

Design and Construction of Circular Wire and Strand Wrapped Prestressed Concrete Structures

Reported by ACI Committee 344



american concrete institute

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October 1988

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PREFACE

ACI Committee 344 was organized in 1961. The committee produced a report "Design and Construction of Circular Prestressed Concrete Structures" (ACI 344R-70) which was published in the September 1970 ACI Journal. It was subsequently added to the ACI Manual of Concrete Practice and made available as a separate publication. The synopsis at the beginning of the 1970 report said in part "Recommendations are primarily applicable to circumferential prestressing by wire winding but do provide guidance for the use of individual tendons."

A consensus on a successor document to the 1970 report has not been reached in ACI 344; however, at the request of Committee 344, TAC agreed to the publication of two subcommittee reports, one on each type of tank, if successfully balloted by Committee 344. Two interim reports are the result: "Design and Construction of Circular Wire and Strand Wrapped Prestressed Concrete Structures" and "Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons." TAC has agreed to the publication of these interim reports so that needed information can be disseminated without further delay. TAC has also encouraged the committee to work toward a consensus and a single combined report.

For the same component of a structure, the two reports still offer somewhat different recommendations. This is true for floors structurally independent of the walls, roofs resting on the walls, and there is no explanation of why steel diaphragms are commonly used in wrapped tanks but not in tendon tanks. The requirements for concrete and shotcrete and testing are not entirely consistent.

While these reports are made available now for information, it is expected that Committee 344 will eventually reach a consensus on those items where there are differences and that there will be one report.

DESIGN AND CONSTRUCTION OF CIRCULAR WIRE AND STRAND WRAPPED PRESTRESSED CONCRETE STRUCTURES

Reported by ACI Committee 344

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This report provides recommendations for the design and construction of wrapped circular prestressed concrete structures commonly used for liquid and bulk storage. These structures utilize thin cylindrical shells of either concrete or shotcrete. A thin steel diaphragm is incorporated in shotcreted and precast concrete walls. Vertical post-tensioning is incorporated in cast-in-place concrete walls. Recommendations are applicable to circumferential prestressing achieved by wire or strand wrapping. In wrapping, the wire or strand is fully tensioned before placement on the structural core wall. Procedures preventing corrosion of the prestressing elements have been emphasized. The design and construction of dome roofs are also covered.

Keywords: admixtures; circular prestressing; concrete construction; connections; corrosion resistance; domes; floors; footings; formwork; joint sealers; joints; loads (forces); prestressed concrete; prestressing steel; reinforced concrete; reinforcing steel; reservoirs; roofs; shotcrete; shrinkage; storage tanks; structural design; tanks; temperature; walls.

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ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning, executing, or inspecting construction. These documents should not be referenced in the Project Documents. If information found in these documents is desired to be part of the Project Documents, it should be phrased in mandatory language and incorporated into the Project Documents.

CHAPTER 1 - GENERAL

1.1 - INTRODUCTION

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

Circular prestressed concrete structures are used predominantly for water storage. This report is concerned principally with recommendations for circular prestressed concrete structures used for liquid storage, but the recommendations may also be applied to similar structures containing low pressure gases, dry materials, chemicals, or other materials capable of creating outward pressures. It also applies to domed concrete roofs over circular structures of all types. Stored materials include water, wastewater, process liquids, cement slurry, petroleum, and other liquid products. Stored gases include gaseous by-products of waste treatment processes and other gaseous material. Stored dry materials include grain, cement, sugar, and other dry granular products.

This report describes current design and construction practices for tanks that are prestressed with circumferential wires or strands applied by a wrapping process that imparts a prestress force prior to contact with the tank wall. See "Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons," reported by ACI 344 for recommendations covering tanks that are prestressed with circumferential tendons stressed after they are placed internally within tank walls or externally on tank walls. These recommendations are not intended to prevent development or use of new advances in engineering practice. The recommendations of this report are not intended for application to nuclear reactor pressure vessels or cryogenic containment structures.

