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Committee Personnel

The AWWA standards subcommittee that reviewed this standard had the following personnel at the time of approval:

Chris Sundberg, *Chair*

Samir A. Arnaout, Hanson Concrete Products Inc., Dallas Texas	(AWWA)
H.H. Bardakjian, Ameron Concrete & Steel Pipe, Rancho Cucamonga, Calif.	(AWWA)
Gerard Bizien, Hyprescon Inc., St. Eustache, Que.	(AWWA)
M.M. Hicks, Montgomery Watson, Walnut Creek, Calif.	(AWWA)
A.E. Romer, Boyle Engineering Corporation, Newport Beach, Calif.	(AWWA)
A.W. Tremblay, Price Brothers Company, Dayton, Ohio	(AWWA)
M.S. Zarghamee, Simpson, Sumpertz & Hegar Inc., Arlington, Mass.	(AWWA)

The AWWA Standards Committee on Concrete Pressure Pipe, which reviewed and approved this standard, had the following personnel at the time of approval:

Lee B. Freese, *Chair*
Chris Sundberg, *Vice-Chair*

Consumer Members

R.R. Beavers, Des Moines Water Works, Des Moines, Iowa	(AWWA)
W.E. Bradbury, Lake Shastina Mutual Water Company, Weed, Calif.	(AWWA)
J.A. Economides, San Diego County Water Authority, San Diego, Calif.	(AWWA)
D.A. Fisseler, Fort Worth Water Department, Fort Worth, Texas	(AWWA)
R.P. Fuerst, Bureau of Reclamation, Denver, Colo.	(USBR)
W.M. Kremkau, Washington Suburban Sanitary Commission, Laurel, Md.	(AWWA)
P.W. Reynolds, Los Angeles Water & Power, Los Angeles, Calif.	(AWWA)
D.A. Wiedyke, Consultant, Clinton Township, Mich.	(AWWA)

General Interest Members

W.R. Brunzell, Brunzell Associates Ltd., Skokie, Ill.	(AWWA)
B.R. Bullert,[*] City of St. Paul Water Utility, St. Paul, Minn.	(AWWA)
R.C. Edmunds, Jones Edmunds & Associates, Gainesville, Fla.	(AWWA)
W.D. Ensor, Gannett Fleming Inc., Newport News, Va.	(AWWA)
A.P. Ferrigno,[*] Standards Engineer Liaison, AWWA, Denver, Colo.	(AWWA)
L.B. Freese, Freese and Nichols Inc., Fort Worth, Texas	(AWWA)
J.K. Haney, HDR Engineering Inc., Austin, Texas	(AWWA)
M.M. Hicks, Montgomery Watson, Walnut Creek, Calif.	(AWWA)
Conrad Hohener Jr.,[†] Boyle Engineering Corporation, Newport Beach, Calif.	(AWWA)

---

[*] Liaison, nonvoting

[†] Alternate

R.Y. Konyalian, Consultant, Huntington Beach, Calif.	(AWWA)
S.A. McKelvie, Parsons Brinckerhoff, Boston, Mass.	(AWWA)
A.E. Romer, Boyle Engineering Corporation, Newport Beach, Calif.	(AWWA)
Chris Sundberg, CH2M Hill, Bellevue, Wash.	(AWWA)
M.S. Zarghamee, Simpson, Gumpertz & Heger Inc., Arlington, Mass.	(AWWA)

Producer Members

S.A. Arnaout, Hanson Concrete Products Inc., Dallas, Texas	(AWWA)
H.H. Bardakjian, Ameron Concrete & Steel Pipe, Rancho Cucamonga, Calif.	(AWWA)
Gerard Bizien, Hyprescon Inc., St. Eustache, Que.	(AWWA)
Martin Doran, Lafarge Pressure Pipe, Stouffville, Ont.	(AWWA)
J.E. Forero, ICHSA, Santa Clara, Mexico	(AWWA)
K.L. Heasley, Cretex Pressure Pipe Inc., South Beloit, Ill.	(AWWA)
S.R. Malcolm, Vianini Pipe Inc., Somerville, N.J.	(AWWA)
Giorgio Napoletani,* Vianini Pipe Inc., Sommerville, N.J.	(AWWA)
D.P. Prosser, American Concrete Pressure Pipe Association, Reston, Va.	(ACPPA)
A.W. Tremblay, Price Brothers Company, Dayton, Ohio	(AWWA)

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*Alternate

Contents

All AWWA standards follow the general format indicated subsequently. Some variations from this format may be found in a particular standard.

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Foreword

This foreword is for information only and is not a part of AWWA C304.

I. Introduction.

I.A. *Background.* This standard establishes the mandatory minimum requirements for the structural design of prestressed concrete cylinder pipe (PCCP) and provides procedures that will ensure that the design requirements are satisfied.

There are two types of PCCP: (1) lined-cylinder pipe (LCP) with a core composed of a steel cylinder lined with concrete which is subsequently prestressed with high-tensile wire wrapped directly on the steel cylinder; and (2) embedded-cylinder pipe (ECP), with a core composed of a steel cylinder encased in concrete which is subsequently prestressed with high-tensile wire wrapped on the exterior concrete surface. The cores of both types of pipe are coated with portland-cement mortar.

Before the procedures and requirements contained in this document were developed, the design of PCCP was determined by two distinct procedures. These are designated methods A and B described in Appendixes A and B of American National Standards Institute/American Water Works Association (ANSI*/AWWA) C301-84, Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type for Water and Other Liquids.

Method A used a semiempirical approach based on (1) W_o, which is nine-tenths of the three-edge bearing test load that causes incipient cracking; and (2) the theoretical hydrostatic pressure P_o, which relieves the calculated residual compression in the concrete core as a result of prestressing. The allowable combinations of three-edge bearing load and internal pressure were determined by a cubic parabola, passing through W_o and P_o, which defined the limits of these combinations. The three-edge bearing loads used in method A were converted to earth loads and transient external loads using bedding factors provided in AWWA Manual M9, *Concrete Pressure Pipe* (1979) and by ACPA† *Concrete Pipe Design Manual* (1988).

Method B was based on a procedure that limited the maximum combined net tensile stress in pipe under static external load and internal pressure to a value equal to $7.5\sqrt{f_c'}$, where f_c' = the 28-day compressive strength of core concrete in pounds per square inch ($0.62\sqrt{f_c'}$, where f_c' = the 28-day compressive strength of core concrete in MPa).

Both design methods limited the working pressure for ECP to P_o and to $0.8P_o$ for LCP, where P_o was the internal pressure required to overcome all compression in the core concrete excluding external load. Under transient conditions, such as those produced by surge pressures and live loads, both methods permitted increased internal pressure and external load.

Although the two methods of design produced similarly conservative results that served PCCP users well for nearly half a century, a unified method of design, described in this standard, was developed to replace methods A and B.

The following objectives for the unified design procedure were established:

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

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

1. It should replace both existing methods, the semiempirical method A and the working stress method B, described in ANSI/AWWA C301-84.
2. It should be based on state-of-the-art procedures for the design and analysis of concrete and prestressed concrete structures.
3. It should account for the state of prestress in the pipe, as well as the combined effects of external loads, pipe and fluid weights, and internal pressures.
4. It should agree with the results of 40 years of experimental data gathered by the American concrete pressure-pipe industry.
5. It should preclude the onset of visible cracking under working plus transient conditions.
6. It should provide adequate safety factors based on elastic and strength limit states.

The method of calculating residual stresses in the concrete core, the steel cylinder, and the prestressing wire was updated to separately account for the effects of elastic deformation, creep, and shrinkage of concrete, and the relaxation of the prestressing wire (see appendix B, item 14). Intrinsic wire relaxation, creep factors, and shrinkage strains obtained from procedures recommended by ACI* Committee 209 (1982) (see appendix B, item 1) were used in a step-by-step integration procedure (see appendix B, item 11) to evaluate the time-related variations of stress in the pipe elements. The results of the step-by-step integration procedure, applied to pipe in a buried environment, were used to develop simplified equations for practical design use.

Calculations of the design creep factor and shrinkage strain for buried pipe are based on the procedures recommended by ACI Committee 209. Creep and shrinkage are computed as functions of time, relative humidity, volume-to-surface ratio, age at loading, curing duration, concrete composition, and method of placement. Design values of creep factor and shrinkage strain are based on a 50-year exposure of pipe to the environment to which typical pipe will be exposed. The default environment is given in the following scenario:

1. The pipe is initially stored outdoors for 270 days.
2. The pipe is buried and kept empty for 90 days.
3. The pipe is filled with water for the duration of its design life.

The periods of time given in items 1 and 2 above may be extended at the purchaser's discretion.

The design wire-relaxation factor was obtained by measuring the intrinsic loss of prestressing wire, manufactured in accordance with ASTM† A648, Specification for Steel Wire, Hard Drawn for Prestressing Concrete Pipe, under constant strain and accounting for the reduction in relaxation loss caused by creep and shrinkage.

The simplified procedure, which separately accounts for concrete creep and shrinkage and wire relaxation, complies with test results (see appendix B, item 16) and with prior design practice (see appendix B, item 15).

The method adopted for determining allowable combinations of internal pressure, external loads, and pipe and fluid weights is based on satisfying certain limit-states design criteria (see appendix B, item 3). The purpose of using limit-states design is to assure the serviceability of pipe that is subject to working plus transient

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

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

design loads and pressures. Limit-states design also offers assurance that the prestress and safety margins for pipe strength will be maintained even if the pipe is subjected to abnormal conditions that may cause visible cracking.

The limit-states design procedure is based on limiting circumferential thrust and bending moment resulting from internal pressure, external loads, and pipe and fluid weights. The procedure specifies that certain limit-states-design criteria are not exceeded when the pipe is subjected to working loads and pressures and to working plus transient loads and pressures.

In the design procedure, three sets of limit-states criteria are used: serviceability, elastic, and strength. To satisfy the three sets of limit-states criteria, combined loads and pressures corresponding to each of these limit states must be calculated. As a result, the combined moments and thrusts in the pipe wall corresponding to the limit states must be calculated, and both uncracked and cracked cross sections must be considered. For accurate calculation of these combined moments and thrusts, the constitutive properties of concrete and mortar in tension must be expressed correctly. A trilinear model for stress–strain relationships of concrete and mortar was adopted for use in the limit-states design of PCCP.

Serviceability limit-states criteria are intended to preclude microcracking in the core and to control microcracking in the coating under working loads and pressures. These criteria are also intended to preclude visible cracking in the core and the coating under working plus transient loads and pressures. Criteria are provided for the following:

1. Core-crack control.
2. Radial tension control.
3. Coating-crack control.
4. Core-compression control.
5. Maximum pressure.

Elastic limit states are defined to limit combined working plus transient loads and pressures so that if cracks develop in a prestressed pipe under the transient condition, the pipe will have an elastic response preventing damage or loss of prestress. Criteria are provided for the following states:

1. Wire-stress control.
2. Steel-cylinder-stress control.

Strength limit states are defined to protect the pipe against yielding of the prestressing wire; crushing of the concrete core under external load; and tensile failure of the wire under internal pressure. Safety factors are applied to loads and pressures that produce the strength limit states. The following criteria are provided:

1. Wire yield-strength control.
2. Core compressive-strength control.
3. Burst-pressure control.
4. Coating bond-strength control.

The limit-states design procedure for PCCP subjected to the combined effects of internal pressure, external loads, and pipe and fluid weights:

1. Is a rational procedure based on state-of-the-art structural engineering practice for concrete structures.

2. Uses parameters resulting from many tests of prestressed concrete pipe and its constitutive materials.

3. Is substantiated by the results of combined-load and three-edge bearing verification tests of LCP and ECP.

The standard includes tables of standard designs for prestressed concrete LCP and a design example for ECP.

I.B. *History.* The AWWA Standards Committee on Concrete Pressure Pipe supported a recommendation that a design standard be developed for PCCP to be manufactured in accordance with ANSI/AWWA C301, Standard for Prestressed Concrete Pressure Pipe, Steel Cylinder Type, for Water and Other Liquids. On June 20, 1989, the C301 Design Subcommittee first met for the purpose of developing the design standard. At its October 1989 meeting, the AWWA Standards Council authorized a separate design standard for PCCP. The first edition of this standard, ANSI/AWWA C304, Standard for Design of Prestressed Concrete Cylinder Pipe, was approved by the Board of Directors on June 18, 1992. This edition was approved on Jan. 24, 1999.

I.C. *Acceptance.* In May 1985, the US Environmental Protection Agency (USEPA) entered into a cooperative agreement with a consortium led by NSF International (NSF) to develop voluntary third-party consensus standards and a certification program for all direct and indirect drinking water additives. Other members of the original consortium included the American Water Works Association Research Foundation (AWWARF) and the Conference of State Health and Environmental Managers (COSHEM). AWWA and the Association of State Drinking Water Administrators (ASDWA) joined later.

In the United States, authority to regulate products for use in, or in contact with, drinking water rests with individual states.[*] Local agencies may choose to impose requirements more stringent than those required by the state. To evaluate the health effects of products and drinking water additives from such products, state and local agencies may use various references, including

1. An advisory program formerly administered by USEPA, Office of Drinking Water, discontinued on Apr. 7, 1990.
2. Specific policies of the state or local agency.
3. Two standards developed according to NSF, ANSI[†]/NSF[‡] 60, Drinking Water Treatment Chemicals—Health Effects, and ANSI/NSF 61, Drinking Water System Components—Health Effects.
4. Other references including AWWA standards, *Food Chemicals Codex, Water Chemicals Codex,*[§] and other standards considered appropriate by the state or local agency.

Various certification organizations may be involved in certifying products in accordance with ANSI/NSF 61. Individual states or local agencies have authority to accept or accredit certification organizations within their jurisdiction. Accreditation of certification organizations may vary from jurisdiction to jurisdiction.

Appendix A, "Toxicology Review and Evaluation Procedures," to ANSI/NSF 61 does not stipulate a maximum allowable level (MAL) of a contaminant for substances not regulated by a USEPA final maximum contaminant level (MCL). The MALs of an unspecified list of "unregulated contaminants" are based on toxicity testing

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[*] Persons in Canada, Mexico, and non-North American countries should contact the appropriate authority having jurisdiction.

[†] American National Standards Institute, 11 W. 42nd St., New York, NY 10036.

[‡] NSF International, 3475 Plymouth Rd., Ann Arbor, MI 48106.

[§] Both publications available from National Academy of Sciences, 2102 Constitution Ave. N.W., Washington, DC 20418.

guidelines (noncarcinogens) and risk characterization methodology (carcinogens). Use of Appendix A procedures may not always be identical, depending on the certifier.

AWWA C304-99 does not address additive requirements. Thus, users of this standard should consult the appropriate state or local agency having jurisdiction in order to

1. Determine additive requirements including applicable standards.
2. Determine the status of certifications by all parties offering to certify products for contact with, or treatment of, drinking water.
3. Determine current information on product certification.

II. Special Issues. The information needed for selection of designs from the tables of standard designs includes:

1. Inside diameter of pipe (in. [mm]).
2. Internal working pressure (psi [kPa]).
3. Type of standard bedding.
4. Height of earth cover over the pipe (ft [m]).

The standard criteria used in the design selection tables are summarized in Sec. 9.4 preceding the design selection tables. If different design criteria are required by the purchaser, they should be specified by the purchaser, stated in the contract documents, and accounted for in the design of the pipe.

III. Use of This Standard. AWWA has no responsibility for the suitability or compatibility of the provisions of this standard to any intended application by any user. Accordingly, each user of this standard is responsible for determining that the standard's provisions are suitable for and compatible with that user's intended application.

III.A. *Purchaser Options and Alternatives.* For LCP designs not included in the standard design tables and for all ECP designs, the design procedures specified in the standard must be implemented. For this purpose, the following information is to be provided by the purchaser:

1. Inside diameter of pipe (in. [mm]).
2. Fluid unit weight (lb/ft^3 [kg/m^3]) if other than fresh water is required.
3. Height of earth cover over the pipe (ft [m]) or external dead load (lb/ft [kg/m]).
4. External surcharge load (lb/ft [kg/m]).
5. External transient load (lb/ft [kg/m]) if other than AASHTO* HS20 loading is required.
6. Internal working pressure (psi [kPa]).
7. Internal transient pressure (psi [kPa]).
8. Internal field-test pressure (psi [kPa]).
9. Installation requirements.
10. Time period of exposure to outdoor environment (days) if more than 270 days.
11. Relative humidity of the outdoor environment.
12. Time exposure of pipe to burial environment before water filling (days) if more than 90 days.

III.B. *Information to Be Provided by the Pipe Manufacturer.* In addition to the information listed above (Sec. III.A), the following information is to be provided by the pipe manufacturer:

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

1. Outside diameter of the steel cylinder (in. [mm]).
2. Thickness of the steel cylinder (in. [mm]).
3. Diameter of prestressing wire (in. [mm]).
4. Class of prestressing wire (II or III).
5. Number of layers of prestressing wire (one, two, or three).
6. Coating thickness over the prestressing wire (in. [mm]).
7. Coating thickness between layers of prestressing wire (in. [mm]).
8. Concrete 28-day compressive strength (psi [MPa]).
9. Concrete modulus of elasticity multiplier, if less than 0.9.
10. Concrete creep factor multiplier, if greater than 1.1.
11. Concrete shrinkage strain multiplier, if greater than 1.1.
12. Prestressing wire intrinsic relaxation multiplier, if greater than 1.1.

III.C. *Modification to Standard.* Any modifications to the provisions, definitions, or terminology in this standard must be provided in the purchaser's specifications.

IV. Major Revisions. The major revisions made to the standard in this edition include the following:

1. The format has been changed to AWWA standard style.
2. The acceptance clause (Sec. I.C) has been revised to approved wording.
3. A second paragraph has been added to Sec. 4.2 Distribution of Loads to clarify the sign convention for moments and thrusts.
4. Changes have been made in Sec. 5.3.6. Creep and shrinkage properties of concrete to clarify the method for calculating creep and shrinkage multipliers.

V. Comments. If you have any comments or questions about this standard, please call the AWWA Volunteer and Technical Support Group, (303) 794-7711 ext. 6283, FAX (303) 795-7603, or write to the group at 6666 W. Quincy Ave., Denver, CO 80235.

American Water Works Association

ANSI/AWWA C304-99
(Revision of ANSI/AWWA C304-92)

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.*

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[*] 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.

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[*] 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.

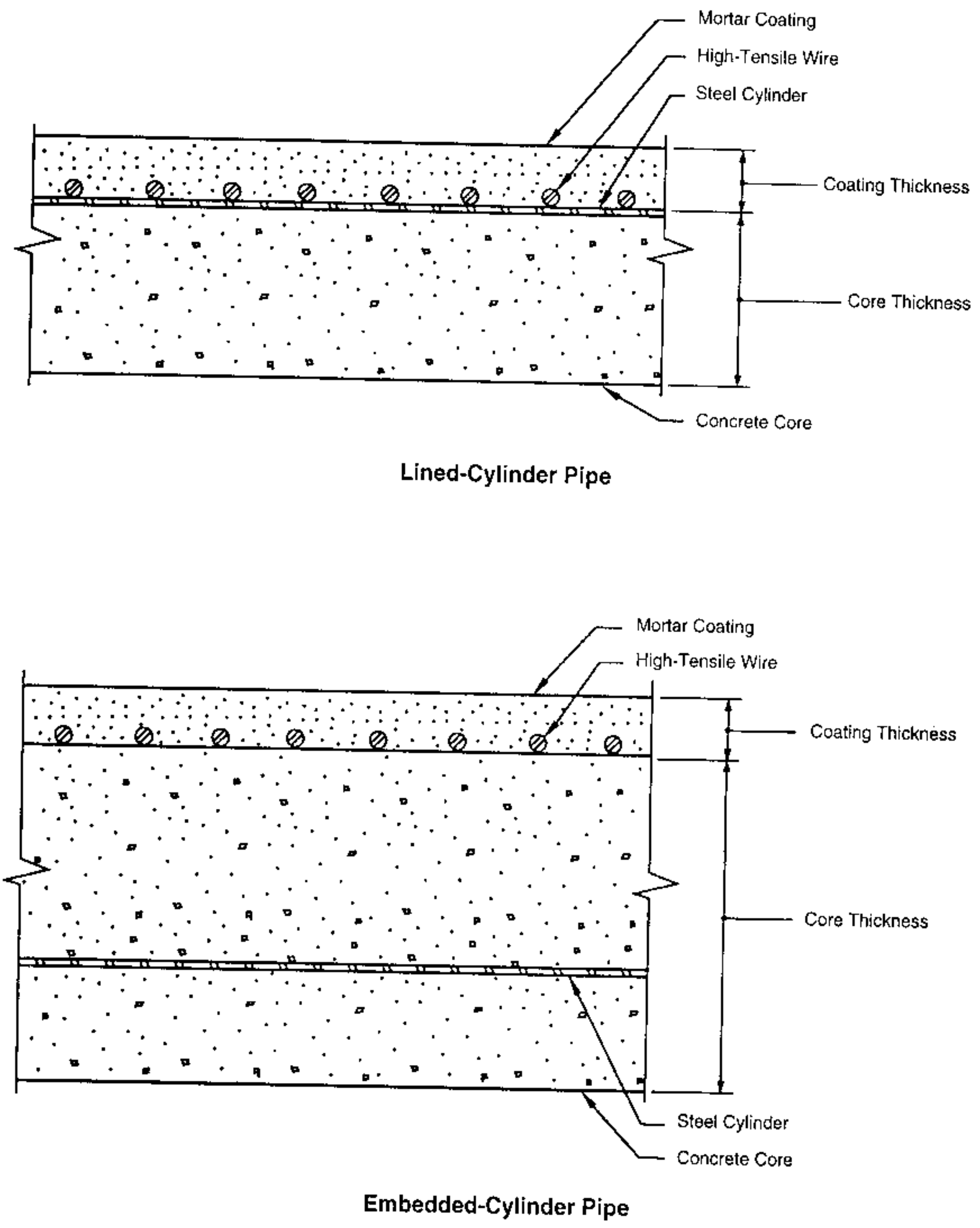

Figure 1 Schematic pipe-wall cross sections for lined- and embedded-cylinder pipe

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 (lbf/ft [N/m])
W_f = weight of fluid (lbf/ft [N/m])
W_p = weight of pipe (lbf/ft [N/m])
W_s = surcharge load (lbf/ft [N/m])
W_t = transient load (lbf/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:

γ_c = 145 lb/ft^3 (2,323 kg/m^3)

γ_m = 140 lb/ft^3 (2,243 kg/m^3)

γ_s = 489 lb/ft^3 (7,833 kg/m^3)

2.3.1.2 Fluid weight, W_f, computed using 62.4 lb/ft^3 (1,000 kg/m^3) 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:

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

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:

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

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:

$$P_{ft} = 1.2P_w \tag{Eq 2-3}$$

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 (lbf/ft, [N/m])
W_f = weight of fluid (lbf/ft [N/m])
W_p = weight of pipe (lbf/ft [N/m])
W_t = transient load (lbf/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/ft^3 (1922 kg/m^3) 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:

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

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

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

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*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:

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

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

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

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

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

Where:

β_1 = 1.1 for ECP and 1.2 for LCP

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

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

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

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

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

Where:

β_2 = 1.3 for ECP and 1.4 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:

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

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

Where:

β_1 = 1.1 for ECP and 1.2 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.

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[*] 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])

$\overline{R}$ = 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

$$N_o = 6D_yP_o \tag{Eq 4-1}$$

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

$$N_o = \tfrac{1}{2}D_yP_o$$

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

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

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

$$N_1 = 6D_yP - [C_{n1e}(W_e + W_t) + C_{n1p}W_p + C_{n1f}W_f] \tag{Eq 4-4}$$

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

Where:

$$\bar{R} = \frac{D_i + h_c + h_m}{2} \tag{Eq 4-6}$$

When D_y is in mm and P is in kPa, substitute ½ 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

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*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

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

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

$$f_t' = 7\sqrt{f_c'} \qquad \text{(Eq 5-1)}$$

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

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[*] 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

$$E_c = 158\gamma_c^{1.51}(f_c')^{0.3} \qquad \text{(Eq 5-2)}$$

Where:

γ_c = 145 lb/ft^3
f_c' = design 28-day compressive strength of concrete in psi

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

Where:

γ_c = 2,323 kg/m^3
f_c' = design 28-day compressive strength of concrete in MPa

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 $\overline{x}$ 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

$$f_c{}'_t = \overline{x} - 0.84s \qquad \text{(Eq 5-3)}$$

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

The modulus of elasticity multiplier is

$$C_E = \frac{E_{ct}}{158\gamma_c^{1.51}(f_c{}'_t)^{0.3}} \qquad \text{(Eq 5-4)}$$

Where:

E_{ct} (psi) = the average of the five or more modulus of elasticity test results
γ_c = 145 lb/ft^3

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

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

Where:

E_{ct} (MPa) = the average of the five or more modulus of elasticity test results
γ_c = 2,323 kg/m^3

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.

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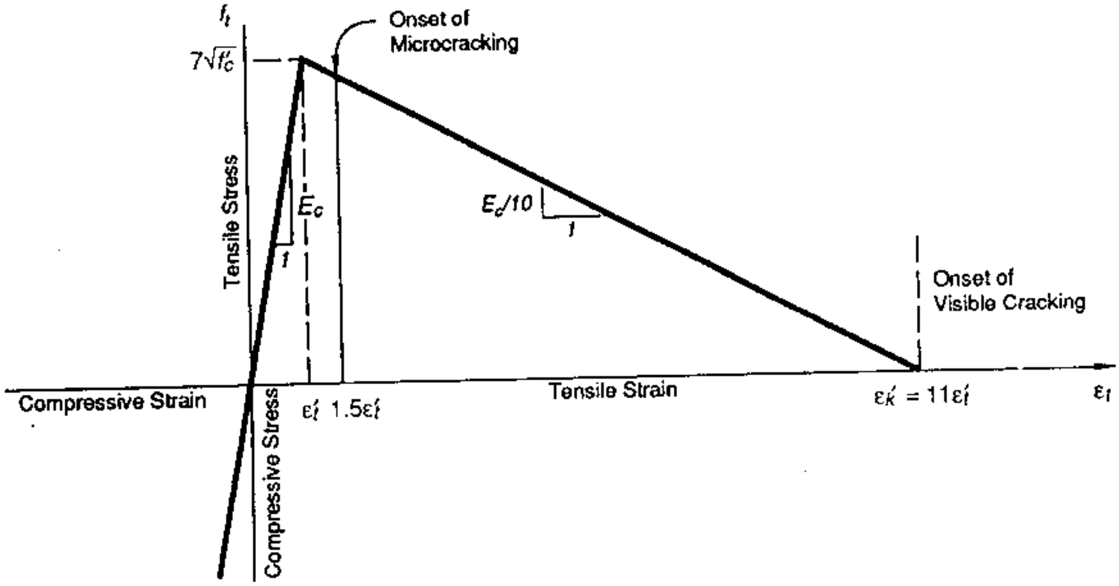
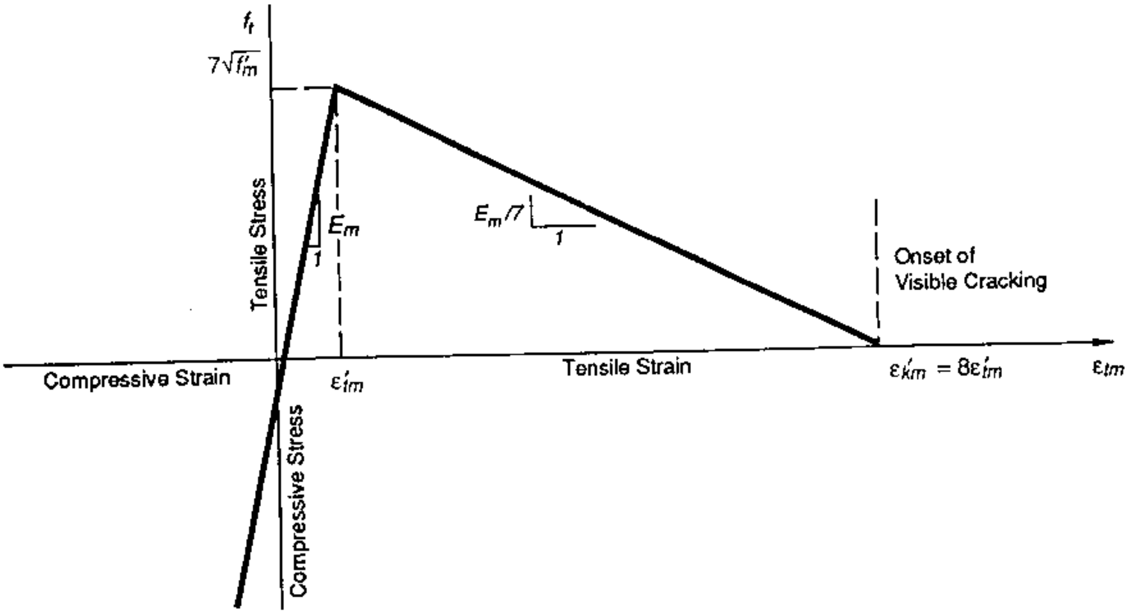
[*] For commentary see appendix A, Sec. A.10.



