

American Water Works Association

ANSI/AWWA C304-99

(Revision of ANSI/AWWA C304-92)



AWWA STANDARD
FOR
**DESIGN OF PRESTRESSED
CONCRETE CYLINDER PIPE**

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AMERICAN WATER WORKS ASSOCIATION

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AWWA STANDARD FOR

DESIGN OF PRESTRESSED CONCRETE

CYLINDER PIPE

SECTION 1: GENERAL

Sec. 1.1 Scope

This standard defines the methods to be used in the structural design of buried prestressed concrete cylinder pipe (PCCP) under internal pressure. These methods are provided for the design of pipe subjected to the effects of working, transient, and field-test load and internal pressure combinations.

The design procedures of this standard are applicable to lined-cylinder pipe (LCP) having inside diameters of 16 in. through 60 in. (410 mm through 1,520 mm) and to embedded-cylinder pipe (ECP) having inside diameters of 24 in. (610 mm) and larger.

Sec. 1.2 References

Standard requirements for the manufacture of PCCP are contained in ANSI*/AWWA C301, Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for Water and Other Liquids. Procedures for installation of the pipe are described in AWWA Manual M9, *Concrete Pressure Pipe* (1995).

This standard references the following documents. In their current editions, they form a part of this standard to the extent specified in this standard. In any case of conflict, the requirements of this standard shall prevail.

AASHTO[†] HB-15—*Standard Specifications for Highway Bridges*.

ACI[‡] 209R-92—*Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures*.

* American National Standards Institute, 11 W. 42nd St., New York, NY 10036.

† American Association of State Highway and Transportation Officials, 444 N. Capitol St. N.W., Washington, DC 20001.

‡ American Concrete Institute, P.O. Box 19150, Detroit, MI 48219.

ASTM* A648—Standard Specification for Steel Wire, Hard Drawn for Pre-stressing Concrete Pipe.

ASTM C33—Standard Specification for Concrete Aggregates.

ASTM C39—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C192/C192M—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

ASTM C469—Standard Test for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

ASTM C512—Standard Test Method for Creep of Concrete in Compression.

ANSI/AWWA C301—Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type.

Concrete Pipe Design Manual. American Concrete Pipe Association.[†]

Concrete Pressure Pipe. AWWA Manual M9. AWWA, Denver, Colo. (1995).

FAA[‡] AC150/5320-6C—Airport Pavement Design and Evaluation.

FAA AC150/5325-5C—Aircraft Data.

Manual for Railway Engineering. American Railway Engineering Association, Washington, DC.

Sec. 1.3 Applications

PCCP is used principally in the transmission and distribution of water in municipal, industrial, and irrigation systems. It is also used in plant piping systems, seawater cooling systems, sewer force mains, and gravity sewers. Other applications include inverted siphons, liners for pressure tunnels, and culverts with high earth covers.

Sec. 1.4 Pipe Structure

Two types of PCCP are produced: LCP and ECP. The cross sections and elements of both types of pipe are shown in Figure 1.

PCCP is made up of the following components:

1. A high-strength concrete core acts as the principal structural component of the pipe and provides a smooth inner surface for high fluid flow. The core includes a steel cylinder that functions as a watertight membrane, provides longitudinal tensile strength, and increases circumferential and beam strength. In ECP, the steel cylinder is contained within the core; in LCP, the steel cylinder forms the outer element of the core. Attached to the steel cylinder are steel bell and spigot joint rings that, together with an elastomeric O-ring, provide a watertight and self-centering joint between sections of pipe. Concrete for ECP is vertically cast within steel molds. LCP concrete is centrifugally cast or placed within the steel cylinder by radial compaction.

2. High-tensile steel wire, helically wrapped around the core under controlled tension, produces uniform compressive prestress in the core that offsets tensile stresses from internal pressure and external loads. PCCP can be designed to provide the optimum amount of prestress needed for required operating conditions.

*American Society for Testing and Materials, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959.

[†]American Concrete Pipe Association, 222 West Las Colinas Blvd., Suite 641, Irving, TX 75039.

[‡]Federal Aviation Administration, 800 Independence Ave., S.W., Washington, DC 20591.

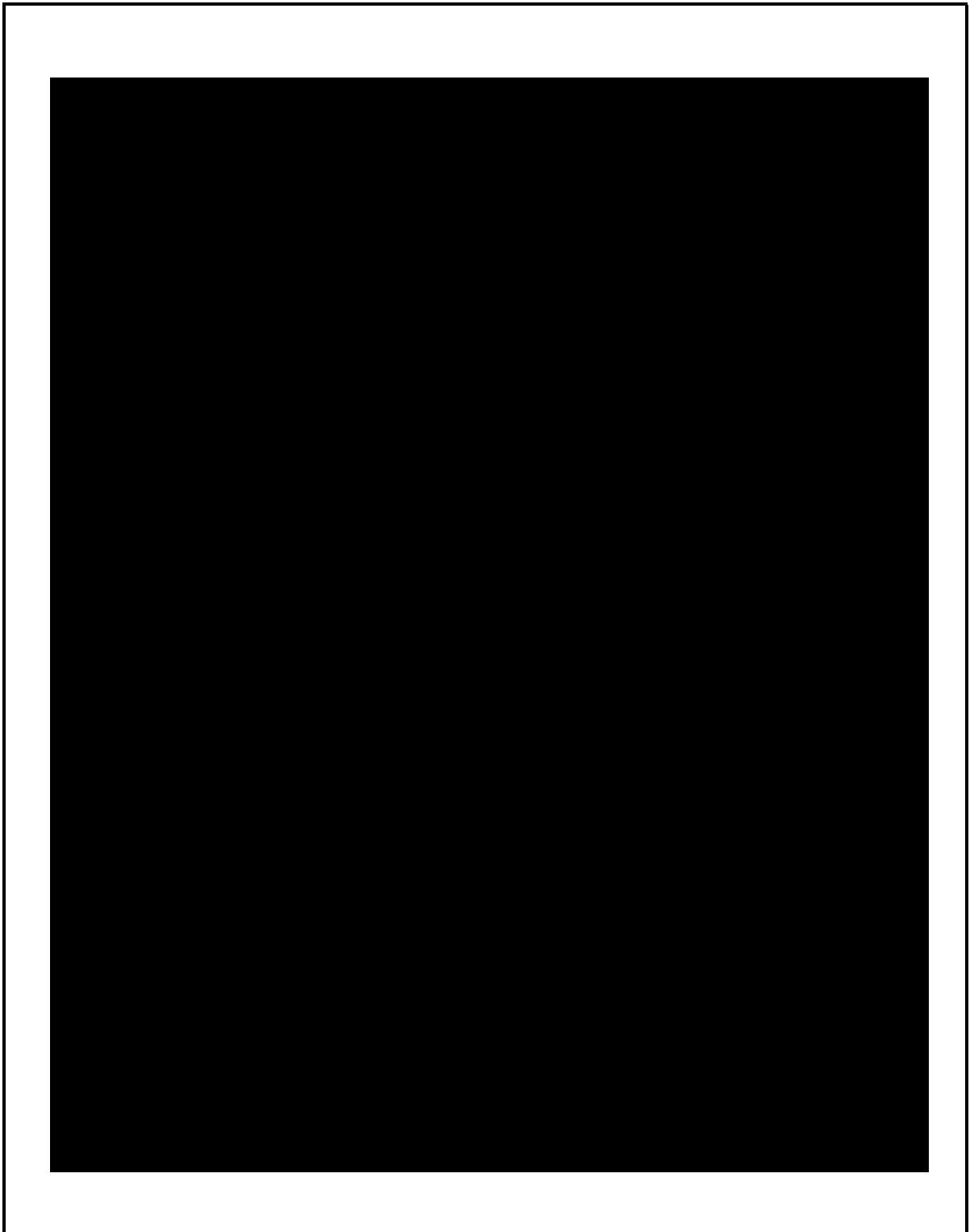


Figure 1 Schematic pipe-wall cross sections for lined- and embedded-cylinder pipe

3. A dense cement–mortar coating encases and protects the wire-wrapped prestressed core from physical damage and external corrosion.

Sec. 1.5 Tolerances

The design procedures of this standard are consistent with the manufacturing tolerances given in ANSI/AWWA C301.

Sec. 1.6 Definitions

1.6.1 *Limit state*: A condition that bounds structural usefulness. The following three types of limit states are considered in the design of PCCP:

1. Serviceability limit states, which ensure performance under service loads.
2. Elastic limit states, which define the onset of material nonlinearity.
3. Strength limit states, which provide safety under extreme loads.

1.6.2 *Limit-states design*: The limit-states design method required definition of all limit states that are relevant to the performance of a particular structure, followed by the design of the structure, so that the probability of not exceeding a limit state is assured.

1.6.3 *Purchaser*: The person, company, or organization that purchases any materials or work to be performed.