1.2 - OBJECTIVE

The objective of this report is to provide guidance to individuals charged with design and construction of circular prestressed concrete structures by recommending practices that have resulted in successful structures.

1.3 - SCOPE

The recommendations in this report are intended to supplement the general requirements for reinforced concrete and prestressed concrete design and construction given in ACI 318 and ACI 301. Design and construction recommendations cover the following elements or components of circular wrapped prestressed concrete tanks :

- a. Floors
 - Reinforced Concrete.
- b. Floor-Wall Connections
 - Hinged
 - Fixed
 - Partially fixed
 - Unrestrained
 - Changing restraint

- c. **Walls**
 - Cast-in-place concrete walls
 - Shotcrete walls with steel diaphragms
 - Precast concrete wall systems with steel diaphragms
- d. **Wall-Roof Connections**
 - Hinged
 - Fixed
 - Partially fixed
 - Unrestrained
- e. **Roofs**
 - Concrete dome roofs with prestressed dome ring including cast-in-place concrete, shotcrete, and precast concrete.
 - Flat concrete roofs
- f. **Wall and Dome Ring Prestressing Systems**
 - Circumferential using wrapped wire or strand systems
 - Vertical using single or multiple high-strength strands, bars or wires, Pretensioned high-strength strands are sometimes used in precast panels.