A. **Assumed for concrete core of the pipe**



B. **Assumed for mortar coating of the pipe**

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 (μ-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

$$f_{tm}' = 7\sqrt{f_m'} \qquad \text{(Eq 5-5)}$$

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*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

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

Where:

γ_m = 140 lb/ft^3
f_m' = 5,500 psi

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

Where:

γ_m = 2,242 kg/m^3
f_m' = 37.9 MPa

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

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

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

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

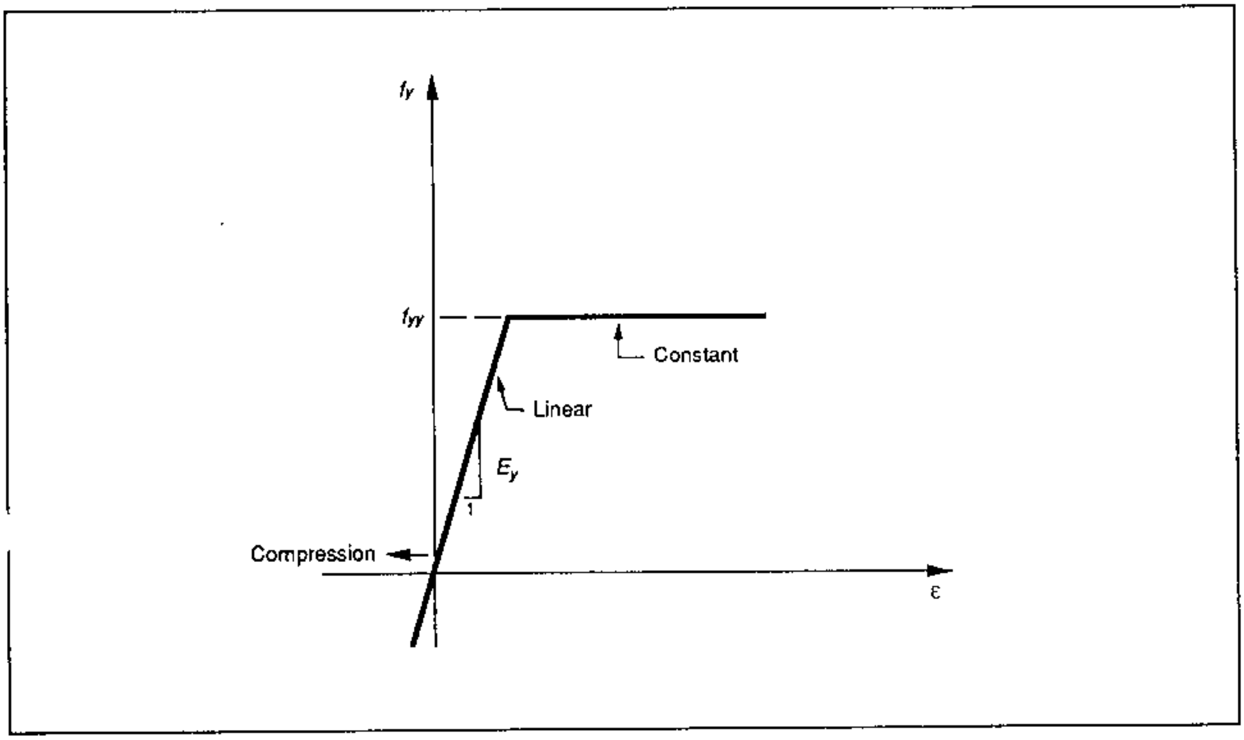

Figure 3 Stress-strain relationship for steel cylinder in tension and compression

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

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

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.

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

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.

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

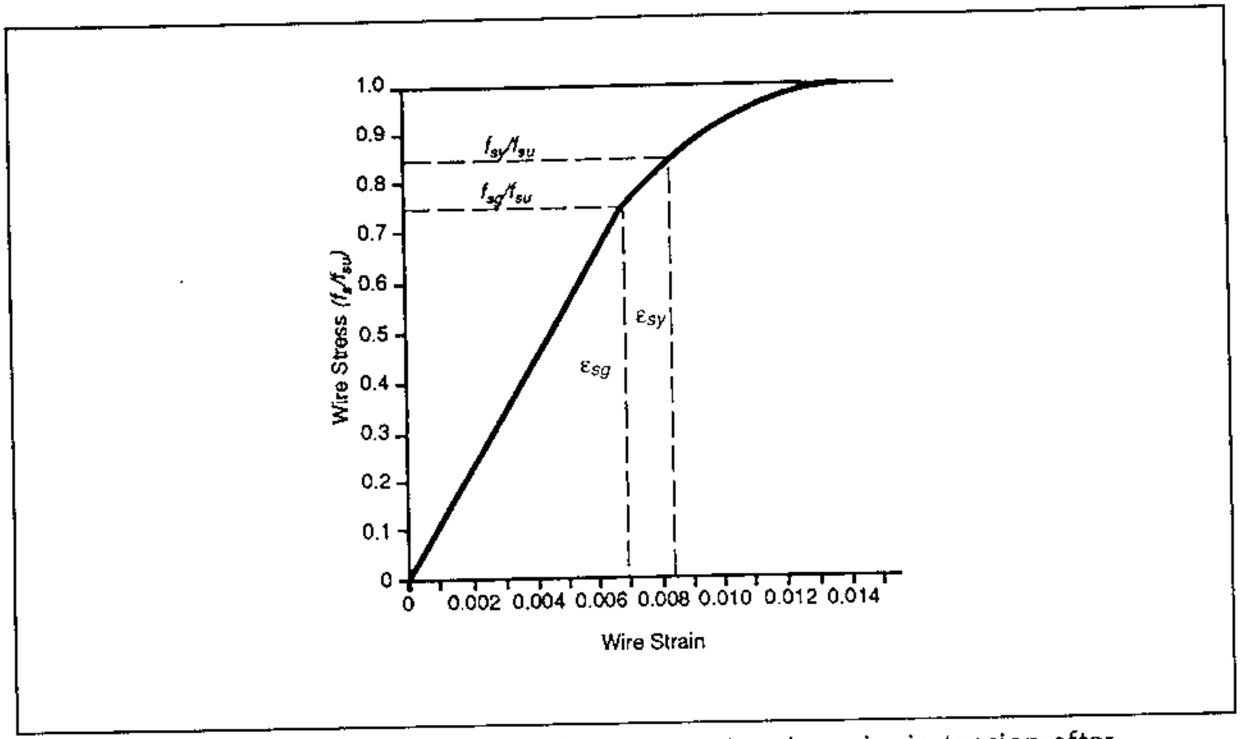

Figure 4 Stress–strain relationship for 6-gauge prestressing wire in tension after wrapping at f_{sg}

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

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

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:

$$f_s = \varepsilon_s E_s \quad \text{for } \varepsilon_s \le f_{sg}/E_s \qquad \text{(Eq 5-7)}$$

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

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[*] 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

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[*] 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

ϕ_{ci}, ϕ_{com}, ϕ_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

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

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

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

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

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

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

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

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

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

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:

$$f_{ic} = f_{ic\,1} + f_{ic\,2} + f_{ic\,3} \qquad \text{(Eq 6-8)}$$

Where:

$$f_{ic\,1} = \frac{A_{s1} f_{sg}}{A_c + n_i A_{s1} + n_i' A_y} \qquad \text{(Eq 6-9)}$$

$$f_{ic\,2} = \frac{A_{s2} f_{sg}}{A_c + n_i(A_{s1} + A_{s2}) + n_i' A_y} \qquad \text{(Eq 6-10)}$$

$$f_{ic\,3} = \frac{A_{s3} f_{sg}}{A_c + n_i(A_{s1} + A_{s2} + A_{s3}) + n_i' A_y} \qquad \text{(Eq 6-11)}$$

The initial prestress for each layer of prestressing wire is

$$f_{is1} = -f_{sg} + n_i(f_{ic\,1} + f_{ic\,2} + f_{ic\,3}) \qquad \text{(Eq 6-12)}$$

$$f_{is2} = -f_{sg} + n_i(f_{ic\,2} + f_{ic\,3}) \qquad \text{(Eq 6-13)}$$

$$f_{is3} = -f_{sg} + n_i\, f_{ic\,3} \qquad \text{(Eq 6-14)}$$

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

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[*] 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

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

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:		
Por el cable n_i	$109\,(f_c')^{-0.3}$	$100\,(f_c')^{-0.3}$
Por el cilindro n_i'	$117\,(f_c')^{-0.3}$	$107\,(f_c')^{-0.3}$
After Maturity:		
Por el cable n_r	$93\,(f_c')^{-0.3}$	$95\,(f_c')^{-0.3}$
Por el cilindro 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

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

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

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.

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*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:

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

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

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

and

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

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

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

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:

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

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

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 days (9 months); t_2 = 90 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:

ρ = 0.8 and ρ' = 0.7 for RH = 70 percent
ρ = ρ' = 1.0 for RH = 40 percent

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

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

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

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

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

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

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

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

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 [mm^2/m])
A_s = total area of prestressing wire (in.^{2}/ft [mm^2/m])
A_y = steel-cylinder area (in.^{2}/ft [mm^2/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_0 = 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

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

ε_k' = tensile strain limit in core concrete at first visible cracking

ε_{km}' = tensile strain limit in coating mortar at first visible cracking

ε_t' = tensile elastic strain corresponding to tensile strength of concrete core, f_t'

ε_{tm}' = tensile elastic strain corresponding to tensile strength of coating mortar, f_{tm}'

ε_w' = tensile strain limit in core concrete for working conditions alone

ε_{wm}' = tensile strain limit in coating mortar for working conditions alone

Sec. 7.2 Limit-States Design

PCCP shall be designed for the following limit states:

1. Serviceability limit states
2. Elastic limit states
3. Strength limit states

Sec. 7.3 Serviceability Limit-States Design Criteria

The serviceability limit-states design criteria for working and working plus transient conditions shall be as follows:

7.3.1 *Core crack control.* The tensile strain at the inside surface of the core shall be limited to the following:

load and pressure combination W1: $\varepsilon_w' = 1.5\varepsilon_t'$

load and pressure combinations FT1, WT1, and WT2: $\varepsilon_k' = 11\varepsilon_t'$

7.3.2 *Radial tension control.* The calculated radial tensile stress at the interface between the inner core and cylinder of ECP shall be a maximum of 12 psi under working-load combination FW1 and under working-plus transient-load combination WT3.

7.3.3 *Coating crack control.* The tensile strain at the outside of the coating shall be limited to the following:

load and pressure combination W1: $\varepsilon_{wm}' = 0.8\varepsilon_{km}'$

load and pressure combinations FT1, WT1, and WT2: $\varepsilon_{km}' = 8\varepsilon_{tm}'$

The tensile strain at the outside surface of the concrete core shall be limited to the following:

load and pressure combination W1: $\varepsilon_w' = 1.5\varepsilon_t'$

load and pressure combinations FT1, WT1, and WT2: $\varepsilon_k' = 11\varepsilon_t'$

7.3.4 *Core compression control.* The maximum compressive stress at the inside surface of the core shall be limited to the following:

load combination W2: $0.55f_c'$

load combination WT3: $0.65f_c'$

7.3.5 *Maximum pressures.* The maximum internal pressure shall be limited to the following:

ECP

load and pressure combination W1: P_o

load and pressure combination WT1: min. $(1.4\, P_o, P_k')$

LCP

load and pressure combination W1: $0.8\, P_o$

load and pressure combination WT1: min. $(1.2\, P_o, P_k')$

Where:

P_k' = the internal pressure that, acting alone, produces (1) strain in the coating of $0.5\, \varepsilon_k'{}_m$; or (2) axial tensile stress in the core of $5\sqrt{f_c'}$ where f_c' is in psi or $0.41\sqrt{f_c'}$ where f_c' is in MPa for ECP, and $3\sqrt{f_c'}$ where f_c' is in psi or $0.25\sqrt{f_c'}$ where f_c' is in MPa for LCP, calculated using the uncracked properties of the net section, whichever is less.

Sec. 7.4 Elastic Limit-States Design Criteria

The elastic limit-states design criteria also represent serviceability requirements, because exceeding the elastic limits does not cause failure of the pipe. These criteria apply to working-pressure and load plus transient-pressure and load conditions or to working-pressure and load conditions if no transient condition is required. The elastic limit-states design criteria are as follows:

7.4.1 *Wire-stress control.* The maximum tensile stress in the prestressing wire from load and pressure combinations FWT1, FWT2, and FT2 shall remain below the gross wrapping stress, f_{sg}, and the maximum compression in the core from the same load combinations shall not exceed $0.75\, f_c'$.

7.4.2 *Steel-cylinder stress control for ECP.* The maximum tensile stress in the steel cylinder of ECP from load and pressure combinations WT1, WT2, and FT1 shall remain below the design yield strength of the steel cylinder f_{yy} should the concrete crack at the inside of the pipe wall at the crown and invert. Also, to preclude separation of the cylinder from the outer core, should the inner core crack, the tensile stress in the cylinder caused by external load alone (with zero pressure) from load combination WT3 shall not exceed the compressive prestress in the cylinder. Although the application of pressure increases the tensile stress in the cylinder, the pressure also compresses the cylinder against the outer core concrete so that the maximum condition for separation occurs with zero pressure in the pipe.

Sec. 7.5 Strength Limit-States Design Criteria

The strength limit-states design criteria, applied to the working plus transient conditions, are as follows:

7.5.1 *Wire yield-strength control.* The maximum tensile stress in the prestressing wire shall not exceed its yield strength, f_{sy}, when the pipe is subjected to the factored load and pressure combinations FWT3 and FWT4.

SECTION 8: CALCULATION OF LIMIT-STATE LOADS AND PRESSURES[*]

Sec. 8.1 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_y = steel-cylinder area (in.^{2}/ft [mm^2/m])
b = width of pipe cross section equal to 1 ft (0.30 m)
d_s = wire diameter (in. [mm])
d_y = distance between midsurface of steel cylinder and inner surface of core (in. [mm])
d_w = clear distance between two layers of prestressing wire in pipe with multiple layers of prestressing (in. [mm])
D_y = outside diameter of steel cylinder (in. [mm])
e = radial distance of line of action of thrust N from inner surface of core (in. [mm])
e_o = radial distance of line of action of thrust N_o from inner surface of core (in. [mm])
E_c, E_m = design modulus of elasticity for core concrete and coating mortar, respectively (psi [MPa])
E_s, E_y = design modulus of elasticity of prestressing wire and steel cylinder, respectively (psi [MPa])
f_c' = design 28-day compressive strength of core concrete (psi [MPa])
f_t' = design tensile strength of core concrete (psi [MPa])
f_{ci} = concrete stress at inner surface of core (psi [MPa])
f_{co} = concrete stress at outer surface of core (psi [MPa])
f_{cr}, f_{yr}, f_{sr} = final prestress in core concrete, steel cylinder, and prestressing wire, respectively, compression is positive (psi [MPa])
f_{cy} = concrete stress at midsurface of steel cylinder (psi [MPa])
f_{mi}, f_{mm}, f_{mo} = stresses at inner, middle, and outer fibers of coating, respectively (psi [MPa])
f_{ms} = coating stress at center of prestressing wire (psi [MPa])
f_{su} = specified minimum tensile strength of wire (psi [MPa])
Δf_s = stress in the outer wire relative to the state of decompressed core concrete (psi [MPa])
$f_c(\varepsilon)$, $f_{sj}(\varepsilon)$, $f_y(\varepsilon)$ = stress in core, the j-th layer of prestressing wire, and steel cylinder, respectively, corresponding to strain ε (psi [MPa])
f_{srf} = final prestress in outer layer of prestressing wire, compression is positive (psi [MPa])
Δf_y = stress in steel cylinder relative to the state of decompressed core concrete (psi [MPa])
f_{yy} = tensile yield strength of steel cylinder (psi [MPa])
f_{yy}^* = design tensile strength of steel cylinder at pipe burst (psi [MPa])

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[*] For commentary see appendix A, Sec. A.18.

$F_{ci}, F_y, F_{co}, F_s, F_m$ = stress resultants in the inner core section, steel cylinder, outer core section, prestressing wire, and coating, respectively (lbf/ft [N/m])

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

h_c = core thickness, including thickness of cylinder (in. [mm])

h_{ci} = $(D_y - D_i)/2 - t_y$ = thickness of inner core concrete (in. [mm])

h_m = coating thickness, including wire diameter (in. [mm])

k, k', k_1 = dimensionless factors related to locations of neutral axis, defined in Sec. 8.9.1 through 8.9.4, separately

m = modular ratio of coating mortar to core concrete

M_1, M_2 = bending moment at invert and crown or springline, respectively (lbf-in./ft [N-m/m])

$M_{ci}, M_y, M_{co}, M_s, M_m$ = moment of stresses in the inner core section, steel cylinder, outer core section, prestressing wire, and coating, respectively (lbf-in. [N-m/m])

n, n' = modular ratio of prestressing wire and steel cylinder to concrete, based on design moduli of elasticity

N_o = thrust, resulting from final prestressing (lbf/ft [N/m])

N_{sg}, N_{sy} = thrust that produces f_{sg} and f_{sy} stresses in prestressing wire (lbf/ft [N/m])

N_{yy} = thrust that produces f_{yy} stress in steel cylinder of ECP (lbf/ft [N/m])

N_1, N_2 = thrust from internal pressure and loads at invert or crown, and springline, respectively (lbf/ft [N/m])

N_K' = maximum thrust limit under working plus transient conditions (lbf/ft [N/m])

P_b = burst pressure (psi [kPa])

P_k' = maximum pressure limit under working plus transient condition, Eq 8-1 and 8-2 (psi [kPa])

t_s = part of core under tensile softening in the descending section of stress–strain diagram (in. [mm])

t_t = part of core under tension in the ascending section of stress–strain diagram (in. [mm])

t_y = thickness of cylinder (in. [mm])

W1, W2 = design working-load and internal-pressure combinations

WT1–WT3 = design working- plus transient-load and internal-pressure combinations

β, β_m = ratio of the depth of Whitney block to the depth of the compression region for core and coating, respectively

$\varepsilon_{ci}, \varepsilon_{co}, \varepsilon_{mi}, \varepsilon_{mm}, \varepsilon_{mo}$ = strain in the inner and outer surfaces of the core, and in the inner, middle, and outer surfaces of the coating, respectively

$\Delta\varepsilon_y, \Delta\varepsilon_s$ = strain increments in the midsurface of steel cylinder and center of the outer layer of wire, relative to the state of decompressed core, respectively

ε_{cr} = concrete strain corresponding to f_{cr}

ε_k' = tensile strain limit in core concrete at first visible cracking

ε_{km}' = tensile strain limit in coating mortar at first visible cracking

$\varepsilon_{sg}, \varepsilon_{sy}, \varepsilon_{su}$ = prestressing wire strains corresponding to f_{sg}, f_{sy}, and f_{su}, respectively

ε_t = tensile strain in the extreme fiber of the core

ε_t' = elastic strain corresponding to tensile strength of core concrete, f_t'

λ = d_y/t_s in Sec. 8.9.1 and $(h_c - d_y)/t_s$ in Sec. 8.9.2
λ_m = $h_m/2h_c$
λ_s = $d_s/2h_c$
λ_{sj} = $[(j - \frac{1}{2})d_s + (j - 1)d_w]/h_c$
λ_y = d_y/h_c
ν = $\varepsilon_k'/\varepsilon_t' - 1 = 10$
ν_2 = $\varepsilon_{co}/\varepsilon_t' - 1$ or $\varepsilon_{ci}/\varepsilon_t' - 1$
ν_m = $\varepsilon_{km}/\varepsilon_{tm}' - 1 = 7$
σ_r = radial tension between inner core and cylinder of ECP (psi [MPa])

Sec. 8.2 Limit-States Design Procedures

The design internal pressures, stresses, strains, and moments in the pipe wall shall not exceed the limiting design criteria given in Table 3 for ECP and in Table 4 for LCP.

Stresses and strains in the pipe wall shall be calculated from moments and thrusts in the pipe wall resulting from internal pressures, external loads, and the weights of pipe and fluid. Moments and thrusts in the pipe wall shall be calculated by the procedures given in Sec. 4 using load and pressure factors presented in Sec. 3 and summarized in Table 1 for ECP and in Table 2 for LCP. The calculation of stresses and strains from moments and thrusts and the calculation of limiting pressures and moments shall follow the procedures defined in this section.

Sec. 8.3 Maximum Pressures

The maximum pressure P_k' as defined in Sec. 7.3.5, is as follows:
For ECP

$$P_k' = P_o \min.\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, 1 + \frac{5\sqrt{f_c'}}{f_{cr}}\right) \qquad \text{(Eq 8-1)}$$

Where f_c' and f_{cr} are in psi.

$$P_k' = P_o \min.\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, 1 + \frac{0.41\sqrt{f_c'}}{f_{cr}}\right)$$

Where f_c' and f_{cr} are in MPa.

For LCP

$$P_k' = P_o \min.\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, 1 + \frac{3\sqrt{f_c'}}{f_{cr}}\right) \qquad \text{(Eq 8-2)}$$

Where f_c' and f_{cr} are in psi.

$$P_k' = P_o \min.\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, 1 + \frac{0.25\sqrt{f_c'}}{f_{cr}}\right)$$

Where f_c' and f_{cr} are in MPa.

Table 3 Design load combinations and calculation references for embedded-cylinder pipe criteria

Limit States and Location	Purpose	Limiting Criteria*	Applicable Load Combinations†	Calculation Reference
Serviceability at Full Pipe Circumference	To preclude core decompression	$P \leq P_o$	W1	(Eq 6-7)
	To preclude coating cracking	Pressure limit: $P \leq \min(P_k', 1.4\ P_o)$	WT1	(Eq 8-1)
Serviceability at Invert/Crown	To preclude onset of core microcracking	Inside core tensile strain limit: $\varepsilon_{ci} \leq 1.5\varepsilon_t'$	W1	Sec. 8.9.1
		Inner core-to-cylinder radial tension limit: $\sigma_r \leq 12$ psi (0.82 MPa)	FW1	(Eq 8-5)
	To preclude onset of core visible cracking	Inside core tensile strain limit: $\varepsilon_{ci} \leq \varepsilon_k' = 11\varepsilon_t'$	WT1, WT2, FT1	Sec. 8.9.1
		Inner core-to-cylinder radial tension limit: $\sigma_r \leq 12$ psi (0.82 MPa)	WT3	(Eq 8-5)
Serviceability at Springline	To preclude onset of core microcracking and to control microcracking of coating	Outer core tensile strain limit: $\varepsilon_{co} \leq 1.5\varepsilon_t'$	W1	Sec. 8.9.2
		Outer coating tensile strain limit: $\varepsilon_{mo} \leq 0.8\varepsilon_{km}' = 6.4\varepsilon_{tm}'$		
	To preclude coating visible cracking	Outer core tensile strain limit: $\varepsilon_{co} \leq \varepsilon_k' = 11\varepsilon_t'$	WT1, WT2, FT1	Sec 8.9.2
		Outer coating tensile strain limit: $\varepsilon_{mo} \leq \varepsilon_{km}' = 8\varepsilon_{tm}'$		
	To control core compression	Inner core compression limit: $f_{ci} \leq 0.55\ f_c'$	W2	Sec. 8.9.2
		Inner core compression limit: $f_{ci} \leq 0.65\ f_c'$	WT3	Sec. 8.9.2
Elastic Limit at Invert/Crown	To preclude exceeding limit stress in steel cylinder	Cylinder stress reaching yield: $-f_{yr} + n'f_{cr} + \Delta f_y \leq f_{yy}$	WT1, WT2, FT1	Sec. 8.9.1
		Onset of tension in cylinder: $-f_{yr} + n'f_{cr} + \Delta f_y \leq 0$	WT3	Sec. 8.9.1
Elastic Limit at Springline	To preclude exceeding wire limit stress, f_{sg}, and maintain core compression below 0.75 f'_c	f_{sg} wire stress limit plus core compression limit: $-f_{sr} + nf_{cr} + \Delta f_s \leq f_{sg}$ $f_{ci} \leq 0.75\ f_c'$	FWT1, FWT2, FT2	Sec. 8.9.2
Strength at Springline	To preclude wire yielding	f_{sy} wire stress limit: $-f_{sr} + nf_{cr} + \Delta f_s \leq f_{sy}$	FWT3, FWT4	Sec. 8.9.2
	To preclude core crushing	Ultimate moment: $M \leq M_{ult}$	FWT5	Sec. 8.9.3
Burst Pressure	To prevent burst failure	$P \leq P_b$	FWT6	(Eq 8-4)

*See Sec. 8

†See Sec. 4

Table 4 Design load combinations and calculation references for lined-cylinder pipe criteria

Limit States and Location	Purpose	Limiting Criteria*	Applicable Load Combinations†	Calculation Reference
Serviceability at Full Pipe Circumference	To preclude core decompression	$P \le 0.8\, P_o$	W1	(Eq 6-7)
	To preclude coating cracking	Pressure limit: $P \le \min\,(P_k', 1.2\, P_o)$	WT1	(Eq 8-2)
Serviceability at Invert/Crown	To preclude onset of core microcracking	Inside core tensile strain limit: $\varepsilon_{ci} \le 1.5\varepsilon_t'$	W1	Sec. 8.9.1
	To preclude onset of core visible cracking	Inside core tensile strain limit: $\varepsilon_{ci} \le \varepsilon_k' = 11\varepsilon_t'$	WT1, WT2, FT1	Sec. 8.9.1
Serviceability at Springline	To preclude onset of core microcracking and to control microcracking of coating	Outer core tensile strain limit: $\varepsilon_{co} \le 1.5\varepsilon_t'$ Outer coating tensile strain limit: $\varepsilon_{mo} \le 0.8\varepsilon_{km}' = 6.4\varepsilon_{tm}'$	W1	Sec. 8.9.2
	To preclude coating visible cracking	Outer core tensile strain limit: $\varepsilon_{co} \le 11\varepsilon_t'$ Outer coating tensile strain limit: $\varepsilon_{mo} \le \varepsilon_{km}' = 8\varepsilon_{tm}'$	WT1, WT2, FT1	Sec. 8.9.2
	To control core compression	Inner core compression limit: $f_{ci} \le 0.55\, f_c'$	W2	Sec. 8.9.2
		Inner core compression limit: $f_{ci} \le 0.65\, f_c'$	WT3	Sec. 8.9.2
Elastic Limit at Springline	To preclude exceeding wire limit stress, f_{sg}, and core compression stress of $0.75\, f_c'$	f_{sg} wire stress limit plus core compression limit: $-f_{sr} + nf_{cr} + \Delta f_s \le f_{sg}$ $f_{ci} \le 0.75\, f_c'$	FWT1, FWT2, FT2	Sec. 8.9.2
Strength at Springline	To preclude wire yielding	f_{sy} wire stress limit: $-f_{sr} + nf_{cr} + \Delta f_s \le f_{sy}$	FWT3, FWT4	Sec. 8.9.2
	To preclude core crushing	Ultimate moment: $M \le M_{ult}$	FWT5	Sec. 8.9.3
Burst Pressure	To prevent burst failure	$P \le P_b$	FWT6	(Eq 8-4)

*See Section 8
†See Section 4

Sec. 8.4 Maximum Thrust

The maximum thrust N_k' is

$$N_k' = 6D_yP_k' \qquad \text{(Eq 8-3)}$$

Where D_y is in in. and P_k' is in psi.

$$N_k' = \tfrac{1}{2}D_yP_k'$$

Where D_y is in mm and P_k' is in kPa.