Sec. 1.7 Metric (SI) Equivalents

The conversion factors in this section are consistent with those provided in ASTM E380-82, "Standard for Metric Practice." Values of constants and variables are given in both US and SI systems of units throughout the standard. In those instances where direct conversion of units is not possible, equations applicable to both US and SI systems of units are given in this standard.

To convert from	to	Multiply by
Area		
square inches (in. ²)	square metres (m ²)	0.000645
Bending Moment		
pound-force inch (lbf-in.)	newton metre (N·m)	0.112985
Force		
pound-force (lbf)	newton (N)	4.448222
Length		
foot (ft)	metre (m)	0.304800
inch (in.)	metre (m)	0.025400
Weight per Unit Volume		
pound per cubic foot (lb/ft ³)	kilogram per cubic metre (kg/m ³)	16.018
Pressure or Stress		
pounds per square inch (psi) (lbf/in. ²)	pascal (Pa)	6894.757
Steel Area per Unit Length of Pipe		
square inch per foot (in. ² /ft)	square millimetre per metre (mm ² /m)	2116.667
Temperature		
degree Fahrenheit (°F)	degree Celsius (°C)	$T_C = (T_F - 32)/1.8$
Volume		
cubic yard (yd ³)	cubic metre (m ³)	0.764555

SECTION 2: LOADS AND INTERNAL PRESSURES

Sec. 2.1 Notation

D_i	=	inside diameter of pipe (in. [mm])
H	=	height of earth cover over pipe (ft [m])
I_f	=	impact factor
P_{ft}	=	internal field-test pressure (psi [kPa])
P_g	=	internal pressure established by the hydraulic gradient (psi [kPa])
P_s	=	internal pressure established by the static head (psi [kPa])
P_t	=	internal transient pressure (psi [kPa])
P_w	=	internal working pressure (psi [kPa]) = max (P_g , P_s)
W_e	=	external dead load (lb/ft [N/m])
W_f	=	weight of fluid (lb/ft [N/m])
W_p	=	weight of pipe (lb/ft [N/m])
W_s	=	surcharge load (lb/ft [N/m])
W_t	=	transient load (lb/ft [N/m])
γ_c	=	unit weight of concrete (lb/ft ³ [kg/m ³])
γ_m	=	unit weight of mortar (lb/ft ³ [kg/m ³])
γ_s	=	unit weight of steel (lb/ft ³ [kg/m ³])

Sec. 2.2 Design Loads and Internal Pressures

To purchase pipe manufactured according to ANSI/AWWA C301, the purchaser must specify the magnitudes of design loads and internal pressures and the distributions of external loads on the pipe. The types of loads and internal pressures given below are those normally required for the design of buried pressure pipe. The references given for determining various external loads and their distributions are guidelines that define acceptable practice. The purchaser may need to specify additional loads for special conditions not covered by this standard.

Sec. 2.3 Loads

2.3.1 *Working loads.* Pipe shall be designed to include the following working loads of long duration.

2.3.1.1 Pipe weight W_p computed using nominal pipe dimensions and the following material unit weights:

$$\gamma_c = 145 \text{ lb/ft}^3 (2,323 \text{ kg/m}^3)$$

$$\gamma_m = 140 \text{ lb/ft}^3 (2,243 \text{ kg/m}^3)$$

$$\gamma_s = 489 \text{ lb/ft}^3 (7,833 \text{ kg/m}^3)$$

2.3.1.2 Fluid weight, W_f , computed using 62.4 lb/ft³ (1,000 kg/m³) as the unit weight of fresh water. If fluids other than fresh water are to be transported by the pipe, then the actual unit weight of these fluids shall be used.

2.3.1.3 External dead load W_e computed as the sum of earth load and surcharge load if any.

Earth load is computed in accordance with AWWA Manual M9; ACPA's *Concrete Pipe Design Manual*; or AASHTO HB-15, division I, section 17.4; or by recognized and documented analytical procedures based on soil-pipe interaction.

Surcharge load, resulting from the dead load of structures or other surface loads that are not transient loads as defined in Sec. 2.3.2, is computed in accordance with ACPA's *Concrete Pipe Design Manual*.

2.3.2 *Transient loads.* Transient load W_t for which the pipe shall be designed includes the following vertical surface loads of short duration, whenever applicable.

2.3.2.1 Highway live load, computed in accordance with AASHTO HB-15, AWWA Manual M9, and ACPA's *Concrete Pipe Design Manual*. HS20 loading shall be used unless other loading is specified by the purchaser.

2.3.2.2 Railroad live load shall be computed in accordance with AREA *Manual for Railway Engineering* and ACPA *Concrete Pipe Design Manual*. Cooper E-72 loading shall be used unless other loading is specified by the purchaser.

2.3.2.3 Aircraft live load shall be computed using appropriate aircraft wheel loads (see FAA AC150/5325-5C, *Aircraft Data*), in accordance with FAA AC150/5320-6C, *Airport Pavement Design and Evaluation* and ACPA *Concrete Pipe Design Manual*.

2.3.2.4 Construction live load, if specified by the purchaser, shall be computed using the specified load and earth cover in accordance with ACPA *Concrete Pipe Design Manual* procedure for highway live load.

2.3.3 *Impact factor.* Computation of W_t shall include application of appropriate impact factors I_f in accordance with the applicable live load standard, or ACPA *Concrete Pipe Design Manual*.

Sec. 2.4 Internal Pressures

2.4.1 *Internal working pressure.* The internal working pressure P_w for which the pipe shall be designed is:

$$P_w = \max(P_g, P_s) \quad (\text{Eq 2-1})$$

2.4.2 *Internal transient pressure.* Internal transient pressure P_t for which the pipe shall be designed is the internal pressure, in excess of the internal working pressure P_w caused by rapid changes in pipeline flow velocity. The hydraulic design of the pipeline should include an analysis of transient effects. In the absence of a design transient pressure specified by the purchaser, the value of P_t for which the pipe shall be designed is:

$$P_t = \max(0.4P_w, 40 \text{ psi [276 kPa]}) \quad (\text{Eq 2-2})$$

2.4.3 *Internal field-test pressure.* Internal field-test pressure P_{ft} is the test pressure to be applied to the pipe after its installation. In the absence of a field-test pressure specified by the purchaser, the value of P_{ft} for which the pipe shall be designed is:

$$P_{ft} = 1.2P_w \quad (\text{Eq 2-3})$$

SECTION 3: LOAD AND INTERNAL-PRESSURE COMBINATIONS

Sec. 3.1 Notation

f_{cr}	=	final prestress in core concrete (psi [kPa])
FT1, FT2	=	design-factored working-load and field-test pressure combinations
FW1	=	design-factored working-load combination
FWT1–FWT6	=	design-factored working plus transient load and internal-pressure combinations
P_{ft}	=	internal field-test pressure (psi [kPa])
P_g	=	internal pressure caused by the hydraulic gradient (psi [kPa])
P_s	=	internal pressure caused by the static head (psi [kPa])
P_t	=	internal transient pressure (psi [kPa])
P_w	=	internal working pressure (psi [kPa]) = max (P_g , P_s)
W1, W2	=	design working load and internal-pressure combinations
W_e	=	external dead load (lb/ft, [N/m])
W_f	=	weight of fluid (lb/ft [N/m])
W_p	=	weight of pipe (lb/ft [N/m])
W_t	=	transient load (lb/ft [N/m])
WT1–WT3	=	design working plus transient load and internal-pressure combinations
β_1	=	factor equal to 1.1 for ECP and 1.2 for LCP
β_2	=	factor equal to 1.3 for ECP and 1.4 for LCP

Sec. 3.2 Load Factors for Limit-States Design*

The factored load combinations given in this section are based on minimum recommended load factors for use with the limit-states design procedures described in Sec. 8.

Sec. 3.3 Minimum Combined Design Loads and Pressures

1. The minimum combined design load and pressure shall be P_w of 40 psi (276 kPa) in combination with W_e equivalent to 6 ft (1.83 m) of earth cover based on trench loading at transition width, and unit earth weight of 120 lb/ft³ (1922 kg/m³) with 45° Olander bedding for earth load and fluid weight and 15° Olander bedding for pipe weight. $P_t = 0$, and $W_t = 0$.

2. The maximum calculated tensile stress in the pipe wall shall not exceed f_{cr} when the pipe weight alone is supported on a line bearing.

Sec. 3.4 Working Loads and Internal Pressures

Pipe shall be designed for all of the following combinations of working loads and internal pressures:

$$W1: W_e + W_p + W_f + P_w \quad (\text{Eq 3-1})$$

$$W2: W_e + W_p + W_f \quad (\text{Eq 3-2})$$

$$FW1: 1.25 W_e + W_p + W_f \quad (\text{Eq 3-3})$$

*For commentary see appendix A, Sec. A.2.

