

ANSI/AWWA **C305-24**
(Revision of ANSI/AWWA C305-18)

AWWA Standard

CFRP Renewal and Strengthening of Prestressed Concrete Cylinder Pipe (PCCP)

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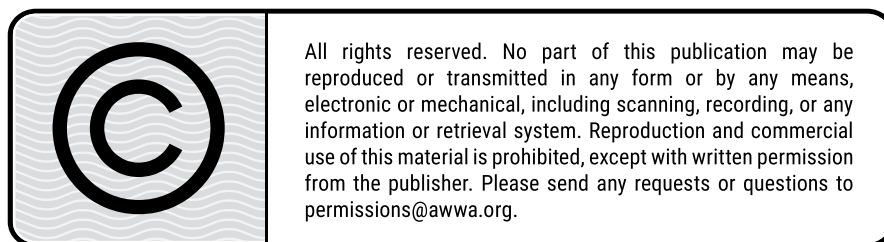
AWWA Standard

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Committee Personnel

The AWWA Standards Subcommittee on ANSI/AWWA C305, which developed this standard, had the following personnel at the time:

Mehdi S. Zarghamee, *Chair*

Anna Pridmore, *Secretary*

S.A. Arnaout, Consultant, Plano, Tex.

S.F. Arnold, Fyfe FRP LLC, San Diego, Calif.

K.R. Baas, American Concrete Pressure Pipe Association, Hattiesburg, Miss.

W.R. Brunzell, Brunzell Associates Ltd., Wilmette, Ill.

R.A. Coates, Professional Engineer, Miami, Fla.

D.L. Davis, Howard County Department of Public Works, Columbia, Md.

C. Dean, Structural Technologies, Columbia, Md.

P. DiMarco, Howard County Department of Public Works, Columbia, Md.

M. Engindeniz, Simpson Gumpertz & Heger Inc., Waltham, Mass.

N.D. Faber, San Diego County Water Authority, San Diego, Calif.

J. Galleher Jr., Pure Technologies, San Diego, Calif.

M.P. Gipsov, Merrick & Company, Ellicott City, Md.

J.K. Johnson, Tarrant Regional Water District, Fort Worth, Tex.

M.R. McReynolds, Brown and Caldwell, Oakton, Va.

M. Najafi, University of Texas, Center for Underground Infrastructure Research and Education (CUIRE), Arlington, Tex.

R. Ortega, Aurora Technical Services LLC, Houston, Tex.

T. Peng, Metropolitan Water District of Southern California, Los Angeles, Calif.

A. Pridmore, Structural Technologies, Columbia, Md.

S. Rahman, KCI Technologies Inc., Dallas, Tex.

A.E. Romer, Industry Consultant, Huntington Beach, Calif.

V.F. Sever, QuakeWrap Inc., Tucson, Ariz.

A. Wagner, Amber Consulting LLC, Seattle, Wash.

R.F. Williams, AECOM, Miami, Fla.

M.S. Zarghamee, Simpson Gumpertz & Heger Inc., Waltham, Mass.

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

Nathan C. Faber, *Chair*
Kevin M. Brown, *Secretary*

General Interest Members

S.A. Arnaout, Consultant, Plano, Tex.
H.H. Bardakjian, Consulting Engineer, Glendale, Calif.
G. Bizien, Industry Consultant, Laval, Que.
W.R. Brunzell, Brunzell Associates Ltd., Wilmette, Ill.
B.C. Coltharp, Freese and Nichols Inc., Dallas, Tex.
D. Faber (*liaison, nonvoting*), Standards Council Liaison, Faber and Associates, Terra Alta, W.Va.
W.C. Hagenburger, Crossland Heavy Contractors, Lowell, Ark.
F.S. Kurtz (*liaison, nonvoting*), Standards Engineer Liaison, AWWA, Denver, Colo.
A.S. Maughn (*alternate*), Freese and Nichols Inc., Dallas, Tex.
R. Ortega, Aurora Technical Services LLC, Houston, Tex.
A. Rodriguez, HDR Engineering Inc., San Antonio, Tex.
A.E. Romer, Industry Consultant, Huntington Beach, Calif.
R.F. Williams, AECOM, Miami, Fla.
M.S. Zarghamee, Simpson Gumpertz & Heger Inc., Waltham, Mass.

