

ACI 372R-13

**Guide to Design and Construction
of Circular Wire- and Strand-
Wrapped Prestressed
Concrete Structures**

Reported by ACI Committee 372



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Guide to Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures

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Guide to Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures

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This guide provides recommendations for the design and construction of circular, wrapped, prestressed concrete structures commonly used for liquid or bulk storage. These structures are constructed using thin cylindrical shells of either concrete or shotcrete. Shotcrete and precast concrete core walls incorporate a thin steel diaphragm that serves both as a liquid barrier and vertical reinforcement. Cast-in-place concrete core walls incorporate either vertical prestressing or a steel diaphragm. Recommendations are given for circumferential prestressing achieved by wire or strand wrapping. In wrapping, the wire or strand is fully tensioned before placing it on the structural core wall. Procedures for preventing corrosion of the prestressing elements are emphasized. The design and construction of dome roofs are also covered.

Many recommendations of this guide can also be applied to similar structures containing low-pressure gases, dry materials, chemicals, or other materials capable of creating outward pressures. This guide is not intended for application to nuclear reactor pressure vessels or cryogenic containment structures.

Keywords: circumferential prestressing; dome; footing; joint sealant; prestressed concrete; prestressing steel; shotcrete; wall.

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CHAPTER 1—GENERAL

1.1—Introduction

The design and construction of circular prestressed concrete structures requires specialized engineering knowledge and experience. The recommendations herein reflect over 6 decades of experience in designing and constructing circular prestressed structures. When designed and built with understanding and care, these structures can be expected to serve for well over 50 years without requiring significant maintenance.

1.2—Objective

This guide provides recommendations for the design and construction of circular wire- and strand-wrapped prestressed concrete structures based on practices used in successful projects.

1.3—Scope

The recommendations supplement the general requirements for reinforced concrete and prestressed concrete design and construction given in ACI 350 and ACI 350.5. Design and construction recommendations cover the following elements or components of circular-wrapped prestressed concrete structures:

- a) Floors
 - i) Reinforced concrete
- b) Floor-wall connections
 - i) Hinged
 - ii) Fixed
 - iii) Partially fixed
 - iv) Unrestrained
 - v) Changing restraint
- c) Walls
 - i) Cast-in-place concrete walls with steel diaphragms or vertical prestressing
 - ii) Shotcrete walls with steel diaphragms
 - iii) Precast concrete walls with steel diaphragms
- d) Wall-roof connections
 - i) Hinged
 - ii) Fixed
 - iii) Partially fixed
 - iv) Unrestrained
- e) Roofs
 - i) Concrete dome roofs with a prestressed dome ring, constructed with cast-in-place concrete, shotcrete, or precast concrete
 - ii) Flat concrete roofs
- f) Wall and dome ring prestressing systems
 - i) Circumferential prestressing using wrapped wire or strand systems
 - ii) Vertical prestressing using single or multiple high-strength strands or bars

1.4—Associated structures

Baffle walls and inner storage walls are frequently constructed inside water storage tanks. Baffle walls are used to increase the chlorine retention time of water as it circulates from the tank inlet to the outlet. The configuration and layout of baffle walls vary depending on the tank geometry, flow characteristics, and the desired effectiveness of the chlorination process. The most common baffle wall configurations are straight, C-shaped, or a combination of the two. Baffle walls can be precast or cast-in-place concrete, masonry block, redwood, shotcrete, metal, or fabric.

Inner storage walls are separate storage cells normally used to provide flexibility in a system's water storage capabilities and hydraulics. Inner walls are typically constructed the same as the outer tank walls and are designed for external and internal hydrostatic pressure.

1.5—History and development

Hewett (1923) first applied circumferential prestressing to a concrete water tank using turnbuckles to connect and tension individual steel tie rods. Long-term results were not effective because the steel used was of low yield strength, limiting applied unit tension to approximately 30,000 psi (210 MPa). Shrinkage and creep of the concrete resulted in a rapid and almost total loss of the initial prestressing force. E. Freyssinet was the first to realize the need to use steel of high quality and strength, stressed to relatively high levels, to overcome the adverse effects of concrete creep and shrinkage (Mautner 1936). Freyssinet successfully

applied prestressing to concrete structures as early as the late 1920s. Vertical wall prestressing was introduced in the 1930s as a means to control horizontal cracking that might permit leakage and subsequent corrosion of circumferential prestressing steel.

In 1941, J. M. Crom (1943a) (the first to apply high-strength prestressing steels to concrete tanks) developed a novel method to apply high-strength wire in a continuous spiral to the exterior surface of concrete tanks. The method is based on mechanically stressing the wire as it is placed on the wall, thus avoiding prestressing loss due to friction between the prestressed reinforcement and the wall. This method of circumferentially prestressing tank walls and dome rings is commonly known as wire winding or wire wrapping. After placement, the prestressed reinforcement is protected from corrosion by encasing it in shotcrete. More than 9000 tanks of various sizes and shapes have been constructed using methods based on this concept. Approximately 75 percent of these structures are in the U.S., and the remaining 25 percent worldwide have been constructed by U.S. companies or their licensees.

