

# Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons

Reported by ACI Committee 373

James R. Libby  
Chairman

Steven R. Close  
Secretary

Robert T. Bates  
Daniel W. Falconer  
G. Craig Freas  
Amin Ghali  
Charles S. Hanskat

Bradley Harris  
Frank J. Heger  
Thomas L. Holben  
Richard R. Imper  
Arthur M. James

Dennis C. Kohl  
Gerard J. McGuire  
Hoshi H. Presswalla  
Morris Schupack

Associate and Consulting ACI 373 Committee Members who contributed to the development of this report:

Troels Brondum-Nielsen

Ib Falk Jorgensen

Miroslav Vejvoda

## FOREWORD

*This report provides recommendations for the design and construction of circular prestressed concrete structures (commonly referred to as “tanks”) post-tensioned with circumferential tendons. These thin cylindrical shells of either cast-in-place or precast concrete are commonly used for liquid and bulk storage. Vertical post-tensioning is often incorporated in the walls as part of the vertical reinforcement. Recommendations are applicable to circumferential prestressing achieved by post-tensioning tendons placed within the wall or on the exterior surface of the wall. Procedures to prevent corrosion of the prestressing elements are emphasized. The design and construction of dome roofs are also covered.*

**Keywords:** circumferential prestressing; concrete; corrosion resistance; domes; floors; footings; joints; loads (forces); prestressed concrete; pre-stressed reinforcement; reinforcing steel; roofs; shotcrete; shrinkage; tanks; temperature; tendons; walls.

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ACI 373R-97 became effective May 8, 1997.

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**CHAPTER 1—GENERAL****1.1—Introduction**

The design and construction of circular prestressed concrete structures using tendons requires specialized engineering knowledge and experience. This report reflects over four decades of experience in designing and constructing circular prestressed concrete structures with tendons. When designed and constructed by knowledgeable individuals, these structures can be expected to serve for fifty years or more without requiring significant maintenance.

This report is not intended to prevent development or use of new advances in the design and construction of circular prestressed concrete structures. This report is not intended for application to nuclear reactor pressure vessels or cryogenic containment structures.

This report describes current design and construction practices for tanks prestressed with circumferential post-tensioned tendons placed within or on the external surface of the wall.

**1.2—Objective**

The objective of this report is to provide guidance in the design and construction of circular prestressed concrete structures circumferentially prestressed using tendons.

**1.3—Scope**

The recommendations in this report are intended to supplement the general requirements for reinforced concrete and prestressed concrete design, materials and construction, given in ACI 318, ACI 301 and ACI 350R.

This report is concerned principally with recommendations for circular prestressed concrete structures for liquid storage. The recommendations contained here may also be applied to circular structures containing low-pressure gases, dry materials, chemicals, or other materials capable of creating outward pressures. The recommendations may also

be applied to domed concrete roofs over other types of circular structures. Liquid storage materials include water, wastewater, process liquids, cement slurry, petroleum, and other liquid products. Gas storage materials include gaseous by-products of waste treatment processes and other gaseous material. Dry storage materials include grain, cement, sugar, and other dry granular products.

The recommendations in this report may also be applicable to the repair of tanks using externally applied tendons.

Design and construction recommendations cover the following elements or components of tendon tanks:

- a. Floors
  - Prestressed Concrete
  - Reinforced Concrete
- b. Floor-Wall Joints
  - Hinged
  - Fixed
  - Partially Fixed
  - Unrestrained
  - Changing Restraint
- c. Walls
  - Cast-in-Place Concrete
  - Precast Concrete
- d. Wall-Roof Joints
  - Hinged
  - Fixed
  - Partially Fixed
  - Free
- e. Roofs
  - Concrete Dome Roofs with Prestressed Dome Ring
    - (1) Cast-in-place Concrete.
    - (2) Shotcrete.
  - Other Roofs
    - (1) Prestressed Concrete.
    - (2) Reinforced Concrete.
- f. Wall and Dome Ring Prestressing Methods
  - Circumferential
    - (1) Individual high-strength strands in plastic sheaths or multiple high-strength strand tendons in ducts positioned within the wall and post-tensioned after placement and curing of the wall concrete, as shown in Fig. 1.1.
    - (2) Individual or multiple high-strength strands and, less frequently, individual high-strength bar tendons, prestressed after being positioned on the exterior surface of the wall.
      - Vertical
        - (1) Individual or multiple high-strength strand or individual high-strength bar tendons, enclosed in sheathing or ducts within the wall, anchored near the wall joints at the bottom and top of the wall.
        - (2) Pretensioned high-strength strands in precast panels.