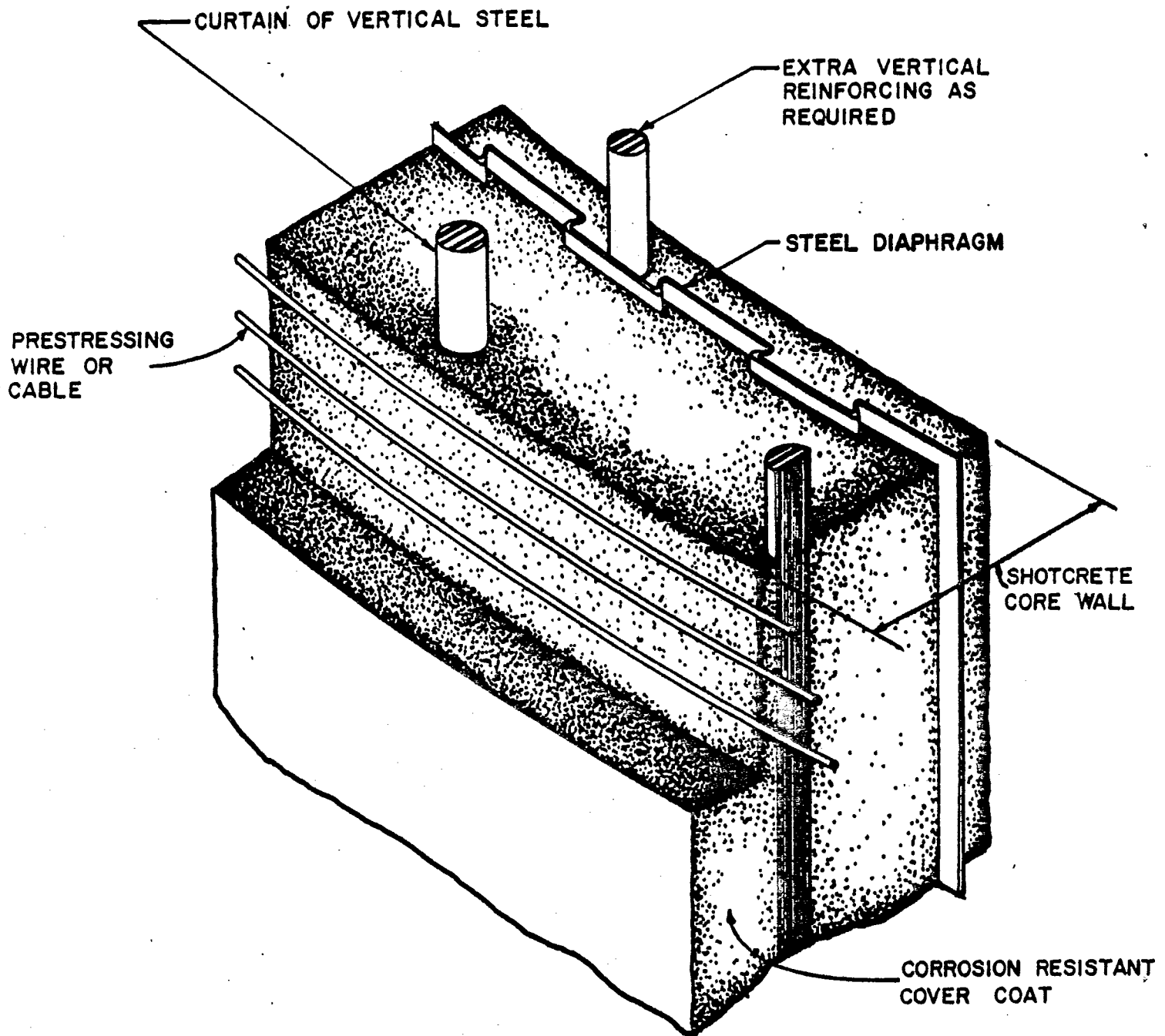
1.4 - HISTORY AND DEVELOPMENT

The first effort to apply circumferential prestressing to a concrete water tank is attributed to W. S. Hewett, who in the early 1920's used 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. Shrinkage and creep of the concrete resulted in a rapid and relatively large loss of the initial prestressing force.

The late Eugene Freyssinet, a distinguished French engineer generally regarded to be the father of prestressed concrete, was the first to realize the need to use steels of high quality and strength, stressed to relatively high levels, in order to overcome the adverse effects of concrete creep and shrinkage. Freyssinet successfully applied prestressing to concrete structures as early as the late 1920's. Vertical wall prestressing was introduced in the 1930's as a means to control horizontal cracking that might permit leakage and corrosion of circumferential prestressing steel.