Producer Members

K.R. Baas (*alternate*), American Concrete Pressure Pipe Association, Hattiesburg, Miss.
K.M. Brown, American Concrete Pressure Pipe Association, Rockledge, Fla.
C.D. Ciobanu, Forterra/Rinker Pipe, Saint-Eustache, Que.
M. DeFranco (*alternate*), Decast Ltd., Utopia, Ont.
D.W. Dunker, Thompson Pipe Group, Grand Prairie, Tex.
B.D. Keil, Northwest Pipe Company, Salt Lake City, Utah
Y. Lan, Decast Ltd., Utopia, Ont.
D. Miceli (*alternate*), Forterra/Rinker Pipe, Saint-Eustache, Que.
R.D. Mielke (*alternate*), Northwest Pipe Company, Raleigh, N.C.

User Members

W.C. Duke, Bureau of Reclamation, Denver, Colo.

N.D. Faber, San Diego County Water Authority, San Diego, Calif.

J.K. Johnson, Tarrant Regional Water District, Fort Worth, Tex.

F. Sy Su, Los Angeles Dept. of Water and Power, Los Angeles, Calif.

A.F. Williams, Louisville Water Company, Louisville, Ky.

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Foreword

This foreword is for information only and is not a part of ANSI/AWWA C305.*

I. Introduction

I.A. *Background.* Prestressed concrete cylinder pipe (PCCP) has had a long and diverse history with many changes in standards and materials. The earliest application of PCCP in the United States was in 1942. That pipe, which is now known as lined-cylinder pipe (LCP), consists of a steel cylinder with cast concrete core overwrapped with steel wire. The continuing scarcity of steel, coupled with successful application to smaller pipe, led to the introduction of embedded-cylinder pipe (ECP) in 1953 (ref. ANSI/AWWA C301 Foreword). Site-manufactured ECP has been constructed as large as 252 in. (6.40 m) in diameter. Both types of PCCP are designed for the specific combination of internal pressure and external loads in accordance with the procedures detailed in ANSI/AWWA C304, Design of Prestressed Concrete Cylinder Pipe.

I.B. *History.* Utilities have taken steps in advance of failure to replace identified degraded pipes or repair them by encasing the degraded pipe in a reinforced concrete block or steel plate wrap, post-tensioning by wrapping tendons around the pipe, or relining. Relineing is typically performed by using a steel liner, by applying carbon fiber reinforced polymeric composites (CFRP) bonded to the inner surface of the pipe, or by sliplining.

The use of CFRP for civil and structural applications began with university testing in the late 1980s, which validated its use for such applications. In the early 1990s, CFRP gained acceptance within the engineering and construction industries through increased awareness, with project applications aided by the issuance of important approvals by building code authorities.

In the late 1990s, CFRP was first used for the strengthening of large-diameter underground PCCP. In the early 2000s, various municipal utilities began the widespread use of CFRP lining for degraded PCCP. The advancements of precision inspection methods increased the demand for CFRP upgrade of PCCP by equipping utility owners with critical information regarding the exact location of at-risk pipes. By about 2007, with the issuance of public contracts by various US and international utilities, installation of CFRP liner inside degraded or weak PCCP had become an acceptable renewal and strengthening system for PCCP.

* American National Standards Institute, 1180 Avenue of the Americas, 10th Floor, New York, NY 10036.

The high strength and stiffness of CFRP laminates make them suitable for pressure pipeline renewal and strengthening applications. Application of CFRP for internal strengthening of PCCP precludes the need for excavation of the pipe and is therefore especially advantageous where excavation is impossible or expensive to perform. Furthermore, the installation can be performed rapidly and therefore is especially advantageous when the available time for repair is very limited. CFRP constituents (carbon fiber and resin) are relatively inert materials and can be compatible for a variety of environments, including raw water, wastewater, and potable water, contingent upon necessary testing. Durability and compatibility should be tested for all environments that the CFRP is anticipated to be subject to during its service life, as provided in this standard.