**1.4—History and development**

The late Eugene Freyssinet, a distinguished French engineer generally regarded as the father of prestressed concrete, was the first to recognize the need to use steel of high quality and strength, stressed to relatively high levels, in

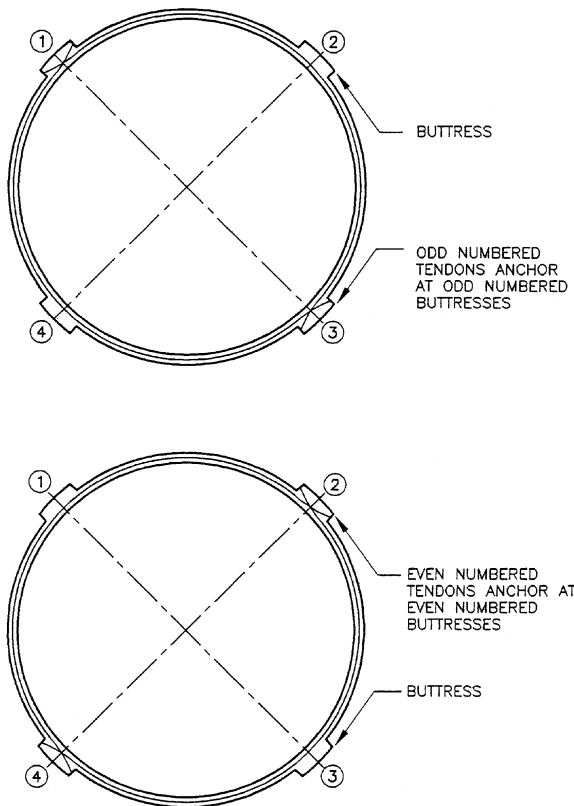


Fig. 1.1—Typical tendon layout.

order to overcome the adverse effects of concrete creep and shrinkage. Freyssinet successfully applied prestressing tendons to concrete structures as early as the late 1920s.

The earliest use of circumferential tendon prestressing in the United States is attributed to the late W. S. Hewett in 1923. He designed and had built several reservoirs using circumferential rods and turnbuckles. A 1932 concrete standpipe in Minneapolis, MN<sup>20</sup> prestressed by tendons, designed with the Hewett System is still in use and in good condition.

In the early 1950s, following methods used successfully in Europe for a number of years, several circular prestressed concrete tanks were constructed in the United States using post-tensioned high tensile-strength wire tendons embedded in the tank walls. The post-tensioned tendons in most early “tendon tanks” were grouted with a portland cement-water mixture after stressing to help protect them against corrosion and to bond the tendons to the concrete tank walls. Others were unbonded paper-wrapped individual wire or strand tendons that depended on a grease coating and the cast-in-place concrete for their corrosion protection. Later, the use of unbonded tendons with corrosion-inhibiting grease coatings and plastic sheaths became more common. Most of the early tendon tanks constructed in the U.S. followed the common European practice of vertically prestressing the tank walls to eliminate or control horizontal cracking. This crack control helped prevent leakage of the contents and corrosion of the prestressing steel.

Several hundred tendon-stressed tanks (with bonded and unbonded tendons) have been constructed in the United States.

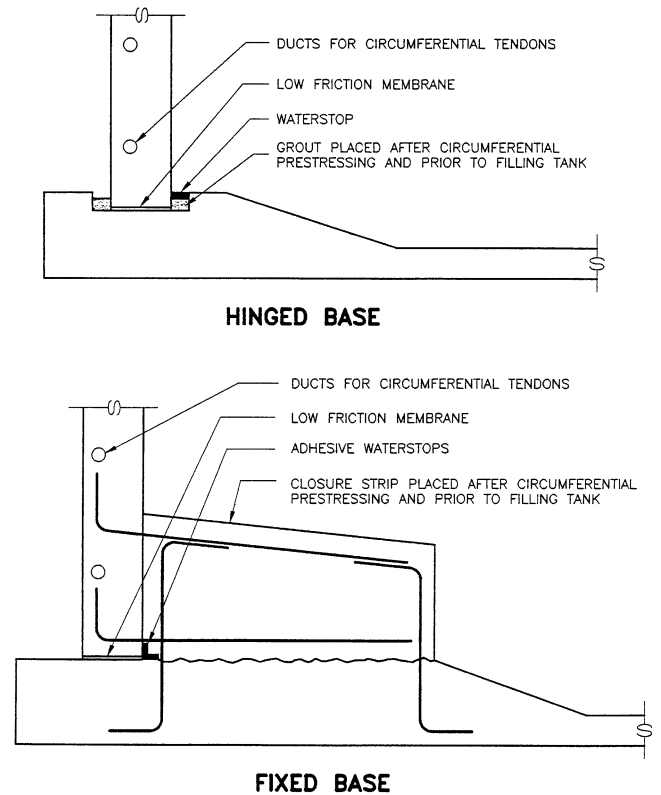


Fig. 1.2—Typical base restraint details.

## 1.5—Definitions

**1.5.1 Core wall**—That portion of a concrete wall that is circumferentially prestressed. Does not include the shotcrete covercoat in an externally post-tensioned tank.

**1.5.2 Joint restraint conditions**—Bottom and top boundary conditions for the cylindrical shell wall. Examples are shown in Fig. 1.2 and 1.3.

**1.5.2.1 Hinged**—Full restraint of radial translation and negligible restraint of rotation.

**1.5.2.2 Fixed**—Full restraint of radial translation and full restraint of rotation.

**1.5.2.3 Partially fixed**—Full restraint of radial translation and partial restraint of rotation.

**1.5.2.4 Unrestrained**—Limited restraint of radial translation and negligible restraint of rotation (free).

**1.5.2.5 Changing restraint**—A joint may be of a different type during and after prestressing. An example is a joint that is unrestrained (free) during prestressing but is hinged after prestressing. The change in joint type is a result of grout installation that prevents radial translation after prestressing.

