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An ACI Standard

Building Code for Concrete Thin Shells—Code Requirements and Commentary

Reported by ACI Committee 318

ACI CODE-318.2-25

American Concrete Institute
Always advancing

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Reported by ACI Committee 318

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PREFACE

This document governs the design of thin shell concrete structures. Where required for design of thin shell concrete structures, provisions of ACI CODE-318 are to be used to complement the provisions of this Code.

KEYWORDS

folded plates; inelastic analysis; ribbed shells; thin shells

NOTES FROM THE PUBLISHER

ACI CODE-318.2-25, Building Code Requirements for Concrete Thin Shells and Commentary, is presented in a side-by-side column format. These are two separate but coordinated documents, with Code text placed in the left column and the corresponding Commentary text aligned in the right column. Commentary section numbers are preceded by an "R" to further distinguish them from Code section numbers.

The two documents are bound together solely for the user's convenience. Each document carries a separate enforceable and distinct copyright.

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CODE

CHAPTER 1—SCOPE

1.1—Scope

This Code provides minimum requirements for the design, analysis, and construction of concrete thin shells.

1.2

Provisions of this Code shall govern for nonprestressed and prestressed concrete thin shell structures, including ribs and edge members.

1.3

All provisions of ACI CODE-318-25 not specifically excluded and not in conflict with provisions of this Code shall apply to thin shell structures.

CHAPTER 2—GENERAL

2.1—Terminology

analysis, elastic—An analysis of deformations and internal forces based on equilibrium, compatibility of strains, and assumed elastic behavior, and representing, to a suitable approximation, the three-dimensional action of the shell together with its auxiliary members.

analysis, experimental—An analysis procedure based on the measurement of deformations, strains, or both, of the structure or its model.

analysis, inelastic—An analysis of deformations and internal forces based on equilibrium, nonlinear stress-strain relations for concrete and reinforcement, consideration of cracking and time-dependent effects, and compatibility of strains. The analysis shall represent, to a suitable approxi-

COMMENTARY

R1—GENERAL

R1.1—Scope

Because this Code applies to concrete thin shells of all shapes, extensive discussion of their design, analysis, and construction in the Commentary is not possible. Additional information can be obtained in Tedesko (1953) and Billington (1982).

R1.2

Discussion of the application of thin shells in structures such as cooling towers and circular prestressed concrete tanks may be found in ACI PRC-334.1, ACI PRC-334.2, ACI PRC-372, and the IASS Working Group No. 5 report (1979).

R1.3

This Code is dependent on ACI CODE-318-25. Common terms, notation, definitions, and references used in this Code are in ACI CODE-318-25. Terms, notation, and definitions unique to this Code are defined herein.

R2—GENERAL

R2.1—Terminology

Elastic analysis of thin shells can be performed using any method of structural analysis based on assumptions that provide suitable approximations to the three-dimensional behavior of the structure. The method should determine the internal forces and displacements needed in the design of the shell proper, the rib or edge members, and the supporting structure. Equilibrium of internal forces and external loads and compatibility of deformations should be satisfied.

Methods of elastic analysis based on classical shell theory, simplified mathematical or analytical models, or numerical solutions using finite element (ACI SP-110), finite differences (ACI SP-28), or numerical integration techniques (ACI SP-28; Billington 1990) are described in the cited references.

The choice of the method of analysis and the degree of accuracy required depends on certain critical factors. These include: the size of the structure, the geometry of the thin shell, the manner in which the structure is supported, the nature of the applied load, and the extent of personal or documented experience regarding the reliability of the given method of analysis in predicting the behavior of the specific type of shell (ACI SP-28).

Depending on the magnitude of the loads, the experimental results may correspond to either elastic response or inelastic behavior of the shell.