In 1952, shotcrete tanks incorporating a light-gauge steel diaphragm fluid barrier (3.3.2.3) within the wall were first built by J. M. Crom based on a concept he patented 9 years before (Crom 1943b; McCarthy and Balck 2012). By the early 1960s, nearly all prestressed shotcrete tanks used a steel diaphragm. In 1966, the first precast-prestressed concrete tanks with a steel diaphragm were built. By 1970, nearly all wire-wound precast concrete tanks incorporated a steel diaphragm or, alternatively, vertical prestressing within the wall (ACI Committee 344 1970). The use of a steel diaphragm or vertical prestressing prevents the stored liquid from penetrating to the outside of the core wall, where it could potentially contribute to the corrosion of the prestressing steel. The diaphragm also serves as vertical reinforcement.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_g	= gross area of unit height of core wall that resists circumferential force, in. ² (mm ²)
A_{gr}	= gross area of wall that resists externally applied circumferential forces, such as backfill, in. ² (mm ²)
A_{ps}	= area of prestressed circumferential reinforcement, in. ² (mm ²)
A_s	= area of nonprestressed circumferential reinforcement, in. ² (mm ²)
B_c	= buckling reduction factor for creep, nonlinearity, and cracking of concrete
B_i	= buckling reduction factor for geometrical imperfection
D	= dead loads or related internal moments and forces, lb/ft ² (kPa)
E_c	= modulus of elasticity of concrete under short-term load, psi (MPa)
E_s	= modulus of elasticity of steel, psi (MPa)
E_v	= vertical seismic load, lb/ft ² (kPa)

f'_c	= specified compressive strength of concrete, psi (MPa)
f'_{ci}	= compressive strength of concrete at time of prestressing, psi (MPa)
f'_g	= specified compressive strength of shotcrete, psi (MPa)
f'_{gi}	= compressive strength of shotcrete at time of prestressing, psi (MPa)
f_{pu}	= specified tensile strength of prestressing wires or strands, psi (MPa)
f_y	= specified yield strength of nonprestressed reinforcement, psi (MPa)
h	= wall thickness, in. (mm)
h_d	= dome shell thickness, in. (mm)
L	= uniformly distributed dome live load, lb/ft ² (kPa)
N	= modular ratio of elasticity = E_s/E_c
P_e	= circumferential force per unit of height of wall caused by the effective prestressing, lb (N)
P_h	= circumferential force per unit of height of wall caused by the external pressure of soil, groundwater, or other loads, lb (N)
P_o	= nominal axial compressive strength of core wall in the circumferential direction per unit of height of wall, psi (MPa)
p_u	= factored design load on dome shell, lb/ft ² (kPa)
r	= inside radius of tank, ft (mm)
r_d	= mean radius of dome, ft (mm)
r_i	= averaged maximum radius of curvature over a dome imperfection area with a diameter of $2.5\sqrt{(r_d h_d/12)}$ ft ($2.5\sqrt{(r_d h_d)}$ mm)
S	= uniformly distributed snow load in accordance with ASCE 7, lb/ft ² (kPa)
S_d	= environmental durability factor from ACI 350
t	= floor slab thickness, in. (mm)
y	= differential floor settlement (between outer perimeter and tank center), in. (mm)
ϕ	= strength-reduction factor

Coefficients in equations that contain $\sqrt{f'_c}$ or $\sqrt{f'_g}$ are based on inch-pound (psi) units. The coefficients to be used with $\sqrt{f'_c}$ and $\sqrt{f'_g}$ in the SI (MPa) system are the inch-pound coefficients divided by 12.

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided here complement that resource.

body coat—layers of shotcrete applied over the outermost wire coat, not in direct contact with prestressing wire or strand.

breathable or breathing-type coating—coating that permits transmission of water vapor without detrimental effects to the coating.

core wall—that portion of a concrete wall that is circumferentially prestressed.

fixed—full restraint of radial translation and full restraint of rotation.

hinged—full restraint of radial translation and negligible restraint of rotation.

joint restraint conditions—top and bottom boundary conditions for the cylindrical shell wall or the dome edge.

membrane floor—thin, highly reinforced, cast-in-place slab-on-ground designed to deflect when the subgrade settles and still retain watertightness.

partially fixed—full restraint of radial translation and partial restraint of rotation.

shotcrete cover coat—shotcrete covering the outermost layer of wrapped prestressing strand or wire, usually consisting of the wire coat plus the body coat.

stress plate—a structural plate designed to transfer the forces from discontinuous circumferential wrapped prestressing across a wall penetration.

tank—a structure commonly used for liquid or bulk storage. As used in this document, the term tank refers to a circular wire- or strand-wrapped prestressed concrete structure.

wire coat—the layer of shotcrete in direct contact with the prestressing wire or strand.

wrapped prestressing—a prestressing system using wire or strand that is fully tensioned before placement on the core wall.

CHAPTER 3—DESIGN

3.1—Strength, serviceability, and durability

3.1.1 General—Structures and their components should be designed to meet both the minimum strength, serviceability, and durability recommendations contained in this guide. These recommendations are intended to provide adequate safety and performance of structures subject to typical loads and environmental conditions. Controlling leakage and protection of all embedded steel from corrosion is necessary for long-term serviceability and durability.