**1.5.3 Membrane floor**—A thin, highly reinforced, slab-on-grade designed to deflect when the subgrade settles and still retain liquid-tightness.

**1.5.4 Shotcrete cover**—Pneumatically-applied mortar covering external tendons.

**1.5.4.1 Tendon coat**—The part of a shotcrete cover in contact with the circumferential prestressing.

**1.5.4.2 Body coat**—The remainder of the shotcrete cover.

**1.5.4.3 Covercoat**—The tendon coat plus the body coat.

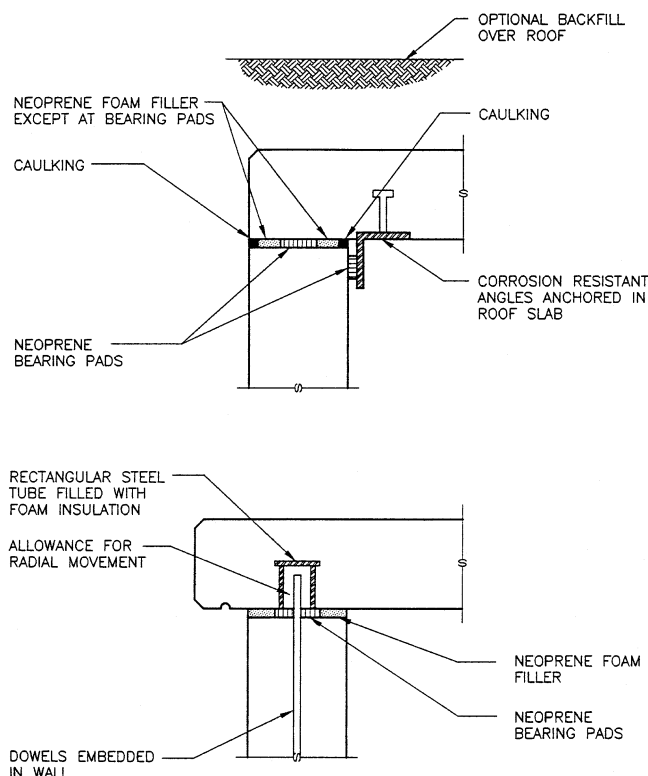


Fig. 1.3—Typical free top details.

**1.5.5 Tendon**—A steel element such as bar or strand, or a bundle of such elements, used to impart compressive stress to concrete through prestressing. In pretensioned concrete the tendon is the steel element alone. In post-tensioned concrete, the tendon includes the complete assembly consisting of end anchorages and/or couplers, prestressing steel and sheathing or ducts completely filled with a corrosion inhibiting material.

**1.5.5.1 Anchorage**—In post-tensioning, a device used to anchor the tendon to the concrete member.

**1.5.5.2 Bonded tendon**—A prestressing tendon that is bonded to the concrete either directly or through grouting. In a bonded tendon the prestressing steel is not free to move relative to the concrete after stressing and grouting.

**1.5.5.3 Circumferential tendon**—A tendon that is placed around the tank circumference, as shown in Fig. 1.1.

**1.5.5.4 Coupler**—A device used to connect two pieces of a tendon.

**1.5.5.5 Prestressing steel**—High-strength steel used to prestress concrete, commonly seven-wire strands, bars, or groups of strands.

**1.5.5.6 Sheathing**—Enclosures, in which post-tensioning tendons are encased, to prevent bonding during concrete placement and to help protect the strand from corrosion. The enclosures are generally referred to as ducts when used for grouted multiple strand tendons.

**1.5.5.7 Unbonded tendon**—A tendon that is not bonded to the concrete section. In an unbonded tendon the prestressing steel is permanently free to move (between fixed anchorages) relative to the concrete.

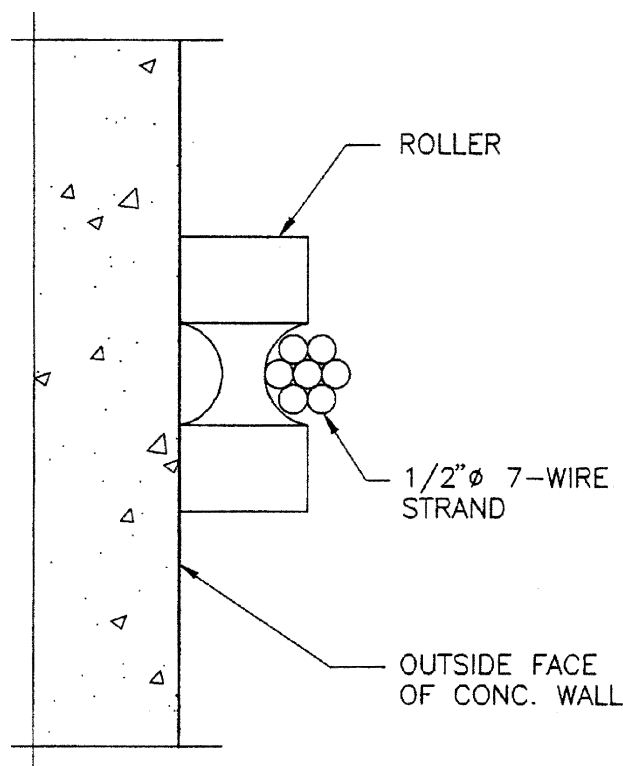


Fig. 1.4—Roller for external prestressing.