Inelastic analysis of thin shells can be performed using a refined method of analysis based on the specific nonlinear material properties; nonlinear behavior due to the cracking of concrete; and time-dependent effects such as creep, shrinkage, temperature, and load history. These effects are mation, the structural response of the shell together with its auxiliary members.

incorporated to trace the response and crack propagation of a reinforced concrete shell through the elastic, inelastic, and ultimate ranges. Such analyses usually require incremental loading and iterative procedures to converge on solutions that satisfy both equilibrium and strain compatibility (Scordelis 1990; Schnobrich 1991).

folded plates—A class of shell structure formed by joining flat, thin slabs along their edges to create a three-dimensional spatial structure.

Folded plates may be prismatic (Billington 1982; ASCE Task Committee 1963), nonprismatic (ASCE Task Committee 1963), or faceted. The first two types consist generally of planar thin slabs joined along their longitudinal edges to form a beam-like structure spanning between supports. Faceted folded plates are made up of triangular or polygonal planar thin slabs joined along their edges to form three-dimensional spatial structures.

members, auxiliary—Ribs or edge beams that serve to strengthen, stiffen, or support the shell. Typically, auxiliary members act jointly with the shell.

Most thin shell structures require ribs or edge beams at their boundaries to resist the shell boundary forces, to assist in transmitting boundary forces to the supporting structure, and to accommodate the increased amount of reinforcement in these areas.

shells, ribbed—Spatial structures with material placed primarily along certain preferred rib lines, with the area between the ribs filled with thin slabs or left open.

Ribbed shells (ACI SP-28; Esquillan 1960) generally have been used for larger spans if the increased thickness of the curved slab alone becomes excessive or uneconomical. Ribbed shells are also used because of the construction techniques used and to enhance the aesthetic impact of the completed structure.

shells, thin—Three-dimensional spatial structures made up of one or more curved slabs or folded plates whose thicknesses are small compared to their other dimensions.

Thin shells are characterized by their three-dimensional load-resisting behavior, which is determined by the geometry of their forms, by the manner in which they are supported, and by the nature of the applied load.

Common types of thin shells are domes (surfaces of revolution) (Billington 1982; ASCE Task Committee 1963), cylindrical shells (ASCE Task Committee 1963), barrel vaults (ACI SP-28), conoids (ACI SP-28), elliptical paraboloids (ACI SP-28), hyperbolic paraboloids (Esquillan 1960), and groined vaults (Esquillan 1960).

2.2—Materials

2.2.1 Design properties for concrete shall be selected to be in accordance with 2.2.1.1 and Chapter 19 of ACI CODE-318-25.

2.2.1.1 Specified compressive strength of concrete at 28 days shall be at least 3000 psi.

2.2.2 Design properties for steel reinforcement shall be selected to be in accordance with 2.2.2.1 and Chapter 20 of ACI CODE-318-25.

2.2.2.1 Maximum value of fy permitted for design calculations shall not exceed 60,000 psi, except for reinforcement

R2.2—Materials

R2.2.2 Determination of the appropriate reinforcement design stress is often independent of the yield stress. Changes in geometry due to nonlinear deflections caused by cracking and creep may change load paths and reduce buckling capacity. Visible cracking may also be unacceptable. In such cases, a design stress less than f_y should be considered.

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resisting hoop tension in shells that are part of bins and silos, where the maximum value is permitted to be 80,000 psi.

2.2.3 Materials, design, and detailing requirements for embedments in concrete shall be in accordance with 20.6 of ACI CODE-318-25.

2.3—Connection to other members

2.3.1 For cast-in-place construction, rib-column, edge-column, and shell-column joints shall satisfy Chapter 15 of ACI CODE-318-25.

2.3.2 For precast construction, connections shall satisfy the force transfer requirements of 16.2 of ACI CODE-318-25.

2.4—Stability

2.4.1 Shell instability shall be investigated and shown by design to be precluded.

2.4.2 In prestressed shells, buckling of the shell, ribs, and edge members shall be considered. If there is intermittent contact between prestressed reinforcement and an oversize duct, member buckling between contact points shall be considered.