3.1.2 Loads and environmental conditions

3.1.2.1 The following loads, forces, and pressures should be considered in the design:

- a) Prestressing forces—circumferential prestressing forces in the walls and dome rings; vertical prestressing, if used in the walls; and roof prestressing, if used
- b) Internal pressure from stored materials, such as fluid pressure in liquid storage vessels, gas pressure in vessels containing gas or materials that generate pressure, and lateral pressure from stored granular materials; for pressure from stored granular materials, refer to ACI 313
- c) External lateral earth pressure, including the surcharge effects of live loads supported by the earth acting on the wall
- d) Weight of the structure
- e) Wind load
- f) Snow and other imposed loads (earth where applicable) on roofs
- g) Hydrostatic pressure on walls and floors due to groundwater
- h) Seismic effects
- i) Equipment and piping supported on roofs or walls

3.1.2.2 In addition to loads and environmental conditions listed in 3.1.2.1, the following effects should also be considered:

- a) Loss of prestressing force due to concrete creep and shrinkage and relaxation of prestressing steel
- b) Temperature and moisture differences between structural elements
- c) Thermal and moisture gradients through the thickness of structural elements
- d) Exposure to freezing-and-thawing cycles
- e) Chemical attack on concrete and metal
- f) Differential settlements

3.1.2.3 One or more of the following means should be used, whenever applicable, to prevent the design loads from being exceeded:

- a) An overflow pipe of adequate size, or other positive means, 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 liquid and granular containment structures. The vent(s) should limit the positive internal pressure to an acceptable value when the tank is being filled at its maximum rate and limit the negative internal pressure to an acceptable value 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 tank pipe being broken immediately outside the tank.

c) Hydraulic pressure-relief valves can be used on nonportable water tanks to control hydrostatic uplift on slabs and the hydrostatic pressure on walls when the tanks are empty or partially full. The use of pressure-relief valves should be restricted to applications where the expected groundwater level is below the operating level of the tank. The valves may also be used to protect the structure during floods. A sufficient number of valves should be used to provide at least 50 percent system redundancy. No fewer than two valves should be used, with at least one valve being redundant. The inlet side of the pressure-relief valves should be interconnected with one of the following:

- i. A layer of free-draining gravel adjacent to and underneath the concrete surface to be protected
- ii. A perforated-type drain system placed in a free-draining gravel adjacent to and underneath the concrete surface to be protected
- iii. A perforated pipe drain system in a free-draining gravel that serves as a collector system for a geomembrane drain system placed against the concrete surface to be protected

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

The spacing and size of pressure-relief valves should be adequate to control the hydrostatic pressure on the structure, and the valves should not be less than 4 in. (100 mm) in diameter and should not be spaced more than 20 ft (6 m) apart. Some or all valves should be placed at the lowest part of the structure, unless the structure has been designed to withstand the pressure imposed by a groundwater level to, or slightly above, the elevation of the valves. The use of spring-controlled, pressure-relief valves is discouraged, as they may be prone to malfunction of the springs. The recommended pressure-relief valves are:

- a) Floor-type pressure-relief valves that operate by hydrostatic pressure lifting a cover where travel is limited by restraining lugs
- b) Wall-type pressure-relief valves with corrosion-resistant hinges operated by hydrostatic pressure against a flap gate

When using floor-type valves, note that operation can be affected by sedimentation within the tank, incidental contact by a scraper mechanism in the tank, or both. When wall-type valves are used in tanks with scraper mechanisms, the valves should be placed to clear the operating scraping mechanisms with the flap gate in any position, taking into account that there can be some increase in elevation of the mechanisms due to buoyancy, buildup of sediment on the floor of the tank, or both.

Gas-pressure-relief valves should be used to limit gas pressure to an acceptable level on the roof and walls of nonvented structures such as digester tanks. The pressure-relief valve should be compatible with the anticipated contained gas and the pressure range. The valve selection should consider any test pressure that may be required for the structure.

3.1.3 Strength

3.1.3.1 General—Structures and structural members should be proportioned to have design strengths at all sections equal to or exceeding the minimum required strengths calculated for the factored loads and forces in such combinations as required in ACI 350 and as recommended in this guide.

3.1.3.2 Required strength—The load factors required in ACI 350 for dead load; live load; wind load; seismic forces; and lateral earth, soil, or groundwater pressure should be used. A load factor of 1.4 should be used for liquid. Load factors for well-defined gas pressure and vacuum loads should be the same as fluid loads, with the exception that the load factor for gas pressure can be reduced to 1.25 for domes with pressure-relief valves. A load factor of 1.4 should be applied to the final effective prestressing forces for determining the required circumferential strength of the core wall. When prestressing restraint moments, in combination with other factored loads and environmental effects, to produce the maximum flexural strength requirements, a load factor of 1.2 should be applied to the maximum applicable initial or final prestressing force. When prestressing restraint moments reduce the flexural strength required to resist other factored loads and environmental effects, a load factor of 0.9 should be applied to the minimum applicable prestressing force. Refer to ACI 313 for load factors for lateral pressures from stored granular materials.

When designing structural floors for hydrostatic uplift, a safety factor of 1.25 against flotation should be used. If the dead weight of the floor is less than the uplift force multiplied by the safety factor, the floor should be designed for hydrostatic uplift fluid loads using a load factor of 1.4.

