

Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons

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 PRESTRESSED CONCRETE STRUCTURES WITH CIRCUMFERENTIAL TENDONS

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This report provides recommendations for the design and construction of circular prestressed concrete structures (commonly referred to as "tanks") that use tendons for the circumferential prestressing. 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 internal or external tendons that are stressed after they are placed within, or on, the wall. Procedures to prevent corrosion of the prestressing elements are emphasized. The design and construction of dome roofs are also covered.

Keywords: admixtures; circumferential prestressing; concrete; connections; corrosion resistance; domes; floors; footings; joint sealers; joints; loads (forces); prestressed concrete; prestressed reinforcement; reinforced concrete; reinforcing steel; roofs; shotcrete; shrinkage; structural design; tanks; temperature; tendons; 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 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 using tendons requires specialized engineering knowledge and experience. This report reflects nearly four decades of experience in the art of designing and constructing circular prestressed 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 concerned principally with recommendations for circular prestressed concrete structures for water storage. The recommendations contained herein may also be applied to circular structures containing low pressure gases (such as sewage digesters with pressures of about 6 in. of water), dry materials, chemicals, or other materials capable of creating outward pressures. The recommendations may also be applied to domed concrete roofs over circular structures of all types. 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.

This report describes current design and construction practices for tanks that are prestressed with circumferential tendons stressed after they are placed internally within the tank walls, or externally on the tank walls. Another method of construction of circular prestressed concrete tanks involves prestressing with circumferential wires or strands applied by a wrapping process that imparts a tension force to the wires or strands prior to contact with the tank wall. See "Design and Construction of Circular Wire and Strand Wrapped Prestressed Concrete Structures", reported by ACI 344 for recommendations covering that construction method.

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 and cryogenic containment structures.

1.2-OBJECTIVE

The objective of this report is to provide guidance in the design and construction of circular prestressed concrete structures which are 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, given in ACI 318, and construction, given in ACI 301. 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
 - . Unrestrained
- e. Roofs
 - . Concrete Dome Roofs with Prestressed Dome Ring
 - Cast-in-place Concrete.
 - Shotcrete.
 - Precast Concrete.
 - . Other Roofs
 - Prestressed Concrete.
 - Reinforced Concrete.
- f. Wall and Dome Ring Prestressing Systems
 - . Circumferential
 - (1) Individual high-strength strands in plastic sheaths or multiple high-strength strand or wire tendons in ducts positioned within the wall and prestressed after placement in the wall (post-tensioning tendon systems), as shown in Figure 1.
 - (2) Individual or multiple high-strength strands or individual high-strength bar tendons, prestressed after positioning on the wall exterior surface.
 - . Vertical
 - (1) Individual or multiple high-strength strand, multiple high-strength wire or individual high-strength bar tendons, enclosed in sheathing or ducts within the wall, anchored near the base-wall joint at the bottom and near the wall-roof joint at the top (post-tensioning tendon systems).
 - (2) Pretensioned high-strength strands in precast panels.

1.4-HISTORY AND DEVELOPMENT

The first effort to apply circumferential post-tensioning 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 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 recognize 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 tendons to concrete structures as early as the late 1920's.

In the early 1950's, following methods used successfully in Europe for several years, several tanks were constructed in the United States using post-tensioned tendons embedded in the tank wall. The post-tensioned tendons in most early "tendon tanks" were grouted with a cement-water mixture after stressing to help protect them against corrosion and to bond the tendons. Others were unbonded paper wrapped individual strand tendons which 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 walls to eliminate or control horizontal cracking. This crack control helped prevent leakage of the contents and corrosion of the prestressing steel.

Over one hundred and fifty tendon-stressed tanks (bonded and unbonded) have been constructed in the United States.

1.5-DEFINITIONS

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

1.5.2 Joint Restraint Conditions-Top and bottom boundary conditions for the cylindrical shell wall. Examples are shown in Figures 2 and 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.

1.5.2.5 Changing Restraint-A joint may be of a different type during and after prestressing. An example is a joint which is unrestrained during prestressing but is hinged after prestressing. The change in joint type is a result of grout installation which 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 Bodycoat-The remainder of the shotcrete cover.

1.5.4.3 Covercoat-The tendon coat plus the bodycoat.

1.5.5 Tendon-A steel element such as wire, bar, or strand, or a bundle of such elements, used 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 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 which 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 goes around the tank circumference, as shown in Figure 1.

1.5.5.4 Coupling-A device which joins 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 wires or strands.

1.5.5.6 Sheathing-Enclosures in which post-tensioning tendons are encased to prevent bonding during concrete placement. The enclosures are generally referred to as ducts when used for grouted multiple strand or wire tendons.