COMMENTARY

R2.4—Stability

R2.4.1 Thin shells, like other structures that experience in-plane membrane compressive forces, are subject to buckling when the applied load reaches a critical value. The surface geometry of shells makes calculating buckling loads complex. If one of the principal membrane forces is tensile, the shell is less likely to buckle than if both principal membrane forces are compressive. The membrane forces that develop in a shell depend on its initial shape and the manner in which the shell is supported and loaded. In some types of shells, post-buckling behavior should be considered in determining safety against instability (IASS Working Group No. 5 1979).

Investigation of thin shells for stability should consider the effect of: 1) anticipated deviation of the geometry of the shell surface as-built from the idealized geometry; 2) local variations in curvature; 3) large deflections; 4) creep and shrinkage of concrete; 5) inelastic properties of materials; 6) cracking of concrete; 7) location, amount, and orientation of reinforcement; and 8) possible deformation of supporting elements.

Measures successfully used to improve resistance to buckling include providing two mats of reinforcement, one near each outer surface of the shell; a local increase of shell curvatures; the use of ribbed shells, and the use of concrete with high tensile strength and low creep.

A procedure for determining critical buckling loads of shells is given in the IASS recommendations (IASS Working Group No. 5 1979). Some recommendations for buckling design of domes used in industrial applications are given in ACI PRC-372 and ACI SP-67.

R2.4.2 In post-tensioned members, if the prestressed reinforcement has intermittent contact with an oversize duct, the member can buckle between contact points due to the axial prestressing force as the member can deflect laterally while the prestressed reinforcement does not. If the prestressed reinforcement is in continuous contact with the member being prestressed or is part of an unbonded tendon with the sheathing not excessively larger than the prestressed reinforcement, the prestressing force will likely not buckle the member.

2.4.3 The influence on shell instability due to increased stresses resulting from concentrated loads shall be considered.

R2.4.3 Concentrated loads normal to the shell may cause local deformations which can initiate buckling. Such loading conditions should be included in the shell analysis and final detailing.

CHAPTER 3—DESIGN LIMITS

3.1—Minimum thickness

3.1.1 The thickness of a shell and the amount of reinforcement shall be proportioned to satisfy strength and serviceability requirements of ACI CODE-318-25.

3.2

In a region where membrane cracking is predicted, the nominal compressive strength parallel to the cracks shall be taken as $0.4f_c'$.

3.3—Stress limits in prestressed shells

3.3.1 Prestressed shells shall be classified as Class U or T in accordance with 24.5.2 of ACI CODE-318-25.

3.3.2 Prestressed shells classified as Class C in accordance with 24.5.2 of ACI CODE-318-25 shall not be permitted.

3.3.3 Stresses in prestressed shells immediately after transfer and at service loads shall not exceed permissible stresses in 24.5.3 and 24.5.4 of ACI CODE-318-25.

3.3.4 The prestress force shall provide a minimum average compressive stress in the shell of 125 psi.

R3—DESIGN LIMITS

R3.1—Minimum thickness

R3.1.1 Thin shell sections and reinforcement are required to be proportioned to satisfy the strength and serviceability provisions of Chapters 22 and 24 of ACI CODE-318-25 and to resist internal forces obtained from a numerical or experimental analysis, or a combination thereof. Reinforcement sufficient to minimize cracking under service load conditions should be provided. The thickness of the shell is often controlled by the required reinforcement and the construction constraints (Gupta 1986), shell stability, or by the minimum cover requirements.

R3.2

If a principal tensile stress produces membrane cracking in the shell, experiments indicate the attainable compressive strength in the direction parallel to the cracks is reduced (Gupta 1984; Vecchio and Collins 1986).

R3.3—Stress limits in prestressed shells

R3.3.4 The 125 psi minimum average prestress is consistent with the ACI CODE-318-25 Section 8.2.3 requirement for two way slabs, applies in the direction of the prestress, and is industry practice.