The required strength for other than compression-controlled sections as defined by ACI 350 should be multiplied by an environmental durability factor, S_d , in accordance with ACI 350.

3.1.3.3 Design strength—The design strength of a member or cross section should be taken as the product of the nominal strength, calculated in accordance with the provisions of ACI 350, and multiplied by the applicable strength reduction factor, except as modified in this guide.

The strength-reduction factor should be as required in ACI 350, except as follows:

- a) Tension in circumferential prestressed reinforcement, $\phi = 0.85$
- b) Circumferential compression in concrete and shotcrete, $\phi = 0.75$

A strength check need not be made for initial prestressing forces that comply with provisions of 3.3.4.2.1.

3.1.4 Serviceability recommendations

3.1.4.1 Liquid-tightness control—Liquid-containing structures should not exhibit visible flow or leakage as defined in 6.3. Acceptance criteria for liquid-tightness are given in Chapter 6.

3.1.4.2 Corrosion protection of prestressed reinforcement—Circumferential prestressed wire or strand placed on the exterior surface of a core wall or a dome ring should be protected by at least 1 in. (25 mm) of shotcrete cover. Each wire or strand should be encased in shotcrete. Vertical prestressed reinforcement should be protected by portland cement or epoxy grout. The requirements for concrete protection of vertical tendon systems and minimum duct and grout requirements are given in ACI 350.

3.1.4.3 Corrosion protection of nonprestressed reinforcement—Nonprestressed reinforcement should be protected by the amount of concrete cover as required in ACI 350 and summarized as follows:

(a) Floor slabs	Minimum cover
<i>From top of slab</i>	
Membrane slabs ($t \leq 6$ in. [150 mm])	1 in. (25 mm)
Slabs-on-ground ($t \leq 8$ in. [200 mm])	... 1-1/2 in. (40 mm)
Structural slabs-on-ground more than 8 in. (200 mm) thick	2 in. (50 mm)
<i>From slab underside</i>	
Membrane slabs ($t \leq 6$ in. 150 mm)) and slabs-on-ground ($t \leq 8$ in. [200 mm]):	
Slabs cast against a stabilized	
subgrade with plastic vapor barrier	1-1/2 in. (40 mm)
Slabs cast against a stabilized	
subgrade without vapor barrier	2 in. (50 mm)
Other slabs cast against non-stabilized subgrade	3 in. (75 mm)
(regardless of subgrade condition, except as provided for ACI 350-06, R7.7)	



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(b) Wall

- From inside face 1 in. (25 mm)
 From outside face (over steel diaphragm) 1 in. (25 mm)

(c) Dome roof

- From top surface 1 in. (25 mm)
 From roof underside 1 in. (25 mm)

(d) Flat roof

- From top surface 2 in. (50 mm)
 From roof underside 2 in. (50 mm)

3.1.4.4 Boundary conditions—The effects of translation, rotation, and other deformations should be considered. The effects originating from prestressing; dead and live loads; and volume changes, such as those produced by thermal and moisture changes, concrete creep, and relaxation of prestressed reinforcement, should also be considered.

3.1.4.5 Other serviceability recommendations for liquid-containing structures—Allowable stresses, provisions for determining prestressing losses, recommendations for liquid barriers or bidirectional prestressing to preclude leakage, and various other design recommendations intended to ensure serviceability of water tanks and other liquid-containing structures are given in 3.2 to 3.4.

3.2—Floor and footing design

3.2.1 Foundations—Refer to Appendix A for recommendations and considerations related to the design and construction of tank foundations.

3.2.2 Floor slabs

3.2.2.1 Membrane floor slabs transmit loads directly to the sub-base without distribution. Settlements should be anticipated and provisions made for their effects. Local hard and soft spots beneath the floor should be avoided or considered in the floor design.

3.2.2.2 The minimum thickness of membrane floor slabs should be 4 in. (100 mm).

3.2.2.3 To limit crack widths and spacing, the minimum ratio of reinforcement area to concrete area should be 0.005 in each orthogonal direction, except as recommended in 3.2.2.8.

3.2.2.4 Additional reinforcement should be provided at the floor edges and other discontinuities as required by the connection design. In tanks with hinged or fixed base walls, additional reinforcement should be provided as required in the edge region to accommodate tension in the floor slab caused by the radial shear forces and bending moments induced by restraint at the wall base.

3.2.2.5 In cases of restraint to floor movement, such as large under-floor pipe encasements, details to limit crack width and spacing should be provided. Where such pipe encasements are bearing on significantly stiffer subgrade than the adjacent floor, anticipated differential settlements need to be accounted for in the design. Details that allow for unrestrained differential vertical movement where the floor meets the pipe encasement may be considered.

Details used successfully include gradual transitions in thickness between pipe encasements and floors, separating pipe encasements from floors through the use of horizontal

joints, and the use of additional reinforcement in pipe encasements not separated from floors.

3.2.2.6 Reinforcement should be either welded-wire fabric or deformed bar. Maximum wire spacing for welded-wire fabric should be 4 in. (100 mm), and adjacent sheets or rolls of fabric should be overlapped a minimum of 6 in. (150 mm). Maximum spacing of bar reinforcement should be the lesser of 12 in. (300 mm) or two times the slab thickness.