1.5.5.7 Unbonded Tendon-A tendon which 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.

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 nonprestressed reinforcement, psi.
f'_c	= specified compressive strength of concrete, psi.
f'_{ci}	= specified compressive strength of concrete at time of initial prestress, psi.
f_{ci}	= the initial stress in the concrete at time t_i , immediately after prestressing, psi.
f'_g	= specified compressive strength of shotcrete, psi.
f_{pu}	= specified tensile strength of prestressing strands, wires or bars, psi.
f_{re}	= relaxation of prestressed steel, psi.
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_c	= 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 $2.5(r_d h_d)^{0.5}$, ft.
t_i	= age of concrete at time of prestressing, days
U	= required strength to resist factored loads or related internal moments and forces
β_1	= buckling reduction factor for geometrical imperfections from a true spherical surface, such as local increases in radius
(beta)	
β_c	= buckling reduction factor for creep, nonlinearity and cracking of concrete
ΔP_c	= Change in compressive strength in the concrete, lbs.
(delta)	
ϵ_{cs}	= free shrinkage of concrete, in./in.
(epsilon)	
η	= aging coefficient
(eta)	
η_{re}	= relaxation reduction factor
ϕ	= strength reduction factor
(phi)	
ϕ_{cr}	= creep coefficient of concrete, defined as the ratio of creep to instantaneous strain

NOTES:

- A. Units may be English or metric, but should be consistent in each equation.
- B. Coefficients in equations which contain $(f'_c)^{0.5}$ or $(f'_p)^{0.5}$ are for inch-pound units. The coefficient for SI units with $(f'_c)^{0.5}$ and $(f'_p)^{0.5}$ is the coefficient for inch-pounds 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 - DESIGN

2.1-STRENGTH AND SERVICEABILITY

2.1.1 General-Structures and components of structures should be designed to provide both the minimum strength and serviceability recommended in this report. Strength and serviceability recommendations given herein are intended to assure 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.

2.1.2-Loads and Environmental Considerations

2.1.2.1-Loads

(a) *Prestressing Forces*-Circumferential prestressing forces in the wall and dome ring, vertical prestressing (if provided in the wall) and roof prestressing which affects the wall should be considered in the wall design. For example, circumferential prestressing with backfill pressure (when applicable) combine to determine the circumferential compressive strength required. Circumferential prestressing also typically causes vertical bending moments which sometimes add to, and sometimes reduce vertical bending moments from other loading conditions. In these cases load factors other than 1.0 are recommended, see Section 2.1.3.

(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. For pressure from stored granular materials, see 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, Ref. 10 and 14.

2.1.2.2-Environmental Considerations

(a) Loss of prestressing force due to creep and shrinkage of concrete, and relaxation of prestressing steel.

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

(c) Thermal and moisture gradients that vary with the height of the wall.

(d) Temperature and moisture difference between structural elements.

(e) Exposure to freeze-thaw cycles.

(f) Chemical attack on concrete and metal.

2.1.2.3-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 liquid or granular 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 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 1) a layer of free-draining gravel adjacent to and underneath the concrete surface to be protected, 2) a perforated pipe drain system in free-draining gravel adjacent to and covering the concrete surface to be protected, or 3) a perforated pipe drain system in free draining gravel which serves as 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 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 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 pressure against a flap gate with a corrosion resistant hinge are recommended.

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 elevation of the scraper due to buoyancy and/or 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 wall (such as in a digester tank) 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.

(e) Freeboard can be provided to minimize hydrodynamic (slosh) effects on a flat roof from earthquakes.

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 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 generally 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 is recommended for fluid and gas pressure, except the load factor for gas pressure may be reduced to 1.25 for the design of domes with pressure relief valves.

$$U = 1.5 F \quad (2-1)$$

(c) A load factor of 1.4 should be applied to the final prestress forces (after long term losses) for determination of the required circumferential compressive strength of the core wall. For example, when prestress is combined with external soil pressure:

$$U = 1.4 P_e + 1.7 H \quad (2-2)$$

(d) Boundary condition restraints in place at the time of application of the prestressing force, or non-linear distributions of prestressing forces, result in bending moments in the wall or other components of a structure. A load factor of 1.2 should be applied to bending moments produced by the initial prestress force (before long term losses) for cases where the prestress, in combination with other factored loads produce the maximum flexural strength requirements. For example, for bending moments or other effects from initial prestress and external loads that are additive:

$$U = 1.2 P_i + 1.7 H \quad (2-3)$$

(e) A load factor of 0.9 should be applied to bending moments produced by the final effective prestress force (after long term losses) for cases where the prestress force reduces the flexural strength required to resist other factored loads. For example, for bending moments or other effects from internal fluid pressure that are reduced by bending effects from final prestress:

$$U = 0.9 P_e + 1.5 F \quad (2-4)$$

2.1.3.3-Design Strength

(a) When considering axial load, moment, shear, and torsion, the design strength of a member or cross-section is the nominal strength calculated in accordance with the provisions of ACI 318, multiplied by the applicable strength reduction factor ϕ as noted in ACI 318, except as modified in this report.