**1.5.5.8 Roller**—A short cylindrical segment, usually including a central concave shaped portion, Fig. 1.4, placed under an external tendon to space the prestressed element away from the core wall and reduce friction by rolling along the surface as the tendon is elongated.<sup>19</sup>

## 1.6—Notation

|           |   |                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|-----------|---|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $A_c$     | = | area of concrete at cross section considered, sq. in.                                                                                                                                                                                                                                                                                                                                                                                                     |
| $A_g$     | = | gross area of unit height of core wall that resists circumferential force due to prestressing, sq. in.                                                                                                                                                                                                                                                                                                                                                    |
| $A_{gr}$  | = | gross area of wall that resists externally applied circumferential forces, such as backfill, sq. in.                                                                                                                                                                                                                                                                                                                                                      |
| $A_{ps}$  | = | area of prestressed reinforcement, sq. in.                                                                                                                                                                                                                                                                                                                                                                                                                |
| $A_s$     | = | area of nonprestressed reinforcement, sq. in.                                                                                                                                                                                                                                                                                                                                                                                                             |
| $A_{st}$  | = | total area of reinforcement, prestressed plus nonprestressed, sq. in.                                                                                                                                                                                                                                                                                                                                                                                     |
| $D$       | = | dead loads, or related internal moments and forces                                                                                                                                                                                                                                                                                                                                                                                                        |
| $E_c$     | = | modulus of elasticity of concrete under short-term load, psi                                                                                                                                                                                                                                                                                                                                                                                              |
| $E_{ci}$  | = | modulus of elasticity of concrete at age $t_i$ , psi                                                                                                                                                                                                                                                                                                                                                                                                      |
| $E_s$     | = | modulus of elasticity of reinforcement, assumed to be the same for prestressed and non-prestressed reinforcement, psi                                                                                                                                                                                                                                                                                                                                     |
| $f'_c$    | = | specified compressive strength of concrete, psi                                                                                                                                                                                                                                                                                                                                                                                                           |
| $f'_{ci}$ | = | specified compressive strength of concrete at time of prestressing, psi                                                                                                                                                                                                                                                                                                                                                                                   |
| $f_{ci}$  | = | the initial stress in the concrete at time $t_i$ , immediately after prestressing (negative for compression), psi                                                                                                                                                                                                                                                                                                                                         |
| $f'_s$    | = | specified compressive strength of shotcrete, psi                                                                                                                                                                                                                                                                                                                                                                                                          |
| $f_{pu}$  | = | specified tensile strength of prestressing strands, wires or bars, psi                                                                                                                                                                                                                                                                                                                                                                                    |
| $f_{re}$  | = | intrinsic relaxation of prestressed reinforcement that occurs in a tendon stretched between two fixed points (constant strain level equal to initial strain), psi. The intrinsic relaxation depends upon the type and quality of the prestressed reinforcement and the initial prestress level in the steel. Use the prestressing tendon manufacturer's relaxation data projected to age 50 years. Reference 13 also contains information on this subject |
| $f_y$     | = | specified yield strength of nonprestressed reinforcement, psi                                                                                                                                                                                                                                                                                                                                                                                             |
| $F$       | = | loads or related internal moments and forces due to weight and pressures of fluids with well defined densities and controllable                                                                                                                                                                                                                                                                                                                           |