3.2.2.7 Reinforcement should be located in the upper 2-1/2 in. (65 mm) of the slab thickness, with the minimum covers recommended in 3.1.4.3, and should be maintained at the correct elevation by support chairs or concrete cubes.

3.2.2.8 Slabs greater than 8 in. (200 mm) thick should have a total minimum reinforcement ratio of 0.005 in each orthogonal direction and distributed into two mats of reinforcing steel, with no less than 1/3 of the reinforcement distributed at any one face. The shrinkage and temperature reinforcement is normally divided equally between both concrete faces. Where special conditions exist that significantly change the rate of drying or cooling on one face of the member, shrinkage and temperature reinforcement may be adjusted accordingly. Minimum covers from the reinforcing steel mats to the top of the slab and the underside should be as recommended in 3.1.4.3. Slabs thicker than 24 in. (600 mm) need not have reinforcement greater than that required for a 24 in. (300 mm) thick slab. In wall footings monolithic with the floor, the minimum ratio of circumferential reinforcement area to concrete area should be 0.005.

3.2.2.9 A floor subjected to hydrostatic uplift pressures that exceed 0.80 times the weight of the floor should be provided with subdrains or pressure-relief valves to control uplift pressures or be designed as structural floors in accordance with the recommendations given in 3.1.3.2 and 3.2.3. Pressure-relief valves will allow contamination of the tank contents by groundwater or contamination of the subgrade by untreated tank contents.

3.2.3 Structural floors—Structural floors should be designed in accordance with ACI 350. Structural floors are required when piles or piers are used because of inadequate soil-bearing capacity, hydrostatic uplift, or expansive subgrade. Structural floors can also be used where excessive localized soil settlements reduce support of the floor slab, such as where there is a potential for sinkholes.

3.2.4 Mass concrete—Concrete floors used to counteract hydrostatic uplift pressures can be mass concrete as defined in ACI 207.1R. Minimum reinforcement recommendations are given in 3.2.2.8. For more information on the effects of restraint, volume change, and reinforcement on cracking of mass concrete, refer to ACI 207.2R.

3.2.5 Floor concrete strength—Minimum concrete strength recommendations are given in 4.1.3.

3.2.6 Floor joints—For liquid-containing structures, membrane floors should be designed so that the entire floor can be cast without cold joints or construction joints. If this is not practical, the floor should be designed to minimize construction joints.

3.2.7 Wall footing

3.2.7.1 A footing should be provided at the base of the wall to distribute vertical and horizontal loads to the sub-base or other support. The footing may be integral with the wall, floor, or both.

3.2.7.2 Recommendations for maximum spacing and minimum ratio for circumferential reinforcement are given in 3.2.2.6 and 3.2.2.8, respectively.

3.2.7.3 The bottoms of footings on the perimeter of a tank should extend at least 12 in. (300 mm) below the adjacent finished grade. A greater depth may be required for frost protection or for adequate soil bearing.

3.3—Wall design

3.3.1 Design methods—The design of the wall should be based on elastic cylindrical shell analyses considering the effects of prestressing, internal loads, backfill, and other external loads. The design should also provide for:

- The effects of shrinkage, elastic shortening, creep, relaxation of prestressed reinforcement, and temperature and moisture gradients (Vitharana and Priestley 1999)
- The joint movements and forces resulting from the restraint of deflections, rotations, and deformations that are induced by prestressing forces, design loads, and volume changes

Coefficients, formulas, and other aids (based on elastic shell analyses) for determining vertical bending moments, and circumferential, axial, and radial shear forces in walls are given in Timoshenko and Woinowsky-Krieger (1959), Flugge (1967), Baker et al. (1973), Ghali (1979), Billington (1982), Heger et al. (1984), and Ghali and Favre (1986).

3.3.2 Wall types—This guide describes four wall types used in liquid-containing structures.

3.3.2.1 Cast-in-place concrete, prestressed circumferentially by wrapping with either high-strength steel wire or strand, wound on the external surface of the core wall and prestressed vertically with grouted steel tendons—Vertical nonprestressed steel reinforcement may be provided near each face for strength and to limit crack width and spacing. Nonprestressed temperature reinforcement should be considered in situations where the core wall is subject to significant temperature variations or shrinkage before circumferential or vertical prestressing is applied. The circumferential prestressing is encased in shotcrete that provides corrosion protection and bonding to the core wall (Fig. 3.3.2.1).