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

- (1) Tension in circumferential prestressing, $\phi = 0.85$
- (2) Circumferential compression in concrete and shotcrete, $\phi = 0.75$

2.1.4-Serviceability Recommendations

2.1.4.1-Watertightness Control

(a) Liquid containment structures should be designed to preclude visible flow or leakage on wall surfaces, as well as leakage at floor-wall connections and through floors and floor joints that results in flow in underdrains.

(b) Watertightness acceptance criteria for tanks are given in Chapter 5.

2.1.4.2-Corrosion Protection of Prestressed Reinforcement

(a) Internal prestressed reinforcement is protected by the combination of concrete cover in accordance with Chapter 7 of ACI 318 and Section 2.1.4.3 of this report and ducts or sheathing filled with corrosion inhibiting materials.

(b) Bonded post-tensioned tendon reinforcement is normally protected by portland cement grout, in accordance with Chapter 18 of ACI 318.

(c) Unbonded single strand tendons are normally protected by continuous plastic sheathing, having a minimum thickness of 0.040 in., which is completely filled with corrosion-inhibiting grease. Cement grout and epoxy grout have been used to protect unbonded bar tendons in smooth plastic ducts. The tendon protection system should be designed to provide complete encapsulation of the prestressing steel, in addition to the normally required concrete cover over the tendon. See Ref. 23, Guide Specifications for Unbonded Single Strand Tendons, for guidance on tendons in "corrosive environments".

(d) Strands having a thermally bonded cross-linked polymer coating for corrosion protection (epoxy coated strands) are available for use in bonded, unbonded, and external tendon applications. Although they have not been used in tanks, they have been used in other applications with similar exposures, Ref. 5.

(e) External tendons are normally protected by shotcrete cover. The external tendons should be protected by at least 1 in. of shotcrete cover. Anchorages and couplers should be completely encapsulated in grout and shotcrete. Anchorages and couplers should be protected by not less than 1-1/2 in. of shotcrete cover. Additional shotcrete cover, reinforced with welded wire fabric may be advisable for bar tendons.

(f) External tendons not protected by a shotcrete covercoat are not normally recommended. They have occasionally been used, however, for such things as repair of concrete tanks. When used, exposed external tendons should be protected by galvanizing or epoxy coatings along with zinc rich paint on the exposed anchorage after tensioning. Exposed external tendons should be inspected at frequent intervals and maintained. Appropriate safety measures such as adequate site fencing to prevent vandalism or devices to contain any tendons which may break should be taken when external tendons are not protected by shotcrete cover.

2.1.4.3 Corrosion Protection of Nonprestressed Reinforcement - Nonprestressed reinforcement should be protected by the concrete cover given in Chapter 7 of ACI 318, except as modified in this Section and in Sections 2.2.1.1 and 2.2.1.2 of this report.

(a) 1 in. of concrete protection is sufficient in two-way post-tensioned walls, roofs and floors exposed to earth, weather, water, or non-aggressive dry materials. 1-1/2 in. is recommended for exposure to wastewater.

(b) 1-1/2 in. of concrete protection is recommended for one-way (circumferentially only) post-tensioned walls exposed to earth, weather, water, and wastewater. 1 in. is sufficient for non-aggressive dry materials.

2.1.4.4 Boundary Conditions-The effects of radial translation and rotation at the tops and bottoms of walls should be considered. This includes the effects caused by prestressing as well as other loads, and volume changes produced by thermal and moisture changes.

2.1.4.5 Other Serviceability Recommendations in Liquid Containment Structures-Allowable stresses, provisions for determining prestress losses, bi-directional prestress or reinforcement recommendations that help to preclude leakage, and various other design recommendations intended to assure serviceability of water tanks and other liquid containment structures, are given in Sections 2.2, 2.3, and 2.4.

2.2-FLOOR AND FOOTING DESIGN

2.2.1 Membrane Floors-Membrane floors transmit loads directly to the subbase. Settlements should be anticipated and provisions made for their effects. Local hard and soft spots beneath the floor, if not avoidable, should be carefully considered in the floor design. Special considerations should be given to floors in tanks founded on more than one type of subbase, such as part cut and part fill.