|                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | maximum heights                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| $h$             | = thickness of wall, in.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $h_d$           | = thickness of dome shell, in.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| $H$             | = loads or related internal moments and forces due to weight and pressure of soil, including water in soil, or stored granular materials                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $L$             | = live loads or related internal moments and forces                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| $n$             | = modular ratio of elasticity, $E_s/E_c$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $n_i$           | = initial modular ratio of elasticity, $E_s/E_{ci}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| $P_e$           | = circumferential force per unit of wall height, lbs., or related internal moments and forces due to the effective circumferential prestressing                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| $P_h$           | = circumferential force per unit of wall height caused by external pressure of soil, ground water in soil, or other loads                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| $P_i$           | = loads or related internal moments and forces due to the initial circumferential prestressing                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| $P_o$           | = nominal axial compressive strength of core wall in the circumferential direction per unit of wall height, psi                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| $P_u$           | = factored unit (uniformly distributed) design load for the dome shell due to dead load and live load, psf                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| $r$             | = inside radius of tank, ft                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| $r_d$           | = inside radius of dome, ft                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| $r_i$           | = averaged maximum radius of curvature over a dome imperfection area with a diameter of $2.5\sqrt{r_d}h_d$ , ft                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| $t$             | = age of concrete at time long term losses are to be calculated, days                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| $t_i$           | = age of concrete at time of prestressing, days                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| $U$             | = required strength to resist factored loads or related internal moments and forces                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| $\beta_i$       | = buckling reduction factor for geometrical imperfections from a true spherical (beta) surface, such as local increases in radius                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| $\beta_c$       | = buckling reduction factor for creep, nonlinearity and cracking of concrete                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| $\Delta P_c$    | = change in compressive force in the concrete, lb                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| $\epsilon_{cs}$ | = free shrinkage strain of concrete. The value of $\epsilon_{cs}$ depends mainly upon the $\epsilon$ ages $t_i$ and $t$ , the relative humidity and the wall thickness. Values for ultimate shrinkage (in an 8-in. wall between age 14 days and a very long time) recommended by some designers for use in conjunction with the creep coefficients suggested below are $110 \times 10^{-6}$ , $260 \times 10^{-6}$ and $420 \times 10^{-6}$ for relative humidities of 90, 70 and 40 percent, respectively. As noted below, others recommend higher values for shrinkage and lower values for creep as may be derived from information in ACI 209R                                     |
| $\eta$          | = aging coefficient for reduction of creep due to prestress loss. A typical value is $\eta = 0.8$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| $\eta_{re}$     | = relaxation reduction factor. A typical value is $\eta_{re} = 0.8$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| $\phi$          | = strength reduction factor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| $\phi_{cr}$     | = creep coefficient of concrete, defined as the ratio of creep to instantaneous strain. The value of $\phi$ depends mainly upon the ages $t_i$ and $t$ , the ambient relative humidity and the wall thickness. Some designers recommend the following coefficients for ultimate creep, after a very long period, in an 8-in. wall prestressed no earlier than age 14 days: 1.6, 2.6 and 2.8 for relative humidities of 90, 70 and 40 percent, respectively. These are used in combination with the values of shrinkage, $\epsilon_{cs}$ , given above. Others recommend lower values of ultimate creep and higher values for shrinkage, as may be derived from information in ACI 209R |

### Notes:

A. Units may be inch-pounds or SI, but should be consistent in each equation.

B. Coefficients in equations that contain  $\sqrt{f'_c}$  or  $\sqrt{f'_g}$  are for inch-pound units. The coefficient for SI units (MPa) with  $\sqrt{f'_c}$  and  $\sqrt{f'_g}$  is the coefficient for inch-pound units divided by 12.

C. Inch-pound units are used in the text. SI conversions are provided in the table in Appendix A.

## CHAPTER 2—MATERIALS

### 2.1—Concrete

**2.1.1 General**—Concrete should meet ACI 301 and the recommendations of ACI 350R, except as indicated in this report.

**2.1.2 Allowable chlorides**—For corrosion protection, the maximum water-soluble chloride ion content should not exceed 0.06 percent by weight of the cementitious materials in concrete or grout for prestressed concrete, as determined by ASTM C 1218.

**2.1.3 Freezing and thawing exposure**—Concrete subject to freezing and thawing cycles should be air-entrained in accordance with ACI 301, Table 4.2.2.4.

**2.1.4 Compressive strength**—The minimum 28-day compressive strength of any prestressed concrete in tanks should be 4000 psi. In addition, concrete for prestressed floors should reach 1500 psi at 3 days to accommodate two-stage stressing. Nonprestressed footings and roofs may have a 28-day compressive strength as low as 3000 psi.

**2.1.5 Water-cement ratio**—The water-cement ratio should be 0.45 or less for walls and floors.

**2.1.6 Permeability of concrete**—It is essential that low-permeability concrete be used for liquid-retaining structures. This can be obtained by using a relatively high cementitious materials content and a low water-cement ratio with high-range water-reducers to help ensure adequate workability. Admixtures such as fly ash, ground-granulated blast-furnace slag and silica fume also decrease permeability. The use of admixtures should follow the recommendations of the suppliers and ACI 212.3R.

### 2.2—Shotcrete

**2.2.1 General**—Unless otherwise indicated here, shotcrete should meet ACI 506.2 and the guidelines given in ACI 506R.

**2.2.2 Allowable chlorides**—Same as for concrete, Section 2.1.2.

**2.2.3 Proportioning**—Shotcrete should be proportioned in accordance with the following recommendations:

**2.2.3.1** The tendon coat should consist of one part portland cement and not more than three parts fine aggregate by weight.

**2.2.3.2** The body coat should consist of one part portland cement and not more than four parts fine aggregate by weight.

**2.2.3.3** When the covercoat is placed in one application, the mix should consist of one part portland cement and not more than 3 parts fine aggregate by weight.

**2.2.4 Compressive strength**—The minimum 28-day compressive strength of shotcrete should be 4000 psi.

**2.2.5 Freezing and thawing exposure**—Dry-mix shotcrete is not recommended for domes in areas subject to freezing and thawing cycles. Wet-mix shotcrete subjected to freezing and thawing cycles should be air-entrained with an in-place air content of 5 percent or greater.

### 2.3—Admixtures

Admixtures should meet ACI 301 and ACI 308.4. Calcium chloride and other admixtures containing chlorides

fluorides, sulfides and nitrates in more than trace amounts should not be used in prestressed concrete because of potential corrosion problems.

High-range water-reducing admixtures, conforming to ASTM C 494 Type F or G, may be used to facilitate placement of concrete.

## 2.4—Grout for bonded tendons

**2.4.1 General**—Grout for tendons normally consists of portland cement, water and admixtures and should meet Chapter 18 of ACI 318.