CHAPTER 4—REQUIRED STRENGTH

4.1—General

4.1.1 Required strength shall be calculated in accordance with the factored loads and load combinations in Chapter 5 of ACI CODE-318-25.

4.1.2 Required strength shall be calculated in accordance with the analysis procedures defined in 4.1.2.1 through 4.1.2.8 and specified in Chapter 6 of ACI CODE-318-25.

4.1.2.1 Equilibrium checks of internal resistances and external loads shall be made to ensure consistency of results.

R4—REQUIRED STRENGTH

R4.1—General

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4.1.2.2 Elastic behavior shall be an accepted basis for determining internal forces and displacements of thin shells. This behavior shall be permitted for calculations based on an analysis of the uncracked concrete structure in which the material is assumed to be linear elastic, homogeneous, and isotropic. Poisson's ratio of concrete shall be permitted to be taken equal to zero.

4.1.2.3 Inelastic analyses shall be permitted to be used if it can be shown that such methods provide a safe basis for design.

4.2.1.4 Experimental or numerical analysis procedures shall be permitted if it can be shown that such procedures provide a safe basis for design.

4.1.2.5 Approximate methods of analysis shall be permitted if it can be shown that such methods provide a safe basis for design.

4.1.2.6 In prestressed shells, the analysis shall consider behavior at the following stages: transfer of prestress, cracking loads, service loads, and factored loads.

4.1.2.7 If tendons are draped within a shell, design shall take into account force components on the shell resulting from the tendon profile not lying in one plane.

4.1.2.8 For prestressed shells, effects of reactions induced by prestressing shall be considered.

COMMENTARY

R4.1.2.2 For types of shell structures where experience, tests, and analyses have shown that the structure can sustain reasonable overloads without undergoing brittle failure, elastic analysis is an acceptable procedure. In such cases, it may be assumed that reinforced concrete is ideally elastic, homogeneous, and isotropic. An analysis should be performed for the shell considering service load conditions. The analysis of shells of unusual size, shape, or complexity should consider behavior through the elastic, cracking, and inelastic stages.

R4.2.1.4 Experimental analysis of elastic models (Sabnis et al. 1983) has been used as a substitute for an analytical solution of a complex shell structure. Experimental analyses of reinforced microconcrete models through the elastic, cracking, inelastic, and ultimate stages should be considered for important shells of unusual size, shape, or complexity.

For model analysis, only those portions of the structure that significantly affect the items under study need be simulated. Every attempt should be made to ensure that the experiments reveal the quantitative behavior of the prototype structure.

Wind tunnel tests of a scaled-down model do not necessarily provide usable results; thus, such tests should be conducted by a recognized expert in wind tunnel testing of structural models.

R4.1.2.5 Solutions that include both membrane and bending effects, and satisfy conditions of compatibility and equilibrium are recommended. Approximate solutions that satisfy statics but not the compatibility of strains may be used only when extensive experience has proved that safe designs have resulted from their use. Such methods include beam-type analysis for barrel shells and folded plates having large ratios of span to either width or radius of curvature, simple membrane analysis for shells of revolution, and others in which the equations of equilibrium are satisfied while the strain compatibility equations are not.

R4.1.2.7 Axial forces due to draped tendons may not lie in one plane, and due consideration should be given to the resulting force components.

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4.2—Factored moment

4.2.1 For shells built integrally with supports, M_u at the support shall be permitted to be calculated at the face of support.

4.3—Factored shear

4.3.1 For shells built integrally with supports, V_u at the support shall be permitted to be calculated at the face of support.

CHAPTER 5—DESIGN STRENGTH

5.1—General

5.1.1 For each applicable factored load combination, design strength at all sections shall satisfy $\phi S_n \geq U$ including (a) through (c). Interaction between load effects shall be considered.