2.2.1.1 Prestressed membrane floors should not be less than 5 in. thick. A final average prestress of 200 psi is effective in preventing cracking, when combined with conventional reinforcement of 0.0015 times the area of the concrete in each orthogonal direction. The prestressed and conventional reinforcement should be alternated within the same planes located within the middle one-quarter of the slab thickness. The tendons should be tensioned as soon as the concrete compressive strength is adequate to resist the anchorage forces. Stressing of the tendons in more than one stage is recommended. Unbonded tendons are typically used for floor prestressing. The maximum recommended spacing of prestressed reinforcement is 24 in.

2.2.1.2 The minimum thickness of a conventionally reinforced slab-on-grade should be 4 in. The ratio of reinforcement area to concrete area should not be less than 0.005 in each orthogonal direction for crack control. See Section 2.2.5.4 for recommendations at thickened areas. The

spacing of reinforcement should not exceed 12 in. for bars and 4 in. for welded wire fabric. The reinforcement should be located in the upper portion of the slab thickness, with a minimum cover of 1 in. from the top of the slab and 2 in. from the bottom of the slab (top of the subgrade). Adjacent sheets or rolls of fabric should be overlapped in accordance with ACI 318, but not less than 6 in.

2.2.1.3 Additional reinforcement at floor edges and other discontinuities should be provided as required by the 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 radial shear forces and bending moments induced by restraint of radial translations and rotations at the wall base.

2.2.1.4 Slabs having a thickness of 8 in. or more should have a minimum reinforcement ratio of 0.006 distributed into two mats. One mat should be located in the upper 2-1/2 in. of the slab thickness, with a minimum cover of 1 in. from the top of the slab. This mat should provide a minimum ratio of reinforcement area to total concrete area of 0.004 in each orthogonal direction. The second mat should be located in the lower 3-1/2 in. of the slab with a minimum cover of 2 in. from the top of the subgrade. This mat should provide a minimum ratio of reinforcement area to total concrete area of 0.002 in each orthogonal direction. Slabs with a thickness greater than 24 in. need not have reinforcement greater than that required for a 24 in. thick slab.

2.2.1.5 Floors subject to hydrostatic uplift pressures that exceed 0.67 times the weight of the floor system should be provided with underfloor drainage or hydrostatic pressure-relief valves to control uplift pressures, or be designed to resist the uplift pressures. Pressure-relief valves should not be used when potable water, petroleum products, and dry materials will be stored in the tanks because of possible contamination of the contents.

2.2.2 Structural Floors-Conventionally reinforced structural floors should be designed using the lower steel stresses or additional load factors of ACI 350R. Structural floors are used when piles or piers are needed to support tank contents because of inadequate soil bearing capacity, expansive subgrade, hydrostatic uplift or a potential for sinkholes exists.

2.2.3 Mass Concrete-Concrete floors used to counteract hydrostatic uplift pressures may be mass concrete as defined in ACI 116R and ACI 207.1R. Minimum reinforcement recommendations are given in Section 2.2.1.4 of this report. The effect of restraint, volume change and reinforcement on cracking of massive concrete is the subject of ACI 207.2R.

2.2.4 Floor Concrete Strength-Minimum concrete strengths are recommended in Section 3.1.4.

2.2.5-Floor Joints

2.2.5.1 Membrane floors for liquid containment structures should be designed for casting the entire floor without cold joints or construction joints. If this is not practical the floor should be designed to minimize construction joints. The construction procedures given in Section 4.1.2 have been effective in minimizing shrinkage cracks and thus producing liquid-tight floors.

2.2.5.2 Waterstops should be provided in all joints of floors not having prestressed reinforcement. Separate alignment footings should be provided below the joints or the slab can be thickened at such joints to make room for the waterstop.

2.2.5.3 Waterstops or sealants are used by most designers at construction joints in prestressed floors.

2.2.5.4 Thickened Slab-If the slab is thickened at construction joints or the circumferential edge, any loss of effective prestress in the slab due to the keying effect between the slab and the subgrade should be considered in the design. If the slab is thickened at construction joints, additional reinforcement sufficient to maintain the reinforcement ratio recommended in Section 2.2.1.2 should be provided parallel to the waterstop. Also, if the slab is thickened at joints, care should be taken to avoid cracks away from the waterstop, such as at the transition to the slab thickness. Whenever the slab is thickened at the perimeter, additional circumferential prestressing or reinforcement, in accordance with Section 2.2.1.1 and 2.2.1.2, should be provided at the thickened slab edge.