Sec. 8.5 Burst Pressure

The burst pressure of the pipe is

$$P_b = \frac{A_y f^*_{yy} + A_s f_{su}}{6D_y} \tag{Eq 8-4}$$

Where A_y and A_s are in in.^{2}, f^*_{yy} and f_{su} are in psi, and D_y is in in.

$$P_b = 2\,\frac{A_y f^*_{yy} + A_s f_{su}}{D_y}$$

Where A_y and A_s are in mm^2, f^*_{yy} and f_{su} are in MPa, and D_y is in mm.

Sec. 8.6 Radial Tension

The maximum radial tension, σ_r, developed between the inner core and steel cylinder of ECP at the invert or crown of the pipe subjected to the bending moment M_1 is computed as the maximum of

$$\begin{aligned}
\sigma_r &= \frac{h_{ci}}{D_y} f_t'(1+\upsilon_2)\left(2-\frac{\lambda_y}{k}\right) \text{ for } \upsilon_2 \le 0 \\
&= \frac{h_{ci}}{D_y} f_t'\left[2-\frac{\nu_2}{\nu}(2-\lambda)\right] \text{ for } \lambda \le 1 \text{ and } \nu_2 > 0 \\
&= \frac{h_{ci}}{D_y} f_t'\left[2(1+\nu_2)-\frac{\nu_2}{\nu}\,\frac{1}{\lambda}(1+\nu)-\nu_2\lambda\right] \text{ for } \lambda > 1 \text{ and } \nu_2 > 0
\end{aligned} \tag{Eq 8-5}$$

as $\nu_2 = \varepsilon_{ci}/\varepsilon_t' - 1$ ranges from –1 to 10. The value of k is computed by the procedure described in Sec. 8.9 for computation of stresses and strains in the pipe wall subjected to moments and thrusts.

Sec. 8.7 Combined Loads and Internal Pressures at Design Limit States

The maximum loads that may be combined with any specified internal pressure and the maximum internal pressures that may be combined with any specified external load for each of the design limit states defined in Sec. 7 shall be determined using the combined moment-thrust design limits described in Sec. 8.2, together with the relationships between internal pressure, external loads, pipe and fluid weights, and moments and thrusts given in Sec. 3 and 4.

Sec. 8.8 Lines of Action of Thrusts

The radial distance from the inside surface of the pipe to the line of prestress thrust N_o is

$$e_o = h_c\,\frac{0.5bh_c + nA_s(1+\lambda_s) + (n'-1)A_y\lambda_y}{bh_c + nA_s + (n'-1)A_y} \tag{Eq 8-6}$$

and to the line of combined-load thrust N resulting from internal pressure and loads is

$$e = h_c \frac{0.5bh_c + (n-m)A_s(1+\lambda_s) + (n'-1)A_y\lambda_y + mbh_m(1+\lambda_m)}{bh_c + (n-m)A_s + (n'-1)A_y + mbh_m} \qquad \text{(Eq 8-7)}$$

Where:

$n = E_s/E_c$

$n' = E_y/E_c$ for both cast and spun concrete

$$m = \begin{cases} \dfrac{E_m}{E_c} & \text{for } -\varepsilon_{mm} \le \varepsilon_{tm}' \\[2ex] \dfrac{E_m}{7E_c}\left(8\dfrac{\varepsilon_{tm}'}{(-\varepsilon_{mm})} - 1\right) & \text{for } \varepsilon_{tm}' < -\varepsilon_{mm} < \varepsilon_{km}' \\[2ex] 0 & \text{for } -\varepsilon_{mm} \ge \varepsilon_{km}' \end{cases} \qquad \text{(Eq 8-8a)}$$

In Eq 8-8a, ε_{mm} refers to the strain in the mortar coating resulting solely from the thrust N_i and is calculated from the following equation:

$$\varepsilon_{mm} = -\frac{N_i}{E_c[bh_c + (n-m)A_s + (n'-1)A_y + mbh_m]} \qquad i = 1,2 \qquad \text{(Eq 8-8b)}$$

For pipe with multiple layers of prestressing, set $A_s = \Sigma A_{sj}$ and $A_s\ (1 + \lambda_s) = \Sigma A_{sj}\ (1 + \lambda_{sj})$.

Sec. 8.9 Conformance With Limit-States Criteria*

The computations of the stresses and strains in the pipe wall and of the moment limits used to ensure that pipe design conforms to all limit-states criteria for the type of pipe selected shall follow the equations and the procedures stated in this section.

The computations of stresses and strains in the pipe wall subjected to moments and thrusts shall follow Sec. 8.9.1 for the invert and crown and Sec. 8.9.2 for the springline. In both cases, the computation procedure is as follows:

1. Assume a strain value for the extreme fiber of core concrete in tension. In Sec. 8.9.1 and 8.9.2, this is done by assuming a value for ν_2.
2. Assume a gradient for the linear strain distribution resulting from the bending moments and thrusts acting on the section of pipe. In Sec. 8.9.1, this is done by assuming a value for k and in Sec. 8.9.2 by assuming a value for k'.

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*For commentary see appendix A, Sec. A.19.

3. Compute the stress distribution over the cross section using the stress–strain relationships for the constituent materials described in Sec. 5 and the residual stresses resulting from prestressing.

4. Compute the stress resultants in the constituent materials and set up the equation for the equilibrium of internal stress resultants and applied thrusts. If the equilibrium of forces is not achieved, change the strain gradient assumed in step 2 and repeat the calculations.

5. Set up the equation for the moment equilibrium of internal stress resultants and the applied bending moment and thrusts. If the equilibrium of moments is not achieved, change the assumed value of the strain at the surface of the core in step 1, and repeat the calculations.

When moment limits corresponding to the strain and stress limit criteria are computed, use the following procedure:

1. Use a strain equal to or less than the strain limit at the stress limit. In Sec. 8.9.1 and 8.9.2, this is done by assuming a value for v_2. Assume a gradient for the linear strain distribution resulting from the applied bending moments and thrusts. In Sec. 8.9.1 this is done by assuming a value for k and in Sec. 8.9.2 by assuming a value for k'.

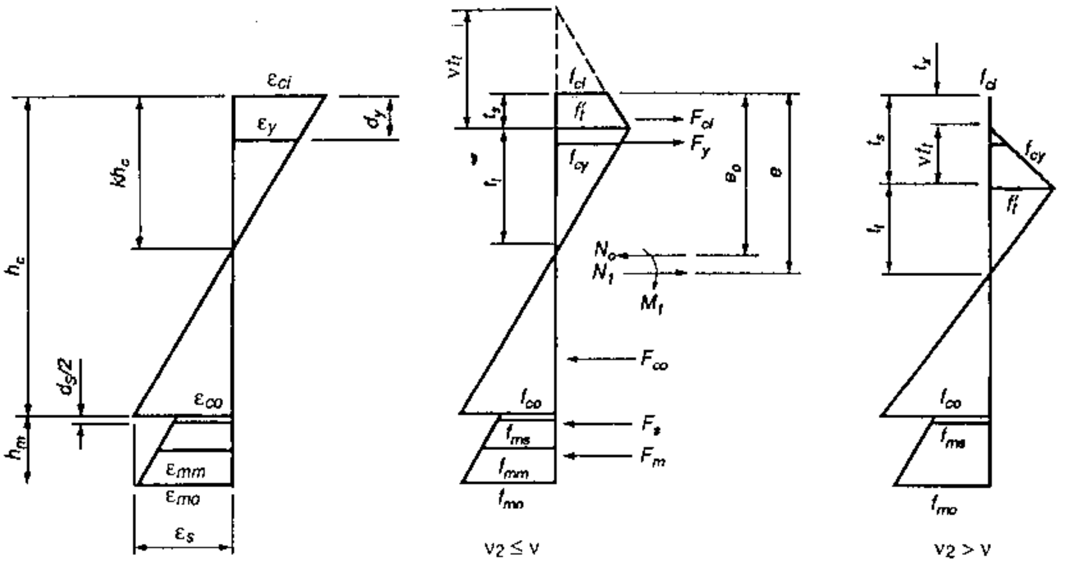
2. Compute the stress distribution over the cross section using the stress–strain relationships for the constituent materials described in Sec. 5 and the residual stresses resulting from prestressing.

3. Compute the stress resultants in the constituent materials and set up the equation for the equilibrium of internal stress resultants and applied thrusts. If the equilibrium of forces is not achieved, change the strain gradient assumed in step 1 and repeat the calculations.

4. Compute the moment from the equilibrium equation for moments considering the internal stress resultants and the applied thrusts. Change the strain in step 1 and repeat the calculations until the maximum moment is found. Set the moment limit equal to the maximum moment.

The computation of the moment limits for the ultimate compressive strength of the pipe wall shall follow Sec. 8.9.3 at the springline and Sec. 8.9.4 at the invert and crown. The computation procedure shall be based on an assumed compressive-strain limit of 0.003 for the extreme fiber of the core or coating and a rectangular (Whitney) compressive-stress block and shall follow the procedure for moment limits corresponding to the strain limit criteria described in this section. The moment limit calculated by the procedure in Sec. 8.9.4 is used in the moment distribution procedure described in Sec. 4.3.3.

8.9.1 *Strains, stresses, thrusts, and moments at invert and crown.* The strain equations stated below express the strains at the critical points of the pipe wall using the assumed value of strain at the inside surface of the core as expressed by the nondimensional factor v_2 and the assumed strain gradient expressed by the nondimensional factor k (see Figure 5). The stress equations stated below are based on the stress–strain relationships of Sec. 5 and the strains at the critical points of the pipe wall.



$$t_t = \frac{1}{1+\nu_2} kh_c$$
$$t_s = \nu_2 t_t$$
$$t_x = (\nu_2 - \nu) t_t$$
$$\lambda = \frac{d_y}{t_s}$$

Strain Diagram

Stress Diagrams

Figure 5 Schematic of strain and stress distributions in pipe-wall cross section at invert and crown

Strain Equations **Stress Equations**

$$\varepsilon_{ci} = (1+\nu_2)\varepsilon_t' \qquad f_{ci} = (1+\nu_2)f_t' \quad \text{for } \nu_2 \le 0$$
$$= \left(1 - \frac{\nu_2}{\nu}\right) f_t' \quad \text{for } 0 < \nu_2 \le \nu$$
$$= 0 \quad \text{for } \nu_2 > \nu$$

$$\Delta\varepsilon_y = \varepsilon_{ci}\left(1 - \frac{\lambda_y}{k}\right) \qquad \Delta f_y = n' f_t'(1+\nu_2)\left(1 - \frac{\lambda_y}{k}\right)$$

$$f_{cy} = f_t'(1+\nu_2)\left(1 - \frac{\lambda_y}{k}\right) \quad \text{for } \nu_2 \le 0 \text{ and all } \lambda$$
$$\text{for all } \nu_2 \text{ and } \lambda \ge 1$$

$$= f_t'\left[1 - \frac{\nu_2}{\nu}(1-\lambda)\right] \quad \text{for } 0 < \nu_2 \le \nu \text{ and } \lambda < 1 \text{ or}$$
$$\text{for } \nu_2 > \nu \text{ and } 1 - \frac{\nu}{\nu_2} < \lambda < 1$$

$$= 0 \quad \text{for } \nu_2 > \nu \text{ and } \lambda \le 1 - \frac{\nu}{\nu_2}$$

$$F_s = A_s(\Delta f_s - f_{ms})$$

$$F_m = F_m' + F_m''$$

Where

e_o and e are given by Eq 8-8 and 8-9, respectively, and

$$M_{ci} = -F_{ci}h_c\left(1+\lambda_s-\frac{k}{3}\right) \qquad \text{for } \nu_2 \le 0$$

$$= -F_{ci}'\left[(1+\lambda_s)h_c-t_t\left(v_2+\frac{1-\nu}{3}\right)\right]-F_{ci}''\left[(1+\lambda_s)h_c+t_t\,\frac{\nu-\nu_2}{3}\right]$$

$$\text{for } 0 < \nu_2 \le \nu$$

$$= -F_{ci}'\left[(1+\lambda_2)h_c-t_t\left(\nu_2+\frac{1-\nu}{3}\right)\right] \qquad \text{for } \nu_2 > \nu$$

$$M_y = -F_yh_c(1+\lambda_s-\lambda_y)$$

$$M_{co} = -F_{co}h_c\left(\frac{1-k}{3}+\lambda_s\right)$$

$$M_m = F_m'h_c\left(\frac{2\lambda_m}{3}-\lambda_s\right)+F_m''h_c\left(\frac{4\lambda_m}{3}-\lambda_s\right)$$

For a pipe with multiple layers of prestressing wire ($f = 2$ or 3), the expressions for $\Delta\varepsilon_s$, Δf_s, f_{sr}, F_s, and A_s defined earlier in this section refer to the outer layer of prestressing wire, and

$$\lambda_{sj} = \frac{(2j-1)d_s+2(j-1)d_w}{2h_c} \qquad \text{for } j = 1, \ldots, f$$

Where:

d_w = the total clear mortar thickness between wire layers.

For the j-th layer of prestressing wire, the strain in the wire, ε_{sj} is

$$\varepsilon_{sj} = \Delta\varepsilon_{sj}-\frac{f_{srj}-nf_{cr}}{E_s}$$

Where:

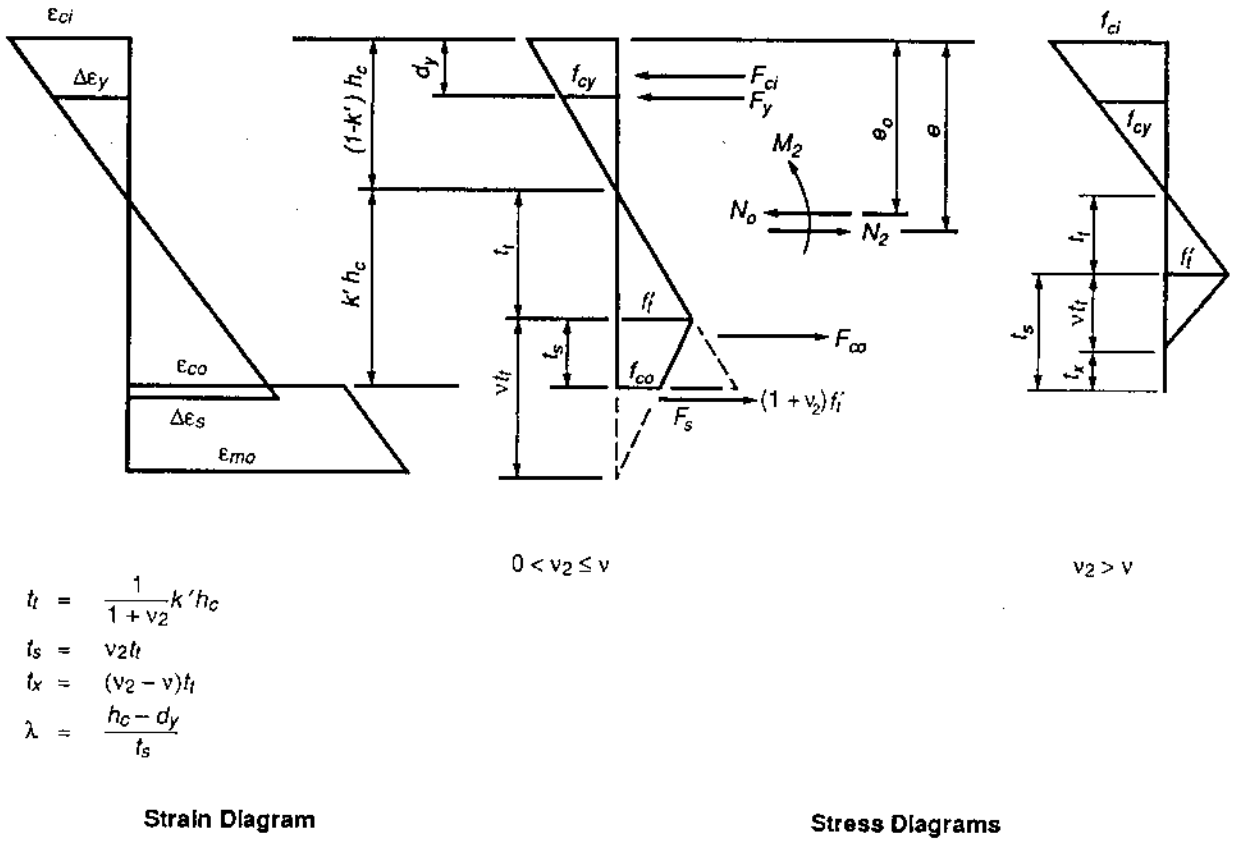
$$\Delta\varepsilon_{sj} = \Delta\varepsilon_s\left[1-\frac{\lambda_{sf}-\lambda_{sj}}{\lambda_{sf}+k'}\right]$$

and $\Delta\varepsilon_s$ is the strain in the outer layer of prestressing wire.

The stress layer in the j-th layer of prestressing wire f_{sj} is calculated from the prestressing wire stress–strain function Eq 5-7 substituting ε_{sj} for ε_s.

In Eq 8-9

$$F_s = \sum_{j=1}^{f} F_{sj}$$



$t_t = \frac{1}{1+\nu_2}k'h_c$

$t_s = \nu_2 t_t$

$t_x = (\nu_2 - \nu)t_t$

$\lambda = \frac{h_c - d_y}{t_s}$

Figure 6 Schematic of strain and stress distributions in pipe-wall cross section at springline

Strain Equations **Stress Equations**

$$\varepsilon_{co} = (1+\nu_2)\varepsilon_t' \qquad f_{co} = (1+\nu_2)f_t' \qquad \text{for } \nu_2 \le 0$$

$$= \left(1-\frac{\nu_2}{\nu}\right)f_t' \qquad \text{for } 0 < \nu_2 \le \nu$$

$$= 0 \qquad \text{for } \nu_2 > \nu$$

$$\varepsilon_{ci} = \varepsilon_{co}\left(\frac{1}{k'}-1\right) \qquad f_{ci} = (1+\nu_2)f_t'\left(\frac{1}{k'}-1\right)$$

$$\Delta\varepsilon_y = \varepsilon_{co}\left(\frac{1-\lambda_y}{k'}-1\right) \qquad \Delta f_y = n'(1+\nu_2)f_t'\left(\frac{1-\lambda_y}{k'}-1\right)$$

$$f_{cy} = (1+\nu_2)f_t'\left(\frac{1-\lambda_y}{k'}-1\right) \qquad \text{for } \nu_2 \le 0 \text{ and all } \lambda \text{ or all } \nu_2 \text{ and } \lambda \ge 1$$

$$= \left[\frac{\nu_2}{\nu}(1-\lambda)-1\right]f_t' \qquad \text{for } 0 < \nu_2 \le \nu \text{ and } \lambda < 1 \text{ or } \nu_2 > \nu \text{ and } 1-\frac{\nu}{\nu_2} \le \lambda < 1$$

$$= 0 \qquad \text{for } \nu_2 > \nu \text{ and } \lambda < 1 - \frac{\nu}{\nu_2}$$

$$\Delta\varepsilon_s = \varepsilon_{co}\left(1 + \frac{\lambda_s}{k'}\right) \qquad \Delta f_s = n(1+\nu_2)f_t'\left(1 + \frac{\lambda_s}{k'}\right) \qquad \text{for } \Delta\varepsilon_s \le \frac{f_{sg} + f_{sr} - nf_{cr}}{E_s}$$

$$\Delta f_s = f_s(\varepsilon_s) + f_{sr} - nf_{cr} \qquad \text{for } \Delta\varepsilon_s > \frac{f_{sg} + f_{sr} - nf_{cr}}{E_s}$$

$$\varepsilon_s = \Delta\varepsilon_s - \frac{f_{sr} - nf_{cr}}{E_s}$$

$$\varepsilon_{mo} = \varepsilon_{co}\left(1 + \frac{2\lambda_m}{k'}\right) + \varepsilon_{cr}$$

Note that $f_s(\varepsilon_s)$ denotes the stress in the prestressing wire calculated for a wire strain of ε_s from the wire stress–strain function (Eq 5-7).

$\Sigma F = 0$ implies

$$N_o - N_2 = F_{ci} + F_y + F_{co} + F_s \qquad \text{(Eq 8-11)}$$

Where:

$$F_{ci} = \tfrac{1}{2}(1-k')bh_c f_{ci}$$

$$F_y = A_y(\Delta f_y - f_{cy})$$

$$F_{co} = -\tfrac{1}{2}bk'h_c(1+\nu_2)f_t' \qquad \text{for } \nu_2 \le 0$$

$$= (F_{co}' + F_{co}'')$$

$$\text{where } F_{co}' = -\tfrac{1}{2}bt_t(1+\upsilon)f_t' \text{ and}$$

$$F_{co}'' = \tfrac{1}{2}bt_t(\nu - \nu_2)f_{co} \qquad \text{for } 0 < \nu_2 \le \nu$$

$$= -\tfrac{1}{2}bt_t(1+\nu)f_t' \qquad \text{for } \nu_2 > \nu$$

$$F_s = -A_s\Delta f_s$$

ΣM about wire = 0 implies

$$M_2 + N_o[(1+\lambda_s)h_c - e_o] - N_2[(1+\lambda_s)h_c - e] = M_{ci} + M_y + M_{co} \qquad \text{(Eq 8-12)}$$

Where:

e_o and e are given in Eq 8-6 and 8-7, respectively, and

$$M_{ci} = F_{ci}\left[(1+\lambda_s)h_c - \frac{(1-k')h_c}{3}\right]$$

$$M_y = F_y h_c(1 + \lambda_s - \lambda_y)$$

$$M_{co} = F_{co}h_c\left(\lambda_s + \frac{k'}{3}\right) \qquad \text{for } \nu_2 \le 0$$

$$= F'_{co}\left[h_c\lambda_s + t_t\left(\nu_2 + \frac{1-\nu}{3}\right)\right] + F''_{co}\left[h_c\lambda_s - t_t\frac{\nu - \nu_2}{3}\right] \qquad \text{for } 0 < \nu_2 \le \nu$$

$$= F_{co}\left[h_c\lambda_s + t_t\left(\nu_2 + \frac{1-\nu}{3}\right)\right] \qquad \text{for } \nu_2 > \nu$$

For serviceability criteria, set $e = e_o$. This requirement is consistent with the requirement that tensile stress in the mortar coating at the springline be neglected.

For a pipe with multiple layers of prestressing (f = 2 or 3), the expressions for $\Delta\varepsilon_s$, Δf_s, f_{sr}, F_s, and A_s defined earlier in this section refer to the outer layer of prestressing wire, and

$$\lambda_{sj} = \frac{(2_j - 1)d_s + 2(j-1)d_w}{2h_c} \qquad j = 1, \ldots, f$$

Where:

d_w = the total clear mortar thickness between wire layers.

For the j-th layer of prestressing wire, the strain in the wire ε_{sj} is

$$\varepsilon_{sj} = \Delta\varepsilon_{sj} - \frac{f_{srj} - nf_{cr}}{E_s}$$

Where:

$\Delta\varepsilon_{sj} = \Delta\varepsilon_s\left(1 - \frac{\lambda_{sf} - \lambda_{sj}}{\lambda_{sf} + k'}\right)$

$\Delta\varepsilon_s$ = the strain in the outer layer of prestressing wire.

The stress in the j-th layer of prestressing wire f_{sj} is calculated from the stress-strain function (Eq 5-7) substituting ε_{sj} for ε_s.

In Eq 8-11

$$F_s = \sum_{j=1}^{f} F_{sj}$$

Where:

$F_{sj} = -A_{sj}\Delta f_{sj}$,

and Δf_{sj} is expressed by Δf_s with λ_s, f_s, and f_{sr} replaced by λ_{sj}, f_{sj}, and f_{srj}, respectively.

ΣM is calculated about the center of the outer layer of prestressing wire by adding

$$M_s = \sum_{j=1}^{f-1} F_{sj}\,h_c(\lambda_{sf} - \lambda_{sj})$$

to the right-hand side of Eq 8-12.

Equation 8-12 is valid for $N_2 \le N_k'$.

For $N_2 > N_k'$, M_2 shall not exceed the M_2-moment limit corresponding to the elastic limit stress f_{sg} in the outer layer of prestressing wire ($f = 1, 2, \text{or } 3$). This will ensure that the limit criterion specified in Tables 3 and 4 is met. The M_2-moment limit at N_2 is computed by linear interpolation between the calculated M_2-moment limit at N_k' and the zero moment corresponding to the axial thrust N_{sg} that causes elastic limit stress in the outer layer of prestressing wire without external load.

$$N_{sg} = A_c f_c(-\varepsilon_{cr} + \Delta\varepsilon_{sg}) + A_y f_y(-\varepsilon_{yr} + \Delta\varepsilon_{sg}) + \sum_{j=1}^{f} A_{sj} f_{sj}(\varepsilon_{srj} + \Delta\varepsilon_{sg})$$

Where:

> $f_c\ (-\varepsilon_{cr} + \Delta\varepsilon_{eg})$, $f_y\ (-\varepsilon_{yr} + \Delta\varepsilon_{sg})$, and $f_{sj}\ (\varepsilon_{srj} + \Delta\varepsilon_{sg})$ are the stresses in the core concrete, steel cylinder, and the j-th layer of prestressing wire, calculated from the stress–strain relationships of Sec. 5.3.5, 5.5.4, and 5.6.4, respectively; $\varepsilon_{yr} = f_{yr}/E_y$; $\varepsilon_{srj} = -f_{srj}/E_s$ is the wire tensile strain corresponding to the final prestress in the j-th layer; and $\Delta\varepsilon_{sg} = \varepsilon_{sg} - \varepsilon_{srf}$ is the circumferential strain increment.