(a) $\phi M_n \geq M_u$ at all sections in each direction of the shell
(b) $\phi V_n \geq V_u$ at all sections in each direction of the shell
(c) $\phi P_n \geq P_u$ at all sections in each direction of the shell

5.1.2 Edge-beams shall be designed in accordance with Chapter 9 of ACI CODE-318-25.

5.1.3 Columns shall be designed in accordance with Chapter 10 of ACI CODE-318-25.

5.1.4 Auxiliary members shall be designed according to the applicable provisions of ACI CODE-318-25. It shall be permitted to assume that a portion of the shell equal to the flange width, as specified in 6.3.2 of ACI CODE-318-25, acts with the auxiliary member. In such portions of the shell, the reinforcement perpendicular to the auxiliary member shall be at least equal to that required for the flange of a T-beam by 7.5.2.3 of ACI CODE-318-25.

5.1.5 The value for ϕ shall be in accordance with Chapter 21 of ACI CODE-318-25.

5.1.6 The value of ϕ for membrane tension shall be 0.90.

5.2—Membrane forces, moment, and shear

5.2.1 Strength design of shell slabs for membrane forces, moments, and shear shall be based on the distribution of stresses and strains as determined from either elastic or inelastic analysis.

5.2.2 Reinforcement for membrane forces, moments, and shear about axes in the plane of the shell slab shall be calculated considering the design strength in accordance with Chapter 22 of ACI CODE-318-25.

5.2.3 The area of shell tension reinforcement shall be limited so that the reinforcement yields before either crushing of concrete in compression or shell buckling.

COMMENTARY

R5—DESIGN STRENGTH

R5.2—Membrane forces, moment, and shear

R5.2.1 The stresses and strains in the shell slab used for design are those determined by analysis. Because of detrimental effects of membrane cracking, the calculated tensile strain in the reinforcement under factored loads should be limited to control cracking.

R5.2.3 The requirement that the tensile reinforcement yields before the concrete crushes is consistent with ACI CODE-318-25. Such crushing can also occur in regions near supports

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and, for some shells, if the principal membrane stresses are approximately equal in magnitude and opposite in sign.

5.2.4 Shell reinforcement shall be provided to resist membrane forces, moments, and twisting moments; to limit shrinkage and temperature crack width and spacing; and to reinforce shell boundaries, load attachments, and shell openings.

R5.2.4 At any point in a shell, two different kinds of internal forces may occur simultaneously: those associated with membrane action and those associated with bending of the shell. Membrane forces are assumed to act in the tangential plane midway between the surfaces of the shell. Flexural effects include bending moments, twisting moments, and associated transverse shears. Limiting membrane crack width and spacing due to shrinkage, temperature, and service load conditions are a major design consideration.

5.2.5 Reinforcement shall be provided in two or more directions and shall be proportioned such that its resistance in any direction equals or exceeds the tensile component of internal forces in that direction. Alternatively, reinforcement for the membrane forces in the shell shall be sufficient to resist axial tensile forces plus the tensile force due to shear-friction required to transfer shear across any cross section of the membrane. The assumed coefficient of friction, μ, shall be in accordance with 22.9.4.2 of ACI CODE-318-25.

R5.2.5 The requirement of ensuring strength in all directions is based on safety considerations. Any method that ensures sufficient strength consistent with equilibrium is acceptable. The direction of the principal membrane tensile force at any point may vary depending on the direction, magnitude, and combination of the various applied loads.

The magnitude of membrane forces, acting at any point due to a specific load, is generally calculated on the basis of elastic theory in which the shell is assumed to be uncracked. Calculation of the required amount of reinforcement to resist membrane forces has been traditionally based on the assumption that concrete does not resist tension. The associated deflections and the possibility of cracking should be investigated in the serviceability phase of design. A working stress design for reinforcement selection may be preferred to provide the required reinforcement and serviceability.

If reinforcement is not placed in the direction of the principal tensile forces and if cracks at the service load level are objectionable, calculation of the amount of reinforcement may have to be based on a more refined approach (Gupta 1984; Fialkow 1991; Medwadowski 1989) that considers the existence of cracks. In the cracked state, the concrete is assumed to be unable to resist either tension or shear. Therefore, equilibrium is attained by equating tensile-resisting forces in reinforcement and compressive-resisting forces in concrete.