3.3.2.2 Cast-in-place concrete with full-height vertically fluted steel diaphragm, prestressed circumferentially by wrapping with either high-strength steel wire or strand—The steel diaphragm is located on the exterior face and the vertical steel reinforcement is near the interior face. Adjacent sections of the diaphragm are joined and sealed, as recommended in 4.10, to form an impervious membrane. The exposed diaphragm is coated first with shotcrete, after which the composite wall is prestressed circumferentially by winding with high-strength wire or strand. Grouted post-tensioned tendons can be provided for vertical reinforcement. The circumferential prestressing is encased in shot-

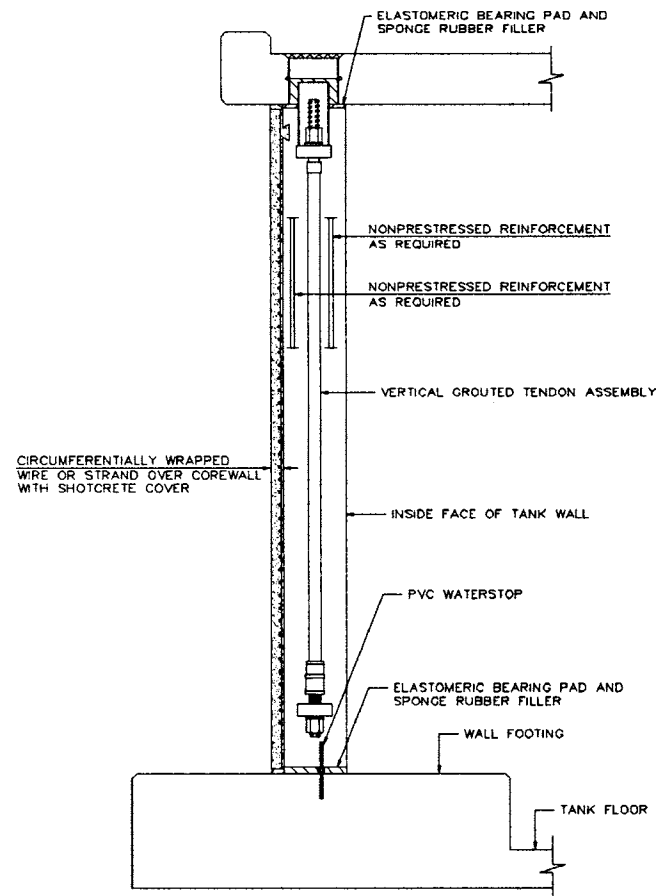


Fig. 3.3.2.1—Typical wall section of a wire- or strand-wrapped, cast-in-place, vertically prestressed tank.

crete that provides corrosion protection and bonding to the core wall (Fig. 3.3.2.2).

3.3.2.3 Shotcrete with full-height vertically-fluted steel diaphragm, prestressed circumferentially by wrapping with either high-strength steel wire or strand—Diaphragm steel is provided near one face, and nonprestressed steel reinforcement is provided near the other face as vertical reinforcement. If needed, additional nonprestressed steel can be provided in the vertical direction near the face with the diaphragm. Adjacent sections of the diaphragm are joined and sealed, as recommended in 4.10, to form an impervious membrane. Grouted post-tensioned tendons can be provided as vertical reinforcement. The circumferential prestressing is encased in shotcrete that provides corrosion protection and bonding to the core wall (Fig. 3.3.2.3).

3.3.2.4 Precast concrete vertical panels curved to tank radius with a full-height vertically fluted steel diaphragm prestressed circumferentially by wrapping with either high-strength steel wire or strand—The vertical panels are connected with sheet steel, and the joints between the panels are filled with cast-in-place concrete, cement-sand mortar, or shotcrete. Adjacent sections of the diaphragm, both within the panels and between the panels, are joined and sealed as recommended in 4.10 to form a solid membrane. The exposed diaphragm is coated first with shotcrete, after which the composite wall is prestressed circumferentially

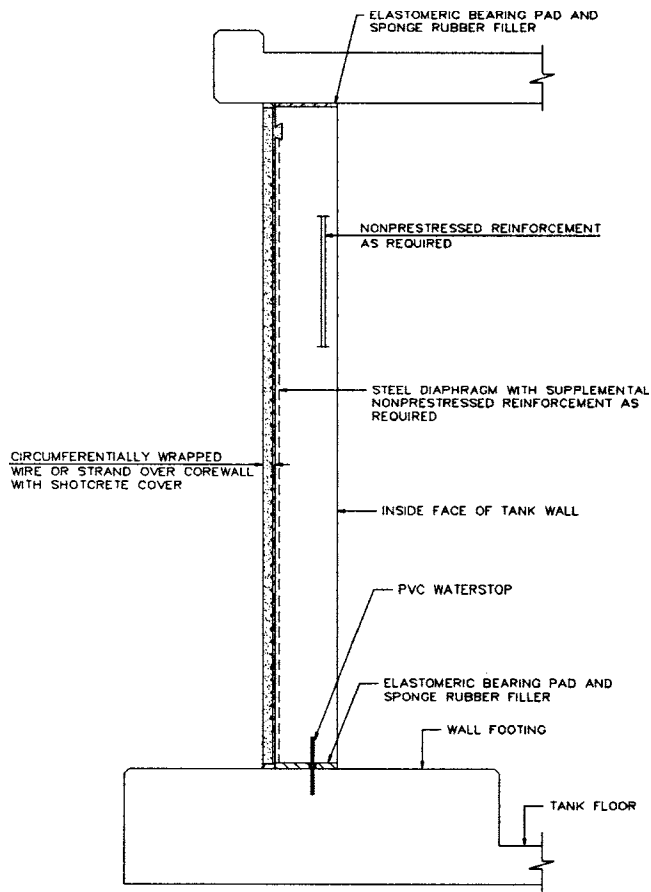


Fig. 3.3.2.2—Typical wall section of a wire- or strand-wrapped, cast-in-place tank with a steel diaphragm.

by winding with high-strength steel wire or strand. Grouted post-tensioned or pretensioned tendons or nonprestressed steel reinforcement may be provided for vertical reinforcement. The circumferential prestressing is encased in shotcrete that provides corrosion protection and bonding to the core wall (Fig. 3.3.2.4).