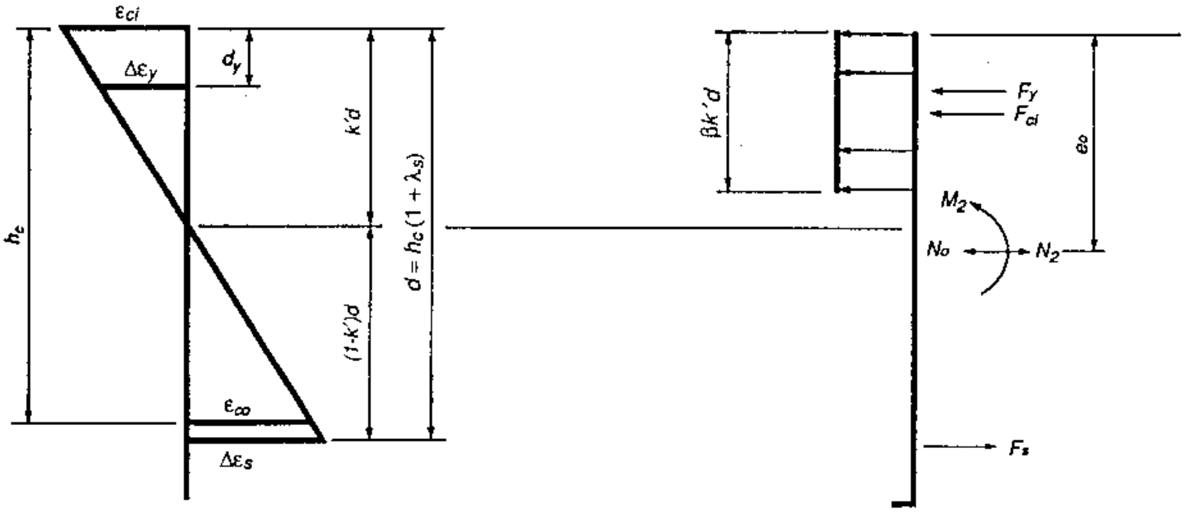
For $N_2 > N_k'$, M_2 shall not exceed the M_2-moment limit corresponding to the yield strength f_{sy} of the outer layer of prestressing wire ($f = 1, 2, \text{or } 3$). This will ensure that the limit criterion specified in Tables 3 and 4 is met. The M_2-moment limit at N_2 is computed by linear interpolation between the calculated M_2-moment limit at N_k' and the zero moment at the axial thrust N_{sy} that causes yielding of the outer layer of prestressing wire without external load.

$$N_{sy} = A_c f_c(-\varepsilon_{cr} + \Delta\varepsilon_{sy}) + A_y f_y(-\varepsilon_{yr} + \Delta\varepsilon_{sy}) + \sum_{j=1}^{f} A_{sj} f_{sj}\,(\varepsilon_{srj} + \Delta\varepsilon_{sy})$$

Where:

> $f_c\ (-\varepsilon_{cr} + \Delta\varepsilon_{sy})$, $f_y\ (-\varepsilon_{yr} + \Delta\varepsilon_{sy})$, and $f_{sj}\ (\varepsilon_{srj} + \Delta\varepsilon_{sy})$ are the stresses in the concrete core, steel cylinder, and the j-th layer of prestressing wire, calculated from the stress–strain relationships of Sec. 5.3.5, 5.5.4, and 5.6.4, respectively; $\varepsilon_{yr} = f_{yr}/E_y$; $\varepsilon_{srj} = -f_{srj}/E_s$ is the wire tensile strain corresponding to the final prestress in the j-th layer; and $\Delta\varepsilon_{sy} = \varepsilon_{sy} - \varepsilon_{srf}$ is the circumferential strain increment.

8.9.3 *M2-Moment limit for ultimate compressive strength of core concrete.* The strain equations stated below express the strains at the critical points of the pipe wall using the ultimate strain of 0.003 at the inner surface of the core and the assumed strain gradient expressed by the nondimensional factor k′ (see Figure 7). The stress equations stated below are based on a rectangular (Whitney) stress block for core concrete in compression, the stress–strain relationships of Sec. 5, and the strains at the critical points of the pipe wall.



Strain Diagram **Stress Diagram**

Figure 7 Schematic of strain and stress distributions for computation of M_2-moment limit for ultimate compressive strength of core concrete

Strain Equations	**Stress Equations**	
$\varepsilon_{ci} = 0.003$	$f_{ci} = 0.85f_c'$	
$\Delta\varepsilon_y = \varepsilon_{ci}\dfrac{k'-\lambda_y/(1+\lambda_s)}{k'}$	$f_{cy} = 0.85f_c'$	for $d_y \le \beta k'd$
	$= 0$	for $d_y > \beta k'd$
	$\Delta f_y = E_y\Delta\varepsilon_y$ and shall not exceed $f_{yy} - f_{yr} + n'f_{cr}$	
$\Delta\varepsilon_s = \varepsilon_{ci}\dfrac{1-k'}{k'}$	$\Delta f_s = f_s(\varepsilon_s) + f_{sr} - nf_{cr}$	

In the above equations, f_s (ε_s) denotes the stress in the prestressing wire calculated for a wire strain of ε_s from the wire stress–strain function (Eq 5-7), and

$$\beta = 0.85 - 0.05\left(\frac{f_c'}{1{,}000} - 4\right) \text{ for } f_c' \ge 4{,}000 \text{ psi}$$

If f_c' is in MPa, substitute 145 f_c' for f_c' in the equation for β.

$\Sigma F = 0$ implies

$$N_0 - N_2 = F_{ci} + F_y + F_s \qquad \text{(Eq 8-13)}$$

Where:

$F_{ci} = b\beta k'd(0.85f_c')$.
$F_y = A_y(\Delta f_y - f_{cy})$.
$F_s = -\Delta f_s A_s$.

Note that if $\Delta\varepsilon_s \geq \Delta\varepsilon_{su} = (1.63 f_{su} + f_{sr} - n f_{cr})/E_s$, then set $\Delta f_s = f_{su} + f_{sr} - n f_{cr}$ and $\Delta\varepsilon_s = \Delta\varepsilon_{su}$. Furthermore, if

$$\frac{f_{sg}}{E_s} < \varepsilon_s < \frac{163 f_{su}}{E_s}, \text{ then set } \Delta f_s = f_{su}\left[1 - \left(1 - 0.6133\frac{\varepsilon_s E_s}{f_{su}}\right)^{2.25}\right] + f_{sr} - n f_{cr}$$

$$\varepsilon_{ci} = \frac{k'}{1-k'}\Delta\varepsilon_s$$

and

$$\Delta\varepsilon_y = \Delta\varepsilon_s \frac{k' - \dfrac{\lambda_y}{1+\lambda_s}}{1-k'}$$

ΣM about wire = 0 implies

$$M_2 + (N_o - N_2)[(1+\lambda_s)h_c - e_o] = M_{ci} + M_y \qquad \text{(Eq 8-14)}$$

Where:

e_o is given by Eq 8-6, and

$$M_{ci} = F_{ci} d\left(1 - \frac{\beta k'}{2}\right)$$

$$M_y = F_y(d - d_y).$$

For a pipe with multiple layers of prestressing wire (f = 2 or 3), the expressions for $\Delta\varepsilon_s$, Δf_s, f_{sr}, F_s, and A_s defined earlier in this section refer to the outer layer of prestressing wire, and

$$\lambda_{sj} = \frac{(2j-1)d_s + 2(j-1)d_w}{2h_c} \qquad \text{for } j = 1, \ldots, f$$

Where:

d_w = the total clear mortar thickness between wire layers.

For the j-th layer of prestressing wire, the strain in the wire ε_{sj} is

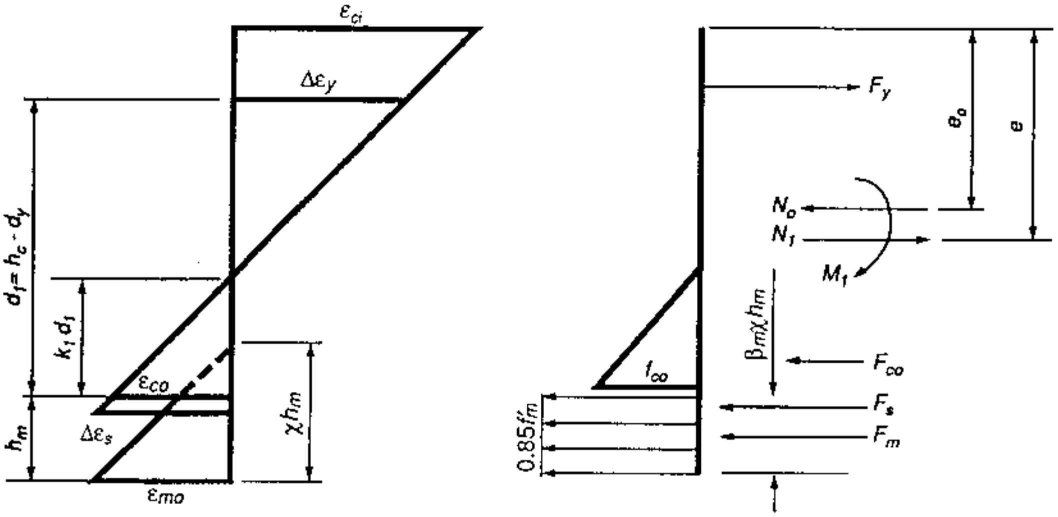
$$\varepsilon_{sj} = \Delta\varepsilon_{sj} - \frac{f_{srj} - n f_{cr}}{E_s}$$

Where:

$$\Delta\varepsilon_{sj} = \Delta\varepsilon_s\left[1 - \frac{\lambda_{sr} - \lambda_{sj}}{\lambda_{sf} + k'}\right]$$

and $\Delta\varepsilon_s$ is the strain in the outer layer of prestressing wire.

The stress in the j-th layer of prestressing wire f_{sj} is calculated from the stress–strain function (Eq 5-7) subsituting ε_{sj} for ε_s.



Strain Diagram

Stress Diagram

Figure 8 Schematic of strain and stress distributions for computation of M_1-moment limit for ultimate compressive strength of coating

In Eq 8-13

$$F_s = \sum_{j=1}^{f} F_{sj}$$

Where:

$$Fsj = -A_{sj} \Delta f_{sj}$$

and Δf_{sj} is expressed by Δf_s with λ_s, f_s, and f_{sr} replaced by λ_{sj}, f_{sj}, and f_{srj}, respectively.

ΣM is calculated about the center of the outer layer of prestressing wire by adding

$$M_s = \sum_{j=1}^{f-1} F_{sj} h_c (\lambda_{sf} - \lambda_{sj})$$

to the right-hand side of Eq 8-14.

8.9.4 *M_1-Moment limit for compressive strength of coating.* The M_1-moment limit for LCP computed in accordance with the procedures of this section is used in the moment-redistribution procedure described in Sec. 4.3.3.

The strain equations stated below express the strains at the critical points of the pipe wall using the ultimate strain of 0.003 at the outer surface of the coating and the assumed strain gradient expressed by the nondimensional factor k_1 (see Figure 8). The stress equations stated below are based on a rectangular (Whitney) stress block for coating mortar in compression, the stress–strain relationships of Sec. 5, and the strains at the critical points of the pipe wall.

Strain Equations

$$\varepsilon_{ci} = \frac{\varepsilon_{mo} + \varepsilon_{cr}}{k_1 d_1 + h_m}[(1-k_1)d_1 + d_y]$$

$$\Delta\varepsilon_y = \frac{\varepsilon_{mo} + \varepsilon_{cr}}{k_1 d_1 + h_m}(1-k_1)d_1$$

$$\varepsilon_{co} = \frac{\varepsilon_{mo} + \varepsilon_{cr}}{k_1 d_1 + h_m} k_1 d_1$$

$$\Delta\varepsilon_s = \frac{\varepsilon_{mo} + \varepsilon_{cr}}{k_1 d_1 + h_m}(k_1 d_1 + h_c \lambda_s)$$

$$\varepsilon_{mo} = 0.003$$

Stress Equations

$$f_{ci} = 0$$

$$\Delta f_y = \frac{(1-k_1)d_1}{k_1 d_1 + h_m} n'(f_{cr} + E_c \varepsilon_{mo})$$

$$\le f_{yy} + f_{yr} - n' f_{cr}$$

$$f_{cy} = f_{co}$$

$$f_{co} = \frac{E_c \varepsilon_{mo} + f_{cr}}{k_1 d_1 + h_m} k_1 d_1 \quad \text{for } k_1 d_1 > 0$$

$$= 0\text{, otherwise}$$

$$\Delta f_s = n\frac{E_c \varepsilon_{mo} + f_{cr}}{k_1 d_1 + h_m}(k_1 d_1 + h_c \lambda_s)$$

$$f_{ms} = 0.85 f_m' \qquad \text{for } h_m - h_c\lambda_s < \beta_m \chi h_m$$

$$= 0 \qquad \text{otherwise}$$

$$f_{mo} = 0.85 f_m' \qquad \text{for } k_1 d_1 > -hM$$

$$= 0 \qquad \text{otherwise}$$

In the above equations,

$$\chi h_m = \frac{\varepsilon_{mo}(k_1 d_1 + h_m)}{\varepsilon_{mo} + \varepsilon_{cr}}$$

The depth of the Whitney block $\beta_m \chi h_m$, in which

$$\beta_m = 0.85 - 0.05\left(\frac{f_m}{1{,}000} - 4\right) \text{ with } f_m' = 5{,}500 \text{ psi}$$

should not be taken greater than the mortar thickness h_m.
If f_c' is in MPa, substitute 145 f_c' for f_c' in the equation for β_m.
$\Sigma F = 0$ implies

$$N_0 - N_1 = F_{ci} + F_y + F_{co} + F_s + F_m \qquad \text{(Eq 8-15)}$$

Where:

$F_{ci} = 0.$
$F_y = -A_y(\Delta f_y - f_{cy}).$
$F_{co} = ½ b k_1 d_1 f_{co}.$
$F_s = A_s(\Delta f_s - f_{ms}).$
$F_m = b\beta_m \chi h_m (f_{mo}).$

ΣM about cylinder = 0 implies

$$M_1 + N_o(e_o - d_y) - N_1(e - d_y) = M_{co} + M_s + M_m \qquad \text{(Eq 8-16)}$$

Where:

e_o and e are given by Eq 8-6 and 8-7, respectively, and

$$M_{co} = F_{co} d_1 \left(1 - \frac{k_1}{3}\right)$$

$$M_s = F_s(d_1 + h_c \lambda_s)$$

$$M_m = F_m(d_1 + h_m - ½\beta_m \chi h_m)$$

For LCP, the cylinder and the first layer of prestressing wire are lumped into an equivalent steel area. Analysis is performed using the following modifications:

1. Set $A_y, d_y = 0$
2. Replace n by n^* where

$$n^* = n\left[1 + \frac{A_y}{A_s}\frac{(n' - 1)}{n}\right] \qquad \text{for } k_1 \geq 0$$

$$= n\left(1 + \frac{A_y}{A_s}\frac{n'}{n}\right) \qquad \text{for } k_1 < 0$$

3. Replace wire diameter d_s by d^*_s where

$$d^*_s = \frac{nA_s d_s - (n' - 1)A_y t_y}{nA_s + (n' - 1)A_y} \qquad \text{for } k_1 \geq 0$$

$$= \frac{nA_s d_s - n'A_y t_y}{nA_s + n'A_y} \qquad \text{for } k_1 < 0$$

For a pipe with multiple layers of prestressing (f = 2 or 3), the expression for $\Delta\varepsilon_s$, Δ_{fs}, F_s, and A_s defined earlier in this section refer to the outer layer of prestressing wire, and

$$\lambda_{sj} = \frac{(2j - 1)d_s + 2(j - 1)d_w}{2h_c} \qquad \text{for } j = 1, \ldots, f$$

Where:

d_w = the total clear mortar thickness between wire layers.

In Eq 8-15

$$F_s = \sum_{j=1}^{f} F_{sj}$$

Where:

$F_{sj} = A_s(\Delta f_{sj} - f_{msj})$

and Δf_{sj} and f_{msj} are given by the expressions for Δf_s and f_{ms} with λ_s replaced by λ_{sj}.

ΣM is calculated about the center of the outer layer of prestressing wire by replacing M_s in Eq 8-16 by

$$M_s = \sum_{j=1}^{f-1} F_{sj}(d_1 + h_c \lambda_{sj})$$

SECTION 9: DESIGN SELECTION TABLES

In order to make AWWA C304 easier to use, design selection tables are included for 16-in. through 60-in. [410-mm through 1,520-mm] LCP. Sec. 9.4 summarizes the criteria used in these tables. Designs for conditions other than those listed in Sec. 9.4 or the selection tables must be obtained by implementing the design procedures specified in this standard. The following three design examples are presented to demonstrate the use of the design selection tables.

Sec. 9.1 Design Example 1

Given conditions are as follows:

pipe size	= 24 in. (610 mm)
working pressure (P_w)	= 175 psi (1,206 kPa)
transient pressure (P_t)	= 0.4 P_w
field-test pressure (P_{ft})	= 1.2 P_w
earth cover	= 12 ft (3.65 m)
soil density	= 120 lb/ft^3 (1,922 kg/m)
bedding	= type R-1

All of the design conditions fall within the criteria given in Sec. 9.4. Using the design selection table for 24-in. (610-mm) LCP with type R-1 bedding, an earth cover of 12 ft (3.65 m), and a system working pressure of 175 psi (1,206 kPa), the required A_s is 0.32 in.^{2}/lin ft (677 mm^2/m).

Sec. 9.2 Design Example 2

Given conditions are as follows:

pipe size	= 36 in. (915 mm)
working pressure (P_w)	= 150 psi (1,034 kPa)
transient pressure (P_t)	= 50 psi (345 kPa)
field-test pressure (P_{ft})	= 165 psi (1,138 kPa)
earth cover	= 8 ft (2.44 m)
soil density	= 120 lb/ft^3 (1,922 kg/m^3)
bedding	= type R-2

The specified transient pressure of 50 psi (345 kPa) is less than the transient pressure used in the selection tables (0.4 × 150 psi = 60 psi [0.4 × 1,034 kPa = 414 kPa]) and the specified field-test pressure of 165 psi (1,138 kPa) is less than the field-test pressure used in the selection tables (1.2 × 150 psi = 180 psi [1.2 × 1,034 kPa = 1,241 kPa]), therefore the selection tables can be used. From the table for 36-in. (915-mm) LCP with type R-2 bedding, an earth cover of 8 ft (2.44 m), and a working pressure of 150 psi (1,034 kPa), the required A_s is 0.37 in.^{2}/lin ft (783 mm^2/m).

Sec. 9.3 Design Example 3

Given conditions are as follows:

pipe size = 48 in. (1,220 mm)
working pressure (P_w) = 150 psi (1,034 kPa)
transient pressure (P_t) = 0.4 P_w
field-test pressure (P_{ft}) = 1.2 P_w
earth cover = 16 ft (4.88 m)
soil density = 120 lb/ft^3 (1,922 kg/m^3)

Find the required A_s for each bedding class.

All of the design conditions fall within the criteria stated in Sec. 9.4. Using the design selection table for 48-in. (1,220-mm) LCP with a working pressure of 150 psi (1,034 kPa) and an earth cover of 16 ft (4.88 m), the required A_s for each of the five bedding details is as follows:

Bedding Detail	Required A_s (in.^{2}/ ft)
R-1	–
R-2	.66++
R-3	.63+
R-4	.58+
R-5	.53

The hyphen (–) in the Required A_s column for R-1 bedding indicates that a special design is required. This could include a second layer of prestressing wire, a larger-diameter prestressing wire, a higher concrete strength, a thicker steel cylinder, a thicker concrete core, or some combination of these items.

The two plus signs (++) next to the A_s value under R-2 bedding indicate that a 28-day compressive strength of 7,000 psi (48.3 MPa) is required. The single plus sign (+) next to the A_s values under R-3 and R-4 beddings indicates that a 28-day compressive strength of 6,500 psi (44.8 MPa) is required. Standard 28-day compressive strength of 6,000 psi (41.4 MPa) is sufficient for the design under R-5 bedding.

Sec. 9.4 Lined-Cylinder Pipe Standard Prestress Design Tables

Tables 5–14 and Figure 9, which follow, list the amount of prestressing wire (A_s), in square inches per linear foot, for working pressure and earth cover combinations commonly used. These designs are based on the criteria specified in this standard and the following:

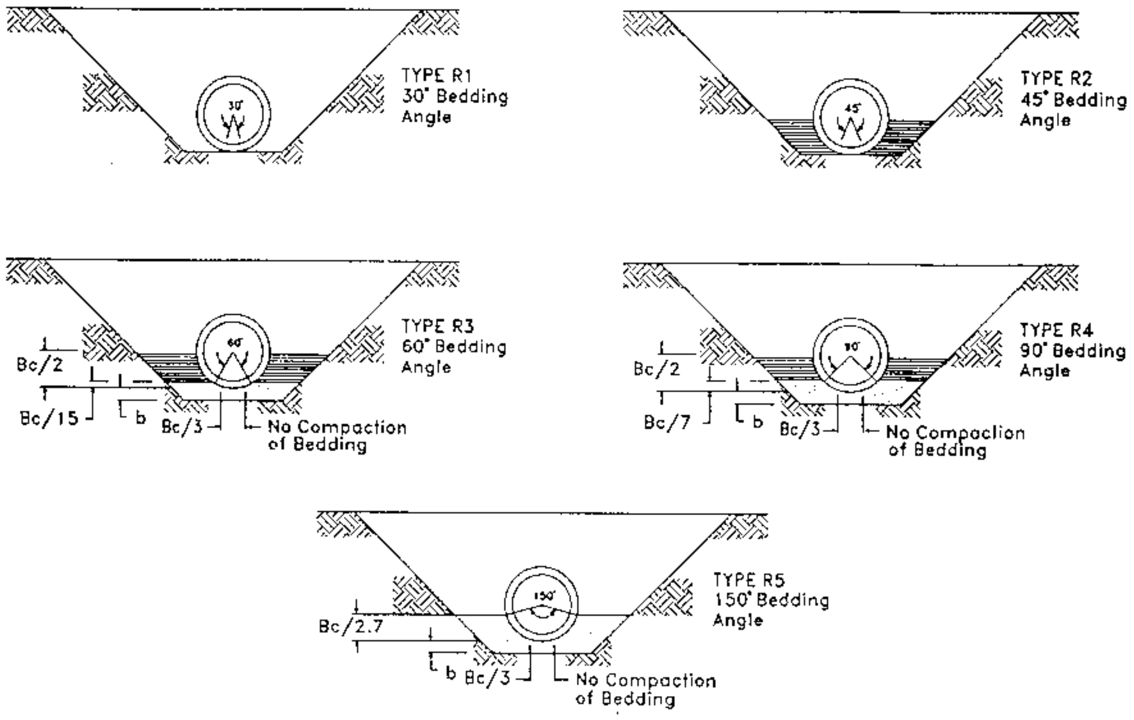
1. Concrete-core thickness = pipe diameter ÷ 16.
2. Mortar-coating thickness = ¾ in. (19 mm) over the wire.
3. Transient pressure (P_t) = 40 percent P_w or 40 psi (276 kPa), whichever is greater.
4. Field-test pressure (P_{ft}) = 1.2 P_w.
5. Transient external load = AASHTO HS20 truck loading (two trucks passing) on unpaved road.
6. Prestressing wire = 6 gauge ASTM A648 class III.
7. Steel-cylinder thickness = 16 gauge (1.52 mm).

8. Minimum 28-day compressive strength of concrete core (f_c') = 6,000 psi (41.4 MPa), except where higher-strength concrete is required as denoted by the following:

   a) + = 6,500 psi (44.8 MPa)
   b) ++ = 7,000 psi (48.3 MPa)
   c) +++ = 7,500 psi (51.7 MPa)

9. Average relative humidity of storage environment = 70 percent.
10. Time in outdoor storage (t_1) = 270 days.
    Burial time after outdoor storage (t_2) = 90 days.
11. Concrete modulus multiplier (C_E) = 1.
    Wire-relaxation multiplier (C_R) = 1.
    Concrete-shrinkage multiplier (C_S) = 1.
    Concrete-creep multiplier ($C\phi$) = 1.
12. Earth loads = Marston/Spangler theory for rigid pipe using transition width trench (same as positive projecting embankment condition).
13. Backfill density = 120 lb/ft^3 (1,922 kg/m^3).
14. Rankine's lateral pressure ratio × coefficient of internal friction = $K\mu = 0.19$.
15. Settlement ratio × projection ratio = $r_{sd}p = 0.5$.
16. Pipe stresses are determined using Olander's coefficients.

Designs to meet criteria different from those stated in this section can be developed using AWWA C304.



Bc = Outside Diameter of Pipe

Depth of Bedding Material Below Pipe

Pipe I.D.	b (minimum)
27 in. and smaller	3 in.
30 in. to 60 in.	4 in.
66 in. and larger	6 in.

LEGEND

☐ Bedding material, free from large clods or rocks, well compacted after pipe is laid, or granular material consolidated after pipe is laid.

▤ Compacted backfill material, free from large clods or rocks.

Embankment condition indicates trench width at top of pipe exceeds transition width.

For bedding types R1 and R2, trench bottom shall be over excavated and bedding material shall extend to depth "b" below bottom of pipe if subgrade is rock or other unyielding material.

The bedding types illustrated above are referenced in Tables 5–14.