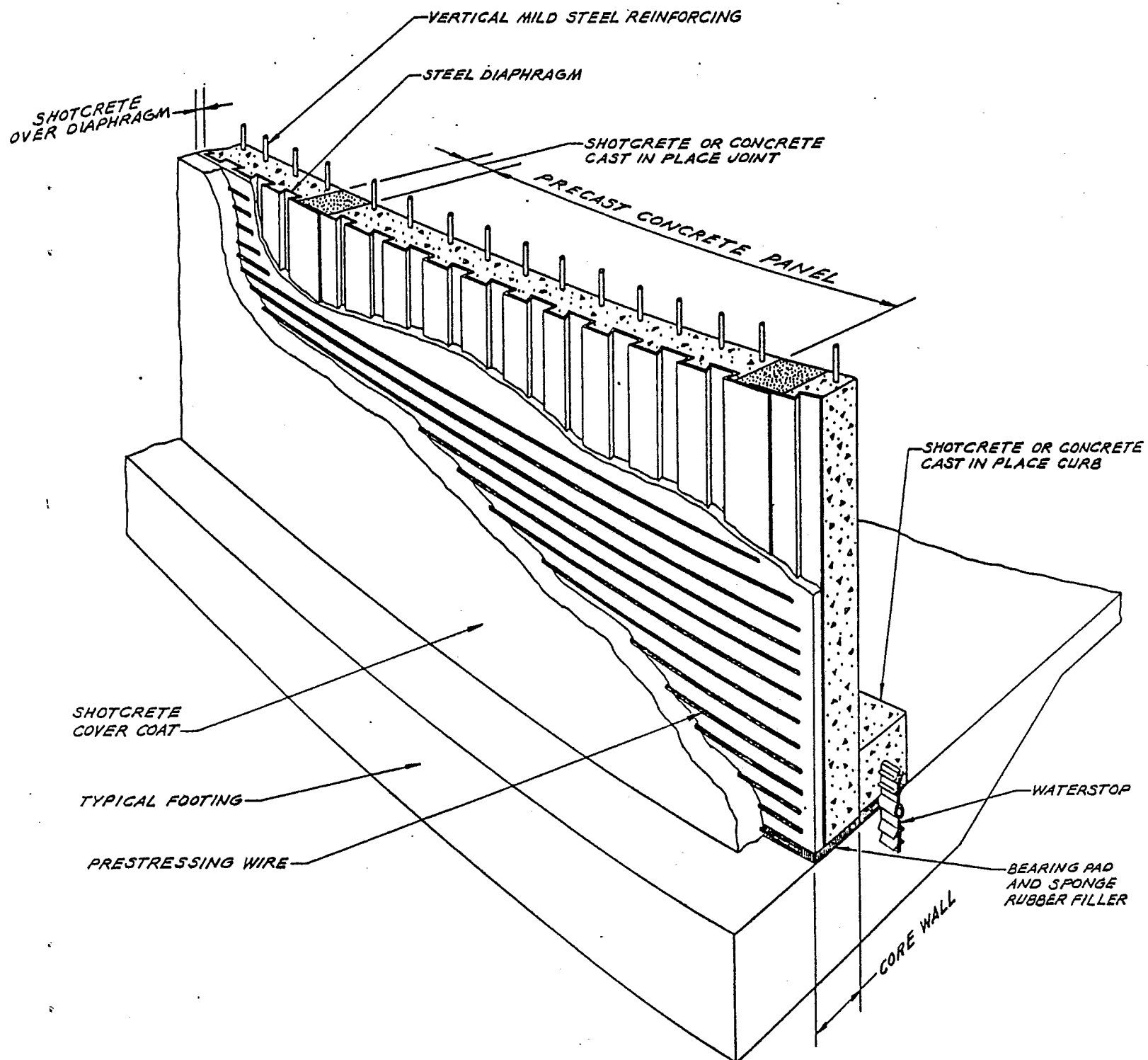
The late J. M. Crom, Sr. (the first to apply high strength prestressing steels to concrete tanks) developed a novel method to apply high-strength wire in a continuous spiral to the exterior surface of concrete tanks in 1942. The method is based on mechanically stressing the wire as it is placed on the wall, thus avoiding loss in prestress from friction between the prestressed reinforcement and the wall. This method of circumferentially prestressing tanks and dome rings is commonly known as "wire winding" or "wire wrapping." After placement, the prestressed reinforcement is protected from corrosion by encasement in shotcrete. More than four thousand tanks of various sizes and shapes have been constructed using methods based on this concept.

In 1952, shotcrete tanks incorporating a light-gauge steel diaphragm fluid barrier (see Figures 1.1 and 1.2) within the wall were first built by J. M. Crom, Sr. By the early 1960's, nearly all prestressed shotcrete tanks utilized the 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 within the wall. The diaphragm helps to prevent corrosion of the prestressing steel from liquid penetration through the wall. The diaphragm also serves as vertical reinforcement.



Typical wall section of a prestressed composite steel-shotcrete water storage tank
Figure 1.1

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Typical wall section of a wirewound precast concrete water storage tank
Figure 1.2

1.5 DEFINITIONS

Core Wall - That portion of a concrete wall that is circumferentially prestressed.

Joint Restraint Conditions - Top and bottom boundary conditions for the cylindrical shell wall or the dome edge.

Hinged - Full restraint of radial translation and negligible restraint of rotation.

Fixed - Full restraint of radial translation and full restraint of rotation.

Partially Fixed - Full restraint of radial translation and partial restraint of rotation.

Changing Restraint - A joint may be of a different type during and after prestressing. An example is a joint unrestrained during prestressing then hinged after prestressing. The change in joint characteristics results from the grout installation after prestressing that prevent further radial translation.

Membrane Floor - a thin, highly reinforced, slab-on-grade designed to deflect when the subgrade settles and still retain watertightness of the slab.