Although CFRP for internal repair and strengthening of PCCP has been applied since 1997, the in-service history is substantially shorter than traditional construction materials. Therefore, utilities have sought consensus guidance for the design and installation of CFRP renewal and strengthening. In response, the AWWA Standards Committee on Concrete Pressure Pipe appointed a subcommittee at the Annual Conference in San Diego, Calif., in June 2009 to develop a proposal for such a standard. In March 2011, the AWWA Standards Council approved the development of a standard on “CFRP Renewal and Strengthening of Prestressed Concrete Cylinder Pipe (PCCP)” and assigned the responsibility to the AWWA Standards Committee on Concrete Pressure Pipe.

During the development of this standard, the Water Research Foundation (WRF) sponsored research and development on the CFRP renewal of PCCP that included literature review of available data, finite-element modeling of CFRP-lined PCCP subjected to external loads and internal pressures as the PCCP continues to degrade with time, full-scale testing of CFRP-lined PCCP with simulated degradation, and watertightness of CFRP during the degradation process of PCCP. The results of this research and development work form the basis of many of the provisions of this first edition of the standard, which was approved by the AWWA Board of Directors on June 9, 2018. This second edition of the standard was approved on March 13, 2024.

I.C. *Water Quality.* 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 direct and indirect drinking water additives. Other members of the original consortium included the Water Research Foundation (formerly 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. Specific policies of the state or local agency.
2. Four standards developed under the direction of NSF:[‡] NSF/ANSI/CAN[§] 60, Drinking Water Treatment Chemicals—Health Effects; NSF/ANSI/CAN 61, Drinking Water System Components—Health Effects; NSF/ANSI/CAN 372, Drinking Water System Components—Lead Content; and NSF/ANSI/CAN 600, Health Effects Evaluation and Criteria for Chemicals in Drinking Water.
3. 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 NSF/ANSI/CAN 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.

NSF/ANSI/CAN 600 (which formerly appeared in NSF/ANSI/CAN 60 and 61 as Annex A, “Toxicology Review and Evaluation Procedures”) 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 guidelines (noncarcinogens) and risk characterization methodology (carcinogens). Use of NSF/ANSI/CAN 600 procedures may not always be identical, depending on the certifier.

ANSI/AWWA C305 does not address additives requirements. Users of this standard should consult the appropriate state or local agency having jurisdiction in order to

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

[†] Persons outside the United States should contact the appropriate authority having jurisdiction.

[‡] NSF International, 789 North Dixboro Road, Ann Arbor, MI 48105.

[§] Standards Council of Canada, 55 Metcalfe Street, Suite 600, Ottawa, ON K1P 6L5 Canada.

[¶] Both publications available from National Academy of Sciences, 500 Fifth Street, NW, Washington, DC 20001.

II. Special Issues.

II.A. *Intent and Suitability.* This standard describes the procedures for material selection, design, installation, and quality control and quality assurance of the CFRP renewal and strengthening of PCCP. This standard provides requirements and recommendations to assist engineers, utility managers, and constructors in the selection of CFRP systems and in design and construction of CFRP renewal of degraded PCCP or strengthening of the PCCP to accept loads in excess of the design load.

II.B. *Advisory Information on Product Application.* The successful application of CFRP renewal or strengthening of PCCP will be the product of design, materials, and installation. CFRP system manufacturers and installers should be contacted for detailed product information and material properties regarding the capabilities of the CFRP system and proper methods of field installation. The design of the renewal system will require knowledge of the existing pipe and surrounding soil.

II.C. *Qualifications.* CFRP renewal and strengthening of PCCP requires understanding of all the physical, chemical, and environmental factors that influence a successful and quality installation. Recognizing the importance of the experience and qualifications of the designer, manufacturer, and constructor involved in these applications and that the consequences of failure are severe, the purchaser should take the necessary steps to assure itself that all personnel in all facets of the work are qualified.

II.D. *Contractual Relations.* AWWA standards do not include provisions involving business relations. Such relations are a proper topic for purchaser specifications but not for AWWA standards. Warranties or guarantees are examples of such relations, as well as many experience requirements. Sec. III.A of this foreword provides guidance on purchaser options and alternatives that a purchaser should provide in a typical bid package for CFRP renewal and strengthening of PCCP, including warranties (Sec. III.A [8] and Sec. III.A [9]) and experience criteria (Sec. III.A [6]). The constructor is responsible for the result of the installation work executed.