Figure 9 Bedding details for prestressed concrete cylinder pipe embankment condition

Table 5 Standard prestress design—16 in. (410 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (ft)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++
	20.0	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++	0.37+++	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++
	20.0	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++	0.37+++	—
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++
	20.0	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++	0.37+++	—
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++
	20.0	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++	0.37+++	—
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.25
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++
	20.0	0.23	0.23	0.23	0.23	0.23	0.28+	0.32++	0.37+++	—

-- Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 6 Standard prestress design—18 in. (460 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31+
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29+	0.34++	0.40+++
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31+
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29+	0.34++	0.40+++
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.2	0.27
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29+	0.34++	0.40+++
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31+
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29+	0.34++	0.40+++
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.24	0.27
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31+
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29+	0.34++	0.40+++

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 7 Standard prestress design—20 in. (510 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.27	0.31
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.33
	20.0	0.23	0.23	0.23	0.23	0.23	0.24	0.26+	0.31++	0.37+++
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.27	0.31
	20.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26+	0.31++	0.37+++
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31
	20.0	0.23	0.23	0.23	0.23	0.23	0.26	0.26+	0.31++	0.37+++
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31+
	20.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26+	0.31++	0.37+++
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.29
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31
	20.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26+	0.31++	0.37+++

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 8 Standard prestress design—24 in. (610 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.27	0.32	0.37
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.34	0.39
	16.0	0.23	0.23	0.23	0.23	0.23	0.25	0.30	0.35	0.40+
	18.0	0.23	0.23	0.23	0.24	0.26	0.29	0.32	0.37+	0.42+
	20.0	0.23	0.23	0.25	0.27	0.30	0.32	0.34+	0.38++	0.43++
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.36
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.27	0.32	0.38
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.29	0.34	0.39
	18.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.40+
	20.0	0.23	0.23	0.23	0.24	0.26	0.29	0.32+	0.37+	0.41++
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.37
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.33	0.38
	18.0	0.23	0.23	0.23	0.23	0.23	0.24	0.29	0.34	0.39+
	20.0	0.23	0.23	0.23	0.23	0.24	0.26	0.31	0.35+	0.40++
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.36
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.27	0.32	0.37+
	20.0	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.33+	0.37++
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	5.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	6.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	7.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	8.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	9.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	10.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	12.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	14.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	16.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34
	18.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.34+
	20.0	0.23	0.23	0.23	0.23	0.23	0.23	0.26	0.30+	0.35++

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 9 Standard prestress design—30 in. (760 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	5.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	6.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	7.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.42
	8.0	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.37	0.44
	9.0	0.23	0.23	0.23	0.23	0.23	0.26	0.32	0.39	0.45
	10.0	0.23	0.23	0.23	0.23	0.23	0.27	0.34	0.40	0.46
	12.0	0.23	0.23	0.23	0.23	0.23	0.30	0.36	0.42	0.49
	14.0	0.23	0.23	0.23	0.25	0.28	0.32	0.38	0.45	0.50+
	16.0	0.23	0.23	0.26	0.29	0.32	0.35	0.41	0.46+	0.52++
	18.0	0.24	0.27	0.30	0.33	0.36	0.39	0.44+	0.48++	0.54+++
	20.0	0.28	0.31	0.34	0.37+	0.40+	0.42++	0.47++	0.51+++	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	5.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	6.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	7.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.42
	8.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.43
	9.0	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.38	0.44
	10.0	0.23	0.23	0.23	0.23	0.23	0.26	0.32	0.39	0.45
	12.0	0.23	0.23	0.23	0.23	0.23	0.28	0.35	0.41	0.47
	14.0	0.23	0.23	0.23	0.23	0.25	0.30	0.37	0.43	0.49+
	16.0	0.23	0.23	0.23	0.26	0.29	0.32	0.39	0.45+	0.51+
	18.0	0.23	0.23	0.27	0.30	0.33	0.36	0.40+	0.46++	0.52++
	20.0	0.24	0.27	0.30	0.33	0.36+	0.39+	0.43++	0.49++	0.54+++
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	5.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	6.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	7.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	8.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.42
	9.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.37	0.43
	10.0	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.38	0.44
	12.0	0.23	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46
	14.0	0.23	0.23	0.23	0.23	0.23	0.29	0.35	0.42	0.48
	16.0	0.23	0.23	0.23	0.23	0.26	0.31	0.37	0.44	0.49+
	18.0	0.23	0.23	0.23	0.27	0.30	0.33	0.39	0.45+	0.50++
	20.0	0.23	0.24	0.27	0.30	0.33	0.35+	0.41+	0.46++	0.52+++
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	5.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	6.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	7.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	8.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	9.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	10.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.42
	12.0	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.38	0.44
	14.0	0.23	0.23	0.23	0.23	0.23	0.27	0.33	0.39	0.46+
	16.0	0.23	0.23	0.23	0.23	0.23	0.28	0.35	0.41	0.46+
	18.0	0.23	0.23	0.23	0.23	0.25	0.30	0.36	0.42+	0.47++
	20.0	0.23	0.23	0.23	0.25	0.28	0.32	0.37+	0.43+	0.49+++
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	5.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	6.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	7.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	8.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	9.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	10.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.40
	12.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.35	0.41
	14.0	0.23	0.23	0.23	0.23	0.23	0.26	0.30	0.36	0.42
	16.0	0.23	0.23	0.23	0.23	0.23	0.26	0.31	0.37	0.43+
	18.0	0.23	0.23	0.23	0.23	0.23	0.26	0.32	0.38+	0.44+
	20.0	0.23	0.23	0.23	0.23	0.23	0.27	0.33+	0.39+	0.45++

— Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 10 Standard prestress design—36 in. (910 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (ft)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	5.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.48
	6.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.43	0.50
	7.0	0.23	0.23	0.23	0.23	0.24	0.30	0.37	0.44	0.52
	8.0	0.23	0.23	0.23	0.23	0.24	0.31	0.39	0.46	0.53
	9.0	0.23	0.23	0.23	0.23	0.26	0.33	0.40	0.47	0.55
	10.0	0.23	0.23	0.23	0.23	0.27	0.34	0.42	0.49	0.56
	12.0	0.23	0.23	0.23	0.27	0.31	0.37	0.45	0.52	0.58+
	14.0	0.23	0.25	0.28	0.32	0.36	0.41	0.48	0.54+	0.61++
	16.0	0.26	0.30	0.34	0.37	0.41	0.45	0.51+	0.57++	0.64++
	18.0	0.32	0.35	0.39	0.43	0.45+	0.49+	0.55++	0.60+++	0.66+++
	20.0	0.37	0.40+	0.43+	0.46++	0.50++	0.53+++	0.59+++	—	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	5.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.47
	6.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.42	0.49
	7.0	0.23	0.23	0.23	0.23	0.24	0.29	0.36	0.43	0.50
	8.0	0.23	0.23	0.23	0.23	0.24	0.30	0.37	0.45	0.52
	9.0	0.23	0.23	0.23	0.23	0.24	0.32	0.39	0.46	0.53
	10.0	0.23	0.23	0.23	0.23	0.26	0.33	0.40	0.47	0.55
	12.0	0.23	0.23	0.23	0.24	0.28	0.36	0.43	0.50	0.57
	14.0	0.23	0.23	0.25	0.29	0.32	0.38	0.46	0.53	0.60+
	16.0	0.23	0.26	0.30	0.33	0.37	0.42	0.48	0.55+	0.62++
	18.0	0.27	0.31	0.34	0.38	0.42	0.45+	0.50++	0.57++	0.64+++
	20.0	0.32	0.36	0.38+	0.42+	0.46++	0.49++	0.54+++	0.60+++	—
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	5.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.47
	6.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.48
	7.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.42	0.50
	8.0	0.23	0.23	0.23	0.23	0.24	0.29	0.36	0.44	0.51
	9.0	0.23	0.23	0.23	0.23	0.24	0.30	0.38	0.45	0.52
	10.0	0.23	0.23	0.23	0.23	0.24	0.32	0.39	0.46	0.53
	12.0	0.23	0.23	0.23	0.23	0.27	0.34	0.41	0.49	0.56
	14.0	0.23	0.23	0.23	0.26	0.30	0.37	0.44	0.51	0.58+
	16.0	0.23	0.23	0.26	0.30	0.34	0.39	0.46	0.53+	0.59++
	18.0	0.23	0.27	0.31	0.34	0.38	0.42	0.48+	0.55++	0.61+++
	20.0	0.28	0.31	0.35	0.38+	0.42+	0.45++	0.51++	0.56+++	—
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	5.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	6.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.47
	7.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.48
	8.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.42	0.49
	9.0	0.23	0.23	0.23	0.23	0.24	0.29	0.36	0.43	0.50
	10.0	0.23	0.23	0.23	0.23	0.24	0.29	0.37	0.44	0.51
	12.0	0.23	0.23	0.23	0.23	0.24	0.32	0.39	0.46	0.53
	14.0	0.23	0.23	0.23	0.23	0.26	0.34	0.41	0.48	0.55+
	16.0	0.23	0.23	0.23	0.25	0.28	0.36	0.43	0.50+	0.56++
	18.0	0.23	0.23	0.25	0.28	0.32	0.38	0.44+	0.51++	0.57+++
	20.0	0.23	0.25	0.28	0.32	0.36	0.39+	0.46++	0.52+++	0.59+++
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	5.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	6.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	7.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.46
	8.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.47
	9.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.47
	10.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.41	0.48
	12.0	0.23	0.23	0.23	0.23	0.24	0.29	0.35	0.42	0.50
	14.0	0.23	0.23	0.23	0.23	0.24	0.29	0.37	0.44	0.51
	16.0	0.23	0.23	0.23	0.23	0.24	0.31	0.38	0.46	0.52+
	18.0	0.23	0.23	0.23	0.23	0.25	0.33	0.40	0.46+	0.53++
	20.0	0.23	0.23	0.23	0.23	0.27	0.34	0.41+	0.47++	0.54+++

— Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 11 Standard prestress design—42 in. (1,070 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.54
	5.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.48	0.56
	6.0	0.23	0.23	0.23	0.23	0.27	0.34	0.42	0.50	0.58
	7.0	0.23	0.23	0.23	0.23	0.27	0.36	0.44	0.52	0.60
	8.0	0.23	0.23	0.23	0.23	0.30	0.38	0.46	0.54	0.62
	9.0	0.23	0.23	0.23	0.25	0.31	0.40	0.48	0.56	0.64
	10.0	0.23	0.23	0.23	0.28	0.33	0.41	0.50	0.58	0.66
	12.0	0.23	0.25	0.29	0.34	0.38	0.45	0.53	0.62	—
	14.0	0.27	0.31	0.35	0.40	0.44	0.50	0.57	0.64+	—
	16.0	0.33	0.37	0.42	0.46	0.50	0.55+	0.61++	—	—
	18.0	0.39	0.44	0.47+	0.51+	0.55+	0.60++	0.66+++	—	—
	20.0	0.45+	0.49+	0.52++	0.57++	0.60+++	0.65+++	—	—	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.53
	5.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.47	0.55
	6.0	0.23	0.23	0.23	0.23	0.27	0.33	0.41	0.49	0.57
	7.0	0.23	0.23	0.23	0.23	0.27	0.34	0.43	0.51	0.59
	8.0	0.23	0.23	0.23	0.23	0.28	0.36	0.44	0.53	0.61
	9.0	0.23	0.23	0.23	0.24	0.30	0.38	0.46	0.54	0.62
	10.0	0.23	0.23	0.23	0.25	0.31	0.40	0.48	0.56	0.64
	12.0	0.23	0.23	0.26	0.30	0.35	0.43	0.51	0.59	0.66++
	14.0	0.23	0.27	0.31	0.36	0.40	0.46	0.54	0.62+	—
	16.0	0.28	0.33	0.37	0.41	0.45	0.51	0.57+	0.64++	—
	18.0	0.34	0.38	0.42	0.47	0.50+	0.54++	0.61++	—	—
	20.0	0.40	0.43+	0.47+	0.51++	0.55++	0.59+++	0.66+++	—	—
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.53
	5.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.54
	6.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.48	0.56
	7.0	0.23	0.23	0.23	0.23	0.27	0.33	0.41	0.50	0.58
	8.0	0.23	0.23	0.23	0.23	0.27	0.35	0.43	0.51	0.59
	9.0	0.23	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.61
	10.0	0.23	0.23	0.23	0.24	0.30	0.38	0.46	0.54	0.62
	12.0	0.23	0.23	0.23	0.27	0.33	0.41	0.49	0.57	0.65+
	14.0	0.23	0.24	0.28	0.32	0.36	0.44	0.52	0.60+	0.66+++
	16.0	0.25	0.29	0.33	0.37	0.41	0.47	0.54+	0.62++	—
	18.0	0.30	0.34	0.38	0.42	0.47	0.51+	0.57++	0.64+++	—
	20.0	0.35	0.39	0.42+	0.47+	0.50++	0.55++	0.61+++	—	—
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.52
	5.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.53
	6.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.54
	7.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.48	0.56
	8.0	0.23	0.23	0.23	0.23	0.27	0.33	0.41	0.49	0.57
	9.0	0.23	0.23	0.23	0.23	0.27	0.34	0.42	0.51	0.59
	10.0	0.23	0.23	0.23	0.23	0.27	0.35	0.44	0.52	0.60
	12.0	0.23	0.23	0.23	0.24	0.30	0.38	0.46	0.54	0.62
	14.0	0.23	0.23	0.23	0.27	0.32	0.40	0.49	0.57	0.64+
	16.0	0.23	0.23	0.27	0.31	0.35	0.43	0.51	0.59+	0.66++
	18.0	0.23	0.27	0.31	0.35	0.39	0.46	0.53+	0.60++	—
	20.0	0.27	0.31	0.35	0.39	0.43+	0.48+	0.55++	0.62+++	—
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.52
	5.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.52
	6.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.52
	7.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.53
	8.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.46	0.54
	9.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.47	0.55
	10.0	0.23	0.23	0.23	0.23	0.27	0.33	0.40	0.48	0.56
	12.0	0.23	0.23	0.23	0.23	0.27	0.34	0.42	0.50	0.58
	14.0	0.23	0.23	0.23	0.23	0.27	0.35	0.44	0.52	0.59+
	16.0	0.23	0.23	0.23	0.23	0.29	0.37	0.46	0.53+	0.60++
	18.0	0.23	0.23	0.23	0.25	0.31	0.39	0.47+	0.54++	0.61+++
	20.0	0.23	0.23	0.24	0.28	0.33	0.40+	0.48++	0.55+++	0.63+++

— Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9.

Table 12 Standard prestress design—48 in. (1,220 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.53	0.62
	5.0	0.23	0.23	0.23	0.23	0.30	0.37	0.46	0.55	0.64
	6.0	0.23	0.23	0.23	0.23	0.30	0.39	0.48	0.57	0.66
	7.0	0.23	0.23	0.23	0.26	0.32	0.41	0.50	0.59	0.66+++
	8.0	0.23	0.23	0.23	0.28	0.35	0.44	0.53	0.62	—
	9.0	0.23	0.23	0.25	0.30	0.37	0.46	0.55	0.64	—
	10.0	0.23	0.24	0.29	0.33	0.39	0.48	0.57	0.66+	—
	12.0	0.26	0.31	0.35	0.40	0.45	0.53	0.62	—	—
	14.0	0.33	0.38	0.42	0.47	0.52	0.59	0.66+	—	—
	16.0	0.40	0.45	0.50	0.55	0.58+	0.65+	—	—	—
	18.0	0.47	0.51+	0.56+	0.60++	0.65++	—	—	—	—
	20.0	0.52++	0.57++	0.62++	0.66+++	—	—	—	—	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.52	0.61
	5.0	0.23	0.23	0.23	0.23	0.30	0.37	0.45	0.54	0.63
	6.0	0.23	0.23	0.23	0.23	0.30	0.38	0.47	0.56	0.65
	7.0	0.23	0.23	0.23	0.24	0.31	0.40	0.49	0.58	0.66+
	8.0	0.23	0.23	0.23	0.26	0.33	0.42	0.51	0.60	—
	9.0	0.23	0.23	0.23	0.29	0.35	0.44	0.53	0.62	—
	10.0	0.23	0.23	0.25	0.30	0.37	0.46	0.55	0.64	—
	12.0	0.23	0.27	0.31	0.36	0.41	0.50	0.59	0.66+++	—
	14.0	0.28	0.33	0.38	0.43	0.47	0.54	0.63	—	—
	16.0	0.35	0.39	0.44	0.49	0.56	0.63+	0.66++	—	—
	18.0	0.41	0.46	0.50	0.54+	0.60++	0.66+++	—	—	—
	20.0	0.47+	0.51+	0.55++	0.59++	0.64+++	—	—	—	—
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.60
	5.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.53	0.62
	6.0	0.23	0.23	0.23	0.23	0.30	0.37	0.46	0.55	0.64
	7.0	0.23	0.23	0.23	0.23	0.30	0.38	0.48	0.57	0.65
	8.0	0.23	0.23	0.23	0.25	0.31	0.41	0.50	0.59	0.66++
	9.0	0.23	0.23	0.23	0.27	0.33	0.43	0.52	0.61	—
	10.0	0.23	0.23	0.23	0.29	0.35	0.44	0.53	0.63	—
	12.0	0.23	0.23	0.28	0.33	0.39	0.48	0.57	0.66	—
	14.0	0.24	0.29	0.34	0.39	0.43	0.51	0.61	—	—
	16.0	0.30	0.35	0.40	0.45	0.49	0.56	0.63	—	—
	18.0	0.36	0.41	0.46	0.49+	0.54+	0.60++	0.66+++	—	—
	20.0	0.42	0.46+	0.51+	0.54++	0.59++	0.64+++	—	—	—
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.58
	5.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.60
	6.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.53	0.62
	7.0	0.23	0.23	0.23	0.23	0.30	0.37	0.46	0.54	0.63
	8.0	0.23	0.23	0.23	0.23	0.30	0.38	0.47	0.56	0.65
	9.0	0.23	0.23	0.23	0.24	0.31	0.40	0.49	0.58	0.66+
	10.0	0.23	0.23	0.23	0.26	0.32	0.41	0.50	0.60	0.66+++
	12.0	0.23	0.23	0.23	0.28	0.35	0.44	0.53	0.62	—
	14.0	0.23	0.23	0.27	0.32	0.38	0.47	0.56	0.65+	—
	16.0	0.23	0.28	0.32	0.37	0.42	0.50	0.58+	0.66+++	—
	18.0	0.28	0.32	0.37	0.42	0.47	0.52+	0.61++	—	—
	20.0	0.33	0.37	0.42	0.46+	0.51+	0.56++	0.63+++	—	—
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.58
	5.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.58
	6.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.59
	7.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.51	0.60
	8.0	0.23	0.23	0.23	0.23	0.30	0.37	0.44	0.53	0.62
	9.0	0.23	0.23	0.23	0.23	0.30	0.37	0.45	0.54	0.63
	10.0	0.23	0.23	0.23	0.23	0.30	0.37	0.46	0.55	0.64
	12.0	0.23	0.23	0.23	0.23	0.30	0.39	0.48	0.57	0.66
	14.0	0.23	0.23	0.23	0.26	0.32	0.41	0.50	0.60	0.66+++
	16.0	0.23	0.23	0.23	0.28	0.34	0.44	0.53	0.61+	—
	18.0	0.23	0.23	0.26	0.31	0.36	0.46	0.54+	0.62++	—
	20.0	0.23	0.25	0.29	0.34	0.39	0.47+	0.55++	0.64+++	—

— Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†Refer to Figure 9

Table 14 Standard prestress design—60 in. (1,520 mm) lined-cylinder pipe*

Bedding Type†	Cover Embankment Loading (*ft*)	System Working Pressure (psi)								
		0	25	50	75	100	125	150	175	200
R1 30° Bedding Angle	4.0	0.23	0.23	0.23	0.28	0.36	0.45	0.56	0.65+	—
	5.0	0.23	0.23	0.23	0.29	0.37	0.47	0.58	0.66+++	—
	6.0	0.23	0.23	0.23	0.31	0.39	0.50	0.61	—	—
	7.0	0.23	0.23	0.26	0.34	0.42	0.52	0.63	—	—
	8.0	0.23	0.23	0.29	0.37	0.44	0.55	0.66	—	—
	9.0	0.23	0.27	0.33	0.40	0.48	0.58	—	—	—
	10.0	0.27	0.33	0.39	0.45	0.52	0.62	—	—	—
	12.0	0.36	0.42	0.48	0.54	0.61	0.66+++	—	—	—
	14.0	0.45	0.51	0.58	0.64	—	—	—	—	—
	16.0	0.54	0.60	0.65+	—	—	—	—	—	—
	18.0	0.62+	0.66+++	—	—	—	—	—	—	—
	20.0	—	—	—	—	—	—	—	—	—
R2 45° Bedding Angle	4.0	0.23	0.23	0.23	0.28	0.36	0.45	0.55	0.65	—
	5.0	0.23	0.23	0.23	0.28	0.36	0.46	0.57	0.65++	—
	6.0	0.23	0.23	0.23	0.30	0.37	0.48	0.59	—	—
	7.0	0.23	0.23	0.24	0.32	0.40	0.51	0.61	—	—
	8.0	0.23	0.23	0.27	0.34	0.42	0.53	0.64	—	—
	9.0	0.23	0.23	0.30	0.37	0.45	0.56	0.66+	—	—
	10.0	0.23	0.29	0.34	0.40	0.49	0.59	—	—	—
	12.0	0.31	0.37	0.43	0.49	0.56	0.65	—	—	—
	14.0	0.39	0.45	0.51	0.57	0.64	—	—	—	—
	16.0	0.47	0.53	0.60	0.65+	—	—	—	—	—
	18.0	0.56	0.61+	0.66++	—	—	—	—	—	—
	20.0	0.62++	—	—	—	—	—	—	—	—
R3 60° Bedding Angle	4.0	0.23	0.23	0.23	0.28	0.36	0.45	0.54	0.64	—
	5.0	0.23	0.23	0.23	0.28	0.36	0.45	0.55	0.66	—
	6.0	0.23	0.23	0.23	0.28	0.36	0.47	0.58	0.65++	—
	7.0	0.23	0.23	0.23	0.30	0.38	0.49	0.60	—	—
	8.0	0.23	0.23	0.24	0.33	0.40	0.51	0.62	—	—
	9.0	0.23	0.23	0.28	0.35	0.43	0.54	0.65	—	—
	10.0	0.23	0.25	0.31	0.38	0.46	0.57	0.66++	—	—
	12.0	0.27	0.33	0.39	0.45	0.51	0.62	—	—	—
	14.0	0.34	0.40	0.46	0.52	0.58	0.66+	—	—	—
	16.0	0.42	0.47	0.54	0.60	0.65+	—	—	—	—
	18.0	0.49	0.55	0.60+	0.66+	—	—	—	—	—
	20.0	0.55+	0.60++	0.66+++	—	—	—	—	—	—
R4 90° Bedding Angle	4.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.62	—
	5.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.64	—
	6.0	0.23	0.23	0.23	0.28	0.36	0.45	0.55	0.66	—
	7.0	0.23	0.23	0.23	0.28	0.36	0.46	0.57	0.66++	—
	8.0	0.23	0.23	0.23	0.30	0.37	0.48	0.59	—	—
	9.0	0.23	0.23	0.24	0.32	0.40	0.50	0.61	—	—
	10.0	0.23	0.23	0.26	0.34	0.42	0.53	0.64	—	—
	12.0	0.23	0.26	0.32	0.38	0.46	0.57	0.66++	—	—
	14.0	0.26	0.32	0.38	0.44	0.50	0.61	—	—	—
	16.0	0.32	0.38	0.44	0.50	0.56	0.64	—	—	—
	18.0	0.38	0.44	0.50	0.55+	0.61	—	—	—	—
	20.0	0.45	0.49+	0.56+	0.61++	0.66+++	—	—	—	—
R5 150° Bedding Angle	4.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.62	—
	5.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.62	—
	6.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.62	—
	7.0	0.23	0.23	0.23	0.28	0.36	0.45	0.53	0.64	—
	8.0	0.23	0.23	0.23	0.28	0.36	0.45	0.55	0.65	—
	9.0	0.23	0.23	0.23	0.28	0.36	0.46	0.56	0.66+	—
	10.0	0.23	0.23	0.23	0.29	0.36	0.47	0.58	0.66+++	—
	12.0	0.23	0.23	0.24	0.32	0.39	0.50	0.61	—	—
	14.0	0.23	0.23	0.27	0.34	0.42	0.53	0.64	—	—
	16.0	0.23	0.25	0.31	0.37	0.45	0.56	0.66+	—	—
	18.0	0.23	0.29	0.35	0.41	0.48	0.58+	—	—	—
	20.0	0.28	0.34	0.40	0.46+	0.51+	0.60++	—	—	—

— Indicates special design required

*Tabular quantities are the amount of prestress wire (A_s) required per linear foot of pipe in in.^{2}/lin ft.

†*Refer to Figure 9.*

APPENDIX A

Commentary

This appendix is for information only and is not a part of AWWA C304.

SECTION A.1: INTRODUCTION

AWWA C304, Standard for Design of Prestressed Concrete Cylinder Pipe, referred to as the standard, provides a unified procedure for the design of PCCP and supersedes all other conflicting or additional requirements on the design of the pipe in the documents referenced in the standard.

SECTION A.2: COMMENTARY FOR SEC. 3.2 OF THE STANDARD

The load factors in this standard were developed by a committee of technical representatives from the structural engineering consultants and from each ACPPA* producer. The committee reviewed the results of industry tests (Zarghamee, Heger, and Dana 1988a; Zarghamee 1990) and compared designs obtained using this standard with the prior experience with prestressed concrete pipe. The developed load factors were also compared with other standards used in the structural engineering practice and were found to be conservative.

SECTION A.3 COMMENTARY FOR SEC. 3.5.1 OF THE STANDARD

The load factors for the load combinations corresponding to the elastic limit states are determined by manufacturing tolerances (that is, material and geometric variabilities of the manufactured pipe) so that the probability of exceeding these limits is less than 0.001. The higher value of β_1 for LCP accounts for the effect of manufacturing tolerances and the smaller dimensions of the pipe on the combined loads that produce the elastic stress limit of the wire.

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*American Concrete Pressure Pipe Association, 11800 Sunrise Valley Dr., Suite 309, Reston, Va. 20191

SECTION A.4: COMMENTARY FOR SEC. 3.5.2 OF THE STANDARD

The higher value of β_2 for LCP accounts for the effect of manufacturing tolerances and the smaller dimensions of the pipe on the combined loads that produce yielding of the wire.

The value of β_2 of 1.3 for ECP for the wire yield criterion is the same as the ultimate strength-load factor used since the early 1980s for dead, water, and earth loads on rigid pipe in the AASHTO* Standard Specifications for Highway Bridges. The same ultimate strength-load factors are also found in the proposed ASCE† Standard for Direct Design of Buried Concrete Pipe. Design studies for typical LCP showed that the wire yield limit does not govern the design of typical LCP, and the actual load factor for wire yield strength is much larger than 1.4. Combined load tests conducted by the industry on ECP (Zarghamee 1990) demonstrated that coating cracks, developed under combined loads at wire yield, disappear or become less than 0.002 in. (0.050 mm) after pressure is removed. These tests demonstrate that the wire yield limit state is actually a damage criterion, rather than an ultimate strength limit state.

SECTION A.5: COMMENTARY FOR SEC. 3.6 OF THE STANDARD

The higher value of β_1 for LCP accounts for the effect of manufacturing tolerances and the smaller dimensions of the pipe on the combined loads that produce the elastic stress limit of the wire.

SECTION A.6: COMMENTARY FOR SEC. 4.3.2 OF THE STANDARD

The moment and thrust coefficients corresponding to the Olander load distribution (Olander 1950) are stated by Smith (1978). Paris presents moment and thrust coefficients in his paper (Paris 1921).

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

†American Society of Civil Engineers, 345 E. 47th St., New York, NY 10017.

SECTION A.7: COMMENTARY FOR SEC. 4.3.3 OF THE STANDARD

A method of analysis for obtaining the moments around the pipe accounting for the tensile softening of coating mortar and concrete core is presented by Zarghamee and Fok (1990). The validity of the simplified moment-redistribution procedure stated in Sec. 4.3.3 is discussed by Zarghamee, Fok, and Sikiotis (1990).

SECTION A.8: COMMENTARY FOR SEC. 5.3.3 AND 5.4.2 OF THE STANDARD

The tensile strength of concrete is based on the results presented by Raphael (1984). Note that this strength is used only to define the peak of an idealized bilinear fit through an otherwise concave and smooth curve of finite curvature.

SECTION A.9: COMMENTARY FOR SEC. 5.3.4 AND 5.4.3 OF THE STANDARD

The modulus of elasticity of concrete is based on the results reported by Pauw (1960). The modulus of elasticity calculated using Pauw's formula concurs with the results obtained using the formula stated by ACI* 318-83, *Building Code Requirements for Reinforced Concrete*, when f_c' is approximately 5,000 psi (34.5 MPa) or less, but it gives lower values for high-strength concrete.

SECTION A10: COMMENTARY FOR SEC. 5.3.5 OF THE STANDARD

The stress–strain relationship of concrete and mortar is idealized to account for the tensile softening and the stiffness of concrete and mortar when strained beyond the microcracking stage. A comprehensive discussion of the implications of this stress–strain relationship is presented by Heger, Zarghamee, and Dana (1990).

When concrete and mortar are stressed in tension, their stress–strain behaviors may be approximated by the trilinear diagrams presented in Figure 2, which depicts the following three distinct states:

1. The virgin state, in which the concrete or mortar is uncracked.
2. The strain-softened state, in which microcracking of the concrete or mortar occurs.
3. The cracked state.

Microcracks are minute, short, unconnected cracks, visible only with the aid of a microscope, usually occurring at the aggregate/cement–mortar interface. Microcracks

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*American Concrete Institute, 22400 W. 7 Mile Rd., Detroit, MI 48219.

occur in a random pattern and are unaligned with the tensile stress field. The phrase, "Onset of microcracking," in Figure 2 indicates the boundary between the virgin state and the strain-softened state. The phrase, "Onset of visible cracking," in Figure 2 refers to the tensile strain at which point no additional stress is transferred across the fracture process zone delineating the boundary between the strain-softened state and the cracked state. Near this point, microcracks coalesce and become aligned with the stress field to form surface fissures, or macrocracks, which become visible to the unaided eye as strain increases.

In the literature on testing of prestressed concrete, Kennison (1960) discusses an "incipient crack" as follows: "This microscopic crack is not readily visible to the naked eye and is defined as a crack, 0.001 in. in width and 12 in. long." Kennison continues, "The first visible crack is defined as a crack 0.002 in. in width and 12 in. long and can usually be observed with normal eyesight if a meticulous examination of the surface is made."

SECTION A.11: COMMENTARY FOR SEC. 5.5.2 OF THE STANDARD

Although f^*_{yy} is empirically obtained, test results show that the average yield strength of steel sheets used in the fabrication of the cylinder is significantly higher than the specified minimum yield strength, and agrees with the value stated in Sec. 5.5.2.

SECTION A.12: COMMENTARY FOR SEC. 5.6.4 OF THE STANDARD

The stress–strain relationship for the prestressing wire was derived from test results performed on the virgin wire and then corrected for the prestretching effect so that the relationship is linear when $f_s \leq f_{sg}$.