**2.4.2 Admixtures**—To enhance corrosion protection of the prestressed reinforcement, particularly at tendon high points, portland cement grout for water tank tendons should contain admixtures that lower the water-cement ratio, improve flowability and minimize bleeding. Expansive characteristics may also be provided if desired. The grout, if providing expansion by the evolution of gas, should have 3 to 8 percent total expansion measured in a 20-in. height. An ad-hoc method for determining whether grout is satisfactory is to place the grout in a 1- to 3-in. diameter plexiglass cylinder 25-in. high ten minutes after mixing, cover to minimize evaporation and let it set. No visible bleeding should occur during the test.

## 2.5—Reinforcement

### 2.5.1 Nonprestressed reinforcement

**2.5.1.1** Nonprestressed reinforcement should meet ACI 301.

**2.5.1.2** Strand for wall-to-footing earthquake cables should be epoxy coated (with grit for bond) or galvanized. Epoxy should be fusion bonded, ASTM A 822. Galvanized strand should meet ASTM A 416, Grade 250 or 270, prior to galvanizing; and ASTM A 586, ASTM A 603 or ASTM A 475 after galvanizing. The zinc coating should meet ASTM A 475, Table 4, Class A or ASTM A 603, Table 2, Class A.

### 2.5.2 Prestressed reinforcement

**2.5.2.1** The most common type of prestressed reinforcement used for tendon tanks is stress-relieved, low-relaxation strand. Bars are also used occasionally. Prestressed reinforcement should comply with the recommendations given in this report and with ACI 301. The prestressed reinforcement should also comply with one of the following ASTM designations:

- (a) Strands: ASTM A 416 or A 779
- (b) Bars: ASTM A 722

**2.5.2.2** Both uncoated and galvanized prestressed reinforcement have been used for tendon tanks. Almost all tanks have been constructed with uncoated reinforcement. When galvanized strand or bars are used for prestressed reinforcement, the strand or bars should have a Class A zinc coating as specified in ASTM A 586. The coated strand or bars should meet the minimum elongation of ASTM A 416 or A 722. Epoxy coated strand should meet ASTM A 882.

## 2.6—Tendon systems of tank walls and domes

Tendon systems should meet ACI 301, except as indicated here.

**2.6.1 Grouted tendons**—Sheathing or duct-forming material should not react with alkalis in the cementitious materials and should be strong enough to retain its shape and resist damage during construction. It should prevent the entrance of cementitious materials slurry from the concrete. Sheathing material left in place should not cause electrolytic action or deterioration. Ducts may be rigid, semi-rigid, or flexible. Ferrous metal and corrugated plastic ducts have been used for tanks. Ducts for grouted tendons should be designed to transfer bond stresses to the adjacent concrete.

### 2.6.1.1 Ferrous metal ducts

(a) Rigid ducts are not normally galvanized by their manufacturer.

(b) Semi-rigid ducts, however, are normally galvanized by their manufacturer, because they are made of a lighter gauge material.

(c) Rigid or semi-rigid ferrous metal ducts typically are used when the prestressing steel is placed in the ducts after the concrete is placed.

**2.6.1.2 Corrugated plastic ducts**—Corrugated plastic ducts have been used for circumferential and vertical tendons. Corrugated plastic ducts can be continuously watertight if directly connected to the anchorage and properly sealed at couplings. Corrugated plastic ducts should be chemically inert and of adequate thickness and toughness to resist the usual construction wear and tear and radial pressures from curved tendons. Care should be taken to prevent excessive wobble. The ability of the ducts to transfer the desired bond stresses and to resist wear through by radial pressure during stressing should be confirmed by tests.

### 2.6.2 Unbonded tendons

**2.6.2.1** Unbonded tendons typically are used for post-tensioned floors and two-way flat-plate roofs. Unbonded tendons have also been used for vertical wall tendons and, on a less frequent basis, for horizontal circumferential tendons.

**2.6.2.2** Prestressing steel, anchorages, sheathing, corrosion preventative coating, and details for providing a complete watertight encapsulation of the prestressing steel, Fig. 2.1, should be in accordance with the Post-Tensioning Institute's "Specification for Unbonded Single Strand Tendons" for tendons in an aggressive (corrosive) environment.<sup>29</sup> Sheathing should be a high-density polypropylene or polyethylene not less than 60 mils thick, extruded under pressure onto the greased strand, with no space between the inside of the sheathing and the coating material. At the anchorages, the voids in sleeves or caps at the anchorages should be completely filled with corrosion-preventative grease. The sheathing should be connected to all stressing, intermediate and fixed anchorages. This provides complete encapsulation of the prestressing steel from end to end. Connections should remain watertight.