Sec. 3.5 Working Plus Transient Loads and Internal Pressures

3.5.1* Pipe shall be designed for all of the following combinations of working plus transient loads and internal pressures:

$$\text{WT1: } W_e + W_p + W_f + P_w + P_t \quad (\text{Eq 3-4})$$

$$\text{WT2: } W_e + W_p + W_f + W_t + P_w \quad (\text{Eq 3-5})$$

$$\text{WT3: } W_e + W_p + W_f + W_t \quad (\text{Eq 3-6})$$

$$\text{FWT1: } \beta_1(W_e + W_p + W_f + P_w + P_t) \quad (\text{Eq 3-7})$$

$$\text{FWT2: } \beta_1(W_e + W_p + W_f + W_t + P_w) \quad (\text{Eq 3-8})$$

Where:

$$\beta_1 = 1.1 \text{ for ECP and } 1.2 \text{ for LCP}$$

3.5.2† Pipe shall be designed for the following factored combinations of working plus transient loads and internal pressures:

$$\text{FWT3: } \beta_2(W_e + W_p + W_f + P_w + P_t) \quad (\text{Eq 3-9})$$

$$\text{FWT4: } \beta_2(W_e + W_p + W_f + P_w) \quad (\text{Eq 3-10})$$

$$\text{FWT5: } 1.6(W_e + W_p + W_f) + 2.0 W_t \quad (\text{Eq 3-11})$$

$$\text{FWT6: } 1.6 P_w + 2.0 P_t \quad (\text{Eq 3-12})$$

Where:

$$\beta_2 = 1.3 \text{ for ECP and } 1.4 \text{ for LCP}$$

Sec. 3.6 Working Loads and Internal Field-Test Pressures‡

Pipe shall be designed for the following combinations of working loads and internal field-test pressures:

$$\text{FT1: } 1.1(W_e + W_p + W_f + P_{ft}) \quad (\text{Eq 3-13})$$

$$\text{FT2: } 1.1\beta_1(W_e + W_p + W_f + P_{ft}) \quad (\text{Eq 3-14})$$

Where:

$$\beta_1 = 1.1 \text{ for ECP and } 1.2 \text{ for LCP}$$

Sec. 3.7 Load and Pressure Factors

The load and pressure factors for the various loading conditions are summarized in Table 1 for ECP and in Table 2 for LCP.

*For commentary see appendix A, Sec. A.3.

†For commentary see appendix A, Sec. A.4.

‡For commentary see appendix A, Sec. A.5.

Table 1 Load and pressure factors for embedded-cylinder pipe

Loading Conditions	Load and Pressures						
	W_e	W_p	W_f	W_t	P_w	P_t	P_{ft}
Working load and pressure combinations							
W1	1.0	1.0	1.0	—	1.0	—	—
W2	1.0	1.0	1.0	—	—	—	—
FW1	1.25	1.0	1.0	—	—	—	—
Working plus transient load and pressure combinations							
WT1	1.0	1.0	1.0	—	1.0	1.0	—
WT2	1.0	1.0	1.0	1.0	1.0	—	—
WT3	1.0	1.0	1.0	1.0	—	—	—
FWT1	1.1	1.1	1.1	—	1.1	1.1	—
FWT2	1.1	1.1	1.1	1.1	1.1	—	—
FWT3	1.3	1.3	1.3	—	1.3	1.3	—
FWT4	1.3	1.3	1.3	1.3	1.3	—	—
FWT5	1.6	1.6	1.6	2.0	—	—	—
FWT6	—	—	—	—	1.6	2.0	—
Field-test condition							
FT1	1.1	1.1	1.1	—	—	—	1.1
FT2	1.21	1.21	1.21	—	—	—	1.21

Table 2 Load and pressure factors for lined-cylinder pipe

Loading Conditions	Load and Pressures						
	W_e	W_p	W_f	W_t	P_w	P_t	P_{ft}
Working load and pressure combinations							
W1	1.0	1.0	1.0	—	1.0	—	—
W2	1.0	1.0	1.0	—	—	—	—
Working plus transient load and pressure combinations							
WT1	1.0	1.0	1.0	—	1.0	1.0	—
WT2	1.0	1.0	1.0	1.0	1.0	—	—
WT3	1.0	1.0	1.0	1.0	—	—	—
FWT1	1.2	1.2	1.2	—	1.2	1.2	—
FWT2	1.2	1.2	1.2	1.2	1.2	—	—
FWT3	1.4	1.4	1.4	—	1.4	1.4	—
FWT4	1.4	1.4	1.4	1.4	1.4	—	—
FWT5	1.6	1.6	1.6	2.0	—	—	—
FWT6	—	—	—	—	1.6	2.0	—
Field-test condition							
FT1	1.1	1.1	1.1	—	—	—	1.1
FT2	1.32	1.32	1.32	—	—	—	1.32

SECTION 4: MOMENTS AND THRUSTS

Sec. 4.1 Notation

$C_{m1e}, C_{m1p}, C_{m1f}$	=	moment coefficients at invert resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f
$C_{m2e}, C_{m2p}, C_{m2f}$	=	moment coefficients at springline resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f
$C_{n1e}, C_{n1p}, C_{n1f}$	=	thrust coefficients at invert resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f
$C_{n2e}, C_{n2p}, C_{n2f}$	=	thrust coefficients at springline resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f
D_i	=	inside diameter of pipe (in. [mm])
D_y	=	outside diameter of steel cylinder (in. [mm])
h_c	=	core thickness, including thickness of cylinder (in. [mm])
h_m	=	coating thickness, including wire diameter (in. [mm])
M_1	=	total moment at invert (lbf-in./ft [N-m/m])
M_2	=	total moment at springline (lbf-in./ft [N-m/m])
M_{2r}	=	redistributed moment at springline (lbf-in./ft [N-m/m])
M_{1cap}	=	moment capacity at invert and crown (lbf-in./ft [N-m/m])
N_1	=	total thrust at invert (lbf/ft [N/m])
N_2	=	total thrust at springline (lbf/ft [N/m])
N_o	=	thrust resulting from final prestress (lbf/ft [N/m])
P	=	internal pressure (psi [kPa])
P_o	=	decompression pressure that relieves final prestress in the core concrete (psi [kPa])
$\bar{R}$	=	radius to the centroid of the coated pipe wall (in. [mm])
W_e	=	external dead load (lbf/ft [N/m])
W_f	=	fluid weight (lbf/ft [N/m])
W_p	=	weight of pipe (lbf/ft [N/m])
W_t	=	transient load (lbf/ft [N/m])

Sec. 4.2 Distribution of Loads

The total working and transient loads on the pipe shall be determined using the provisions of Sec. 2. The earth-pressure distribution on the pipe and moments and the thrusts in the wall resulting from the working and transient loads shall be determined from recognized and accepted theories, taking into account the characteristics of installation, such as those given by Olander (1950) and Paris (1921) (see appendix B). The bedding angle for Olander and Paris distributions shall be selected on the basis of design pipe-soil installation. Unless provisions are made to support the pipe weight over a wider width, the bedding angle for pipe weight shall be 15° for installation on soil beddings.

Sign conventions for moments and thrusts in the references cited above may differ. The sign convention for moments and thrusts in this standard is

1. A thrust in the pipe wall is positive when creating tension in the pipe wall and negative when creating compression in the pipe wall.
2. In the vicinity of the crown and invert, a moment is positive when creating tension at the inside surface of the pipe and negative when creating compression at the inside surface of the pipe.

3. In the vicinity of the springline, a moment is positive when creating tension at the outside surface of the pipe and negative when creating compression at the outside surface of the pipe.

Sec. 4.3 Moments and Thrusts

4.3.1 *Prestress thrust.* The thrust at invert, crown, and springline resulting from prestressing is

$$N_o = 6D_y P_o \quad (\text{Eq 4-1})$$

Where:

P_o = the decompression pressure that relieves the final prestress in the core, as defined in Sec. 6.3.3. D_y is in in., and P_o is in psi. The metric equivalent of Eq 4-1, with D_y in mm and P_o in kPa is

$$N_o = \frac{1}{2} D_y P_o$$

4.3.2 *Moments and thrusts from combined loads.** The thrusts and moments resulting from pressure, external loads (earth, surcharge, transient, and construction loads), and the weights of pipe and fluid, for a pipe with uniform wall are

$$M_1 = \bar{R} [C_{m1e}(W_e + W_t) + C_{m1p}W_p + C_{m1f}W_f] \quad (\text{Eq 4-2})$$

$$M_2 = \bar{R} [C_{m2e}(W_e + W_t) + C_{m2p}W_p + C_{m2f}W_f] \quad (\text{Eq 4-3})$$

$$N_1 = 6D_y P - [C_{n1e}(W_e + W_t) + C_{n1p}W_p + C_{n1f}W_f] \quad (\text{Eq 4-4})$$

$$N_2 = 6D_y P - [C_{n2e}(W_e + W_t) + C_{n2p}W_p + C_{n2f}W_f] \quad (\text{Eq 4-5})$$

Where:

$$\bar{R} = \frac{D_i + h_c + h_m}{2} \quad (\text{Eq 4-6})$$

When D_y is in mm and P is in kPa, substitute $\frac{1}{2} D_y$ for $6D_y$ in Eq 4-4 and 4-5.