SECTION A.13: COMMENTARY FOR SEC. 6 OF THE STANDARD

An accurate procedure for computing the state of stress in buried prestressed concrete in an environment with a varying relative humidity, similar to that of a buried pipe, is presented by Zarghamee and Dana (1991). Based on the results of this procedure, the simplified procedure presented in this standard was developed. The justification of the simplified procedure and a discussion of the accuracy of this procedure is presented by Zarghamee, Heger, and Dana (1990).

SECTION A.14: COMMENTARY FOR SEC. 6.4.1 OF THE STANDARD

In the proposed procedure for computing the final prestress in prestressed concrete pipe with multiple layers of prestressing, the part of the coating that becomes partially prestressed by the second and third layers of prestressing is neglected. Small-diameter pipe manufactured with relatively large intermediate coating thickness between wire layers requires special design.

SECTION A.15: COMMENTARY FOR SEC. 6.6 OF THE STANDARD

For a design relative humidity of less than 40 percent, creep and shrinkage may be computed from the model by Bazant, Kim, and Panula (1991, 1992). Their results show that when relative humidity is decreased to less than 40 percent, the increase in creep and shrinkage is small. For practical purposes, the creep factor and shrinkage strain computed for a design relative humidity of 40 percent may be used for drier environments.

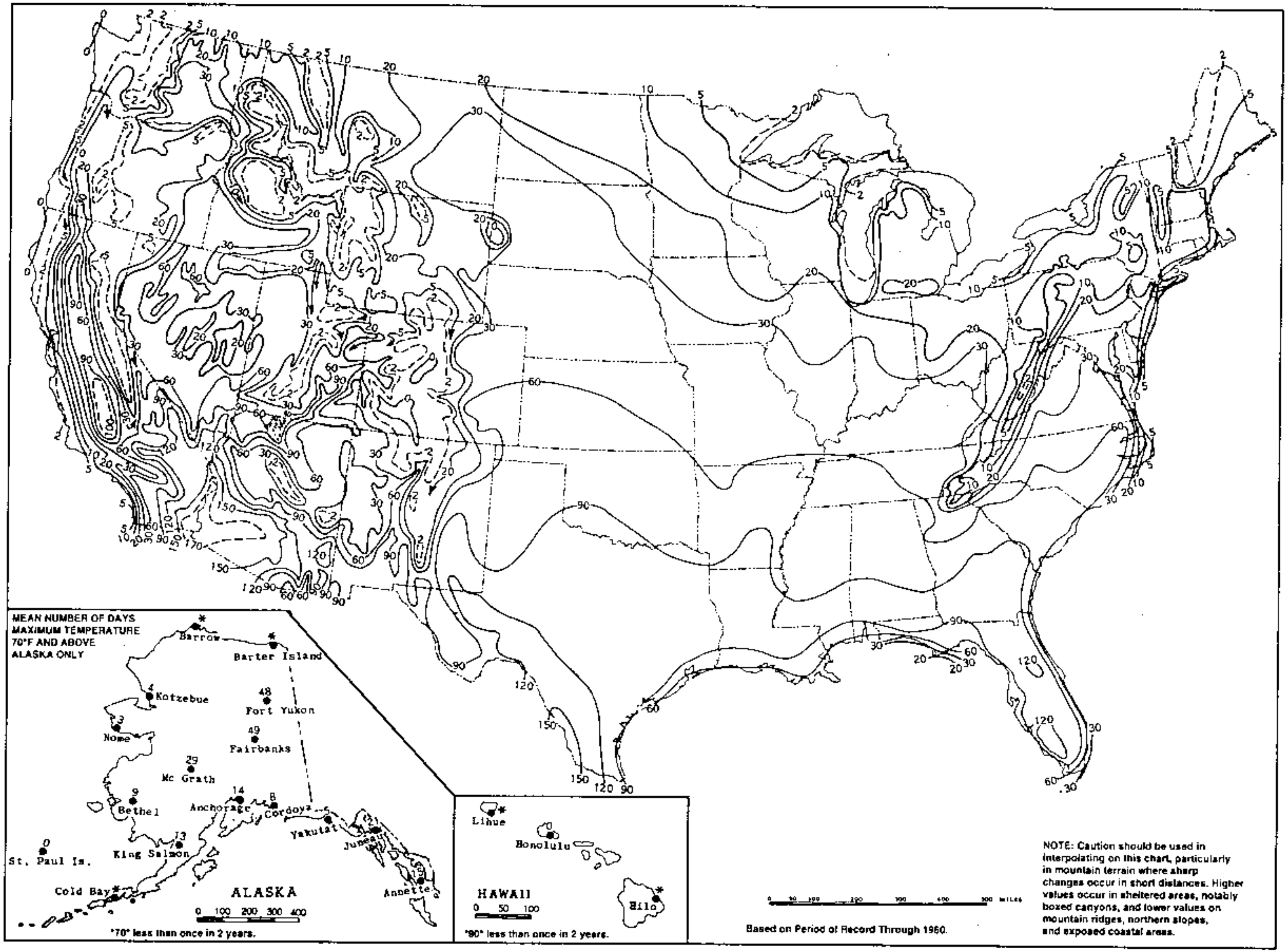
SECTION A.16: COMMENTARY FOR SEC. 7 OF THE STANDARD

A comprehensive discussion of the limit-states design criteria, including the experimental justification of each criterion and comparisons of the results of carefully conducted combined-load tests with the calculated combined-load limits corresponding to these criteria, is presented by Heger, Zarghamee, and Dana (1990).

SECTION A.17: COMMENTARY FOR SEC. 7.5.5 OF THE STANDARD

A simplified rule for determining if pipe manufactured within the continental United States must be protected against hot environments, as defined in Sec. 7.5.5, is that protection is necessary only for pipe manufactured from May 15 to September 15 at locations where, for 60 days or more, the maximum temperature exceeds 90°F (32°C). These locations are shown on the accompanying US Department of Commerce, Environmental Services Administration, Environmental Data Services' map of the mean annual number of days during which the maximum temperature is 90°F (32°C) and above (Figure A.1).

Application of white paint to the exterior surface of mortar-coated PCCP was shown by one series of tests to reduce the surface temperature of pipe exposed to solar radiation from about 135°F (57°C) to about 90°F (32°C).



Based on Period of Record Through 1960.

NOTE: Caution should be used in interpolating on this chart, particularly in mountain terrain where sharp changes occur in short distances. Higher values occur in sheltered areas, notably boxed canyons, and lower values on mountain ridges, northern slopes, and exposed coastal areas.

Figure A.1 Mean annual number of days maximum temperature of 90°F (32°C) and above, except 70°F (21°C) and above in Alaska

To determine if pipe manufactured within the continental United States must be protected against arid environments, as defined in Sec. 7.5.5, consult the accompanying mean relative humidity maps, prepared by the aforementioned services, for different months of the year (Figures A.2 through A.5).

SECTION A.18: COMMENTARY FOR SEC. 8 OF THE STANDARD

For further details and a discussion of the procedure for calculating the limit-state loads and pressures, see the paper by Zarghamee, Fok, and Sikiotis (1990). An example of the design procedure is presented in appendix C of this standard.

SECTION A.19: COMMENTARY FOR SEC. 8.9 OF THE STANDARD

The methodology of AWWA C304 is based on extensive theoretical work reported by Zarghamee and Fok (1990) and on extensive experimental work, including combined load tests reported, and compared with the simplified procedures that are the basis of this standard by Heger, Zarghamee, and Dana (1990). These references state that the standard's assumptions and simplifications are consistent with test results. One of the assumptions of Sec. 8.9 is that applied thrusts act on a circular reference axis. Zarghamee and Fok state, "Although the location of the reference axis . . . is arbitrary, it is recommended that it be at the centroid of the coated pipe cross section calculated for the pressured pipe in absence of any bending moments from external loads and pipe and fluid weights."

As shown in Figure 5 of Sec. 8.9.1 and Figure 6 of Sec. 8.9.2, the reference line of action of the computed thrust is at the centroid of the transformed coated pipe cross section calculated for the total thrust. The total thrust is comprised of the thrusts applied by external loads, pipe self weight, contained fluid weight, and internal pressure. An exception to this selection of the line of action of the computed thrust is in the computation for serviceability criteria at the springline, in which a simplifying approximation of neglecting the coating while setting $e = e_0$ was compared with actual test results and was determined to be valid (Zarghamee, Fok, and Sikiotis, 1990).

Computations of moments and thrusts from the combined loads are based on elastic theory for a circular ring of constant thickness and radius $\overline{R}$ to the geometric centroid of the cross section. Although $\overline{R}$ does not coincide with the radius to the center of the cross section used in Figure 5 and Figure 6, the resulting difference is negligibly small. The use of $\overline{R}$ for the computation of applied moments and the use of the transformed centroid as the location for the application of thrust to the cross section is consistent with accepted engineering practices for the design of statically indeterminate structures.

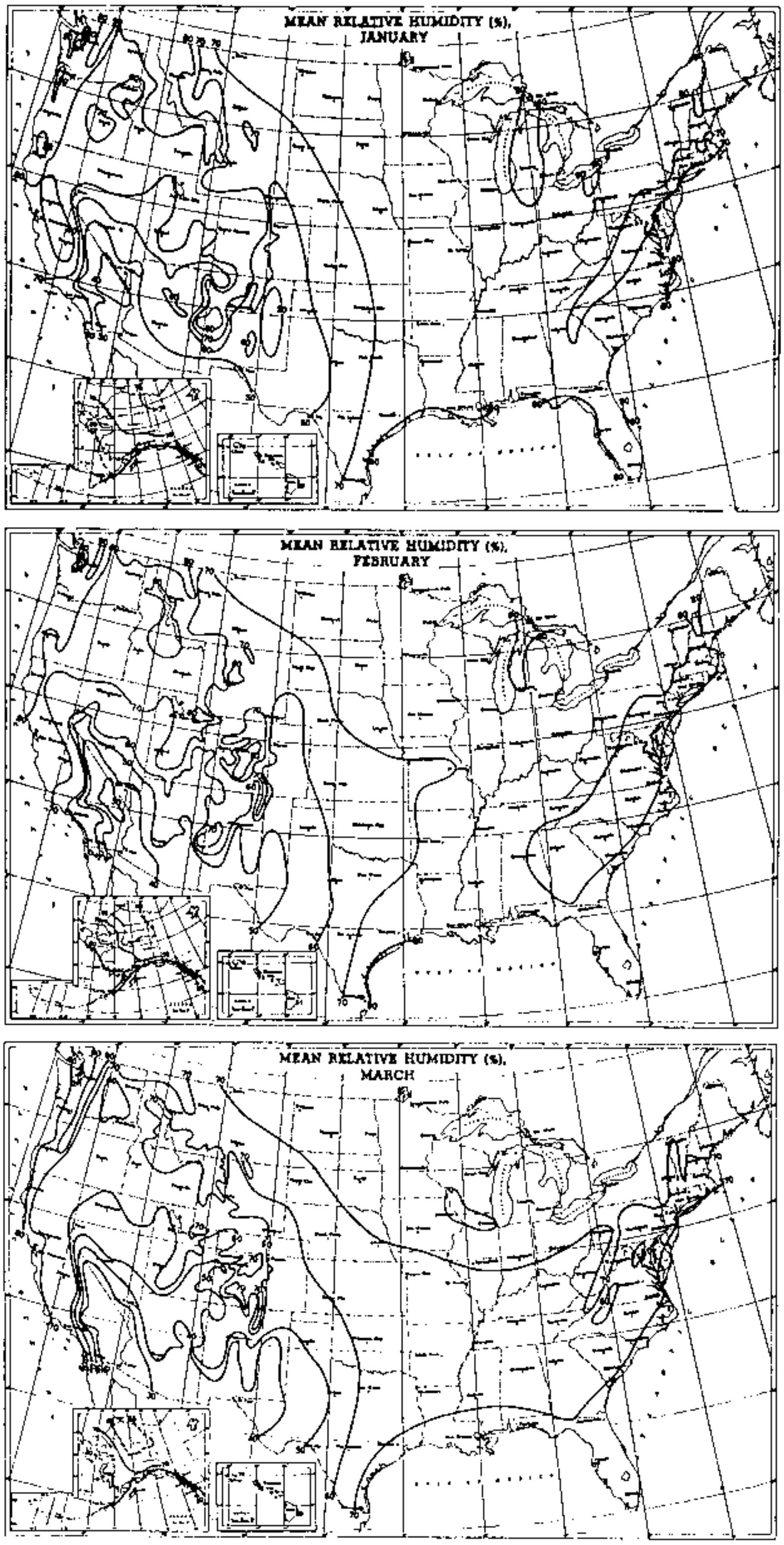


Figure A.2 Mean relative humidity (January-March)

APPENDIX C
Pipe-Design Example

This appendix is for information only and is not a part of AWWA C304.

SECTION C.1: INTRODUCTION

The design example included in this appendix uses the US system of units. If designs using the SI system of units are required, proper equations should be used where direct conversions of units are not possible. These equations are provided in AWWA C304-99.

The design procedure requires calculation of the following: **References**[1]

1. Residual stresses in the concrete and steel elements of the pipe from prestressing after losses caused by the creep and shrinkage of concrete and wire relaxation.
2. Moments and thrusts at invert and springline of the pipe resulting from the factored load and pressure combinations specified in Table 1 for ECP and Table 2 for LCP.
3. Internal-pressure capacities and moment capacities in the pipe wall.
4. Strains and stresses in the pipe wall resulting from moments and thrusts caused by the factored load and pressure combinations.

The internal pressures, moments, strains, and stresses in the pipe wall are compared with the internal-pressure capacities, moment capacities, and strain and stress limits specified in Table 3 for ECP and Table 4 for LCP.

The design procedure is iterative. An initial wire area is assumed and, using this area, all design criteria are checked. If any of the criteria are violated, a new larger wire area must be assumed. If none of the criteria is violated, the initial wire area must be decreased. If an estimate of the final wire area is not available, the following systematic procedure may be used:

	References
1. Compute the minimum and maximum allowable wire areas for the pipe from the AWWA C301 wire-spacing requirements.	AWWA C301-99, Sec. 3.2.2
2. Compute the wire area required by the burst pressure criterion.	Eq 8-4

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References

3. Compute the wire area required from the maximum pressure criterion. — Eq 8-1, Eq 8-2
4. Check all other criteria using the minimum wire area that satisfies the maximum wire spacing, the burst pressure, and maximum pressure requirements. — Sec. 8.2
5. If any criterion is violated, a design using the maximum wire area that satisfies the minimum wire spacing requirement may be checked to determine if a feasible design exists.
6. If a feasible design exists, the smallest acceptable wire area may be determined by trial and error. If no feasible design exists, other design parameters such as wire diameter, number of layers of prestressing wire, concrete strength, and core thickness must be modified.

In this example, representative calculations are presented to illustrate the design procedure. It is assumed that the final design wire area for the example pipe has already been determined; the calculations presented are for checking the design.

SECTION C.2: DESIGN PARAMETERS

References[1]

Pipe: 72-150 ECP with cast core

Core: $D_i = 72$ in., $D_y = 75.5$ in., $h_c = 5.5$ in.

Pressures: $P_w = 150$ psi, $P_t = 60$ psi, $P_{ft} = 180$ psi

Earth load and fluid weight:

$W_e = 6{,}000$ lb/ft, $W_t = 0$

$$W_f = \frac{\pi D_i^2 \gamma_f}{4 \times 144} = \frac{\pi \times 72^2 \times 62.4}{4 \times 144} = 1{,}764 \text{ lb/ft}$$

Wire: 6 gauge, $d_s = 0.192$ in., Class III, $f_{sg} = 189{,}000$ psi, $f_{su} = 252{,}000$ psi, $E_s = 28 \times 10^6$ psi

$$f_{sy} = 0.85\, f_{su} = 0.85 \times 252{,}000 = 214{,}200 \text{ psi}$$

Sec. 5.6.2

$$\lambda_s = \frac{d_s}{2h_c} = \frac{0.192}{2 \times 5.5} = 0.0175$$

Sec. 8.1

$$\varepsilon_{sg} = \frac{f_{sg}}{E_s} = \frac{189{,}000}{28 \times 10^6} = 6{,}750 \times 10^{-6}$$

Sec. 8.1

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$\varepsilon_{sy} = \dfrac{f_{sy}}{E_s} = \dfrac{214,200}{28 \times 10^6} = 7,650 \times 10^{-6}$ Sec. 8.1

Coating: $h_m = 0.75 + d_s = 0.75 + 0.192 = 0.942 \text{ in.}$ AWWA C301-99 Sec. 3.1.5

$\lambda_m = \dfrac{h_m}{2h_c} = \dfrac{0.942}{2 \times 5.5} = 0.0856$ Sec. 8.1

$\overline{R} = \dfrac{D_i + h_c + h_m}{2} = \dfrac{72 + 5.5 + 0.942}{2} = 39.22 \text{ in.}$ Sec. 4.1

Cylinder: 16 gauge, $t_y = 0.0598$ in., $f_{yy} = 33,000$ psi,
$f_{yy}^* = 45,000$ psi, $E_y = 30 \times 10^6$ psi

$h_{ci} = \dfrac{D_y - D_i}{2} - t_y = \dfrac{75.5 - 72}{2} - 0.0598 = 1.69 \text{ in.}$ Sec. 8.1

$d_y = \dfrac{D_y - D_i}{2} - \dfrac{t_y}{2} = \dfrac{75.5 - 72}{2} - \dfrac{0.0598}{2} = 1.72 \text{ in.}$ Sec. 8.1

$\lambda_y = \dfrac{d_y}{h_c} = \dfrac{1.72}{5.5} = 0.313$ Sec. 8.1

Steel cylinder and concrete cross-sectional areas:

$A_y = 12\, t_y = 12 \times 0.0598 = 0.7176 \text{ in.}^2\text{/ft}$ Sec. 8.1

$A_c = 12\,(h_c - t_y) = 12\,(5.5 - 0.0598) = 65.28 \text{ in.}^2\text{/ft}$ Sec. 8.1

Concrete: $f_c' = 5,500$ psi (cast)

$E_c = 158 \gamma_c^{1.51} f_c'^{\,0.3} = 158 \times 145^{1.51} \times 5,500^{0.3}$
$= 3.84 \times 10^6$ psi Eq 5-2

$n = \dfrac{E_s}{E_c} = \dfrac{28 \times 10^6}{3.84 \times 10^6} = 7.29$ Sec. 8.1

$n' = \dfrac{E_y}{E_c} = \dfrac{30 \times 10^6}{3.84 \times 10^6} = 7.81$ Sec. 8.1

$f_t' = 7\sqrt{f_c'} = 7\sqrt{5,500} = 519 \text{ psi}$ Eq 5-1

$\varepsilon_t' = \dfrac{f_t'}{E_c} = \dfrac{519}{3.84 \times 10^6} = 135 \times 10^{-6}$ Figure 2

$\varepsilon_k' = 11\varepsilon_t' = 11 \times 135 \times 10^{-6} = 1,487 \times 10^{-6}$ Figure 2

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

Mortar: $f_m' = 5{,}500$ psi

$E_m = 158 \times 140^{1.51} \times 5{,}500^{0.3} = 3.64 \times 10^6$ psi Eq 5-6

$m = \frac{E_m}{E_c} = \frac{3.64 \times 10^6}{3.84 \times 10^6} = 0.948$ before softening Sec. 8.8

$f_{tm}' = 7\sqrt{f_m'} = 7\sqrt{5,500} = 519$ psi Eq 5-5

$\varepsilon_{tm}' = \frac{f_{tm}'}{E_m} = \frac{519}{3.64 \times 10^6} = 143 \times 10^{-6}$ in./in. Figure 2

$\varepsilon_{km}' = 8\varepsilon_{tm}' = 8 \times 143 \times 10^{-6} = 1{,}144 \times 10^{-6}$ Figure 2

Environment: RH = 70%, $t_1 = 270$ days, $t_2 = 90$ days Sec. 6.6

Sec. C.2.1 Moment and Thrust Coefficients

References[1]

Earth load (bedding: 90° Olander):

$C_{m1e} = 0.1247$, $C_{m2e} = 0.0885$, $C_{n1e} = 0.3255$, $C_{n2e} = 0.5386$

Pipe weight (bedding: 15° Olander):

$C_{m1p} = 0.2157$, $C_{m2p} = 0.1016$, $C_{n1p} = 0.1029$, $C_{n2p} = 0.3026$

Fluid weight (bedding: 90° Olander):

$C_{m1f} = 0.1208$, $C_{m2f} = 0.0878$, $C_{n1f} = -0.2703$, $C_{n2f} = -0.0617$

SECTION C.3: MAXIMUM AND MINIMUM WIRE AREAS

Sec. C.3.1 Maximum Prestressing-Wire Area Based on Minimum Wire Spacing

References[1]

The minimum allowable center-to-center wire spacing is twice the wire diameter or 0.384 in. Therefore, the maximum prestressing-wire area based upon the minimum wire spacing is AWWA C301-99, Sec. 3.2.2

$$A_{s\max} = \frac{\pi d_s^2}{4} \times \frac{12}{0.384} = \frac{3.14 \times 0.192^2}{4} \times \frac{12}{0.384} = 0.905 \text{ in.}^2/\text{ft}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.3.2 Minimum Allowable Prestressing-Wire Area Based on Maximum Wire Spacing

References[1]

The maximum allowable center-to-center spacing of wire is 1.5 in.; therefore,

AWWA C301-99, Sec. 3.2.2

$$A_{s\min} = \frac{\pi d_s^2}{4} \times \frac{12}{1.5} = \frac{3.14 \times 0.192^2}{4} \times \frac{12}{1.5} = 0.232 \text{ in.}^2/\text{ft}$$

Sec. C.3.3 Minimum Prestressing-Wire Area Based on Burst Pressure

References[1]

The pipe shall have the necessary strength against burst when subjected to the load combinations FWT6.

Sec. 7.5.3

$$P_b = 1.6\,P_w + 2.0\,P_t = 1.6 \times 150 + 2.0 \times 60 = 360 \text{ psi}$$

Eq 3-12

$$P_b = \frac{A_y f_{yy}^* + A_s f_{su}}{6D_y} \rightarrow A_s = \frac{6D_y P_b - A_y f_{yy}^*}{f_{su}}$$

Eq 8-4

$$A_s = \frac{6 \times \cancel{1}75.5 \times 360 - 0.7176 \times 45,000}{252,000} = 0.519 \text{ in.}^2/\text{ft}$$

Thus, the prestressing-wire area required for the burst pressure criterion (0.519 in.²/ft) is the minimum allowable prestressing-wire area.

D_y = Diametro exterior cilindro

A_y área cilindro in²/ft

f_{yy}^* esfuerzo mínimo especificado de fluencia del acero

→ [illegible] tensión de diseño [illegible] la cédula A 18

SECTION C.4: STATE OF STRESS CALCULATIONS

Sec. C.4.1 Modular Ratios

	References[1]
$n_i = 109\,(f_c')^{-0.3} = 109\,(5,500)^{-0.3} = 8.23$	Sec. 6.5
$n_i' = 117\,(f_c')^{-0.3} = 117\,(5,500)^{-0.3} = 8.83$	Sec. 6.5
$n_r = 93\,(f_c')^{-0.3} = 93\,(5,500)^{-0.3} = 7.02$	Sec. 6.5
$n_r' = 99\,(f_c')^{-0.3} = 99\,(5,500)^{-0.3} = 7.47$	Sec. 6.5

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.4.2 Creep, Shrinkage, and Wire Relaxation

References[1]

For RH = 70%, $\phi_1 = 1.76$ and $\phi_2 = 1.79$.

Sec. 6.6

Sec. C.4.2.1 *Volume-to-surface ratios*

References[1]

$$h_{co} = h_c - \frac{D_y - D_i}{2} = 5.5 - \frac{75.5 - 72.0}{2} = 3.75 \text{ in.}$$

$$\gamma(h_{ci}) = {}^2\!/_3\left(1 + 1.13e^{-0.54h_{ci}}\right)$$

Eq 6-24

$$= {}^2\!/_3\left(1 + 1.13e^{-0.54 \times 1.69}\right) = 0.969$$

$$\gamma(h_{co} + h_m) = {}^2\!/_3\left[1 + 1.13e^{-0.54(h_{co} + h_m)}\right]$$

Eq 6-24

$$= {}^2\!/_3\left[1 + 1.13e^{-0.54(3.75 + 0.942)}\right] = 0.726$$

$$\gamma(h_m) = {}^2\!/_3\left(1 + 1.13e^{-0.54h_m}\right)$$

Eq 6-24

$$= {}^2\!/_3\left(1 + 1.13e^{-0.54 \times 0.942}\right) = 1.120$$

Sec. C.4.2.2 *Creep factor*

References[1]

$$\phi_{ci} = \phi_1\gamma(h_{ci}) = 1.76 \times 0.969 = 1.705$$

Eq 6-18

$$\phi_{com} = \phi_2\gamma(h_{co} + h_m) = 1.79 \times 0.726 = 1.300$$

Eq 6-19

$$\phi_m = \phi_2\gamma(h_m) = 1.79 \times 1.12 = 2.005$$

Eq 6-20

$$\phi = \frac{(h_{co} + h_m)\phi_{com} - h_m\phi_m + h_{ci}\phi_{ci}}{h_{ci} + h_{co}}$$

Eq 6-16

$$= \frac{(3.75 + 0.942)1.3 - 0.942 \times 2.005 + 1.69 \times 1.705}{1.69 + 3.75} = 1.304$$

Sec. C.4.2.3 *Shrinkage factor*

References[1]

$$\gamma'(h_{ci}) = 1.2e^{-0.12h_{ci}} = 1.2e^{-0.12 \times 1.69} = 0.980$$

Eq 6-25

$$\gamma'(h_{co} + h_m) = 1.2e^{-0.12(h_{co} + h_m)} = 1.2e^{-0.12(3.75 + 0.942)} = 0.683$$

Eq 6-25

$$\gamma'(h_m) = 1.2e^{-0.12h_m} = 1.2e^{-0.12 \times 0.942} = 1.072$$

Eq 6-25

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

For RH = 70%, $s_1 = 184 \times 10^{-6}$ and $s_2 = 299 \times 10^{-6}$ Sec. 6.6

$$s_{ci} = s_1\gamma'(h_{ci}) = 184 \times 10^{-6} \times 0.980 = 180.3 \times 10^{-6} \qquad \text{Eq 6-21}$$

$$s_{com} = s_2\gamma'(h_{co} + h_m) = 299 \times 10^{-6} \times 0.683 = 204.2 \times 10^{-6} \qquad \text{Eq 6-22}$$

$$s_m = s_2\gamma'(h_m) = 299 \times 10^{-6} \times 1.072 = 320.5 \times 10^{-6} \qquad \text{Eq 6-23}$$

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

$$= \frac{(3.75 + 0.942)204.2 - 0.942 \times 320.5 + 1.69 \times 180.3}{(1.69 + 3.75)} \times 10^{-6}$$

$$= 177 \times 10^{-6}$$

Sec. C.4.2.4 *Wire relaxation*

References[1]

$$R = 0.111 - 3.5\left(\frac{A_s}{A_c}\right) = 0.111 - 3.5\left(\frac{0.519}{65.28}\right) = 0.0832 \qquad \text{Eq 6-30}$$

Sec. C.4.3 Initial Prestress

References[1]

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

$$= \frac{0.519 \times 189{,}000}{65.28 + 8.23 \times 0.519 + 8.83 \times 0.7176} = 1{,}293 \text{ psi}$$

$$f_{iy} = n_i' f_{ic} = 8.83 \times 1{,}293 = 11{,}417 \text{ psi} \qquad \text{Eq 6-2}$$

$$f_{is} = -f_{sg} + n_i' f_{ic} = -189{,}000 + 8.23 \times 1{,}293 = -178{,}359 \text{ psi} \qquad \text{Eq 6-3}$$

n_i

Sec. C.4.4 Final Prestress

References[1]

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

$$= \frac{1{,}293(65.28 + 7.02 \times 0.519 + 7.47 \times 0.7176)}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)} \qquad 96049.02 \;\; \rightarrow 86.03$$

$$- \frac{(0.519 \times 28 \times 10^6 + 0.7176 \times 30 \times 10^6)177 \times 10^{-6}}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)} \qquad 6382.62$$

$$- \frac{0.519 \times 0.0832 \times 189{,}000}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)} \qquad 8161.17$$

$$= 947 \text{ psi} \; \checkmark$$

(72" [illegible] psi)

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$$\varepsilon_{cr} = \frac{f_{cr}}{E_c} = \frac{947}{3.84 \times 10^6} = 247 \times 10^{-6}$$

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

$$= 11{,}417 + \frac{65.28(1{,}293 \times 1.304 \times 7.47 + 30 \times 10^6 \times 177 \times 10^{-6})}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)}$$

$$- \frac{0.0832 \times 0.519 \times 189{,}000 \times 7.47(1 + 1.304)}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)}$$

$$= 23{,}371 \text{ psi}$$

$$f_{sr} = f_{is} + Rf_{sg} + \frac{A_c(f_{ic}\phi n_r + E_{\overset{S}{sg}}) - RA_s f_{sg} n_r(1+\phi)}{A_c + (n_r A_s + n_r' A_y)(1+\phi)} \qquad \text{Eq 6-6}$$

$$= -178{,}359 + 0.0832 \times 189{,}000 \quad \underset{A}{-} 162\,634.70$$

$$+ \frac{65.28(1{,}293 \times 1.304 \times 7.02 + 28 \times 10^6 \times 177 \times 10^{-6})}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)} \nearrow 1'096\,196.48$$

$$- \frac{0.0832 \times 0.519 \times 189{,}000 \times 7.02(1 + 1.304)}{65.28 + (7.02 \times 0.519 + 7.47 \times 0.7176)(1 + 1.304)} \rightarrow 131\,999.44 \quad = -151{,}426 \text{ psi}$$

Sec. C.4.5 Decompression Pressure

References[1]

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

$$= \frac{947(65.28 + 7.02 \times 0.519 + 7.47 \times 0.7176)}{6 \times 75.5} = 155.3 \text{ psi}$$

SECTION C.5: MINIMUM PRESTRESSING-WIRE AREA BASED ON MAXIMUM PRESSURE

The minimum prestressing-wire area shall meet the following requirements:

Criterion:	Load combination:	**References**[1]
$P_w \le P_o$	W1	Sec. 7.3.5
$P_w + P_t \le \min(P_k', 1.4\,P_o)$	WT1	Sec. 7.3.5

$P_w = 150$ psi $< P_o = 155.3$ psi; therefore, loading condition W1 is satisfied.