Shotcrete Cover - Shotcrete covering the wrapped prestressing strand or wire.

Wire Coat - The portion of the shotcrete cover in direct contact with the prestressing wire or strand.

Bodycoat - The layers of shotcrete in the shotcrete cover that do not directly touch the prestressing wire or strand.

Covercoat - The wire coat plus the bodycoat.

Tendon - A steel element such as wire, bar or strand, or a bundle of elements, tensioned to impart compressive stress to concrete. In pretensioned concrete the tendon is just the steel element. In post-tensioned concrete the tendon includes the complete assembly consisting of end anchorages and/or couplers, prestressing steel and sheathing filled with corrosion inhibiting grout.

Bonded Tendon - A prestressing tendon bonded to the concrete either directly or through grouting.

Anchorage - A device used to anchor the tendon to the concrete. The anchorage transfers the tensile force from the tendon into the concrete.

Wrapped Prestressing - A prestressing system using wire or strand that is fully tensioned before placement on the core wall.

1.6 - NOTATION

A_g	=	Gross area of unit height of core wall that resists circumferential force as defined in Section 2.3.3.1(b)(3), (sq. in.)
A_{gr}	=	Gross area of wall that resists externally applied circumferential forces, such as backfill, (sq. in.)
A_s	=	Area of non-prestressed circumferential reinforcement, (sq. in.)
A_{ps}	=	Area of prestressed circumferential reinforcement, (sq. in.)
D	=	Dead loads or related internal moments and forces
E_c	=	Modulus of elasticity of concrete under short time load, (psi)
f'_c	=	Specified compressive strength of concrete, (psi)
f'_{ci}	=	Compressive strength of concrete at time of prestressing, (psi)
f'_g	=	Specified compressive strength of shotcrete, (psi)
f'_{gi}	=	Compressive strength of shotcrete at time of prestressing, (psi)
f_{pu}	=	Specified tensile strength of prestressing wires or strands, (psi)
f_y	=	Specified yield strength of non-prestressed reinforcement, (psi)
h	=	Wall thickness, (in.)
h_d	=	Dome shell thickness, (in.)
L	=	Live loads or related internal moments and forces
P_e	=	Circumferential force per unit of wall height caused by the effective prestressing, (lbs.)
P_h	=	Circumferential force per unit of wall height caused by the external pressure of soil, ground water or other loads, (lbs.)
P_o	=	Nominal axial compressive strength of core wall in the circumferential direction per unit of wall height, (psi)
p_u	=	Factored unit design pressure on dome shell, (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 $2.5 (r_d h_d)^{0.5}$, (ft.)
B_i	=	Buckling reduction factor for geometrical imperfections

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- B_c = Buckling reduction factor for creep, non-linearity, and cracking of concrete
 ϕ = Strength reduction factor

NOTES:

- A. Units may be English or metric, but must be consistent in each equation.
- B. Coefficients in equations that contain $(f'_c)^{0.5}$ or $(f'_s)^{0.5}$ are for psi units. The coefficient for SI units (MPa) with $(f'_c)^{0.5}$ and $(f'_s)^{0.5}$ is the coefficient divided by 12.
- C. Inch-pound units are used in the text. SI conversions are provided in the table in Appendix A.

CHAPTER 2 - DESIGN

2.1 - STRENGTH AND SERVICEABILITY

2.1.1 - General

Structures and their components should be designed to meet both the minimum strength and serviceability recommended in this report. These recommendations are intended to assure adequate safety and performance of structures subject to typical loads and environmental conditions. Control of leakage and protection of all embedded steel from corrosion are necessary for adequate serviceability.

2.1.2 - Loads and Environmental Conditions

2.1.2.1 - Loads

- (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, see ACI 313.
- (c) Lateral earth pressure, including the surcharge effects of live loads supported by the earth acting on the wall.
- (d) Weight of structure.
- (e) Wind loads.
- (f) Earth, snow, and other live loads on roofs.
- (g) Hydrostatic pressure on walls and floors due to ground water.
- (h) Seismic effects.
- (i) Equipment and piping supported on roofs or walls.

