous flexural shear and torsion, the following interaction equation may be used to represent the strength of the member:

\[
\left(\frac{V_u}{0.75 V_n}\right)^2 + \left(\frac{T_u}{0.75 T_c}\right)^2 = 1.0
\]
Example # 1
Determine if the following applied factors loads can be applied to the given pole section properties:
Factored Torsional Load = 30,000 lbs-ft
Factored Shear Load = 10,000 lbs
Compressive strength of Concrete $f'_c = 10,000$ psi
Spiral Wire dia = 0.1875 in
$f_y = 60000$ psi
Spiral Spacing = 1.25 in
Prestress Strand: # of strands = 16
  Initial prestress force = 17840 lbs
% of prestress loss = 20%
Design of Concrete Poles

Example # 1 (Cont.):
Pole Properties:
OD = 14”, ID = 8”, Wall thick = 3”

Ans:

\[ A_g = \left(\frac{\pi}{4}\right) \times (OD^2 - ID^2) = 104 \text{ in}^2 \]

\[ I_g = \left(\frac{\pi}{64}\right) \times (OD^4 - ID^4) = 1685 \text{ in}^4 \]

Torsional MOI “J” = \( \left(\frac{\pi}{32}\right) \times (OD^4 - ID^4) = 3369 \text{ in}^4 \)

Moment of area above centroid “Q”
= \( \frac{1}{12} \times (OD^3 - ID^3) = 186 \text{ in}^3 \)

\[ A_v \text{ Spiral Area} = 2 \times \left(\frac{\pi}{4}\right) \times (0.1875^2) = 0.0552 \text{ in}^2 \]
Example # 1 (Cont.):
Assume cover to center of spiral wire = 1 in
Distance for spiral wire “d” = OD – 2 x 1 = 12 in

\[ F_t = 4 \sqrt{f'_c} = 400 \text{ psi} \]

\[ f_{pc} = \left\{ \text{(\# of strands) (initial prestress force) (1-% prestress loss)} \right\} / A_g = 16 \times 17840 \times 0.8 / 104 = 2203 \text{ psi} \]

Wall thickness “t” = 3 in
MOI “I” = 1685 in^4
Q = 186 in^3
Design of Concrete Poles

Example # 1

Therefore:

\[ V_c = 55,449 \text{ lbs} \]

\[ A_v = 0.0552 \text{ in}^2 \]

\[ f_y = 60000 \text{ psi} \]

\[ "d" = \text{OD} - 2 \times 1 = 12 \text{ in} \]

\[ s = 1.25 \text{ in} \]

\[ V_s = 31,809 \text{ lbs} \]

For circular prestressed concrete members:

\[ V_c = \frac{\sqrt{F_t^2 + F_t f_{pc}}}{Q / 2It} \]

where

\[ F_t = \text{tensile strength of concrete taken as } 4 \sqrt{f_c'} \]

\[ f_{pc} = \text{effective compressive stress in concrete due to prestress} \]

\[ Q = \text{moment of area above centroid} \]

\[ I = \text{moment of inertia of cross section} \]

\[ t = \text{wall thickness} \]

For the shear force \( V_s \) contributed by the steel:

\[ V_s = \frac{A_v f_y d}{s} \]

where \( A_v \) is the area of the shear reinforcement within a distance \( s \), \( f_y \) is the yield strength of the steel, and \( d \) is the distance from the compression force to the centroid of the pre-stressing steel, or 0.8 times the outside diameter of the section, whichever is greater.
Example # 1
Therefore:
\[ V_n = V_c + V_s = 87,257 \text{ lbs} \]
\[ \Phi = \text{Capacity reduction factor} = 0.75 \]
\[ V_u = 0.75 \times 87,257 = 65,443 \text{ lbs} \]

Torsional Moment:

For circular cross sections:

\[ T_c = \frac{J}{r_o} \sqrt{F_t^2 + F_t f_{pc}} \]

where \( J \) is the polar moment of inertia and \( r_o \) is the outside radius of the section.
Example # 1
Torsional Moment:
\[ J = 3369 \text{ in}^4 \]
\[ r_o = \frac{\text{OD}}{2} = 7 \text{ in} \]
\[ T_c = 491,117 \text{ lbs-in} = 40,926 \text{ lbs-ft} \]
\[ \Phi = \text{Capacity reduction factor} = 0.75 \]
\[ T_c = 0.75 \times 40,926 = 30,695 \text{ lbs-ft} \]
Example # 1

Combined Shear and Torsion:

For members subject to simultaneous flexural shear and torsion, the following interaction equation may be used to represent the strength of the member:

$$\left( \frac{V_t}{0.75 V_n} \right)^2 + \left( \frac{T_t}{0.75 T_c} \right)^2 = 1.0$$