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

To check the loading condition WT1, first calculate

References[1]

$$P_k' = P_o \min\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, 1 + \frac{5\sqrt{f_c'}}{f_{cr}}\right)$$

$$= \min\left[P_o\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}, P_o\left(1 + \frac{5\sqrt{f_c'}}{f_{cr}}\right)\right]$$

Because,

$$P_o\left(1 + \frac{5\sqrt{f_c'}}{f_{cr}}\right) = 155.3\left(1 + \frac{5\sqrt{5{,}500}}{947}\right) = 216.1 \text{ psi}$$

and

$$P_o\left(\frac{0.5\varepsilon_{km}'}{\varepsilon_{cr}}\right) = 155.3\left(\frac{0.5 \times 1{,}144 \times 10^{-6}}{247 \times 10^{-6}}\right) = 359.6 \text{ psi}$$

$$P_k' = \min\ [216.1, 359.6] = 216.1 \text{ psi}$$

and

$$\min\ (P_k', 1.4\ P_o) = \min\ (216.1, 1.4 \times 155.3) = 216.1 \text{ psi}$$

Therefore,

$$P_w + P_t = 150 + 60 = 210 \text{ psi} < 216.1 \text{ psi}$$

and loading condition WT1 is satisfied.

SECTION C.6: STRESS FROM PRESTRESSING FOR FINAL DESIGN AREA

The prestressing-wire area for the final design that satisfies all design criteria, determined using a computer program to perform iterations, is 0.565 in.²/ft. This area is greater than the minimum wire area needed to satisfy the burst-pressure requirements described in Sec. 3.3. The state-of-stress calculation for $A_s = 0.565$ in.²/ft follows the calculation procedure stated in Sec. C.4 for $A_s = 0.519$ in.²/ft and produces the following results:

References[1]

$$f_{cr} = 1{,}028 \text{ psi}$$

$$\varepsilon_{cr} = \frac{f_{cr}}{E_c} = \frac{1{,}028}{3.84 \times 10^6} = 268 \times 10^{-6}$$

$$f_{yr} = 24{,}918 \text{ psi}$$

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$$\varepsilon_{yr} = \frac{f_{yr}}{E_y} = \frac{24{,}918}{30 \times 10^6} = 831 \times 10^{-6}$$

$$f_{sr} = -150{,}192 \text{ psi}$$

$$\varepsilon_{sr} = \frac{f_{sr}}{E_s} = -\frac{150{,}192}{28 \times 10^6} = -5{,}364 \times 10^{-6}$$

$$P_o = 169.36 \text{ psi}$$

$$N_o = 6D_y P_o = 6 \times 75.5 \times 169.36 = 76{,}720 \text{ lb/ft} \qquad \text{Eq 4-1}$$

Using the above prestress values, P_k' can be computed as shown earlier.

$$P_k' = 230.44 \text{ psi}$$

$$N_k' = 6D_y P_k' = 6 \times 75.5 \times 230.44 = 104{,}389 \text{ lb/ft} \qquad \text{Eq 8-3}$$

Pipe weight can now be computed for $A_s = 0.565$ in.^{2}/ft.

$$W_p = \frac{\pi}{144}\Big[(D_i + h_c)h_c\gamma_c + (D_i + 2h_c + h_m)h_m\gamma_m + (D_y - t_y)t_y(\gamma_s - \gamma_c) + (D_i + 2h_c + d_s)\frac{A_s}{12}(\gamma_s - \gamma_m)\Big]$$

$$= \frac{\pi}{144}\Big[(72 + 5.5)5.5 \times 145 + (72 + 2 \times 5.5 + 0.942)0.942 \times 140 + (75.5 - 0.0598)\,0.0598\,(489 - 145) + \frac{(72 + 2 \times 5.5 + 0.192)0.565(489 - 140)}{12}\Big] = 1{,}654 \text{ lb/ft}$$

Furthermore, the location of the neutral axis for prestress thrust is

$$e_o = h_c\frac{0.5bh_c + nA_s(1 + \lambda_s) + (n' - 1)A_y\lambda_y}{bh_c + nA_s + (n' - 1)A_y} \qquad \text{Eq 8-6}$$

$$= 5.5\Big[\overset{37.19}{\frac{0.5 \times 12 \times 5.5 + 7.29 \times 0.565(1 + 0.0175)}{12 \times 5.5 + 7.29 \times 0.565 + (7.81 - 1)0.7176}} + \overset{1.53}{\frac{(7.81 - 1)0.7176 \times 0.313}{\underset{75}{12 \times 5.5 + 7.29 \times 0.565 + (7.81 - 1)0.7176}}}\Big] = 2.839 \text{ in.} \checkmark$$

$$5.5\Big[\frac{37.19 + 1.53}{75}\Big] = 2\,839$$

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

SECTION C.7: SERVICEABILITY AT FULL PIPE CIRCUMFERENCE

The serviceability at full pipe circumference includes the following criteria and load combinations:

Criterion:	Load combination:	**References**[1]
Core decompression limit	W1	Table 3
Coating cracking	WT1	Table 3

In other words, the prestressing-wire area must satisfy for loading combination W1:

$$P_w \leq P_o$$

$$P_w = 150 \text{ psi} < P_o = 169.36 \text{ psi}$$

and for loading combination WT1:

$$P_w + P_t \leq \min(P_k', 1.4\,P_o)$$

Because

$$\min(P_k', 1.4\,P_o) = \min(230.44, 1.4 \times 169.36) = 230.44 \text{ psi},$$

$$P_w + P_t = 150 + 60 = 210 \text{ psi} \leq 230.44 \text{ psi}$$

Therefore, both requirements are satisfied.

SECTION C.8: SERVICEABILITY AT INVERT/CROWN

Limit states of serviceability at invert/crown include the following criteria and load combinations:

Criterion:	Load combination:	**References**[1]
Inside core cracking	W1	Table 3
Inside core visible cracking	WT1, WT2, FT1	Table 3
Inner core-to-cylinder radial tension	FW1, WT3	Table 3

Calculation procedures for all of the criteria and load combinations are similar. The detailed calculations for the inside core visible cracking criterion under the load combination WT1 are shown below; the results for other criteria are summarized at the end of the section.

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Applied moment and thrust at invert for load combination WT1:

References[1]

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

$$= 39.22[0.1247(6{,}000 + 0) + 0.2157 \times 1{,}654 + 0.1208 \times 1{,}764]$$

$$= 51{,}694 \text{ lb-in./ft}$$

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

$$= 6 \times 75.5(150 + 60) - [0.3255(6{,}000 + 0) + 0.1029 \times 1{,}654$$

$$+(-0.2703) \times 1{,}764] = 93{,}484 \text{ lb/ft}$$

The procedure for determining the strain and the stress distribution in the cross section caused by applied loads is iterative and requires satisfying the force and moment equilibrium equations. An iteration cycle is demonstrated below for trial values of

$$\nu_2 = 1.696$$

$$k = 0.704$$

Sec. C.8.1 Constants

References[1]

$$t_t = \frac{kh_c}{1+\nu_2} = \frac{0.704 \times 5.5}{1 + 1.696} = 1.4362 \text{ in.} \qquad \text{Sec. 8.9.1}$$

$$t_s = \nu_2 t_t = 1.696 \times 1.4362 = 2.4358 \text{ in.} \qquad \text{Sec. 8.9.1}$$

$$\lambda = \frac{d_y}{t_s} = \frac{1.72}{2.4358} = 0.706 \qquad \text{Sec. 8.9.1}$$

The location of the neutral axis under the thrust N_1 is given by

$$e = h_c\left[\frac{0.5bh_c + (n-m)A_s(1+\lambda_s) + (n'-1)A_y\lambda_y + mbh_m(1+\lambda_m)}{bh_c + (n-m)A_s + (n'-1)A_y + mbh_m}\right] \qquad \text{Eq 8-7}$$

$$= 5.5\left[\frac{0.5 \times 12 \times 5.5 + (7.29 - 0.365)0.565(1 + 0.0175)}{12 \times 5.5 + (7.29 - 0.365)0.565 + (7.81 - 1)0.7176 + 0.365 \times 12 \times 0.942}\right.$$

$$\left. + \frac{(7.81 - 1)0.7176 \times 0.313 + 0.365 \times 12 \times 0.942(1 + 0.0856)}{12 \times 5.5 + (7.29 - 0.365)0.565 + (7.81 - 1)0.7176 + 0.365 \times 12 \times 0.942}\right]$$

$$= 2.996 \text{ in.}$$

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

→ Where:

m = 0.365 is calculated by trial and error for tensile softened coating when the pipe is subjected to a tensile thrust of N_1 alone.

References[1]

The tensile strain in the coating is

$$\varepsilon_{mm} = -\frac{N_1}{E_c[bh_c + (n-m)A_s + (n'-1)A_y + mbh_m]}$$

Eq 8-8b

$$m = \frac{E_m}{7E_c}\left[8\,\frac{\varepsilon_{tm}'}{-\varepsilon_{mm}} - 1\right]$$

Eq 8-8a

For trial value of m = 0.365,

$$\varepsilon_{mm} = -\frac{93{,}484}{3.84\times10^{6}[12\times5.5 + (7.29-0.365)0.565 + (7.81-1)0.7176 + 0.365\times12\times0.942]}$$

$$= -309\times10^{-6}$$

$$m = \frac{3.64\times10^{6}}{7\times3.84\times10^{6}}\left(8\frac{143\times10^{-6}}{309\times10^{-6}} - 1\right) = 0.365$$

Sec. C.8.2 Strains

References[1]

$$\varepsilon_{ci} = (1+\nu_2)\varepsilon_t' = (1+1.696)135\times10^{-6} = 364\times10^{-6}$$

Sec. 8.9.1

$$\Delta\varepsilon_y = \varepsilon_{ci}\left(1-\frac{\lambda_y}{k}\right) = 364\times10^{-6}\left(1-\frac{0.313}{0.704}\right) = 202\times10^{-6}$$

Sec. 8.9.1

$$\varepsilon_{co} = \varepsilon_{ci}\left(\frac{1}{k}-1\right) = 364\times10^{-6}\left(\frac{1}{0.704}-1\right) = 153\times10^{-6}$$

Sec. 8.9.1

$$\Delta\varepsilon_s = \varepsilon_{ci}\left(\frac{1+\lambda_s}{k}-1\right) = 364\times10^{-6}\left(\frac{1+0.0175}{0.704}-1\right) = 162\times10^{-6}$$

Sec. 8.9.1

$$\varepsilon_{mm} = \varepsilon_{ci}\left(\frac{1+\lambda_m}{k}-1\right) - \varepsilon_{cr} = 364\times10^{-6}\left(\frac{1+0.0856}{0.704}-1\right) - 268\times10^{-6}$$

Sec. 8.9.1

$$= -71\times10^{-6}$$

$$\varepsilon_{mo} = \varepsilon_{ci}\left(\frac{1+2\lambda_m}{k}-1\right) - \varepsilon_{cr} = 364\times10^{-6}\left(\frac{1+2\times0.0856}{0.704}-1\right) - 268\times10^{-6}$$

Sec. 8.9.1

$$= -26\times10^{-6}$$

---

[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.8.3 Stresses

References[1]

Because $0 < \nu_2 = 1.696 < \nu = 10$ and $\lambda = 0.706 < 1$,

$$f_{ci} = \left(1 - \frac{\nu_2}{\nu}\right) f_t' = \left(1 - \frac{1.696}{10}\right) 519 = 431 \text{ psi}$$

Sec. 8.9.1

$$\Delta f_y = n' f_t' (1 + \nu_2)\left(1 - \frac{\lambda_y}{k}\right) = 7.81 \times 519 \times (1 + 1.696)\left(1 - \frac{0.313}{0.704}\right)$$
$$= 6{,}069 \text{ psi}$$

Sec. 8.9.1

$$f_{cy} = f_t'\left[1 - \frac{\nu_2}{\nu}(1 - \lambda)\right] = 519\left[1 - \frac{1.696}{10}(1 - 0.706)\right] = 493 \text{ psi}$$

Sec. 8.9.1

$$f_{co} = f_t'(1 + \nu_2)\left(\frac{1}{k} - 1\right) = 519(1 + 1.696)\left(\frac{1}{0.704} - 1\right) = 588 \text{ psi}$$

Sec. 8.9.1

$$\Delta f_s = n f_t' (1 + \nu_2)\left(\frac{1 + \lambda_s}{k} - 1\right) = 7.29 \times 519(1 + 1.696)\left(\frac{1 + 0.0175}{0.704} - 1\right)$$
$$= 4{,}542 \text{ psi}$$

Sec. 8.9.1

$$f_{ms} = m\left[f_t'(1 + \nu_2)\left(\frac{1 + \lambda_s}{k} - 1\right) - f_{cr}\right]$$

Sec. 8.9.1

$$= 0.948\left[519(1 + 1.696)\left(\frac{1 + 0.0175}{0.704} - 1\right) - (1{,}028)\right] = -384 \text{ psi}$$

$$f_{mm} = m\left[f_t'(1 + \nu_2)\left(\frac{1 + \lambda_m}{k} - 1\right) - f_{cr}\right]$$

$$= 0.948\left[519(1 + 1.696)\left(\frac{1 + 0.0856}{0.704} - 1\right) - 1{,}028\right] = -256 \text{ psi}$$

$$f_{mo} = m\left[f_t'(1 + \nu_2)\left(\frac{1 + 2\lambda_m}{k} - 1\right) - f_{cr}\right]$$

Sec. 8.9.1

$$= 0.948\left[519(1 + 1.696)\left(\frac{1 + 2 \times 0.0856}{0.704} - 1\right) - 1{,}028\right] = -94 \text{ psi}$$

Where:

m = 0.948 corresponds to the condition of no tensile softening of mortar, because the tensile strain in the coating is $-\varepsilon_{mm} = 71 \times 10^{-6} < \varepsilon_{t\,m}' = 143 \times 10^{-6}$.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.8.4 Internal Forces

References[1]

$$F_{ci}' = -\tfrac{1}{2} b t_t (1 + \nu) f_t' = -\tfrac{1}{2} \times 12 \times 1.4362\,(1 + 10)\,519$$

$$= -49{,}196 \text{ lb/ft}$$

Sec. 8.9.1

$$F_{ci}'' = \tfrac{1}{2} b t_t (\nu \overset{-}{\cancel{+}} \nu_2) f_{ci} = \tfrac{1}{2} \times 12 \times 1.4362\,(10 - 1.696)\,431$$

$$= 30{,}841 \text{ lb/ft}$$

Sec. 8.9.1

$$F_{ci} = F_{ci}' + F_{ci}'' = -49{,}196 + 30{,}841 = -18{,}355 \text{ lb/ft}$$

Sec. 8.9.1

$$F_y = -A_y(\Delta f_y - f_{cy}) = -0.7176(6069 - 493) = -4{,}001 \text{ lb/ft}$$

Sec. 8.9.1

$$F_{co} = \frac{b h_c}{2}(1 - k) f_{co} = \frac{12 \times 5.5}{2}(1 - 0.704)588 = 5{,}744 \text{ lb/ft}$$

Sec 8.9.1

$$F_s = A_s(\Delta f_s - f_{ms}) = 0.565(4{,}542 + 384) = 2{,}783 \text{ lb/ft}$$

Sec. 8.9.1

$$F_m' = \tfrac{1}{2}\, b h_m m (f_{co} - f_{cr}) = \tfrac{1}{2} \times 12 \times 0.942 \times 0.948(588 - 1{,}028)$$

$$= -2{,}358 \text{ lb/ft}$$

Sec. 8.9.1

$$F_m'' = \tfrac{1}{2}\, b h_m f_{mo} = \tfrac{1}{2} \times 12 \times 0.942 \times (-94) = -531 \text{ lb/ft}$$

Sec. 8.9.1

$$F_m = F_m' + F_m'' = -2{,}358 - 531 = -2{,}889 \text{ lb/ft}$$

Sec. 8.9.1

Sec. C.8.5 Sum of Forces

References[1]

$$\Sigma F = N_o - N_1 - (F_{ci} + F_y + F_{co} + F_s + F_m)$$

Eq 8-9

$$= 76{,}720 - 93{,}484 - (-18{,}355 - 4{,}001 + 5{,}744 + 2{,}783 - 2{,}889)$$

$$= -46 \approx 0$$

Sec. C.8.6 Internal Moments

References[1]

$$M_{ci} = -F_{ci}'\left[(1 + \lambda_s)h_c - t_t\left(\nu_2 + \frac{1 - \nu}{3}\right)\right] - F_{ci}''\left[(1 + \lambda_s)h_c + t_t\frac{\nu - \nu_2}{3}\right]$$

Sec. 8.9.1

$$= 49{,}196\left[(1 + 0.0175)5.5 - 1.4362\left(1.696 + \frac{1 - 10}{3}\right)\right]$$

$$-\,(30{,}841)\left[(1 + 0.0175)5.5 + 1.4362\frac{10 - 1.696}{3}\right] = 72{,}248 \text{ lb-in./ft}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$$M_y = -F_y h_c(1 + \lambda_s - \lambda_y) = 4{,}001 \times 5.5\ (1 + 0.0175 - 0.313)$$ Sec. 8.9.1

$$= 15{,}503 \text{ lb-in./ft}$$

$$M_{co} = -F_{co} h_c\left(\frac{1-k}{3} + \lambda_s\right) = -5{,}744 \times 5.5\left(\frac{1-0.704}{3} + 0.0175\right)$$ Sec. 8.9.1

$$= -3{,}670 \text{ lb-in./ft}$$

$$M_m = F_m' h_c\left(\frac{2\lambda_m}{3} - \lambda_s\right) + F_m'' h_c\left(\frac{4\lambda_m}{3} - \lambda_s\right)$$ Sec. 8.9.1

$$= -\,2{,}358 \times 5.5\left(\frac{2 \times 0.0856}{3} - 0.0175\right) -$$

$$531 \times 5.5\left(\frac{4 \times 0.0856}{3} - 0.0175\right) = -\,795 \text{ lb-in./ft}$$

Sec. C.8.7 Sum of Moments

References[1]

$$\Sigma M = M_1 - N_o [(1 + \lambda_s)h_c - e_o] + N_1[(1 + \lambda_s)h_c - e] - M_{ci} - M_y - M_{co} - M_m$$ Eq 8-10

$$= 51{,}694 - 76{,}720[(1 + 0.0175)5.5 - 2.839] + 93{,}484[(1 + 0.0175)5.5 - 2.996] - 72{,}248 - 15{,}503 + 3{,}670 + 795 = -46 \approx 0$$

Therefore, equations for equilibrium of forces and moments at the invert are satisfied.

Note that $\varepsilon_{ci} = 364 \times 10^{-6} < \varepsilon_k' = 1{,}487 \times 10^{-6}$ and, therefore, the strain limit corresponding to the visible crack control inside the core is satisfied.

References[1]

To check the radial tension when there is no fluid pressure, repeat the same calculations iteratively until ν_2 and k values that satisfy both equations of equilibrium are determined. Because the strain in the inner fiber of the core for both loading conditions FW1 and WT3 is not tensile, radial tension does not develop. Sec. 8.6

The results for the final iteration cycle for all serviceability limit states at invert/crown obtained using a computer program are summarized in Table C.1. Note that small differences with hand calculations are caused by roundoff.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Table C.1 Summary of calculations for serviceability at invert/crown

Limit-State Criterion	Load Combination	N_1 (lb/ft)	M_1 (lb-in./ft)	ν_2	k	Strain or Stress	Limiting Value	Criterion Satisfied
Inside core tensile strain ($\varepsilon_{ci} \leq 1.5\ \varepsilon_t'$)	W1	66,304	51,685	–0.199	0.368	108×10^{-6}	203×10^{-6}	Yes
Inside core tensile strain ($\varepsilon_{ci} \leq \varepsilon_k'$)	WT1	93,484	51,685	1.684	0.704	363×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
	WT2	66,304	51,685	–0.199	0.368	108×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
	FT1	87,883	56,853	1.210	0.641	299×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
Core-to-cylinder radial tension ($\sigma_r \leq 12$ psi)	FW1	–2,135	59,018	–1.773	–0.363	–26 psi	12 psi	Yes
	WT3	–1,646	51,685	–1.917	–0.491	–28 psi	12 psi	Yes

SECTION C.9: SERVICEABILITY AT SPRINGLINE

Limit states of serviceability at springline include the following criteria and load combinations:

Criterion:	Load combination:	**References**[1]
Outer core microcracking	W1	Table 3
Coating microcracking	W1	Table 3
Outer core visible cracking	WT1, WT2, FT1	Table 3
Coating visible cracking	WT1, WT2, FT1	Table 3
Inner core compression	W2, WT3	Table 3

Calculation procedures for all of the criteria and load combinations are similar. The detailed calculations for outer core visible cracking and coating visible cracking under load combination WT1 are shown below. The results for other criteria are summarized at the end of the section.

Applied moment and thrust at springline for load combination WT1:

References[1]

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

$$= 39.22[0.0885(6{,}000 + 0) + 0.1016 \times 1{,}654 + 0.0878 \times 1{,}764]$$

$$= 33{,}491 \text{ lb-in./ft}$$

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

$$= 6 \times 75.5(150 + 60) - [0.5386(6{,}000 + 0) + 0.3026$$

$$\times 1{,}654 - 0.0617 \times 1{,}764] = 91{,}507 \text{ lb/ft}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

The procedure for determining the strain and the stress distribution in the pipe cross section at springline caused by the applied loads is iterative and requires satisfying the force and moment equilibrium equations. An iteration cycle is demonstrated below for the trial values of

$$\nu_2 = 0.296$$

$$k' = 0.702$$

Sec. C.9.1 Constants

References[1]

$$t_t = \frac{1}{1+\nu_2} k' h_c = \frac{1}{1+0.296} 0.702 \times 5.5 = 2.979 \text{ in.} \qquad \text{Sec. 8.9.2}$$

$$t_s = \nu_2 \, t_t = 0.296 \times 2.979 = 0.882 \text{ in.} \qquad \text{Sec. 8.9.2}$$

$$\lambda = \frac{h_c - d_y}{t_s} = \frac{5.5 - 1.72}{0.882} = 4.286 \qquad \text{Sec. 8.9.2}$$

Sec. C.9.2 Strains

References[1]

$$\varepsilon_{co} = (1+\nu_2)\,\varepsilon_t' = (1+0.296) \times 135 \times 10^{-6} = 175 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$\varepsilon_{ci} = \varepsilon_{co}\left(\frac{1}{k'} - 1\right) = 175 \times 10^{-6}\left(\frac{1}{0.702} - 1\right) = 74 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$\Delta\varepsilon_y = \varepsilon_{co}\left(\frac{1-\lambda_y}{k'} - 1\right) = 175 \times 10^{-6}\left(\frac{1-0.313}{0.702} - 1\right) = -4 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$\Delta\varepsilon_s = \varepsilon_{co}\left(1 + \frac{\lambda_s}{k'}\right) = 175 \times 10^{-6}\left(1 + \frac{0.0175}{0.702}\right) = 179 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$\varepsilon_s = \Delta\varepsilon_s - \frac{f_{sr} - nf_{cr}}{E_s} = 179 \times 10^{-6} - \frac{-150{,}192 - 7.29 \times 1{,}028}{28 \times 10^6}$$

$$= 5{,}811 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$\varepsilon_{mo} = \varepsilon_{co}\left(1 + \frac{2\lambda_m}{k'}\right) + \varepsilon_{cr} = 175 \times 10^{-6}\left(1 + \frac{2 \times 0.0856}{0.702}\right) + 268 \times 10^{-6} \qquad \text{Sec. 8.9.2}$$

$$= 486 \times 10^{-6}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.9.3 Stresses

References[1]

For $\nu_2 = 0.296$ satisfying the inequality $0 < \nu_2 < \nu = 10$,

$f_{co} = \left(1-\frac{\nu_2}{\nu}\right) f_t' = \left(1-\frac{0.296}{10}\right)519 = 504$ psi Sec. 8.9.2

$f_{ci} = (1+\nu_2) f_t'\left(\frac{1}{k'}-1\right) = (1+0.296)\times 519\left(\frac{1}{0.702}-1\right) = 286$ psi Sec. 8.9.2

$\Delta f_y = n'(1+\nu_2) f_t'\left(\frac{1-\lambda_y}{k'}-1\right) = 7.81(1+0.296)519\left(\frac{1-0.313}{0.702}-1\right)$

$= -112$ psi Sec. 8.9.2

$\lambda = 4.286 > 1$; therefore,

$f_{cy} = (1+\nu_2) f_t'\left(\frac{1-\lambda_y}{k'}-1\right) = (1+0.296)519\left(\frac{1-0.313}{0.702}-1\right)$

$= -14$ psi Sec. 8.9.2

$\Delta f_s = n(1+\nu_2) f_t'\left(1+\frac{\lambda_s}{k'}\right) = 7.29(1+0.296)519\left(1+\frac{0.0175}{0.702}\right)$

$= 5{,}026$ psi Sec. 8.9.2

Sec. C.9.4 Internal Forces

References[1]

$F_{ci} = \frac{1}{2}(1-k')bh_c f_{ci} = \frac{1}{2}(1-0.702)12 \times 5.5 \times 286 = 2{,}813$ lb/ft Sec. 8.9.2

$F_y = A_y(\Delta f_y - f_{cy}) = 0.7176(-112+14) = -70$ lb/ft Sec. 8.9.2

$F'_{co} = -\frac{1}{2}bt_t(1+\nu)f_t' = -\frac{1}{2} \times 12 \times 2.979(1+10)519 = -102{,}043$ lb/ft Sec. 8.9.2

Because $0 < \nu_2 = 0.296 \le \nu = 10$,

$F''_{co} = \frac{1}{2}bt_t(\nu-\nu_2)f_{co} = \frac{1}{2} \times 12 \times 2.979(10-0.296)504 = 87{,}418$ lb/ft Sec. 8.9.2

$F_{co} = F'_{co} + F''_{co} = -102{,}043 + 87{,}418 = -14{,}625$ lb/ft Sec. 8.9.2

$F_s = -A_s\Delta f_s = -0.565 \times 5{,}026 = -2.840$ lb/ft Sec. 8.9.2

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.9.5 Sum of Forces

References[1]

$$\Sigma F = N_o - N_2 - (F_{ci} + F_y + F_{co} + F_s)$$

Eq 8-11

$$= 76{,}720 - 91{,}507 - (2{,}813 - 69 - 14{,}625 - 2{,}840) = -66 \approx 0$$

Sec. C.9.6 Internal Moments

References[1]

$$M_{ci} = F_{ci}\left[(1+\lambda_s)h_c - \frac{(1-k')h_c}{3}\right]$$

Sec. 8.9.2

$$= 2{,}813\left[(1+0.0175)5.5 - \frac{(1-0.702)5.5}{3}\right] = 14{,}205 \text{ lb-in./ft}$$

$$M_y = F_y h_c(1 + \lambda_s - \lambda_y) = -70 \times 5.5(1 + 0.0175 - 0.313) = -271 \text{ lb-in./ft}$$

Sec. 8.9.2

Because $0 < \nu_2 = 0.296 \leq \nu = 10$,

$$M_{co} = F_{co}'\left[h_c\lambda_s + t_t\left(\nu_2 + \frac{1-\nu}{3}\right)\right] + F_{co}''\left[h_c\lambda_s - t_t\frac{\nu - \nu_s}{3}\right]$$

Sec. 8.9.2

$$= -102{,}043\left[5.5 \times 0.0175 + 2.979\left(0.296 + \frac{1-10}{3}\right)\right]$$

$$+ 87{,}418\left(5.5 \times 0.0175 - 2.979\frac{10-0.296}{3}\right)$$

$$= -21{,}795 \text{ lb-in./ft}$$

Sec. C.9.7 Sum of Moments About Wire

References[1]

$$\Sigma M = M_2 + N_o\,[(1+\lambda_s)\,h_c - e_o] - N_2\,[(1+\lambda_s)\,h_c - e] - (M_{ci} + M_y + M_{co})$$

Eq 8-12

$$= 33{,}491 + 76{,}720\,[(1+0.0175)\,5.5 - 2.839] - 91{,}507\,[(1+0.0175)\,5.5$$

$$- 2.839] - (14{,}205 - 271 - 21{,}795) = 581 \text{ lb-in./ft}$$

For serviceability limit states at springline, the contribution of mortar stress to force and moment equilibrium has been neglected, the coating in computing the line of action of thrust N_2, that is, $e = e_o$, has been neglected at the same time.