II.E. *Limitations.* The CFRP system is best suited for the renewal of degraded PCCP with broken wires with a relatively smooth interior surface. When the inner core concrete is degraded partially through the wall thickness (e.g., due to the chemistry of water), the degraded concrete should be removed, and the surface should be restored with structurally sound concrete or other approved materials. The surface of the restored areas shall be finished to adequate roughness before application of CFRP (see Sec. 4.4.1). The application of CFRP to severely deformed PCCP as described in Sec. 2.1.2.3 is beyond the scope of this standard.

III. Use of This Standard. It is the responsibility of the user of an AWWA standard to determine that the products described in that standard are suitable for use in the particular application being considered.

III.A. Purchaser Options and Alternatives. The following information should be provided by the purchaser in a typical bid package related to CFRP renewal and strengthening of PCCP:

1. Standard used—that is, ANSI/AWWA C305, of latest revision.
2. Details of federal, state, and local requirements (Sec. 3.1).
3. Whether compliance with NSF/ANSI/CAN 61, Drinking Water System Components—Health Effects, is required.
4. Constructability-related details.
 - a. Access and staging considerations
 - b. Location of access holes relative to pipe segments requiring work
 - c. Minimum manhole diameter that allows for access to job site
 - d. Location of pipes to be strengthened
 - e. Water intrusion, leakage, and flood potential
 - f. Plan and profile of the pipeline
 - g. Time permitted for construction
 - h. Working hours allotted
 - i. Noise mitigation requirements
 - j. Special safety issues
5. Design-related details.
 - a. Diameter of the pipe, design drawings containing PCCP parameters, specifications, and year of construction of PCCP
 - b. Laying schedule, pipe and joint design details, and as-built drawings
 - c. Working and transient pressures and all other loads required in design of CFRP renewal (see Sec. 2.4 for details)
 - d. Installation condition, cover height, in situ and backfill soils, and compaction level
 - e. Condition of interior surface of the PCCP and surface preparation requirements before CFRP installation
 - f. Joint condition and design details of CFRP termination and continuity through the joint
 - g. The thrust force to be transmitted through the joints
 - h. Fittings and special features on the pipe segments selected for CFRP renewal

6. The experience and submittal requirements for the CFRP designer, material manufacturer, CFRP installer and inspector, and a requirement that the submittals be provided concurrently with the bid.

7. Allocation of responsibility for construction-related activities.

- a. Traffic control
- b. Dewatering of the pipeline
- c. Chlorination and disinfection procedure
- d. Permitting
- e. Public relations
- f. Disposal of waste materials created during construction
- g. Bulkhead installation and removal
- h. Confined space entry and lockout/tagout
- i. Monitoring of groundwater to control leakage into the pipe

8. Whether a warranty on the materials and workmanship of the constructor for the CFRP system used for renewal or strengthening of the pipe is required, and the terms of the warranty.

9. Whether the warranty, if required, is a bonded warranty and the length of the bonded warranty period.

III.B. *Modification to Standard.* Any modification to the provisions, definitions, or terminology in this standard shall be provided by the purchaser.

IV. Major Revisions. Major changes made to the standard in this edition include the following:

1. The definition for *laminate rupture* has been added to the definitions, Sec. 1.2.
2. The definition for *rupture* has been added to the definitions, Sec. 1.2.
3. Equation Eq 2-17 has been modified (Sec. 2.9.3).
4. Numerous editorial improvements have been made throughout the standard.

V. Comments. If you have any comments or questions about this standard, please call AWWA Engineering and Technical Services at 303.794.7711; write to the department at 6666 West Quincy Avenue, Denver, CO 80235-3098; or e-mail at standards@awwa.org.



**American Water Works
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ANSI/AWWA C305-24
(Revision of ANSI/AWWA C305-18)

AWWA Standard

CFRP Renewal and Strengthening of Prestressed Concrete Cylinder Pipe (PCCP)

SECTION 1: GENERAL

Sec. 1.1 Scope, Purpose, and Application

The purpose of this standard is to provide the minimum requirements for material selection, design, installation, quality control, and quality assurance of the carbon fiber reinforced polymer (CFRP) renewal and strengthening of prestressed concrete cylinder pipe (PCCP). The scope of this standard covers all PCCP, including embedded-cylinder pipe (ECP) and lined-cylinder pipe (LCP). The scope of this standard is limited to the wet lay-up application of CFRP; this standard does not apply to pre-cured laminates adhered to the pipe wall, dry lay-up application, or automated/robotic CFRP installation methods (see Sec. 2.1.1). This standard is not applicable to the design of CFRP liner for severely deformed PCCP as described in Sec. 2.1.2.3.