### 2.6.3 External tendons

**2.6.3.1** External tendons are usually spaced away from the wall on rollers or other low-friction supports, Fig. 1.4. They are usually stressed at in-line anchorages or couplers. They may be protected by galvanizing in accordance with Section 2.5.2.2 and 3.1.4.2 (e), by sheathing in accordance

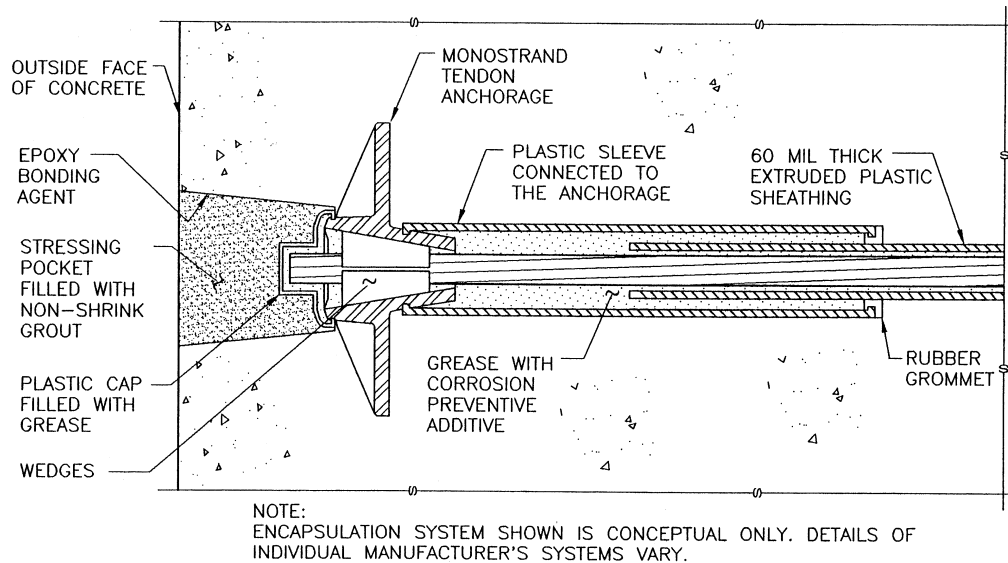


Fig. 2.1—Fully encapsulated monostrand tendon anchorage.

with Sections 3.1.4.2 (e), 4.2.3.5 and 4.5.3.3, or by epoxy in accordance with Section 3.1.4.2 (d).

## 2.7—Waterstop, bearing pad, and filler materials

**2.7.1 Waterstops**—Waterstops should be composed of plastic or other suitable materials. Plastic waterstops of polyvinyl chloride meeting CRD-C-572 are recommended. Splices should be made in accordance with the manufacturer's recommendations. Materials proposed for use on the job site should be certified by the manufacturer based on laboratory tests, or other tests should be made that will ensure compliance with the specification.

**2.7.2 Elastomeric bearing pads**—Bearing pads should be composed of neoprene, natural rubber, polyvinyl chloride, or other materials that have demonstrated acceptable performance under similar conditions and applications.

**2.7.2.1 Neoprene bearing pads** should have a minimum ultimate tensile strength of 1500 psi, a minimum elongation of 500 percent (ASTM D 412), and a maximum compressive set of 50 percent (ASTM D 395, Method A), with a hardness of 30 to 60 durometers (ASTM D 2240, Type A Durometer). Neoprene bearing pads should comply with ASTM D 2000, Line Call-Out M2BC4105A14B14.

**2.7.2.2 Natural rubber bearing pads** should comply with ASTM D 2000, Line Call-Out M4AA414A13.

**2.7.2.3 Polyvinyl chloride for bearing pads** should meet the CRD-C-572.

**2.7.3 Sponge filler**—Sponge filler should be closed-cell neoprene or rubber capable of taking a head of 50 ft. of liquid concrete without absorbing grout and becoming hard. It should also meet ASTM D 1056, Type 2, Class A and Grades 1 through 4. The minimum grade sponge filler recommended for use with cast-in-place concrete walls should be Type 2, Class A and Grade 3.

## 2.8—Epoxy injection

Epoxy used for injection into cracks, minor honeycombing, separated shotcrete covercoats or wet spots should

conform to ASTM C 881, Type I, Grade 1 and should be a two-component, 100-percent-solids, moisture-insensitive epoxy system.

## 2.9—Epoxy adhesives

Epoxy used for increasing the bond between hardened concrete and plastic concrete should be a two-component, 100-percent-solids, moisture-insensitive epoxy adhesive meeting ASTM C 881, Type II, Grade 2, ACI 503.2 also contains information on this subject. The bonding agent should produce a bond strength (ASTM C 882) not less than 1500 psi 14 days after the plastic concrete is placed.

## 2.10—Coatings for outer surfaces of tank walls and domes

**2.10.1 Above-grade**—In some cases, such as tanks located in areas subject to salt spray and landscape sprinklers, coatings may be desired to seal the exterior surface of above-grade shotcrete domes and shotcrete protection for external tendons. Coatings suitable for sealing the exterior of the tank should be permeable to water vapor so as not to trap the higher vapor pressure inside the tank wall. These include polyvinyl chloride-latex and polymeric vinyl-acrylic paints and cementitious materials based coatings.

**2.10.2 Below-grade**—Coatings are recommended to seal the exterior surface of below-grade tanks that contain dry materials and for protection against aggressive soils. Coatings suitable for sealing the exterior of the tank wall include coal-tar epoxies and bitumastic compounds.