3.3.3 Liquid tightness—In a shotcrete, cast-in-place, or precast concrete wall, liquid tightness is achieved by the circumferential prestressing and by a liquid-tight steel diaphragm incorporated into the core wall. A cast-in-place wall can also achieve liquid tightness by using both circumferential and vertical prestressed reinforcement. Considerations of special importance with respect to liquid tightness are:

- A full-height, vertically fluted steel diaphragm with sealed edge joints that extends throughout the wall area and provides a positive means of achieving liquid tightness;
- vertical prestressing, in cast-in-place core walls without a diaphragm, provides a positive means of limiting horizontal crack width, thus providing liquid tightness;
- circumferential (horizontal) construction joints between the wall base and the top should not be permitted in the core wall; only the wall base joint and vertical joints should be permitted. The necessity of obtaining concrete free of honeycombing and cold joints cannot be overemphasized; and

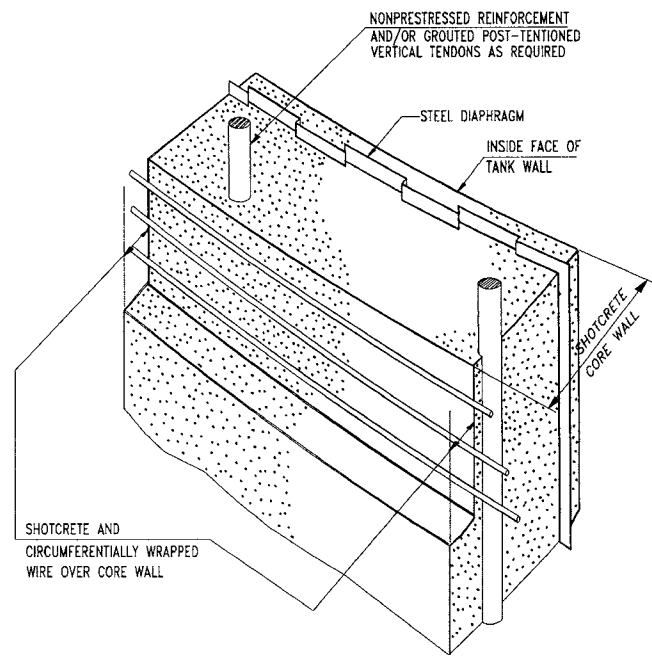


Fig. 3.3.2.3—Typical wall section of wire- or strand-wrapped shotcrete tank with steel diaphragm.

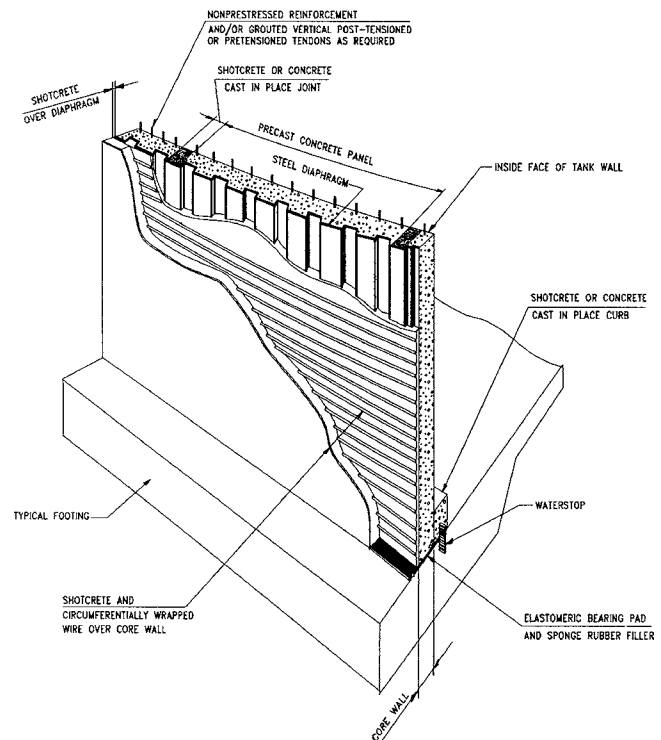


Fig. 3.3.2.4—Typical wall section of wire- or strand-wrapped precast tank with steel diaphragm.

- all vertical construction joints in cast-in-place concrete core walls without a metal diaphragm should contain waterstops to provide liquid tightness.

3.3.4 Wall proportions

3.3.4.1 Minimum core wall thickness—Experience in wrapped prestressed tank design and construction has shown that the minimum core wall thickness should be as follows:

- 7 in. (180 mm) for cast-in-place concrete walls.

b) 3-1/2 in. (90 mm) for shotcrete walls with a steel diaphragm

c) 4 in. (100 mm) for precast-concrete walls with a steel diaphragm

3.3.4.2 Circumferential compressive stress

3.3.4.2.1 Maximum stress at initial prestressing—The circumferential compressive stress in extreme fiber in the core wall produced by the unfactored initial prestressing force should not exceed $0.55f_{ci}'$ for concrete and $0.55f_{gi}'$ for shotcrete. The stress should be determined based on the net core wall area after deducting all openings, ducts, and recesses, including the effects of diaphragm joints.