Sec. 1.2 Definitions

Terms in this standard pertaining to CFRP shall be defined as in ASTM D883, Standard Terminology Relating to Plastics; ASTM D3878, Standard Terminology for Composite Materials; and ASTM D907, Standard Terminology of Adhesives.

When definitions of terms are in conflict, definitions in ASTM D3878 shall have precedence.

Additional important terms and definitions are as follows:

1. *Acceptance test*: A test or series of tests conducted to determine whether a material system or component conforms to the specified requirements.
2. *Additives*: Substances added to the polymer resin to aid in the processing of the CFRP material.
3. *Adhesive*: A substance capable of holding materials together by surface attachment.
4. *Amine blush*: Surface oiliness or “sweating” that occurs when epoxy is cured in a cool or high-humidity environment.
5. *Blister*: Void that contains fluid.
6. *Bond length*: The length along the axis of the pipe of the bond area at terminations between the laminate and the metallic substrate.
7. *Bubble*: Void that contains air.
8. *Buckling*: A limit state involving a sudden change in the geometry of the structure or structural elements thereof due to compressive forces exceeding stable equilibrium.
9. *Carbon fiber*: A solid semicrystalline organic material consisting of the atomic level of planar two-dimensional arrays of carbon atoms. Carbon fibers are used in CFRP renewal and strengthening in the form of unidirectional fabric.
10. *CFRP*: Abbreviation for a carbon fiber reinforced polymer material that consists of a polymer-resin-based matrix reinforced with carbon fibers.
11. *Characteristic value*: A statistically based property value representing the 80 percent lower confidence bound on the 5th-percentile value of a specified population, determined in accordance with ASTM D7290.
12. *Characteristic value of stiffness*: Material stiffness of a member or connection using standard test methods and characteristic value, as stipulated in this standard.
13. *Characteristic value of strength*: Material strength (tension, flexure, compression, and shear) of members (CFRP laminate) or connections (terminations) determined using standard test methods and characteristic value, as stipulated in this standard.
14. *Constructor*: The party that provides the work and materials for placement or installation.
15. *Crazing*: Microcracking.

16. *Creep*: Time-dependent deformation under constant load.
17. *Debond*: Separation between the CFRP laminate and the substrate.
18. *Delamination*: Interply separation.
19. *Design strength*: Nominal resistance in end-use condition, R_n , multiplied by resistance factor, ϕ , and time effect factor, λ .
20. *Dry lay-up*: The process of saturation of CFRP reinforcing fabric with resin after the fabric has already been placed onto the host structure. The dry lay-up method is not permitted in this standard.
21. *Edge lift*: A gap located at the edge of the fabric.
22. *End-use conditions*: The chemical and load exposure conditions to which the structure is subjected to during its service.
23. *Engineer of record*: The licensed professional who is responsible for sealing the design documents related to CFRP renewal and strengthening (also denoted as *engineer*).
24. *Factored load*: Product of design load and a load factor.
25. *Fatigue*: A progressive development of damage, such as cracking, fretting, and similar effects, resulting from repeated application of loads.
26. *Fiber orientation*: The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.
27. *Fillers*: Substance added in the matrix or adhesive material to alter its engineering properties, performance, and/or cost.
28. *General fabric misalignment*: General misalignment of the primary fiber direction.
29. *Glass transition temperature (T_g)*: Temperature at which the polymer matrix changes from a glassy to a rubbery state.
30. *Gravity load*: Vertical loads, including earth load, pipe and fluid weights, surcharge, and surface live loads.
31. *Hold points*: Steps within the installation procedure that require the approval of the purchaser's inspector before proceeding with subsequent steps of the CFRP system installation process.
32. *Joint harness*: A component that transmits the forces and moments in the pipe across a joint.
33. *Lamina*: A layer of reinforcing fabric and resin.
34. *Laminate architecture*: Construction of the laminate from laminae with different types and orientations of unidirectional carbon fiber fabrics and unidirectional and woven glass fabrics.