**2.10.3** Additional information on coatings for concrete is given in ACI 515.1R.

## CHAPTER 3—DESIGN

### 3.1—Strength and serviceability

**3.1.1 General**—Structures and components of structures should be designed to provide both the minimum strength and serviceability recommended in this report. The minimum serviceability recommendations given in this report are

intended to ensure adequate safety and performance of structures subject to typical loads and environmental conditions. The control of leakage and protection of embedded steel from corrosion are necessary for adequate serviceability.

### 3.1.2 Loads and environmental considerations

#### 3.1.2.1 Loads

(a) *Prestressing forces*—Circumferential prestressing forces in the wall and dome ring, vertical prestressing (if provided in the wall) and roof prestressing that affects the wall, should be considered in the wall design. For example, circumferential prestressing with backfill pressure (when applicable) combines to determine the circumferential compressive strength required. Circumferential prestressing also typically causes vertical bending moments that may add to, and may reduce vertical bending moments from other loading conditions. In these cases load factors other than 1.0 are recommended, as described in Section 3.1.3.

The reduction in prestressing forces with the passage of time due to the inelastic effects of concrete creep, shrinkage and the relaxation of the prestressed reinforcement must be considered.

(b) *Internal pressure from stored materials*—Fluid pressure in liquid storage vessels, gas pressure in vessels containing gas or materials that generate gas, and lateral pressure from stored granular materials should be considered, as appropriate. Pressure from stored granular materials described in ACI 313.

(c) External lateral earth pressure including the surcharge effects of live and other loads supported by the earth acting on the walls.

- (d) Weight of structure.
- (e) Wind loads.
- (f) Earth, snow, and other live loads on roofs.
- (g) External hydrostatic pressure on walls and floors due to ground water.
- (h) Seismic effects.
- (i) Equipment and piping supported on roofs or walls.
- (j) Ice pressure from freezing water in environments where significant amounts of ice form inside tanks.<sup>15, 21</sup>

#### 3.1.2.2 Environmental considerations

(a) Thermal and moisture gradients through the thickness of structural elements.

(b) Thermal and moisture gradients along the height of the wall.

(c) Temperature and moisture difference between structural elements.

(d) Exposure to freezing and thawing cycles.

(e) Chemical attack on concrete and metal.

#### 3.1.2.3 Control of loads

(a) Positive means, such as an overflow pipe of adequate size, should be provided to prevent overfilling liquid containment structures. Overflow pipes, including their inlet and outlet details, should be capable of discharging the liquid at a rate equal to the maximum fill rate when the liquid level in the tank is at its highest acceptable level.

(b) One or more vents should be provided for containment structures. The vents should limit the positive internal pressure to an acceptable level when the tank is being filled at its

maximum rate and limit the negative internal pressure to an acceptable level when the tank is being emptied at its maximum rate. For liquid containment structures, the maximum emptying rate may be taken as the rate caused by the largest pipe being broken immediately outside of the tank.

(c) Hydraulic pressure-relief valves may be used on non-potable water tanks to control hydrostatic uplift on floor slabs and walls when the tanks are empty or partially full. The use of pressure-relief valves should be restricted to applications where the expected ground-water level is below the operating level of the tank. The valves may also be used to protect the structure during floods. The inlet side of pressure-relief valves should be interconnected with 1) a layer of free-draining gravel adjacent to and underneath the concrete surface to be protected, 2) a perforated pipe drain system placed in free-draining gravel adjacent to the concrete surface to be protected, or 3) a perforated pipe drain system in free-draining gravel that serves as collector system for a geotechnical drain system placed against the concrete surface to be protected.

The free-draining gravel should be protected against the intrusion of fine material by a sand filter or a geotextile filter. The pressure-relief valve's inlet should be protected against the intrusion of gravel by a corrosion-resistant screen, an internal corrosion-resistant strainer, or by connection to a perforated pipe drain system.

The spacing and size of pressure-relief valves should be adequate to control the hydrostatic pressure on the structure and in general the valves should not be less than 4 in. in diameter or spaced farther than 20-ft apart. Ideally, the valves or a portion of the valves should be placed at the low point of the structure unless the structure has been designed to withstand the pressure imposed by a ground-water level to, or slightly above, the elevation of the valves.

The use of spring-controlled pressure-relief valves is discouraged because of mechanical problems in the past. Floor-type pressure-relief valves that operate by hydrostatic pressure, and wall-type pressure-relief valves having corrosion-resistant hinges operated by pressure against a flap gate, are recommended. The recommended type of pressure relief valves for floors have covers that are lifted by hydrostatic pressure. They also have restraining lugs that limit the travel of the cover.

Caution should be exercised in using floor-type valves where the operation could be affected by sedimentation within the tank or by incidental contact by a scraper mechanism in the tank. When wall-type valves are used in tanks with scraper mechanisms, the valves should be positioned to clear the operating mechanisms with a flap gate in the opened or closed position, taking into account that there may be some increase in the elevation of the scraper due to buoyancy and/or build-up of sediment on the floor of the tank.

(d) Gas pressure-relief valves should be used to limit gas pressure to acceptable levels on the roofs and walls of non-vented structures such as digester tanks. The type of pressure-relief valve selected should be compatible with the contained gas and the pressure range anticipated. Not less than two valves should be used, at least one of which should be redundant and at least 50 percent redundancy should be