An alternative method to calculate orthogonal reinforcement is the shear-friction method. It is based on the assumption that shear integrity of a shell should be maintained at factored loads. It may not be necessary to calculate principal stresses if this alternative approach is used.

5.2.6 In regions of high tension, reinforcement shall be placed in the general directions of the principal tensile membrane forces. If this is not practical, it shall be permitted to place reinforcement in two or more component directions.

R5.2.6 Generally, for all shells, and particularly in regions of substantial tension, the orientation of reinforcement should approximate the directions of the principal tensile membrane forces. However, in some structures it is not possible to detail the reinforcement to follow the stress trajectories. For such cases, orthogonal component reinforcement is allowed.

5.2.7 If the direction of reinforcement varies more than 10 degrees from the direction of principal tensile membrane force, the amount of reinforcement shall be reviewed in relation to cracking at service loads.

R5.2.7 If the directions of reinforcement deviate significantly (more than 10 degrees) from the directions of the principal membrane stresses, higher strains in the shell are required to develop the reinforcement. This may lead to the development of unacceptable crack widths. Crack widths should be estimated and limited if necessary.

Reasonable crack widths for service loads under different environmental conditions are given in ACI PRC-224. Crack widths can be limited by an increase in the amount of reinforcement used, by reducing the stress at the service load level, by providing reinforcement in three or more directions in the plane of the shell, by using closer spacing of smaller-diameter bars, or by a combination of these actions.

5.2.8 If the magnitude of the principal tensile membrane stress within the shell varies greatly over the area of the shell surface, reinforcement resisting the total tension shall be permitted to be concentrated in the regions of largest tensile stress if it can be shown that this provides a safe basis for design.

R5.2.8 The practice of concentrating tensile reinforcement in the regions of maximum tensile stress has led to a number of successful and economical designs, primarily for long folded plates, long barrel vault shells, and domes.

5.2.9 Reinforcement required to resist bending moments shall be proportioned with due regard to the simultaneous action of membrane axial forces at the same location.

R5.2.9 The design method should ensure that the concrete sections, including consideration of the reinforcement, are capable of developing the internal forces required by the equations of equilibrium (Gupta 1986).

5.2.10 Transmission of concentrated loads using inserts shall conform to Chapter 17 of ACI CODE-318-25.

CHAPTER 6—REINFORCEMENT LIMITS

R6—REINFORCEMENT LIMITS

6.1—Minimum reinforcement in nonprestressed shells

6.1.1 The minimum area of reinforcement at any section as measured in two orthogonal directions shall be at least 0.0018 times the gross area of the section.

6.1.2 The minimum area of reinforcement in the tension zone shall be at least 0.0035 times the gross area of the section.

R6.1—Minimum reinforcement in nonprestressed shells

R6.1.1 Minimum membrane reinforcement corresponding to slab shrinkage and temperature reinforcement should be provided in at least two approximately orthogonal directions even if the calculated membrane forces are compressive in one or more directions.

R6.1.2 The requirement of providing minimum reinforcement in tension zones is intended to limit the width and spacing of cracks.

6.2—Minimum reinforcement in prestressed shells

6.2.1 For shells with bonded or unbonded tendons, the minimum area of bonded deformed reinforcement $A_{s,min}$ shall be in accordance with Table 6.2.1.

Table 6.2.1—Minimum bonded deformed longitudinal reinforcement $A_{s,min}$ in shells slabs with bonded or unbonded tendons

Calculated effective prestress in area tributary to tendon	$A_{s,min}$, in.^{2}	
≥ 125 psi	None required	(a)
< 125 psi	$0.0018A_g$	(b)

R6.2—Minimum reinforcement in prestressed shells

R6.2.1 The geometry of shell structures may result in variation in effective prestress. Table 6.2.1 recognizes that areas of a shell may not have the minimum level of prestress and in such areas minimum bonded reinforcement is required.