The moment and thrust coefficients are obtained from the assumed distribution of earth pressure selected for the design installation.

4.3.3 *Moment redistribution.†* When the moment, M_1 , given by Eq 4-2 is greater than the moment capacity at the invert, M_{1cap} , the moments at the invert and springline, M_1 and M_2 , obtained using Eq 4-2 and 4-3, shall be redistributed as

*For commentary see appendix A, Sec. A.6.

†For commentary see appendix A, Sec. A.7.

described in this section. M_{1cap} for ECP is the M_1 -moment limit at the invert corresponding to the steel-cylinder stress reaching a limiting value and is computed according to the procedure in Sec. 7.4.2 and 8.9.1. M_{1cap} for LCP is the M_1 -moment limit at the invert corresponding to the coating strain reaching the compressive strain limit after cracking of the core and is computed according to the procedure in Sec. 8.9.4. For loads exceeding the limiting load that produces M_{1cap} at the invert, the redistributed moment at the springline M_{2r} is

$$M_{2r} = M_1 + M_2 - M_{1cap} \quad (\text{Eq 4-7})$$

Where:

M_1 and M_2 are given by Eq 4-2 and 4-3

SECTION 5: DESIGN MATERIAL PROPERTIES

Sec. 5.1 Notation

C_E	=	concrete modulus of elasticity multiplier
C_S	=	concrete shrinkage strain multiplier
C_ϕ	=	concrete creep-factor multiplier
E_c	=	design modulus of elasticity of core concrete (psi)
E_{ct}	=	average modulus of elasticity of test concrete (psi [MPa])
E_m	=	design modulus of elasticity of coating mortar (psi [MPa])
E_s	=	design modulus of elasticity of prestressing wire (psi [MPa])
E_y	=	design modulus of elasticity of steel cylinder (psi [MPa])
f'_c	=	design 28-day compressive strength of core concrete (psi [MPa])
f'_{ci}	=	core concrete compressive strength at wrapping (psi [MPa])
f'_{ct}	=	design compressive strength of test concrete (psi [MPa])
f'_m	=	design 28-day compressive strength of coating mortar (psi [MPa])
f'_{tm}	=	design 28-day tensile strength of coating mortar (psi [MPa])
f'_t	=	design tensile strength of core concrete (psi [MPa])
f_s	=	tensile stress in prestressing wire (psi [MPa])
f_{sg}	=	gross wrapping tensile stress in wire (psi [MPa])
f_{su}	=	specified minimum tensile strength of prestressing wire (psi [MPa])
f_{sy}	=	tensile yield strength of prestressing wire (psi [MPa])
f_{yy}	=	design tensile or compressive yield strength of steel cylinder (psi [MPa])
f_{yy}^*	=	design tensile strength of steel cylinder at pipe burst (psi [MPa])
$s(18,250)$	=	extrapolated shrinkage strain of concrete test specimens at 50 years (18,250 days)
$s_t(n)$	=	shrinkage strain of concrete test specimens on n -th day after loading
ϵ_s	=	strain in prestressing wire
γ_c	=	unit weight of concrete (lb/ft ³ [kg/m ³])
γ_m	=	unit weight of mortar (lb/ft ³ [kg/m ³])
$\phi(18,250)$	=	creep factor at 50 years (18,250 days)

Sec. 5.2 Materials and Manufacturing Standard

The concrete core, mortar coating, steel cylinder, and prestressing wire shall conform to the requirements of ANSI/AWWA C301.

Sec. 5.3 Properties of Core Concrete

The core concrete may be placed by the centrifugal-casting method, by the vertical casting method, or by the radial-compaction method. The concrete placed by the centrifugal method is referred to in this standard as spun concrete and that placed by the vertical casting method as cast concrete. Concrete placed by radial compaction, which has been shown to have strength, shrinkage, and creep properties equivalent to spun concrete, is also considered as spun concrete in this standard.

5.3.1 *Compressive strength of concrete.* The minimum design compressive strength of the core concrete, based on 28-day tests of concrete cylinders in accordance with ANSI/AWWA C301, shall be as follows:

Cast concrete $f'_c = 4,500$ psi (31.0 MPa)

Spun concrete $f'_c = 6,000$ psi (41.4 MPa)

5.3.2 *Minimum compressive strength of concrete at wrapping.* The minimum compressive strength of the core concrete, based on tests of concrete cylinders in accordance with ANSI/AWWA C301, at the time of wrapping shall be as follows:

Cast concrete $f'_{ci} = 3,000$ psi (20.7 MPa)

Spun concrete $f'_{ci} = 4,000$ psi (27.6 MPa)

but not less than 1.8 times the initial prestress in the core (that is, the initial prestress in the core shall not exceed $0.55 f'_{ci}$).

5.3.3 *Tensile strength of concrete.*^{*} The design tensile strength of the core concrete is

$$f'_t = 7 \sqrt{f'_c} \quad (\text{Eq 5-1})$$

Where:

f'_c = design 28-day compressive strength of core concrete in psi

$$f'_t = 0.58 \sqrt{f'_c}$$

Where:

f'_c = design 28-day compressive strength of core concrete in MPa

^{*}For commentary see appendix A, Sec. A.8.

5.3.4 *Modulus of elasticity of concrete.** The design modulus of elasticity of the core concrete is

$$E_c = 158\gamma_c^{1.51}(f'_c)^{0.3} \quad (\text{Eq 5-2})$$

Where:

$$\begin{aligned} \gamma_c &= 145 \text{ lb/ft}^3 \\ f'_c &= \text{design 28-day compressive strength of concrete in psi} \end{aligned}$$

$$E_c = 0.074\gamma_c^{1.51}(f'_c)^{0.3}$$

Where:

$$\begin{aligned} \gamma_c &= 2,323 \text{ kg/m}^3 \\ f'_c &= \text{design 28-day compressive strength of concrete in MPa} \end{aligned}$$

Each factory where PCCP is to be manufactured shall perform a quality-assurance test to determine the modulus of elasticity of the concrete mix with the aggregates and cement to be used in the pipe manufacture. If the measured modulus of elasticity is less than the value computed from Eq 5-2, the design modulus of elasticity shall be modified for all pipe manufactured using these aggregates and cement.

The average modulus of elasticity of concrete produced at the factory shall be determined from tests of at least five molded cylindrical test specimens of concrete meeting the requirements of ANSI/AWWA C301. The test specimens shall be molded and cured in accordance with ASTM C192 and tested in accordance with ASTM C469 at an age of 28 days to determine their modulus of elasticity.

Five companion test specimens shall be molded and cured in accordance with ASTM C192 and tested in accordance with ASTM C39. The mean 28-day compressive strength $\bar{x}$ and the standard deviation s of the sample of five test specimens shall be computed. The design 28-day compressive strength of the test concrete shall be

$$f'_{ct} = \bar{x} - 0.84s \quad (\text{Eq 5-3})$$

For purposes of these tests, f'_{ct} shall range between 4,500 and 6,500 psi (31.0 to 44.8 MPa).

The modulus of elasticity multiplier is

$$C_E = \frac{E_{ct}}{158\gamma_c^{1.51}(f'_{ct})^{0.3}} \quad (\text{Eq 5-4})$$

Where:

$$\begin{aligned} E_{ct} \text{ (psi)} &= \text{the average of the five or more modulus of elasticity test results} \\ \gamma_c &= 145 \text{ lb/ft}^3 \end{aligned}$$

*For commentary see appendix A, Sec. A.9.

$$C_E = \frac{E_{ct}}{0.074\gamma_c^{1.51}(f'_c)^{0.3}}$$

Where:

E_{ct} (MPa) = the average of the five or more modulus of elasticity test results
 γ_c = 2,323 kg/m³

If C_E is less than 0.9 for all pipe manufactured using the aggregates and cement used in the test, the design modulus of elasticity shall be reduced by multiplying the result of Eq 5-2 by C_E , and the modular ratios given in Sec. 6 and 8 shall be increased by dividing them by C_E .

The quality-assurance test to determine modulus of elasticity shall be made annually or whenever the sources of aggregate or cement are changed.

5.3.5 *Stress-strain relationship of concrete.** The design stress-strain relationship of the core concrete is shown in Figure 2A.

5.3.6 *Creep and shrinkage properties of concrete.* Each factory that manufactures PCCP shall perform a quality-assurance test of concrete creep and shrinkage on a mix with the aggregates and cement to be used in the manufacture of pipe (without additives or admixtures). If either the measured concrete creep factor or shrinkage strain is more than the value computed in accordance with ACI 209R-82, the design creep factor and shrinkage strain shall be modified for all pipe manufactured using these aggregates and cement.