Experience with the previously mentioned maximum initial compressive stress is limited to a maximum design concrete strength f_c' of 5000 psi (35 MPa), and shotcrete strength f_g' of 4500 psi (31 MPa), as discussed in McCarthy and Balck (2012). Caution is advised if higher-compressive-strength concrete is used. If higher concrete strengths are used, additional design considerations, such as buckling and stability, should be investigated.

3.3.4.2.2 Resistance to final prestressing—The compressive strength of any unit height of wall for resisting final circumferential prestressing force (after all losses recommended in the following) should satisfy Eq. (3.3.4.2.2).

$$0.85f_c'\phi(A_g + [2n - 1]A_s) \geq 1.4P_e \quad (3.3.4.2.2)$$

Replace f_c' with f_g' if shotcrete is to be used.

3.3.4.2.3 Resistance to external load effects—For resisting factored external load effects, such as backfill, the compressive strength of any unit height of wall should be the compressive strength of the wall reduced by the core wall strength required to resist 1.4 times the final circumferential prestressing force, satisfying Eq. (3.3.4.2.3).

$$\phi(0.85f_c'A_{gr} + A_s f_y) \left\{ 1 - \frac{1.4P_e}{0.85f_c'\phi[A_g + (2n - 1)A_s]} \right\} \geq 1.7P_h \quad (3.3.4.2.3)$$

Replace f_c' with f_g' if shotcrete is to be used.

3.3.4.2.4 Compressive strain limit—The wall should be proportioned so that the compressive axial strain remains within the elastic range under the effects of prestressing plus other external loads, such as backfill. The following compressive stress limit is recommended for determining the minimum wall thickness under final prestressing combined with other external effects such as backfill, satisfying Eq. (3.3.4.2.4).

$$\frac{P_e}{(A_g + (2n - 1)A_s)} + \frac{P_h}{[A_g + (2n - 1)A_s + (n - 1)A_{ps}]} \leq 0.45f_c' \text{ psi (MPa)} \quad (3.3.4.2.4)$$

Replace f_c' with f_g' if shotcrete is to be used.

3.3.4.2.5 For unusual conditions, such as those listed in 3.3.10, wall thickness should be determined based on analysis.

3.3.5 Circumferential prestressing

3.3.5.1 Initial stress in the prestressed reinforcement should not be more than $0.70f_{pu}$ in wire-wrapped systems and $0.74f_{pu}$ in strand-wrapped systems.

3.3.5.2 After deducting prestressing losses, ignoring the compressive effects of backfill, and with the tank filled to design level, there should be residual circumferential compression in the core wall. The residual prestressing force should result in the following minimum core wall compression values:

a) 200 psi (1.4 MPa) for the above-ground portion of the tank wall, tapering linearly to 50 psi (0.34 MPa) at 6 ft (1.8 m) below grade.

b) 400 psi (2.8 MPa) at the top of an open-top tank, reducing linearly to not less than 200 psi (1.4 MPa) at $0.6\sqrt{(rh)}$ ft [$(2.078\sqrt{(rh)})$ mm] below the open top.

This level of residual stress is effective in limiting crack width and spacing due to temperature, moisture, and discontinuity of the shell at the top of open-top tanks.

Even when the base of the wall is hinged or fixed, the prestressing force should provide the stated residual circumferential stresses, assuming the bottom of the wall is unrestrained.

3.3.5.3 The total assumed prestressing loss caused by shrinkage, creep, and relaxation should be at least 25,000 psi (175 MPa).

Losses may be larger than 25,000 psi (175 MPa) in tanks that are not intended for water storage or that are expected to remain empty for long periods of time (1 year or longer).

When calculating prestressing loss due to elastic shortening, creep, shrinkage, and steel relaxation, consider the properties of the materials and systems used, the service environment, the load duration, and the stress levels in the concrete and prestressing steel. Refer to Magura et al. (1964), PCI Committee on Prestress Losses (1975), Zia et al. (1979), and ACI 209R for guidance in calculating prestressing losses.

3.3.5.4 Spacing of prestressed reinforcement—Minimum clear spacing between wires or strands should be 1.5 times the wire or strand diameter, or 1/4 in. (6 mm) for wires, and 3/8 in. (10 mm) for strands, whichever is greater. Maximum center-to-center spacing should be 2 in. (50 mm) for wires, and 6 in. (150 mm) for strands, except as provided for wall openings in 3.3.8.

3.3.6 Wall-edge restraints and other secondary bending—Wall-edge restraints, discontinuities in applying prestressing, and environmental conditions result in vertical and circumferential bending. Design consideration should be given to:

a) Edge restraint of deformations due to applied loads at the wall floor joint and at the wall roof joint. Various joint details have been used to minimize restraint of joint translation and rotation. These include joints that use neoprene pads and other elastomeric materials combined with flexible waterstops.

b) Changing base restraint to a joint of a different type during and after prestressing. An example is a joint unrestrained during prestressing then hinged after grouting, using the change in joint characteristics as a result from grout installation.