Because the equations of equlibrium of forces and moments are satisfied, convergence has been achieved and the calculated stresses and strains are correct for the loading condition WT1.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Table C.2 Summary of calculations for serviceability at springline

Limit-State Criterion	Load Combination	N_2 *(lb/ft)*	M_2 *(lb-in./ft)*	ν_2	k'	Strain or Stress	Limiting Value	Criterion Satisfied
Outer core tensile strain ($\varepsilon_{co} \leq 1.5\ \varepsilon_t'$)	W1	64,327	33,482	−0.478	0.300	70×10^{-6}	203×10^{-6}	Yes
Outer coating tensile strain ($\varepsilon_{mo} \leq 0.8\ \varepsilon_{k'm}$)	W1	64,327	33,482	−0.478	0.300	378×10^{-6}	912×10^{-6}	Yes
Outer core tensile strain ($\varepsilon_{co} \leq \varepsilon_k'$)	WT1	91,507	33,482	0.296	0.702	175×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
	WT2	64,327	33,482	−0.478	0.300	70×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
	FT1	85,708	36,830	0.183	0.606	160×10^{-6}	$1{,}487 \times 10^{-6}$	Yes
Outer coating tensile strain ($\varepsilon_{mo} \leq \varepsilon_{k'm}$)	WT1	91,507	33,482	0.296	0.702	486×10^{-6}	$1{,}144 \times 10^{-6}$	Yes
	WT2	64,327	33,482	−0.478	0.300	378×10^{-6}	$1{,}144 \times 10^{-6}$	Yes
	FT1	85,708	36,830	0.183	0.606	473×10^{-6}	$1{,}144 \times 10^{-6}$	Yes
Inner core compression								
($f_{ci} \leq 0.55\ f_c'$)	W2	−3,623	33,482	−2.223	−0.705	1,536 psi	3,025 psi	Yes
($f_{ci} \leq 0.65\ f_c'$)	WT3	−3,623	33,482	−2.223	−0.705	1,536 psi	3,575 psi	Yes

The outer core tensile strain limit is satisfied, because $\varepsilon_{co} = 175 \times 10^{-6} < \varepsilon_k' = 1{,}487 \times 10^{-6}$.

The outer coating tensile strain limit is satisfied, because $\varepsilon_{mo} = 486 \times 10^{-6} < \varepsilon_{k'm} = 1{,}144 \times 10^{-6}$.

It could be demonstrated, following the same calculational procedure, that all other criteria are satisfied for all relevant load combinations. The results for the final iteration cycle obtained using a computer program are summarized in Table C.2.

SECTION C.10: ELASTIC LIMIT AT INVERT/CROWN

The elastic limit states at invert/crown include the following criteria and load combinations:

Criterion:	Load combination:	**References**[1]
Yielding of cylinder	WT1, WT2, FT1	Table 3
Onset of tension in cylinder	WT3	Table 3

Calculation procedures for all of the criteria and load combinations are similar. For the load combination WT1, stresses and strains in the pipe invert satisfying the equations of equilibrium of forces and moments have already been calculated. Using Δf_y already calculated for WT1, yielding of the cylinder does not occur, because

$$
\begin{aligned}
f_y &= -f_{yr} + n' f_{cr} + \Delta f_y \\
&= -24{,}918 + 7.81 \times 1{,}028 + 6{,}069 = -10{,}820 \text{ psi} \leq f_{yy} = 33{,}000 \text{ psi}
\end{aligned}
$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Table C.3 Summary of calculations for elastic limit at invert/crown

Limit-States Criterion	Load Combination	N_1 *(lb/ft)*	M_1 *(lb-in./ft)*	v_2	k	Cylinder Stress *(psi)*	Limiting Stress *(psi)*	Criteria Satisfied
Yielding of cylinder $-f_{yr} + n' f_{cr} + \Delta f_y \leq f_{yy}$	WT1	93,485	51,685	1.684	0.704	–10,840	+33,000	Yes
	WT2	66,304	51,685	–0.199	0.368	–16,400	+33,000	Yes
	FT1	87,883	56,853	1.210	0.641	–12,296	+33,000	Yes
Onset of tension in cylinder $-f_{yr} + n' f_{cr} + \Delta f_y \leq 0$	WT3	–1,646	51,685	–1.917	–0.491	–22,973	0	Yes

The steel cylinder is in compression and, therefore, cannot yield in tension. The results for the final iteration cycle for all elastic limit states at invert/crown obtained using a computer program are summarized in Table C.3.

SECTION C.11: ELASTIC AND WIRE-YIELD STRENGTH LIMITS AT SPRINGLINE

Elastic limit and the wire-yield criteria at springline and the corresponding load combinations are as follows:

Criterion:	Load combination:	**References**[1]
Wire elastic limit	FWT1, FWT2, FT2	Table 3
Inside core compression limit	FWT1, FWT2, FT2	Table 3
Wire-yield limit	FWT3, FWT4	Table 3

The calculational procedure for the wire elastic and yield limits and core compression limit of 0.75 f_c' is similar to the previously shown procedure for serviceability limits. The calculation for the wire-yield criterion is demonstrated below, because that criterion controls the design. The calculation procedure is shown for $N_2 > N_k'$. Under this condition, the criterion check is performed by comparing the moment at springline with the moment capacity at springline. The moment at springline is computed accounting for the moment redistribution, because the moment capacity at invert is exceeded, and moment is redistributed from invert to springline. The computation of critical thrust at invert at cylinder yield is presented in Sec. C.11.2. This is required for calculating the moment capacity at invert and moment at springline after redistribution, stated in Sec. C.11.3.

Sec. C.11.1 Limit State of Wire Yielding at Springline

Moments and thrusts corresponding to load combination FWT3 are calculated using the load and pressure factors stated in Sec. 3 of the standard and the equations stated in Sec. 4 of the standard.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$$N_1 = 1.3 \times 6 \times 75.5\,(150 + 60) - 1.3\,[0.3255\,(6{,}000 + 0) + 0.1029 \times 1{,}654 - 0.2703 \times 1{,}764] = 121{,}529 \text{ lb/ft}$$

Eq 4-4

$$M_1 = 1.3 \times 39.22\,[0.1247\,(6{,}000 + 0) + 0.2157 \times 1{,}654 + 0.1208 \times 1{,}764] = 67{,}202 \text{ lb-in./ft}$$

Eq 4-2

$$N_2 = 1.3 \times 6 \times 75.5\,(150 + 60) - 1.3\,[0.5386\,(6{,}000 + 0) + 0.3026 \times 1{,}654 - 0.0617 \times 1{,}764] = 118{,}959 \text{ lb/ft}$$

Eq 4-5

$$M_2 = 1.3 \times 39.22\,[0.0885\,(6{,}000 + 0) + 0.1016 \times 1{,}654 + 0.0878 \times 1{,}764] = 43{,}538 \text{ lb-in./ft}$$

Eq 4-3

Sec. C.11.2 Critical Thrust at Invert at Cylinder Yield, N_{yy}

References[1]

When the invert is subjected to thrust alone, the tensile strain in the core at cylinder yield is given by

$$\varepsilon_c = -\varepsilon_{cr} + \Delta\varepsilon_{yy} = -\varepsilon_{cr} + \frac{f_{yy} + f_{yr}}{E_y} = -268 \times 10^{-6} + \frac{33{,}000 + 24{,}918}{30 \times 10^{6}} = 1{,}633 \times 10^{-6}$$

Sec. 8.9.1

Because $\varepsilon_c > \varepsilon_k' = 1{,}487 \times 10^{-6}$, $f_c\,(-\varepsilon_{cr} + \Delta\varepsilon_{yy}) = 0$.

The strain in the prestressing wire at cylinder yield is

$$\varepsilon_s = -\varepsilon_{sr} + \Delta\varepsilon_{yy} = 5{,}364 \times 10^{-6} + \frac{33{,}000 + 24{,}918}{30 \times 10^{6}} = 7{,}295 \times 10^{-6}$$

Sec. 8.9.1

Because wire strain ε_s is greater than the strain at the elastic limit of the wire $f_{sg}/E_s = 189{,}000/28 \times 10^{6} = 6{,}750 \times 10^{-6}$, the stress in the wire must be computed from the nonlinear stress–strain relationship of the wire. Therefore, the critical thrust at cylinder yield is

$$f_s = f_{su}\left[1 - \left(1 - 0.6133\varepsilon_s \frac{E_s}{f_{su}}\right)^{2.25}\right]$$

Eq 5-7

$$f_s = 252{,}000\left[1 - \left(1 - 0.6133 \times 7{,}295 \times 10^{-6}\,\frac{28 \times 10^{6}}{252{,}000}\right)^{2.25}\right] = 198{,}333 \text{ psi}$$

$$N_{yy} = A_c f_c + A_y f_{yy} + A_s f_s = 65.28 \times 0 + 0.7176 \times 33{,}000 + 0.565 \times 198{,}333 = 135{,}739 \text{ lb/ft}$$

Sec. 8.9.1

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Sec. C.11.3 Moment Capacity at Invert and Redistributed Moment at Springline

References[1]

Because $N_k' < N_1 < N_{yy}$, moment capacity at the invert M_{1cap} is calculated by linear interpolation between the moment capacity at N_k' and zero moment capacity at N_{yy}. — Sec. 8.9.1

Moment capacity at N_k' at invert, $M_{cap}(N_k')$ is equal to the moment capacity based on the cylinder yield at N_k', but not greater than the moment capacity based on the onset of tension in the cylinder for the thrust calculated with zero pressure and unfactored earth load, and pipe and fluid weights. — Sec. 7.4.2

The calculation procedure for computing the moment capacity for a given thrust is iterative and similar to the procedure described before for elastic limit at the invert. For each selected trial value of k and ν_2, the stresses and strains are computed and the equilibria of forces and moments are checked. The only difference is that the new values of ν_2 are determined from the condition in which the stress in the cylinder reaches yield rather than from the equilibrium of moments equation. In this example, in the final iteration cycle ν_2 = 17.771 and k = 0.908. Stress in the cylinder is

References[1]

$$\Delta f_y = n' f_t' (1+\nu_2)\left(1-\frac{\lambda_y}{k}\right) \qquad \text{Sec. 8.9.1}$$

$$= 7.81 \times 519(1+17.771)\left(1-\frac{0.313}{0.908}\right) = 49{,}858 \text{ psi}$$

$$f_y = -f_{yr} + n' f_{cr} + \Delta f_y = -24{,}918 + 7.81 \times 1{,}028 + 49{,}858$$

$$= 32{,}969 \approx 33{,}000 \text{ psi}$$

Moment capacity based on the cylinder yield at $N_1 = N'_k$, denoted here as $M_{1yy}(N'_k)$, is calculated from the sum of moments about the wire at invert:

$$\begin{aligned} M_{1yy}(N'_k) = {} & N_o[(1+\lambda_s)\,h_c - e_o] - N_k'\,[(1+\lambda_s)\,h_c - e] + M_{ci} + M_y \qquad \text{Eq 8-10} \\ & + M_{co} + M_m = 76{,}720\ [(1+0.0175)\times 5.5 - 2.839] - 104{,}389 \\ & [(1+0.0175)\ 5.5 - 2.973] + 15{,}196 + 138{,}745 - 800 + 5{,}093 \\ & = 95{,}932 \text{ lb-in./ft} \end{aligned}$$

where the location of the line of action of thrust, e = 2.973 in., and the moments on the right-hand side of the equation are calculated following the procedure in Sec. C.8.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

The moment capacity at the onset of tension in the cylinder is calculated similarly at pressure equal to zero with

References[1]

$$\begin{aligned} N_1 &= -[C_{n1e}\,(W_e + W_t) + C_{n1p}\,W_p + C_{n1f}\,W_f] \qquad \text{Eq 4-4} \\ &= -[0.3255\,(6{,}000 + 0) + 0.1029 \times 1{,}654 - 0.2703 \times 1{,}764] \\ &= -1{,}646 \text{ lb/ft} \end{aligned}$$

In the last iteration, when the cylinder stress reaches the onset of tension, $\nu_2 = 8.247$ and $k = 0.569$. Stress in the cylinder is

$$\begin{aligned} \Delta f_y &= 7.81 \times 519(1 + 8.247)\left(1 - \frac{0.313}{0.569}\right) = 16{,}864 \text{ psi} \qquad \text{Sec. 8.9.1} \\ f_y &= -f_{yr} + n'\,f_{cr} + \Delta f_y = -24{,}918 + 7.81 \times 1{,}028 + 16{,}864 \\ &= -25 \text{ psi} \approx 0 \qquad \text{Sec. 8.9.1} \end{aligned}$$

Moment capacity, based on onset of tension in the cylinder at N_k', denoted here as $M_{yo}(N_k')$, is calculated following the above procedure for moment capacity at cylinder yield. The result is shown below.

$$\begin{aligned} M_{1yo}(N_k') = {} & 76{,}720\ [(1 + 0.0175)\ 5.5 - 2.839] + \qquad \text{Eq 8-10} \\ & 1{,}646\ [(1 + 0.0175)\ 5.5 - 3.216] + 42{,}424 + \\ & 45{,}982 - 45{,}814 + 14{,}602 = 272{,}648 \text{ lb-in./ft} \end{aligned}$$

Because $M_{1yy}(N_k') < M_{1yo}(N_k')$, the moment capacity at N_k' at invert is $M_{1cap}(N_k') = 95{,}932$ lb-in./ft.

The moment capacity at N_1 is calculated by linear interpolation:

$$\begin{aligned} M_{1cap} &= \frac{N_{yy} - N_1}{N_{yy} - N_k'}\, M_{1cap}(N_k') = \frac{135{,}739 - (121{,}529)}{135{,}739 - (104{,}389)} 95{,}932 \\ &= 43{,}483 \text{ lb-in./ft} \qquad \text{Sec. 8.9.1} \end{aligned}$$

Because $M_1 > M_{1cap}$, the applied moment redistributes from invert to springline, as follows:

$$\begin{aligned} M_{2r} &= M_1 + M_2 - M_{1cap} = 67{,}202 + 43{,}538 - 43{,}483 \\ &= 67{,}257 \text{ lb-in./ft} \qquad \text{Eq 4-6} \end{aligned}$$

Sec. C.11.4 Critical Thrust at Wire Yield, N_{sy}

References[1]

When the stress in the prestressing wire reaches yield, $f_s = 0.85\ f_{su}$ and $\varepsilon_{sy} = 0.92883\ f_{su}/E_s$, because for this value of ε_{sy}

$$\frac{f_s}{f_{su}} = 1 - (1 - 0.6133 \times 0.92883)^{2.25} = 0.85 \qquad \text{Eq 5-7}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

References[1]

$$f_{sy} = 0.85\, f_{su} = 0.85 \times 252{,}000 = 214{,}200 \text{ psi}$$

Sec 5.6.2

$$\varepsilon_{sy} = \frac{0.92883\, f_{su}}{E_s} = \frac{0.92883 \times 252{,}000}{28 \times 10^6} = 8{,}359 \times 10^{-6}$$

$$\begin{aligned} \varepsilon_c &= -\varepsilon_{cr} + \Delta\varepsilon_{sy} = -\varepsilon_{cr} + \varepsilon_{sy} - \varepsilon_{sr} \\ &= -268 \times 10^{-6} + 8{,}359 \times 10^{-6} + 5{,}364 \times 10^{-6} \\ &= 13{,}455 \times 10^{-6} \end{aligned}$$

Sec. 8.9.2

Because $\varepsilon_c > \varepsilon_k' = 1{,}487 \times 10^{-6}$, $f_c\,(-\varepsilon_{cr} + \Delta\varepsilon_{sy}) = 0$

Figure 2

$$\begin{aligned} \varepsilon_y &= -\varepsilon_{yr} + \Delta\varepsilon_{sy} = -\varepsilon_{yr} + \varepsilon_{sy} - \varepsilon_{sr} \\ &= -831 \times 10^{-6} + 8{,}359 \times 10^{-6} - 5{,}364 \times 10^{-6} \\ &= 12{,}892 \times 10^{-6} \end{aligned}$$

Sec. 8.9.2

Sec. 8.9.2

Since $\varepsilon_y > \varepsilon_{yy} = \dfrac{f_{yy}}{E_y} = \dfrac{33{,}000}{30 \times 10^6} = 1{,}100 \times 10^{-6}$, $f_y = f_{yy}$

$= 33{,}000$ psi

Figure 3

$$\begin{aligned} N_{sy} &= A_c f_c + A_y f_y + A_s f_{sy} = 65.28 \times 0 + 0.7176 \times 33{,}000 \\ &\quad + 0.565 \times 214{,}200 = 144{,}704 \text{ lb/ft} \end{aligned}$$

Sec. 8.9.2

Sec. C.11.5 Moment Capacity at Wire Yield

Because $N_k' < N_2 < N_{sy}$, the wire yielding criterion is not checked by comparing the stress in the wire with its yield strength, but the criterion is checked by comparing the applied moment with the moment capacity at springline at wire yield. The moment capacity at wire yield is calculated by linear interpolation between the moment capacity at N_k' and the zero moment capacity at N_{sy}.

Moment capacity at wire yield at the springline for $N_2 = N_k'$, denoted here as $M_{2sy}(N_k')$, is calculated iteratively following the procedure similar to the procedure described for the calculation of the moment capacity of cylinder yield at invert at N_k'. Calculations of stresses and strains are performed following the procedure of Sec. C.9. In the last iteration, when the wire stress reaches wire-yield stress, $\nu_2 = 18.745$ and $k' = 0.790$. The strain in the wire can be checked as follows:

References[1]

$$\varepsilon_{co} = (1 + \nu_2)\, \varepsilon_t' = (1 + 18.745)\, 135 \times 10^{-6} = 2{,}666 \times 10^{-6}$$

Sec. 8.9.2

$$\Delta\varepsilon_s = \varepsilon_{co}\left(1 + \frac{\lambda_s}{k'}\right) = 2{,}666 \times 10^{-6}\left(1 + \frac{0.0175}{0.790}\right) = 2{,}725 \times 10^{-6}$$

Sec. 8.9.2

$$\begin{aligned} \varepsilon_s &= \Delta\varepsilon_s - \frac{f_{sr} - nf_{cr}}{E_s} = 2{,}725 \times 10^{-6} - \frac{-150{,}192 - 7.29 \times 1{,}028}{28 \times 10^6} \\ &= 8{,}357 \times 10^{-6} = \varepsilon_{sy} \end{aligned}$$

Sec. 8.9.2

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Table C.4 Summary of calculations for elastic limits and wire yield limit at springline

Limit-State Criterion	Load Combination	N_2 *(lb/ft)*	M_2 or M_{2r} *(lb-in./ft)*	ν_2	k'	Applied Stress or Moment	Limiting Value	Criterion Satisfied
Wire elastic limit, $f_s \le f_{sg}$	FWT1	100,657	36,830	3.103	0.754	173,574	189,000	Yes
	FWT2	70,759	36,830	0.197	0.431	162,403	189,000	Yes
	FT2	94,279	40,513	2.296	0.690	170,476	189,000	Yes
Core compression limit, $f_c \le 0.75\,f_c'$	FWT1	100,657	36,830	3.103	0.754	694	4,125	Yes
	FWT2	70,759	36,830	0.197	0.431	820	4,125	Yes
	FT2	94,279	40,513	2.296	0.690	769	4,125	Yes
Wire-yield limit for $N_2 > N_k',\ M_2 \le M_{2sy}$	FWT3	118,959	43,526	—	—	67,238	67,997	Controls
	FWT4	83,625	43,526	1.223	0.579	166,357	214,520	Yes

Finally, the moment capacity at springline at $N_2 = N_k'$, denoted here as $M_{2sy}\ (N_k')$, is calculated from the sum of moments at springline as follows:

References[1]

$$M_{2sy}\ (N_k') = -N_o\ [(1 + \lambda_s)\ h_c - e_o] + N_k'\ [(1 + \lambda_s)\ h_c - e] + M_{ci} + M_y + M_{co} \qquad \text{Eq 8-12}$$

$$= -76{,}720\ [(1 + 0.0175)\ 5.5 - 2.839] + 104{,}389\ [(1 + 0.0175)\ 5.5 - 2.973]$$

$$+ 98{,}690 - 27{,}675 - 26{,}829 = 106{,}488 \text{ lb-in./ft}$$

where the location of the line of thrust, $e = 2.973$ in., and the moments on the right-hand side of the equation are calculated following the procedure in Sec. C.8.

The moment capacity at N_2, denoted here as $M_{2sy}\ (N_2)$, is calculated by linear interpolation:

$$M_{2sy}(N_2) = \frac{N_{sy} - N_2}{N_{sy} - N_k'} M_{2sy}(N_k') = \frac{144{,}704 - (118{,}959)}{144{,}704 - (104{,}380)}\ 106{,}488$$

$$= 68{,}003 \text{ lb-in./ft} \qquad \text{Sec. 8.9.2}$$

Because the applied moment at springline after redistribution is $M_{2r} = 67{,}257$ lb-in./ft $\approx M_{2sy}(N_2)$, this criterion is satisfied and controls the design.

The results for the final iteration cycle for all elastic-limit and wire-yield criteria at springline obtained using a computer program are listed in Table C.4.

SECTION C.12: CORE CRUSHING AT SPRINGLINE

The limit state of core crushing at springline requires that the applied moment at springline for the load combination FWT5 does not exceed the moment limit for ultimate compressive strength of core concrete.

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

Moment and thrust at springline for the load combination FWT5 are calculated as

References[1]

$$\begin{aligned} M_2 &= \bar{R}\,(1.6\, C_{m2e}\, W_e + 2\, C_{m2e}\, W_t + 1.6\, C_{m2p}\, W_p + 1.6\, C_{m2f}\, W_f) \\ &= 39.22\,(1.6 \times 0.0885 \times 6{,}000 + 0 + 1.6 \times 0.1016 \times 1{,}654 \\ &\quad + 1.6 \times 0.0878 \times 1{,}764) = 53{,}586 \text{ lb-in./ft} \end{aligned}$$

Eq 4-3

$$\begin{aligned} N_2 &= -(1.6\, C_{n2e}\, W_e + 2\, C_{n2e}\, W_t + 1.6\, C_{n2p}\, W_p + 1.6\, C_{n2f}\, W_f) \\ &= -(1.6 \times 0.5386 \times 6{,}000 + 0 + 1.6 \times 0.3026 \times 1{,}654 \\ &\quad - 1.6 \times 0.0617 \times 1{,}764) = -5{,}797 \text{ lb/ft} \end{aligned}$$

Eq 4-5

Following the procedure given in Sec. C-11, it is shown that $M_1 < M_{1cap}$, and there is no moment redistribution from invert to springline.

The location of the neutral axis is calculated by trial and error until force equilibrium is satisfied. In the last iteration, $k' = 0.4597$.

Sec. C.12.1 Constants

References[1]

$$\beta = 0.85 - 0.05\,(f_c'/1{,}000 - 4) = 0.85 - 0.05\,(5{,}500/1{,}000 - 4) = 0.775$$

Sec. 8.9.3

$$d = h_c\,(1 + \lambda_s) = 5.5\,(1 + 0.0175) = 5.596 \text{ in.}$$

Figure 7

Sec. C.12.2 Strains

References[1]

$$\varepsilon_{ci} = 0.003$$

Sec. 8.9.3

$$\Delta\varepsilon_y = \varepsilon_{ci}\frac{k' - \dfrac{\lambda_y}{(1+\lambda_s)}}{k'},\ = 0.003\frac{0.4597 - \dfrac{0.313}{(1+0.0175)}}{0.4597}$$

$$= 992 \times 10^{-6}$$

Sec. 8.9.3

$$\Delta\varepsilon_s = \varepsilon_{ci}\frac{1-k'}{k'} = 0.003\frac{1-0.4597}{0.4597} = 3{,}526 \times 10^{-6}$$

Sec. 8.9.3

$$\begin{aligned} \varepsilon_s &= \varepsilon_{cr} - \varepsilon_{sr} + \Delta\varepsilon_s = 268 \times 10^{-6} + 5{,}364 \times 10^{-6} \\ &\quad + 3{,}526 \times 10^{-6} \end{aligned}$$

Sec. 8.9.3

$$= 9{,}158 \times 10^{-6} > \varepsilon_{sg} = \frac{f_{sg}}{E_s} = \frac{189{,}000}{28 \times 10^6} = 6{,}750 \times 10^{-6}$$

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[1] Where no AWWA standard number is given, the reference is to AWWA C304-99.

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6666 West Quincy Avenue, Denver, Colorado 80235