The creep and shrinkage-strain properties of concrete produced at the factory shall be determined from tests of at least one set of molded cylindrical test specimens of concrete meeting the requirements of ANSI/AWWA C301. The test specimens shall be molded in accordance with ASTM C192. Each set of test specimens shall include 5 specimens for creep tests, 5 specimens for shrinkage tests, 5 specimens for modulus-of-elasticity tests, and 10 specimens for compressive-strength tests. Each of the specimens shall be cured and stored in accordance with the requirements for "Standard Curing" in Section 6.1 of ASTM C512. Creep specimens shall be tested in accordance with ASTM C512. Compressive strength and modulus of elasticity shall be determined in accordance with ASTM C39 and C469, respectively.

Immediately before loading the creep specimens, the compressive strength of concrete shall be determined by testing five of the strength specimens in accordance with ASTM C39.

Creep-test specimens shall be loaded at 7 days to a compressive stress level ranging from 30 to 40 percent of the compressive strength of the concrete at loading age.

Strain readings of loaded specimens shall be taken immediately before and after loading, 7 days after loading, and 28 days after loading. Shrinkage strains shall be measured at the same times as strain readings of loaded specimens. Additional strain readings may be taken at other times.

The 28-day compressive strength of concrete shall be determined by testing the remaining five strength specimens in accordance with ASTM C39 and averaging their results. The 28-day modulus of elasticity of concrete shall be determined by testing five test specimens in accordance with ASTM C469 and averaging their results.

*For commentary see appendix A, Sec. A.10.

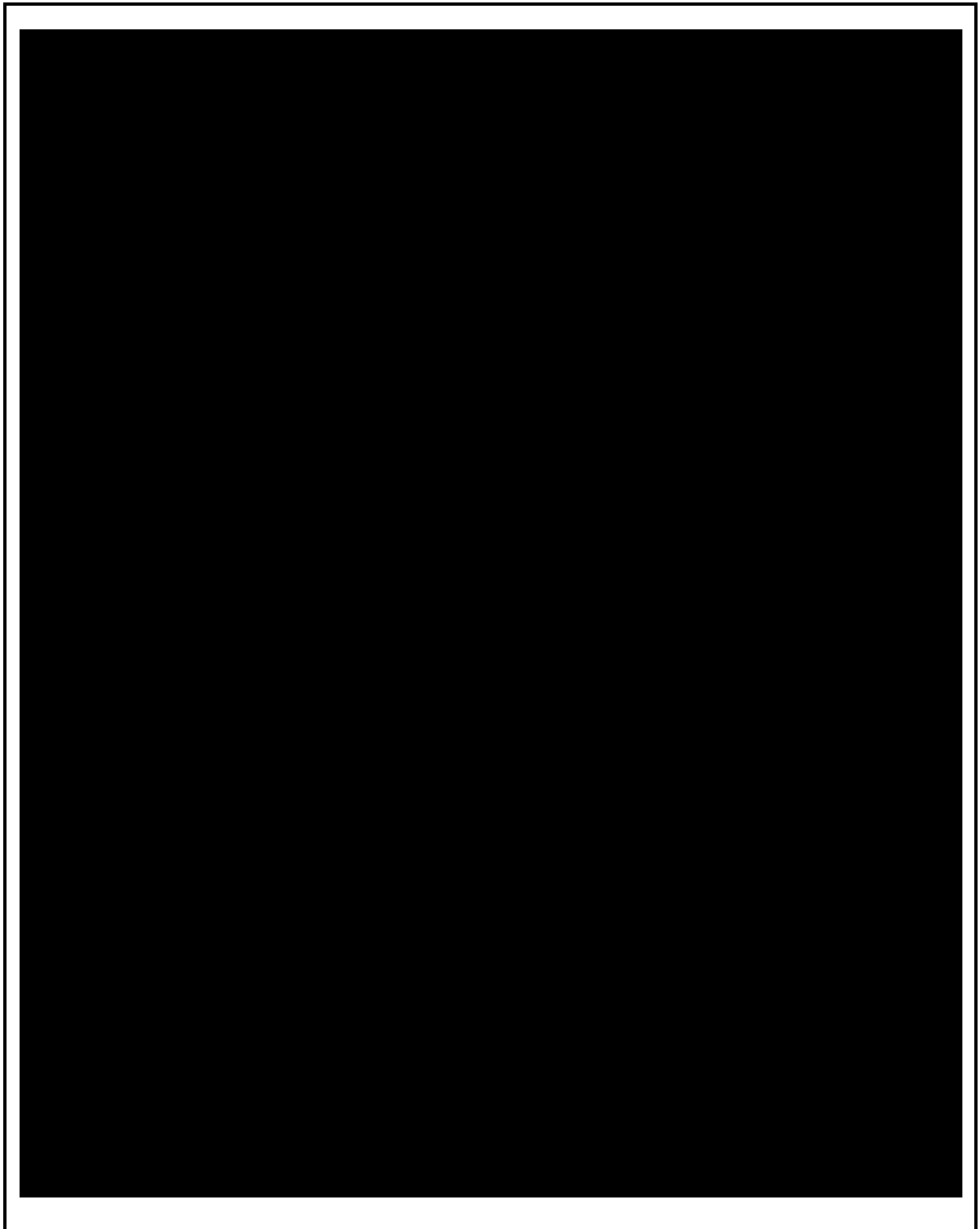


Figure 2 Stress-strain relationships for concrete and mortar in tension and compression

In addition to the items required by ASTM C512 to be included in the report, the following items shall be reported:

1. Shrinkage strains at designated ages ($\mu\text{-in./in.}$ [mm/mm]).
2. Compressive strength at 28 days of age (psi [MPa]).
3. Modulus of elasticity at 28 days of age (psi [MPa]).
4. Cement content of the concrete (lb/yd^3 [kg/m^3]).
5. Water/cement ratio.

The average of five specific creep strains plus the initial elastic strains measured up to 28 days after loading shall be extrapolated using the BP-KX model of drying creep (Bazant, Kim, and Panula [1991, 1992]) or the ACI 209R-92 model of drying creep to compute the specific creep plus instantaneous strain at 50 years. A procedure for the extrapolation is discussed in Ojdrovic and Zarghamee (1996). The resulting creep factor at 50 years is computed by dividing the specific creep strain at 50 years, $\phi(18,250)$ by the specific initial strain.

The concrete creep factor multiplier C_ϕ is the ratio of the creep factor at 50 years to the computed value of the creep factor using ACI 209R-92.

$$C_\phi = \frac{\phi(18,250)}{2.0}$$

If C_ϕ is greater than 1.1, for all pipe to be manufactured using the aggregates and cement used in the test, the design creep factor shall be increased by multiplying the creep factor ϕ given in Eq 6-16 by C_ϕ .

The average of five shrinkage strains measured at 28 days after loading of the creep specimens shall be extrapolated using the BP-KX model of shrinkage (Bazant, Kim, and Panula [1991, 1992]) or the ACI 209R-92 model of shrinkage to compute the shrinkage strain at 50 years, $s(18,250)$. A procedure for the extrapolation is discussed in Ojdrovic and Zarghamee (1996). The concrete shrinkage strain multiplier C_s is the ratio of the shrinkage strain at 50 years to the computed value of the shrinkage strain using ACI 209R-92.

$$C_s = \frac{s(18,250)}{700}$$

If C_s is greater than 1.1 for all pipe to be manufactured using the aggregates and cement used in the test, the design shrinkage strain shall be increased by multiplying the shrinkage strain s given in Eq 6-17 by C_s .

Creep and shrinkage measurements shall be made whenever the sources of aggregate or cement are changed.

Sec. 5.4 Properties of Coating Mortar

The mortar coating is a cement-rich mixture of sand and cement that is applied as a dense and durable coating with a minimum thickness of 0.75 in. over the outer layer of prestressing wire.

5.4.1 *Compressive strength of mortar.* The design compressive strength of the coating mortar is $f'_m = 5,500$ psi [37.9 MPa].

5.4.2 *Tensile strength of mortar.** The design tensile strength of the coating mortar is

$$f'_{tm} = 7\sqrt{f'_m} \quad (\text{Eq 5-5})$$

*For commentary see appendix A, Sec. A.8.

Where:

f_m' = design 28-day compressive strength of coating mortar in psi

$$f_{tm}' = 0.58 \sqrt{f_m'}$$

Where:

f_m' = design 28-day compressive strength of coating mortar in MPa

5.4.3 *Modulus of elasticity of mortar.** The design modulus of elasticity of the coating mortar is

$$E_m = 158 \gamma_m^{1.51} (f_m')^{0.3} \quad (\text{Eq 5-6})$$

Where:

$$\begin{aligned} \gamma_m &= 140 \text{ lb/ft}^3 \\ f_m' &= 5,500 \text{ psi} \end{aligned}$$

$$E_m = 0.074 \gamma_m^{1.51} (f_m')^{0.3}$$

Where:

$$\begin{aligned} \gamma_m &= 2,242 \text{ kg/m}^3 \\ f_m' &= 37.9 \text{ MPa} \end{aligned}$$

5.4.4 *Stress-strain relationship of mortar.* The design stress-strain relationship of coating mortar is shown in Figure 2B (page 16).