CHAPTER 7—REINFORCEMENT DETAILING

7.1—General

7.1.1 Concrete cover shall be in accordance with 7.2.

7.1.2 Development lengths and splices shall be in accordance with 7.3.

7.1.3 Bundled bars shall be in accordance with 25.6 of ACI CODE-318-25.

7.1.4 Reinforcement spacing shall be in accordance with 7.4.

7.1.5 Reinforcement placement shall be in accordance with 7.5.

7.2—Specified concrete cover

7.2.1 Unless the general building code requires a greater concrete cover for fire protection, the minimum specified concrete cover shall be in accordance with 7.2.2 through 7.2.5.

7.2.2 Cast-in-place nonprestressed concrete shells shall have specified concrete cover for reinforcement at least that given in Table 7.2.2.

Table 7.2.2—Specified concrete cover for cast-in-place nonprestressed concrete shells

Concrete exposure	Reinforcement	Specified cover, in.
Exposed to weather or in contact with ground	No. 6 bar and larger	2
	No. 5 bar, W31 or D31 wire, and smaller	1-1/2
Not exposed to weather or in contact with ground	No. 6 bar and larger	3/4
	No. 5 bar, W31 or D31 wire, and smaller	1/2

7.2.3 Cast-in-place prestressed concrete shells shall have specified concrete cover for reinforcement, ducts, and end fittings at least that given in Table 7.2.3.

R7—REINFORCEMENT DETAILING

R7.2—Specified concrete cover

R7.2.1 In 7.2.2 through 7.2.4, the condition "exposed to earth or weather or in contact with ground" refers to direct exposure to moisture changes and not just to temperature changes. Thin shell soffits are not usually considered directly exposed to weather or in contact with ground unless subject to alternate wetting and drying, including that due to condensation conditions or direct leakage from exposed top surface, run off, or similar effects.

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Table 7.2.3—Specified concrete cover for cast-in-place prestressed concrete shells

Concrete exposure	Reinforcement	Specified cover, in.
Exposed to weather or in contact with ground	Prestressing tendons and prestressing reinforcement; No. 8 bar, W31 or D31 wire, and smaller	1
	No. 9 bar and larger	d_b
Not exposed to weather or in contact with ground	Prestressing tendons and prestressing reinforcement	3/4
	No. 6 bar and larger	d_b
	No. 5 bar, W31 or D31 wire, and smaller	3/8

7.2.4 Precast nonprestressed or prestressed shells manufactured under plant conditions shall have specified concrete cover for reinforcement, ducts, and end fittings at least that given in Table 7.2.4.

Table 7.2.4—Specified concrete cover for precast nonprestressed or prestressed concrete shells manufactured under plant conditions

Concrete exposure	Reinforcement	Specified cover, in.
Exposed to weather or in contact with ground	No. 6 through No. 11 bars; tendons and prestressing reinforcement larger than 5/8 in. diameter through 1-1/2 in. diameter	1-1/2
	No. 5 bar, W31 or D31 wire, and smaller; tendons and strands 5/8 in. diameter and smaller	1-1/4
Not exposed to weather or in contact with ground	Prestressing tendons and prestressing reinforcement	3/4
	No. 6 bar and larger	5/8
	No. 5 bar, W31 or D31 wire, and smaller	3/8

7.2.5 *Specified concrete cover requirements for corrosive environments*

7.2.5.1 In corrosive environments or other severe exposure conditions, the specified concrete cover shall be in accordance with 20.5.1.4 of ACI CODE-318-25.

7.3—Development and splices in reinforcement

7.3.1 Development lengths of deformed and prestressed reinforcement shall be in accordance with 25.4 of ACI CODE-318-25.

7.3.2 Splices of deformed reinforcement shall be in accordance with 25.5 of ACI CODE-318-25 and satisfy (a) through (c).

(a) Tension lap splice lengths of shell reinforcement shall be at least the greater of $1.2\ell_{st}$ and 18 in.