Ratio = \((10000/65443)^2 + (30000/30695)^2 = 0.979 < 1.0\) it is SAFE
Design of Concrete Poles

Example # 2:

- Calculate the cracking moment \( (M_{cr}) \) for the hollow and circular cross section for a spun concrete pole:

  Outside Dia (OD) = 24 in;  Inside Dia (ID) = 18 in

  Compressive strength of Concrete \( f'_c = 10,000 \text{ psi} \)

  Modulus of rupture \( f_r = 7.5 \sqrt{f'_c} \)

  Ultimate compressive strain = 0.003

  (20) -1/2, 7-wire grade 270 k strand

  Initial Prestress = 0.5 \( f_{ui} \); Concrete Cover = \( \frac{3}{4}^\prime \) and

  Total prestress loss = 25%
Design of Concrete Poles

Example # 2 (Cont.):

2'-0" (OD)

1'-6" (ID)

(20) - 1/2" STRANDS

3/4" COVER OVER STRAND

CROSS SECTION VIEW
Design of Concrete Poles

Example # 2 (Cont.):

Ans: Cracking Moment:

\[ M_{cr} = \frac{f_r I_g}{y_t} + \frac{P I_g}{A_g y_t} \]

Where:
- \( f_r \) = modulus of rupture of concrete (psi)
- \( I_g \) = Gross Moment of Inertia (in\(^4\))
- \( y_t \) = Distance from centroid to extreme fiber (in)
- \( P \) = Total effective prestress force (lbs)
- \( A_g \) = Gross Area of the section (in\(^2\))
Design of Concrete Poles

Example # 2 (Cont.):
Ans: Cracking Moment: \[ M_{cr} = \frac{f_r I_g}{y_t} + \frac{P I_g}{A_g y_t} \]
Pole Properties:
OD = 24”, ID = 18”, Wall thick = 3”
\[ A_g = \left(\frac{\pi}{4}\right) \times (OD^2 - ID^2) = 198 \text{ in}^2 \]
\[ I_g = \left(\frac{\pi}{64}\right) \times (OD^4 - ID^4) = 11,133 \text{ in}^4 \]
\[ f_r = 7.5 \times \sqrt{f'_c} = 7.5 \times \sqrt{10000} = 750 \text{ psi} \]
\[ y_t = OD/2 = 12” \]
P = (# of strand) x (initial prestress force) x (Area of strand) x (1- % prestress loss)
Example # 2 (Cont.):

Ans: Cracking Moment:

\[ M_{cr} = \frac{f_{r}I_{g}}{y_{t}} + \frac{P I_{g}}{A_{g}y_{t}} \]

# of strand = 20

Initial Prestress force = \(0.5f_{ui}\)

\[ = 0.5 \times 270,000 = 135,000 \text{ lbs} \]

Area of strand for \(\frac{1}{2}''\) strand (from PCI) = 0.153 in\(^2\)

\[ P = (# \text{ of strand}) \times (\text{initial prestress force}) \times (\text{Area of strand}) \times (1 - \% \text{ prestress loss}) = \]

\[ = 20 \times 135000 \times 0.153 \times (1 - 0.25) = 309,825 \text{ lbs} \]
Example # 2 (Cont.):

Ans: Cracking Moment:

\[
M_{cr} = \frac{f_r}{y_t} + \frac{P}{A_g y_t}
\]

\[
M_{cr} = (750 \times 11133/12) + (309825 \times 11133)/(198 \times 12)
\]

\[
= 2,148,118 \text{ lb-in} = 179 \text{ k-ft}
\]
Manufacturing of Concrete Poles

Spun Concrete Poles:
- To manufacture spun-cast concrete poles, concrete is pumped or placed into a steel consisting of two separable halves equipped with rolling rings. These rings rest on the wheels of a spinning machine that rotates the form at high speeds.
Manufacturing of Concrete Poles

Spun Concrete Poles (Cont.):
Manufacturing Tolerances:
Product tolerances are defined by the customer and mutually agreed upon with manufacturer.
Manufacturing of Concrete Poles

Spun Concrete Poles (Cont.):
Quality Assurance:
Each pole shall be uniquely marked and inspected per the procedures and a detailed written inspection report on record.
Spun Concrete Poles (Cont.):
Concrete Cylinder Tests:
Testing is to be integral part of the total QC program and must follow the manufacturer’s proven Standards, unless otherwise specified
Spun Concrete Poles (Cont.):

Inspection of Concrete poles:

• Certain QC inspections and records of inspections are important to the process review and manufacturing traceability for poles produced

• Rejection criteria should be established and agreed upon prior to the start of any fabrication

• All structures ready for shipment should have complete and proper identification to avoid confusion at the job site

• Pole markings should coincide with the type, length, GLM, weight, and ID # required by the customer and approved on the shop drawings