Sec. 5.5 Properties of Steel Cylinder

The cylinder shall be fabricated from either hot-rolled or cold-rolled steel sheet, conforming to the requirements of ANSI/AWWA C301. The minimum wall thickness of the steel cylinder shall be USS 16 gauge (1.52 mm).

5.5.1 *Yield strength of steel cylinder.* The design yield strength of the steel cylinder in tension shall be

$$f_{yy} = 33,000 \text{ psi (227 MPa)}$$

or the specified minimum yield strength, whichever is greater.

5.5.2 *Strength of steel cylinder at burst.†* The usable design strength of the steel cylinder at burst for a pipe subjected to hydrostatic pressure shall be

$$f_{yy}^* = 45,000 \text{ psi (310 MPa)}$$

*For commentary see appendix A, Sec. A.9.

†For commentary see appendix A, Sec. A.11.



Figure 3 Stress-strain relationship for steel cylinder in tension and compression

If the specified minimum yield strength of the cylinder steel is greater than 45,000 psi [310 MPa], the larger value may be used for f_{yy}^*

5.5.3 *Modulus of elasticity of steel cylinder.* The design modulus of elasticity of the steel cylinder shall be

$$E_y = 30,000,000 \text{ psi (206,850 MPa)}$$

5.5.4 *Stress-strain relationship of steel cylinder.* The design stress-strain relationship for the steel cylinder is shown in Figure 3.

Sec. 5.6 Properties of Prestressing Wire

The prestressing wire shall be hard drawn steel wire conforming to ANSI/AWWA C301. The minimum diameter of wire shall be USS 6 gauge (4.88 mm) for all pipe sizes (see Figure 4).

5.6.1 *Gross wrapping stress of wire.* The design gross wrapping stress f_{sg} , the stress in the wire during wrapping, is 75 percent of the specified minimum tensile strength of the wire.

$$f_{sg} = 0.75f_{su}$$

5.6.2 *Yield strength of wire.* The design yield strength of wire f_{sy} is 85 percent of the specified minimum tensile strength of the wire.

$$f_{sy} = 0.85f_{su}$$

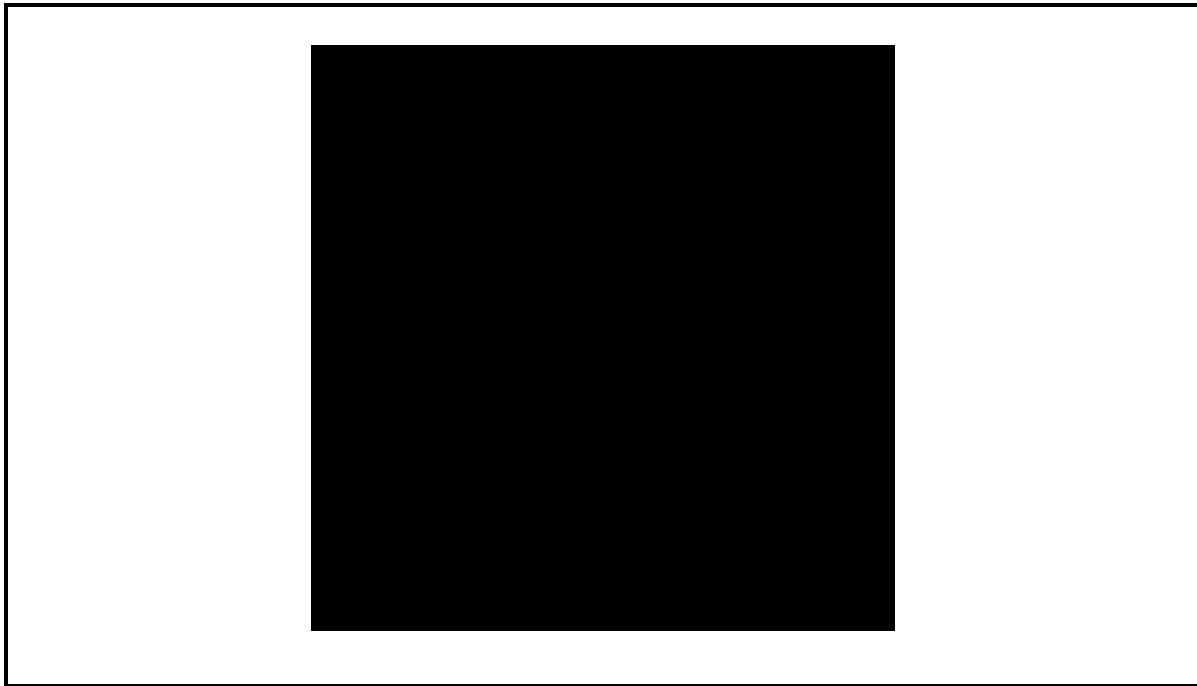


Figure 4 Stress-strain relationship for 6-gauge prestressing wire in tension after wrapping at f_{sg}

This stress level corresponds to the 0.2 percent strain offset in a wire before prestressing.

5.6.3 *Modulus of elasticity of wire.* The design modulus of elasticity of wire, after wrapping at f_{sg} , for stress levels below f_{sg} , shall be

$$E_s = 28,000,000 \text{ psi (193,050 MPa)}$$

5.6.4 *Stress-strain relationship of wire.** The design stress-strain relationship for prestressing wire, after wrapping at f_{sg} , is shown in Figure 4 and is given in the following equation:

$$f_s = \epsilon_s E_s \quad \text{for } \epsilon_s \leq f_{sg}/E_s \quad (\text{Eq 5-7})$$

$$= f_{su} \{ 1 - [1 - 0.6133(\epsilon_s E_s / f_{su})]^{2.25} \} \quad \text{for } \epsilon_s > f_{sg}/E_s$$

*For commentary see appendix A, Sec. A.12.

SECTION 6: STRESSES FROM PRESTRESSING*

Sec. 6.1 Notation

A_c	=	core concrete area, excluding steel-cylinder area (in. ² /ft [mm ² /m])
A_s	=	total area of prestressing wire (in. ² /ft [mm ² /m])
A_{sj}	=	area of the j -th layer of prestressing wire (in. ² /ft [mm ² /m])
A_{sf}	=	area of the final layer of prestressing wire (in. ² /ft [mm ² /m])
A_y	=	steel-cylinder area (in. ² /ft [mm ² /m])
C_E	=	concrete modulus of elasticity multiplier
C_R	=	wire intrinsic-relaxation multiplier
C_s	=	concrete shrinkage strain multiplier
C_ϕ	=	concrete creep factor multiplier
D_y	=	outside diameter of steel cylinder (in. [mm])
E_c	=	design modulus of elasticity of core concrete (psi [MPa])
E_s	=	design modulus of elasticity of prestressing wire (psi [MPa])
E_y	=	design modulus of elasticity of steel cylinder (psi [MPa])
f'_c	=	design 28-day compressive strength of core concrete (psi [MPa])
f_{ic}	=	initial prestress in core concrete (psi [MPa])
f_{icj}	=	initial prestress in core concrete after applying the j -th layer of prestressing (psi [MPa])
f_{cr}	=	final prestress in core concrete (psi [MPa])
f_{sg}	=	gross wrapping stress in prestressing wire = $0.75 f_{su}$ (psi [MPa])
f_{is}	=	initial stress in a single layer of prestressing wire (psi [MPa])
f_{isj}	=	initial stress in the j -th layer of prestressing wire (psi [MPa])
f_{sr}	=	final prestress in a single layer of prestressing wire (psi [MPa])
f_{srj}	=	final prestress in the j -th layer of prestressing wire (psi [MPa])
f_{su}	=	specified minimum tensile strength of prestressing wire (psi [MPa])
f_{iy}	=	initial prestress in steel cylinder (psi [MPa])
f_{yr}	=	final prestress in steel cylinder (psi [MPa])
h_{ci}	=	thickness of inner core concrete (in. [mm])
h_{co}	=	thickness of outer core concrete (in. [mm])
h_m	=	thickness of coating, including wire diameter (in. [mm])
I	=	intrinsic relaxation of wire at 1,000 h, percent of initial stress
n_i, n_r	=	modular ratios of prestressing wire to core concrete at wrapping and at maturity, respectively
n'_i, n'_r	=	modular ratios of steel cylinder to core concrete at wrapping and at maturity, respectively
P_o	=	decompression pressure that relieves final prestress in the core concrete (psi [kPa])
R	=	wire-relaxation factor for a single layer of prestressing
R_f	=	wire-relaxation factor for the outer layer of prestressing
R_j	=	wire-relaxation factor for the j -th layer of prestressing
RH	=	relative humidity (percent)
s	=	design shrinkage strain for a buried pipe

*For commentary see appendix A, Sec. A.13.