35. *Laminate rupture*: A failure mode involving fiber breakage in one or more layers of laminate and resulting in loss of ability to carry load.

36. *Limit state*: A condition in which a structure or component thereof is judged either to be no longer useful for its intended function (serviceability limit state) or to have reached its ultimate load-carrying capacity (strength or stability limit states).

37. *Load and resistance factor design (LRFD)*: A method of proportioning structural components (members, connectors, connecting elements, and assemblages) accounting for variabilities of both load and resistance and reliability of such components—i.e., the probability that the design strength equals or exceeds the required strength for all applicable limit states is acceptable.

38. *Load duration (time effect)*: The period of continuous application of a load or the cumulative period of intermittent applications of a load.

39. *Load factor*: A factor that accounts for variability of the actual load from the nominal load and for uncertainties in the analysis that transforms the load into a load effect.

40. *Long-term strength*: Strength of CFRP under sustained load with duration equal to the service life of the structure.

41. *Manufacturer*: The party that manufactures, fabricates, produces, or supplies materials or products.

42. *Material adjustment factor*: Factors that define the resistance in the end-use condition in terms of laboratory strength values.

43. *Matrix*: The continuous constituent of a CFRP system that surrounds the fibers. It consists of 100 percent solids, volatile organic compounds (VOC)–compliant epoxy resin with fillers, and additives.

44. *Miner's Rule*: A procedure for combining the effects of cyclic loads of different intensities.

45. *Nominal loads*: The loads and load combinations specified for the design.

46. *Nominal strength or nominal resistance*: The strength of a structure or component in the end-use conditions (without resistance factor or time effect factors applied) developed in accordance with the provisions of this standard.

47. *Overlap separation*: Unacceptable separation between fabric sheets; typically resulting from insufficient overlap.

48. *Potable water*: Water that is safe and satisfactory for drinking and cooking.

49. *Pre-cured laminates:* Composite materials in which the reinforcing fabric has been saturated with resin and cured off-site. The use of pre-cured laminates is not permitted in this standard.

50. *Prestressed concrete cylinder pipe (PCCP):* A concrete pressure pipe consisting of a concrete core with a watertight steel cylinder, prestressed by spirally wrapped high-tension wires, and coated with mortar or concrete.

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

52. *Quality assurance:* The administrative and procedural requirements established by the purchaser's documents to confirm that the constructed composite components and system are in compliance with applicable standards, purchaser's documents, and manufacturer's quality control program.

53. *Quality control:* Set of activities instituted by the engineer, manufacturer, or constructor intended to ensure that the constructed work meets the quality requirements.

54. *Rational engineering analysis:* Analysis based on theory that is appropriate for the situation, relevant test data if available, and sound engineering judgment.

55. *Reclaimed water:* Wastewater that becomes suitable for beneficial use as a result of treatment.

56. *Relaxation:* Time-dependent reduction in stress under a constant strain.

57. *Required strength:* The load effect or structural action (force, moment, or stress) acting on a structural system, member, or connection as determined by structural analysis from the factored loads and considered in appropriate combinations.

58. *Resin:* The polymeric material used to bind together the reinforcing fibers in CFRP.

59. *Resistance:* Generic term describing the capacity of a structure, component, or connection to withstand the effects of load; determined from specified material strengths, stiffnesses, dimensions, and formulas derived from accepted principles of structural mechanics or by field or laboratory tests of scaled models, allowing for modeling effects and differences between laboratory and field conditions.

60. *Resistance factor:* A factor that accounts for variabilities of the actual strength and the bias of the nominal strength.

61. *Rupture*: A failure mode involving fiber breakage resulting in loss of ability to carry load.

62. *Service load combination*: Load combination under which serviceability limit states are evaluated.

63. *Serviceability limit state*: A limiting condition affecting the ability of a structure to preserve its function, appearance, maintainability, and durability.

64. *Short-term strength*: Strength of CFRP laminate under loads applied at the loading rate equal to that specified by the relevant ASTM standard.

65. *Stability limit state*: A limit state at which a slight disturbance in the loads or geometry of a structure in a state of equilibrium produces large departures from the equilibrium state.

66. *Strength limit state*: A limiting state at which failure (e.g., laminate rupture) occurs in a structure, component, or connection, compromising safety and ability to carry load.