2.1.2.2 - Environmental and Other Effects

- (a) Loss of prestressing force due to creep, shrinkage of concrete and shotcrete, 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 freeze-thaw cycles.
- (e) Chemical attack on concrete and metal.

2.1.2.3 - Recommendations for Control of Loads

- (a) Positive means, such as an overflow pipe of adequate size, should be provided to preclude 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) Venting 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 may be used on non-potable 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 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 all pressure-relief valves should be interconnected with a layer of free-draining gravel adjacent to and underneath the concrete surface to be protected, interconnected with a perforated type drain system in a free-draining gravel adjacent to and underneath the concrete surface to be protected, or interconnected by a perforated pipe drain system in a free-draining gravel which serves as a collector system for a geotechnical drain system placed against the concrete surface to be protected.

The free-draining gravel in all systems should be protected against the intrusion of fine material by a sand filter or geotextile filter. The pressure-relief valve inlet should be protected against the intrusion of gravel by a corrosion resistant screen, by an internal corrosion resistant strainer or by connecting it 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 further 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. Floor-type pressure relief valves which operate by hydrostatic pressure lifting a cover, but having restraining lugs limiting the travel and wall-type pressure-relief valves operated by hydrostatic pressure against a flap gate with corrosion-resistant hinge are recommended.

Caution should be exercised in using floor-type valves where their operation could be effected by sedimentation within the tank and/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 placed to clear the operating mechanisms with the flap gate in an open or closed position, taking into account there may be some elevation of the mechanisms due to buoyancy and/or a buildup of sediment on the floor of the tank.

(d) Pressure-relief valves designed for gases should be used to limit gas pressure on the roof and walls (such as in digester tanks) to an acceptable level. 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 valve should be redundant and at least 50 percent redundancy should be provided. The valve selection should consider any test pressure that may be required for the structure.

2.1.3 - Strength

2.1.3.1 - General

Structures and structural members should be proportioned to have 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 Chapter 9 of ACI 318, and as recommended in this report.

2.1.3.2 - Required Strength

(a) The load factors required in Chapter 9 of ACI 318 for dead load, live load, wind load, seismic forces, and lateral earth pressure should be used. The load factor for lateral earth pressure should be used for lateral pressure from stored solids.

(b) A load factor of 1.5 should be used for liquid and gas pressure, except the load factor for gas pressure may be reduced to 1.25 for domes with adequate pressure relief valves.

(c) A load factor of 1.4 should be used for the final prestress forces.

(d) When restraints result in bending moments in the components of a structure, a load factor of 1.2 should be applied to the maximum applicable initial or final prestress force for cases where prestress in combination with other factored loads and environmental effects produce the maximum flexural strength requirements.

(e) When restraints result in bending moments in the components of a structure, a load factor of 0.9 should be applied to the minimum applicable prestress force for cases where prestress reduces the flexural strength required to resist other factored loads and environmental effect.

2.1.3.3 - Design Strength

(a) The design strength of a member or cross section when considering axial force, moment, shear, and torsion, except as modified in this report, should be taken as the nominal strength calculated in accordance with recommendations and assumptions given in ACI 318, multiplied by the applicable strength reduction factor, ϕ .

(b) The strength reduction factor, ϕ , should be as required in Chapter 9 of ACI 318, except as follows:

- | | |
|--|------|
| (1) Tension in circumferential prestressed reinforcement: | 0.85 |
| (2) Circumferential compression in concrete and shotcrete: | 0.75 |

(c) A strength check need not be made for initial prestress forces that comply with requirements in Section 2.3.3.1(a).

2.1.4 - Serviceability Recommendations

2.1.4.1 - Watertightness Control

(a) Liquid-containing structures should be designed to preclude visible flow or leakage as defined in Section 5.3.