- s_{ci}, s_{com}, s_m = shrinkage strain for inner core, outer core and coating, and coating only, respectively
 s_1, s_2 = shrinkage strain for inner core and outer core, respectively, when volume-to-surface correction factor = 1.0
 t_1 = time period of exposure of pipe to outdoor environment (day)
 t_2 = time period of exposure of pipe to burial environment before water filling (day)
 ϕ = design creep factor for a buried pipe
 $\phi_{ci}, \phi_{com}, \phi_m$ = creep factor for inner core, outer core and coating, and coating only, respectively
 ϕ_1, ϕ_2 = creep factor for inner core and outer core, respectively, when volume-to-surface correction factor = 1.0
 γ, γ' = creep and shrinkage volume-to-surface ratio correction factor, respectively
 ρ, ρ' = creep and shrinkage relative humidity correction factor, respectively

Sec. 6.2 Prestress Losses

The state of stress in PCCP is governed by the prestress losses resulting from creep and shrinkage of concrete and mortar and relaxation of the wire.

Sec. 6.3 State of Stress With a Single Layer of Prestressing

6.3.1 *Initial prestress.* The initial prestress in the concrete core, the steel cylinder, and the prestressing wire is

$$f_{ic} = \frac{A_s f_{sg}}{A_c + n_i A_s + n_i' A_y} \quad (\text{Eq 6-1})$$

$$f_{iy} = n_i' f_{ic} \quad (\text{Eq 6-2})$$

$$f_{is} = -f_{sg} + n_i f_{ic} \quad (\text{Eq 6-3})$$

where compression is taken as positive, and tension is taken as negative.

6.3.2 *Final prestress.* The final prestress in the concrete, the steel cylinder, and the prestressing wire, after creep and shrinkage of the concrete core and the mortar coating and relaxation of the prestressing wire, is

$$f_{cr} = \frac{f_{ic}(A_c + n_r A_s + n_r' A_y) - (A_s E_s + A_y E_y)s - A_s R f_{sg}}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-4})$$

$$f_{yr} = f_{iy} + \frac{A_c(f_{ic}\phi n_r' + E_y s) - R A_s f_{sg} n_r'(1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-5})$$

$$f_{sr} = f_{is} + R f_{sg} + \frac{A_c(f_{ic}\phi n_r + E_s s) - R A_s f_{sg} n_r(1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-6})$$

6.3.3 *Decompression pressure.* The decompression pressure P_o , the pressure that just overcomes the final prestress in the core, is

$$P_o = \frac{f_{cr}(A_c + n_r A_s + n_r' A_y)}{6D_y} \quad (\text{Eq 6-7})$$

Sec. 6.4 State of Stress With Multiple Layers of Prestressing

6.4.1 *Applicability.** This section applies to pipe with multiple layers of prestressing where the clear radial distance between layers is nominally equal to one wire diameter. For designs with greater radial distance between prestressing layers, special designs are required.

6.4.2 *Initial prestress.* The initial prestress in concrete for a pipe with multiple layers of prestressing is the sum of the initial prestress caused by each layer of prestressing:

$$f_{ic} = f_{ic1} + f_{ic2} + f_{ic3} \quad (\text{Eq 6-8})$$

Where:

$$f_{ic1} = \frac{A_{s1} f_{sg}}{A_c + n_i A_{s1} + n_i' A_y} \quad (\text{Eq 6-9})$$

$$f_{ic2} = \frac{A_{s2} f_{sg}}{A_c + n_i(A_{s1} + A_{s2}) + n_i' A_y} \quad (\text{Eq 6-10})$$

$$f_{ic3} = \frac{A_{s3} f_{sg}}{A_c + n_i(A_{s1} + A_{s2} + A_{s3}) + n_i' A_y} \quad (\text{Eq 6-11})$$

The initial prestress for each layer of prestressing wire is

$$f_{is1} = -f_{sg} + n_i(f_{ic1} + f_{ic2} + f_{ic3}) \quad (\text{Eq 6-12})$$

$$f_{is2} = -f_{sg} + n_i(f_{ic2} + f_{ic3}) \quad (\text{Eq 6-13})$$

$$f_{is3} = -f_{sg} + n_i f_{ic3} \quad (\text{Eq 6-14})$$

The initial prestress in the steel cylinder is given in Eq 6-2.

*For commentary see appendix A, Sec. A.14.

6.4.3 Final prestress. The final prestress is given in Eq 6-4 for concrete core and Eq 6-5 for steel cylinder, with $A_s = A_{s1} + A_{s2} + A_{s3}$. The final prestress in the j -th layer of prestressing is

$$f_{srj} = f_{isj} + R_j f_{sg} + \frac{A_c(f_{ic}\phi n_r + E_s s) - \left(\sum_{k=1}^3 R_k A_{sk} \right) f_{sg} n_r (1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-15})$$

6.4.4 Decompression pressure. The decompression pressure for a pipe with multiple layers of prestressing is given in Eq 6-7, with $A_s = A_{s1} + A_{s2} + A_{s3}$.

Sec. 6.5 Modular Ratios

The modular ratios for concrete where f_c' is in psi are as follows:

	Cast Concrete	Spun Concrete
At Wrapping:		
n_i	$109 (f_c')^{-0.3}$	$100 (f_c')^{-0.3}$
n_i'	$117 (f_c')^{-0.3}$	$107 (f_c')^{-0.3}$
After Maturity:		
n_r	$93 (f_c')^{-0.3}$	$95 (f_c')^{-0.3}$
n_r'	$99 (f_c')^{-0.3}$	$102 (f_c')^{-0.3}$

Where f_c' is in MPa, replace f_c' in the above equations with $145 f_c'$.

Based on the quality-assurance test of concrete modulus of elasticity discussed in Sec. 5.3.4, if the design modulus of elasticity needs to be reduced, then the modular ratios described in this section shall be increased by dividing them by C_E .

Sec. 6.6 Design Creep Factor and Design Shrinkage Strain for Buried Pipe*

For a buried pipe, the creep factor ϕ and shrinkage strain s are

$$\phi = \frac{(h_{co} + h_m)\phi_{com} - h_m\phi_m + h_{ci}\phi_{ci}}{h_{ci} + h_{co}} \quad (\text{Eq 6-16})$$

$$s = \frac{(h_{co} + h_m)s_{com} - h_m s_m + h_{ci}s_{ci}}{h_{ci} + h_{co}} \quad (\text{Eq 6-17})$$

Where:

ϕ_{ci} , ϕ_{com} , ϕ_m , s_{ci} , s_{com} , and s_m are creep factors and shrinkage strains for the inner core, the outer core plus the coating, and for the coating, respectively.

If, based on the quality-assurance tests of concrete creep and shrinkage discussed in Sec. 5.3.6, the design creep factor and shrinkage strain need to be increased, the values of ϕ and s computed in Eq 6-16 and 6-17 shall be multiplied by C_ϕ and C_s respectively.

*For commentary see appendix A, Sec. A.15.

The volume-to-surface ratio of a cylinder with only one exposed surface is equal to its thickness. Creep factors and shrinkage strains are expressed in terms of volume-to-surface ratios as follows:

$$\phi_{ci} = \phi_1 \gamma(h_{ci}) \quad (\text{Eq 6-18})$$

$$\phi_{com} = \phi_2 \gamma(h_{co} + h_m) \quad (\text{Eq 6-19})$$

$$\phi_m = \phi_2 \gamma(h_m) \quad (\text{Eq 6-20})$$

and

$$s_{ci} = s_1 \gamma'(h_{ci}) \quad (\text{Eq 6-21})$$

$$s_{com} = s_2 \gamma'(h_{co} + h_m) \quad (\text{Eq 6-22})$$

$$s_m = s_2 \gamma'(h_m) \quad (\text{Eq 6-23})$$

Where:

γ and γ' are volume-to-surface correction factors for creep and shrinkage.

ϕ_1 , s_1 , ϕ_2 , and s_2 are the creep factors and shrinkage strains for inner core concrete and outer core concrete for the special case of $\gamma = \gamma' = 1.0$. The functions $\gamma(h)$ and $\gamma'(h)$ of the volume-to-surface ratio h are:

$$\gamma(h) = {}^{2/3}_3 [1 + 1.13 e^{-0.54h}] \quad (\text{Eq 6-24})$$

$$\gamma'(h) = 1.2 e^{-0.12h} \quad (\text{Eq 6-25})$$

Values of ϕ_1 , ϕ_2 , s_1 , and s_2 are determined on the basis of the following design scenario for exposure of buried pipe:

1. The inner and outer surfaces of the pipe are exposed to an outdoor environment with a specific relative humidity RH for t_1 days.
2. The inner and outer surfaces of the pipe are exposed to a burial environment with 92.5 percent relative humidity for an additional t_2 days.
3. The inner surface of the pipe is exposed for the remainder of the pipe's service life to a 100 percent relative humidity environment (water-filled condition), while the outer surface continues to be exposed to the burial environment.

The minimum values of t_1 and t_2 for which the pipe shall be designed are

$$t_1 = 270 \text{ days (9 months); } t_2 = 90 \text{ days (3 months).}$$

Longer exposure periods may be specified by the purchaser.