67. *Stress range*: Magnitude of change in stress due to the repeated application and removal of service loads, used in checking susceptibility to fatigue.

68. *Structural system*: An assemblage of load-carrying components that are joined together to work as an interdependent unit in resisting loads.

69. *Time effect factor*: The ratio of the creep rupture strength of laminate subjected to sustained load to the strength under short-term loading.

70. *Toughness (area under stress-strain curve or moment rotation curve)*: The ability of a material to absorb energy. Toughness can be quantified by computing work per unit mass of material.

71. *Wastewater*: A combination of the liquid and water-carried waste from residences, commercial buildings, industrial plants, and institutions, together with any groundwater, surface water, and stormwater that may be present.

72. *Weibull distribution*: A probability distribution function used in evaluation of strength and life data.

73. *Wet lay-up*: The process of on-site saturation of the reinforcement fabric with resin followed by application of the saturated fabric to the host structure to cure in-place.

74. *Wet surface*: A surface that depicts visible moisture on a tissue that is held to the surface of the pipe for a minimum of 30 s.

75. *Wrinkle*: Localized misalignment and raised surface of the primary fiber direction.

Sec. 1.3 References

This standard references the following documents. In their latest editions, they form a part of this standard to the extent specified within the standard. Except as noted, the standard or specification in effect on the effective date of this standard shall be used. In any case of conflict, the requirements of this standard shall prevail.

AASHTO* LRFD—Bridge Design Specifications.

ANSI†/AWWA C304—Design of Prestressed Concrete Cylinder Pipe.

ANSI/AWWA C651—Disinfecting Water Mains.

ASCE‡ 7—Minimum Design Loads for Buildings and Other Structures.

ASCE MOP 63—Structural Plastics Selection Manual.

ASTM§ C581—Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service.

ASTM D570—Standard Test Method for Water Absorption of Plastics.

ASTM D696—Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between -30°C and 30°C with a Vitreous Silica Dilatometer.

ASTM D790—Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.

ASTM D883—Standard Terminology Relating to Plastics.

ASTM D907—Standard Terminology of Adhesives.

ASTM D1141—Standard Practice for the Preparation of Substitute Ocean Water.

ASTM D2240—Standard Test Method for Rubber Property—Durometer Hardness.

ASTM D2247—Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity.

ASTM D2344—Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates.

ASTM D2369—Standard Test Method for Volatile Content of Coatings.

ASTM D2990—Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics.

* American Association of State Highway and Transportation Officials, 555 12th Street NW, Suite 1000, Washington, DC 20004.

† American National Standards Institute, 1180 Avenue of the Americas, 10th Floor, New York, NY 10036.

‡ American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191.

§ ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428.

ASTM D3039—Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.

ASTM D3045—Standard Practice for Heat Aging of Plastics Without Load.

ASTM D3479—Standard Test Method for Tension–Tension Fatigue of Polymer Matrix Composite Materials.

ASTM D3878—Standard Terminology for Composite Materials.

ASTM D4065—Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures.

ASTM D4541—Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.

ASTM D5379—Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method.

ASTM D6641—Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture.

ASTM D7234—Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers.

ASTM D7290—Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications.

ASTM D7616—Standard Test Method for Determining Apparent Overlap Splice Shear Strength Properties of Wet Lay-Up Fiber-Reinforced Polymer Matrix Composites Used for Strengthening Civil Structures.

ASTM E104—Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions.

ASTM E337—Standard Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures).

ASTM E2160—Standard Test Method for Heat of Reaction of Thermally Reactive Materials by Differential Scanning Calorimetry.

AWWA—Manual M9, *Concrete Pressure Pipe*.

AWWA—Manual M45, *Fiberglass Pipe Design*.

ICRI[‡] Technical Guideline No. 310.2R, *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair*.

[‡] International Concrete Repair Institute Inc., 1601 Utica Avenue South, Suite 213, Minneapolis, MN 55416.

NSF^{**}/ANSI/CAN 61—Drinking Water System Components—Health Effects.

OSHA^{††}—Standard 29 CFR 1910.146

SSPC^{‡‡}-SP 10 / NACE^{§§} No. 2—Near-White Blast Cleaning.