(b) The number of principal tensile reinforcement splices shall be kept to a practical minimum.

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R7.3—Development and splices in reinforcement

R7.3.2 On curved shell surfaces it is difficult to control the alignment of prefabricated reinforcement. This should be considered to avoid insufficient lap splice and development lengths. Extra length is specified to achieve the lap splice and development lengths on curved surfaces. The 1.2 times the required splice length in (a) is to ensure that the splice is attained in the field.

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(c) Tension lap splices shall be staggered at least ℓ_d with not more than one-third of the reinforcement spliced at any section.

7.4—Reinforcement spacing

7.4.1 Minimum spacing ***s*** shall be in accordance with 25.2 of ACI CODE-318-25.

7.4.2 Shell reinforcement spacing in any direction shall not exceed the lesser of **5***h* and 18 in. If the principal membrane tensile stress on the gross concrete area due to factored loads exceeds $\phi 4\lambda\sqrt{f_c'}$, reinforcement spacing shall not exceed the lesser of 3*h* and 18 in.

7.4.3 Shell reinforcement at the junction of the shell and supporting members or edge members shall be embedded in or extended through such members at least $1.2\ell_d$ but not less than 18 in.

7.5—Reinforcement placement

7.5.1 Where analysis indicates that shell reinforcement is required near only one face to resist bending moments, an equal amount of reinforcement shall be placed near the opposite face of the shell. Alternatively, reinforcement shall be designed to be placed at the center of the shell thickness.

CHAPTER 8—CONSTRUCTION

8.1—Construction and inspection requirements

8.1.1 Design information that the licensed design professional shall specify in the construction documents shall be in accordance with 8.2 and ACI CODE-318-25 Chapter 26, if applicable.

8.1.2 Compliance requirements that the licensed design professional shall specify in the construction documents shall be in accordance with 8.3 and ACI CODE-318-25 Chapter 26, if applicable.

8.1.3 Inspection requirements that the licensed design professional shall specify in the construction documents shall be in accordance with ACI CODE-318-25 Chapter 26, if applicable.

8.2—Design information

(a) Tolerances for the shape of the shell

8.3—Compliance requirements

(a) If removal of formwork is based on a specific modulus of elasticity of concrete because of stability or deflection considerations, the value of the modulus of elasticity, E_c, shall be determined from flexural tests of field-cured beam specimens. The number of test specimens, the dimensions of

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R7.5—Reinforcement placement

R7.5.1 The sign of bending moments may change rapidly from point to point of a shell and around concentrated loads. For this reason, reinforcement to resist bending, if required, is to be placed near both surfaces of the shell or centered in the shell thickness. In many cases, the thickness required to provide specified concrete cover and spacing for the multiple layers of reinforcement may govern the design of the shell thickness.

R8—CONSTRUCTION

R8.3—Compliance requirements

(a) When early removal of forms is necessary, the magnitude of the modulus of elasticity at the time of proposed form removal should be investigated to ensure safety of the shell with respect to buckling and to restrict deflections (Tedesko 1953, 1980). The value of the modulus of elasticity, E_c, should

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beam test specimens, and test procedures shall be specified by the licensed design professional.

(b) If construction results in deviations from the shape greater than the specified tolerances, an analysis of the effect of the deviations shall be made and any required remedial actions shall be taken to ensure safe behavior.

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be obtained from flexural tests of field-cured specimens. It is not sufficient to determine the modulus from the formula in ACI CODE-318-25 even if the compressive strength of concrete is determined for the field-cured specimens.

(b) In some types of shells, small local deviations from the theoretical geometry of the shell can cause relatively large changes in local stresses and in overall safety against instability. These changes can result in local cracking and yielding that may make the structure unsafe or can greatly affect the critical load, producing instability. The effect of such deviations should be evaluated and any necessary remedial actions should be taken. Attention is needed when using air-supported form systems (Huber 1986).

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