Values for ϕ_1 , ϕ_2 , s_1 , and s_2 are given in the following table for $t_1 = 270$ days, $t_2 = 90$ days, and two different relative humidities of the preburial environment. The design relative humidity before burial may not exceed 70 percent. For a design relative humidity between 70 and 40 percent, the constants ϕ_1 , ϕ_2 , s_1 , and s_2 shall be computed by linear interpolation between the values given in the table. For a design

relative humidity less than 40 percent, the constants ϕ_1 , ϕ_2 , s_1 , and s_2 shall be those given in the table for RH = 40 percent.

Constant	Cast Core		Spun Core	
	RH = 70%	RH = 40%	RH = 70%	RH = 40%
ϕ_1	1.76	2.12	1.06	1.27
ϕ_2	1.79	2.14	—	—
s_1	184×10^{-6}	262×10^{-6}	111×10^{-6}	157×10^{-6}
s_2	299×10^{-6}	377×10^{-6}	—	—

Values of ϕ_1 , ϕ_2 , s_1 , and s_2 for cast core concrete when $t_1 \neq 270$ days or $t_2 \neq 90$ days may be calculated from the following expressions:

$$\phi_1 = 2.35 \left[\frac{\rho - 0.65}{1 + 10/t_1^{0.6}} + \frac{0.05}{1 + 10/(t_1 + t_2)^{0.6}} + 0.6 \right] \quad (\text{Eq 6-26})$$

$$\phi_2 = 2.35 \left[\frac{\rho - 0.65}{1 + 10/t_1^{0.6}} + 0.65 \right] \quad (\text{Eq 6-27})$$

$$s_1 = 312 \times 10^{-6} \left[\frac{(\rho' - 0.225)t_1}{t_1 + 55} + \frac{0.225(t_1 + t_2)}{t_1 + t_2 + 55} \right] \quad (\text{Eq 6-28})$$

$$s_2 = 780 \times 10^{-6} \left[\frac{(0.4\rho' - 0.09)t_1}{t_1 + 55} + 0.225 \right] \quad (\text{Eq 6-29})$$

Where:

$$\begin{aligned} \rho &= 0.8 \text{ and } \rho' = 0.7 \text{ for RH} = 70 \text{ percent} \\ \rho &= \rho' = 1.0 \text{ for RH} = 40 \text{ percent} \end{aligned}$$

Values of ϕ_1 , ϕ_2 , s_1 , and s_2 for spun core concrete are 60 percent of the values calculated for cast concrete.

Sec. 6.7 Wire-Relaxation Factor

6.7.1 The wire-relaxation factors for pipe with a single layer of prestressing, using ASTM A648 wire with normal intrinsic relaxation and prestretched to $f_{sg} = 0.75 f_{su}$, are as follows:

$$R = 0.111 - 3.5(A_s/A_c) \text{ for cast concrete} \quad (\text{Eq 6-30})$$

$$R = 0.132 - 3.1(A_s/A_c) \text{ for spun concrete} \quad (\text{Eq 6-31})$$

6.7.2 The wire-relaxation factors for multiple layers of prestressing, using ASTM A648 wire with normal intrinsic relaxation and prestretched to $f_{sg} = 0.75 f_{su}$, are as follows:

$$R_1 = 0.113 - 5.8 \left[0.64 \frac{A_{s1}}{A_c} + 0.36 \left(\frac{A_s}{A_c} - \frac{A_{s1}}{A_c} \right) \right] \text{ for cast concrete} \quad (\text{Eq 6-32})$$

$$R_f = 0.127 - 5.0 \left[0.17 \left(\frac{A_s}{A_c} - \frac{A_{sf}}{A_c} \right) + 0.83 \frac{A_{sf}}{A_c} \right] \text{ for cast concrete} \quad (\text{Eq 6-33})$$

$$R_1 = 0.101 - 2.5 \left[0.65 \frac{A_{s1}}{A_c} + 0.35 \left(\frac{A_s}{A_c} - \frac{A_{s1}}{A_c} \right) \right] \text{ for spun concrete} \quad (\text{Eq 6-34})$$

$$R_f = 0.127 - 2.5 \left[0.06 \left(\frac{A_s}{A_c} - \frac{A_{sf}}{A_c} \right) + 0.94 \frac{A_{sf}}{A_c} \right] \text{ for spun concrete} \quad (\text{Eq 6-35})$$

Where:

R_1 = the relaxation factor for the first layer

R_f = the relaxation factor for the final layer of prestressing

The relaxation factors for the other layers of prestressing are obtained by linear interpolation.

6.7.3 Each factory where ASTM A648 wire is made for PCCP shall perform a quality-assurance test of wire relaxation. The normal intrinsic relaxation of wire for an initial stress of $0.7 f_{su}$ at 1,000 h, determined in accordance with the requirements of ASTM A648, is denoted by I . For normal intrinsic relaxation, $I = 6.8$ percent of the initial stress. The wire intrinsic relaxation multiplier, $C_R = I/6.8$, is the ratio of the intrinsic relaxation of wire to normal intrinsic relaxation. If $C_R > 1.1$, the wire-relaxation factors shall be calculated based on the provisions of Sec. 6.7.4 and 6.7.5.

6.7.4 The wire-relaxation factors for pipe with a single layer of prestressing, using ASTM A648 wire with higher than normal intrinsic relaxation and prestretched to $f_{sg} = 0.75 f_{su}$, are

$$R = -0.035 + 0.146 C_R - (0.95 + 2.55 C_R)(A_s/A_c) \text{ for cast concrete} \quad (\text{Eq 6-36})$$

$$R = 0.004 + 0.128 C_R - (2.01 + 1.09 C_R)(A_s/A_c) \text{ for spun concrete} \quad (\text{Eq 6-37})$$

6.7.5 The wire-relaxation factors for multiple layers of prestressing, using wire with higher than normal intrinsic relaxation and prestretched to $f_{sg} = 0.75 f_{su}$, are

$$R_1 = 0.044 + 0.069 C_R - 5.8 \left[0.64 \frac{A_{s1}}{A_c} + 0.36 \left(\frac{A_s}{A_c} - \frac{A_{s1}}{A_c} \right) \right] \text{ for cast concrete} \quad (\text{Eq 6-38})$$

$$R_f = 0.050 + 0.077 C_R - 5.0 \left[0.17 \left(\frac{A_s}{A_c} - \frac{A_{sf}}{A_c} \right) + 0.83 \frac{A_{sf}}{A_c} \right] \text{ for cast concrete} \quad (\text{Eq 6-39})$$

$$R_1 = 0.032 + 0.069 C_R - 2.5 \left[0.65 \frac{A_{s1}}{A_c} + 0.35 \left(\frac{A_s}{A_c} - \frac{A_{s1}}{A_c} \right) \right] \text{ for spun concrete (Eq 6-40)}$$

$$R_f = 0.050 + 0.077 C_R - 2.5 \left[0.06 \left(\frac{A_s}{A_c} - \frac{A_{sf}}{A_c} \right) + 0.94 \frac{A_{sf}}{A_c} \right] \text{ for spun concrete (Eq 6-41)}$$

SECTION 7: CRITERIA FOR LIMIT-STATE LOADS AND PRESSURES*

Sec. 7.1 Notation

- A_c = core concrete area, excluding steel-cylinder area (in.²/ft [mm²/m])
 A_s = total area of prestressing wire (in.²/ft [mm²/m])
 A_y = steel-cylinder area (in.²/ft [mm²/m])
 d = center-to-center wire spacing (in. [mm])
 d_s = wire diameter (in. [mm])
 D_y = outside diameter of steel cylinder (in. [mm])
 E_c = design modulus of elasticity of core concrete (psi [MPa])
 E_m = design modulus of elasticity of coating mortar (psi [MPa])
 f_{cr} = final prestress in core concrete (psi [MPa])
 f'_c = design 28-day compressive strength of core concrete (psi [MPa])
 f'_m = design 28-day compressive strength of coating mortar (psi [MPa])
 f_{sg} = $0.75 f_{su}$ = gross wrapping stress (psi [MPa])
 f_{su} = specified minimum tensile strength of wire (psi [MPa])
 f_{sy} = $0.85 f_{su}$ = wire tensile yield strength, corresponding to 0.2 percent offset strain (psi [MPa])
 f_{yy} = design tensile yield strength of steel cylinder (psi [MPa])
 f'_t = design tensile strength of core concrete (psi [MPa])
 f'_{tm} = design tensile strength of coating mortar (psi [MPa])
 FT1, FT2 = design factored working-load and field-test pressure combinations
 FW1 = design factored working-load combination
 FWT1–FWT6 = design factored working- plus transient-load and internal-pressure combinations
 P_o = decompression pressure (psi [kPa])
 P_k' = maximum internal-pressure limit under working plus transient condition (psi [kPa])
 W1, W2 = design working-load and internal-pressure combinations
 WT1–WT3 = design working- plus transient-load and internal-pressure combinations

*For commentary see Appendix A, Sec. A.16.