Zarghamee, M. and M. Engindeniz. 2016. Watertightness of CFRP Liners: Addendum to CFRP Renewal of Prestressed Concrete Cylinder Pipe. Web Report No. 4592. Denver: Water Research Foundation.

Zarghamee, M., M. Engindeniz, and N. Wang. 2013. CFRP Renewal of Prestressed Concrete Cylinder Pipe. Web Report No. 4352. Denver: Water Research Foundation.

Sec 1.4 Notation

- A = fatigue constant determined through testing in accordance with ASTM D3479 standard test method for tension-tension fatigue of polymer matrix composite materials (see Sec. 3.7)
- C = material adjustment factor that accounts for retained strength in the end-use conditions (see Sec. 2.6)
- C' = material adjustment factor that accounts for retained modulus in the end-use conditions (see Sec. 2.6)
- D = pipe diameter measured to the neutral axis of pipe wall (in.) (see Sec. 2.8)
- D_f = diameter measured to neutral axis of CFRP liner (in.) (see Sec. 2.8)
- D_L = deflection lag factor (see Sec. 2.8)
- E_c = modulus of the concrete core (psi) (see Sec. 2.8)
- $\overline{E_c}$ = the mean value of modulus in psi of the CFRP laminate in the direction specified (psi) (see Sec. 2.8)
- E_{Cc} = the characteristic value of the modulus of CFRP laminate in the circumferential direction (psi) (see Sec. 2.6)
- E_{Cn} = nominal value of modulus of CFRP laminate in the circumferential direction, equal to the characteristic value of modulus, E_C , adjusted for the end-use condition, used for determining buckling strength (psi) (see Sec. 2.6)

^{**} NSF International, 789 North Dixboro Road, Ann Arbor, MI 48105.

^{††} Occupational Safety and Health Administration, 200 Constitution Ave, NW, Washington, DC 20210.

^{‡‡} Association for Materials Protection and Performance (formerly The Society for Protective Coatings), 800 Trumbull Dr, Pittsburgh, PA 15205.

^{§§} Association for Materials Protection and Performance (formerly NACE International), 15835 Park Ten Place, Houston, TX 77084.

- E_{Lc} = the characteristic value of the modulus of CFRP laminate in the longitudinal direction (psi) (see Sec. 2.6)
- E_{Ln} = nominal value of modulus of CFRP laminate in the longitudinal direction (relative to pipe axis) in psi, equal to the characteristic value of modulus, E_L , adjusted for the end-use condition used for determining buckling strength (psi) (see Sec. 2.6)
- F = load effect from pressure-induced thrust force (see Sec. 2.4.4)
- f'_c = concrete compressive strength (psi) (see Sec. 2.8)
- f'_t = concrete tensile strength (psi) (see Sec. 2.8)
- G_{LT} = in-plane shear modulus of laminate (psi) (see Sec. 3.3)
- I = moment of inertia per unit length of the CFRP for a stand-alone CFRP system or the transformed moment of inertia for the CFRP and concrete composite, using concrete modulus reduced by a multiplicative factor of 0.25 to account for microcracking and cracking of concrete core (in.⁴/in.) (see Sec. 2.8)
- i_L = moment of inertia of the CFRP liner in the longitudinal direction (in.⁴/in.)
- K_x = bedding coefficient (see Sec. 2.8)
- L_b = minimum required length of bond between CFRP laminate and steel joint ring or steel cylinder at termination points (in.) (see Sec. 2.8)
- M = fatigue constant determined through testing in accordance with ASTM D3479 standard test method for tension-tension fatigue of polymer matrix composite materials (see Sec. 3.7)
- M_s = soil constrained modulus (psi) (see Sec. 2.8)
- n = number of stress cycles that the structure must sustain during its service period (see Sec. 3.7)
- N_f = maximum longitudinal stress resultant in the CFRP laminate at terminations from all loading conditions (lb/in.) (see Sec. 2.10)
- P_{cr} = circumferential buckling strength of a flexible CFRP liner within a degraded PCCP host pipe (psi) (see Sec. 2.8)
- P_{gw} = external pressure from ground water, a long-term loading (psi) (see Sec. 2.4)
- P_t = internal transient pressure, measured from P_w a short-term loading (psi) (see Sec. 2.4)
- P_w = internal working pressure, a long-term loading (psi) (see Sec. 2.4)