An ACI Standard and Report

Building Code Requirements for Concrete Thin Shells (ACI 318.2-14)

Commentary on Building Code Requirements for Concrete Thin Shells (ACI 318.2R-14)

ACI 318.2-14

Reported by ACI Committee 318

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Building Code Requirements for Concrete Thin Shells

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Reported by ACI Committee 318

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PREFACE

This document governs the design of thin shell concrete structures, previously presented in ACI 318-11 Chapter 19. Where required for design of thin shell concrete structures, provisions of ACI 318 are to be used to complement the provisions of this Code. Transition keys showing how the code was reorganized are provided on the ACI website on the 318 Resource Page under Topics in Concrete.

KEYWORDS

folded plates; inelastic analysis; ribbed shells; thin shells

NOTES FROM THE PUBLISHER

ACI 318.2-14, Building Code Requirements for Concrete Thin Shells, and ACI 318.2R-14, Commentary, are 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—GENERAL REQUIREMENTS

1.1—Scope

This Code provides information on the design, analysis, and construction of concrete thin shells.

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

1.1.2 All provisions of ACI 318-14 not specifically excluded, and not in conflict with provisions of this Code, shall apply to thin shell structures.

CHAPER 2—TERMINOLOGY

2.1—Terminology

2.1.1 *Thin shells*—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-carrying 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.

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

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

2.1.4 *Auxiliary members*—Ribs or edge beams that serve to strengthen, stiffen, or support the shell; usually, auxiliary members act jointly with the shell.

2.1.5 *Elastic analysis*—An analysis of deformations and internal forces based on equilibrium, compatibility of strains, and assumed elastic behavior, and representing, to a

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R1—GENERAL REQUIREMENTS

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 from the references. Performance of shells and folded plates requires attention to detail (refer to Tedesko [1980]).

R1.1.1 Discussion of the application of thin shells in structures such as cooling towers and circular prestressed concrete tanks may be found in ACI 334.1R, ACI 334.2R, ACI 372R, and the IASS Working Group No. 5 report (1979).

R1.1.2 This Code is dependent on ACI 318. Common terms, symbols, definitions and references used in this Code are in ACI 318. Terms, symbols and definitions unique to this Code are defined herein.

R2—TERMINOLOGY

R2.1—Terminology

R2.1.1 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).

R2.1.2 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.

R2.1.3 Ribbed shells (ACI SP-28; Esquillan 1960) generally have been used for larger spans where the increased thickness of the curved slab alone becomes excessive or uneconomical. Ribbed shells are also used because of the construction techniques employed and to enhance the aesthetic impact of the completed structure.

R2.1.4 Most thin shell structures require ribs or edge beams at their boundaries to resist the shell boundary forces, to assist in transmitting them to the supporting structure, and to accommodate the increased amount of reinforcement in these areas.

R2.1.5 Elastic analysis of thin shells and folded plates can be performed using any method of structural analysis based on assumptions that provide suitable approxima-

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suitable approximation, the three-dimensional action of the shell together with its auxiliary members.

2.1.6 *Inelastic analysis*—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 approximation three-dimensional action of the shell together with its auxiliary members.

2.1.7 *Experimental analysis*—An analysis procedure based on the measurement of deformations or strains, or both, of the structure or its model; experimental analysis is based on either elastic or inelastic behavior.

CHAPTER 3—STRUCTURAL ANALYSIS AND DESIGN

3.1—Analysis and design

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

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

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tions 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 or folded plate, 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) or folded plate (ASCE Task Committee 1963).

R2.1.6 Inelastic analysis of thin shells and folded plates 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 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).

R3—STRUCTURAL ANALYSIS AND DESIGN

R3.1—Analysis and design

R3.1.1 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, having identical properties in all directions. 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.

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

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

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

3.1.6 In prestressed shells, the analysis shall also consider behavior under loads induced during prestressing, at cracking load, and at factored load. Where 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.

3.1.7 The thickness of a shell and its reinforcement shall be proportioned for the required strength and serviceability requirements of ACI 318.

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

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R3.1.4 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 analysis 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 and should be conducted by a recognized expert in wind tunnel testing of structural models.

R3.1.5 Solutions that include both membrane and bending effects, satisfy conditions of compatibility, and equilibrium are encouraged. 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.

R3.1.6 If the shell is prestressed, the analysis should include its strength at factored loads as well as its adequacy under service loads, under the load that causes cracking, and under loads induced during prestressing. Axial forces due to draped tendons may not lie in one plane, and due consideration should be given to the resulting force components. The effects of post-tensioning of shell-supporting members should be taken into account.

R3.1.7 Thin shell sections and reinforcement are required to be proportioned to satisfy the strength provisions of ACI 318 and to resist internal forces obtained from an analysis, an experimental model study, or a combination thereof. Reinforcement sufficient to minimize cracking under service load conditions should be provided. The thickness of the shell is often dictated by the required reinforcement and the construction constraints (Gupta 1986), shell stability, or by the ACI 318 minimum thickness requirements.

R3.1.8 Thin shells, like other structures that experience in-plane membrane compressive forces, are subject to buckling when the applied load reaches a critical value. Because of the surface-like geometry of shells, the problem of calculating buckling loads is 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 kinds of 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 the provision of 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 1979). Some recommendations for buckling design of domes used in industrial applications are given in ACI 372R and ACI SP-67.

3.1.9 Auxiliary members shall be designed according to the applicable provisions of ACI 318. It shall be permitted to assume that a portion of the shell equal to the flange width, as specified in ACI 318, 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 ACI 318.

3.1.10 Strength design of shell slabs for membrane and bending forces shall be based on the distribution of stresses and strains as determined from either elastic or an inelastic analysis.

R3.1.10 The stresses and strains in the shell slab used for design are those determined by analysis. Because of detrimental effects of membrane cracking, the computed tensile strain in the reinforcement under factored loads should be limited.

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

R3.1.11 Where 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).

CHAPTER 4—DESIGN STRENGTH

4.1—Concrete and steel reinforcement properties

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

4.1.2 Specified yield strength of nonprestressed reinforcement shall not exceed 60,000 psi.

4.2—Strength reduction factor

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

4.2.2 The value for ϕ for other conditions may be found in Chapter 21 of ACI 318.

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CHAPTER 5—CONCRETE COVER

5.1—Specified concrete cover for thin shells

Unless a greater concrete cover is required by the General Building Code for fire protection, specified concrete cover shall be in accordance with 5.1.1 through 5.1.3. For shells subjected to corrosive environments, 5.1.4 shall apply.

5.1.1 *Cast-in-place nonprestressed concrete*—Nonprestressed cast-in-place concrete shells shall have specified cover for reinforcement shall be at least that given in Table 5.1.1.

Table 5.1.1—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

5.1.2 *Cast-in-place prestressed concrete*—Cast-in-place prestressed concrete shells shall have specified cover for reinforcement, ducts, and end fittings at least that given in Table 5.1.2.

Table 5.1.2—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

5.1.3 *Precast nonprestressed or prestressed concrete manufactured under plant control conditions*—Precast nonprestressed or prestressed shells manufactured under plant conditions shall have specified cover for reinforcement, ducts, and end fittings at least that given in Table 5.1.3.

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R5—CONCRETE COVER

R5.1—Specified concrete cover for thin shells

In 5.1.1 through 5.1.3, 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 5.1.3—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

5.1.4 *Specified concrete cover requirements for corrosive environments*

5.1.4.1 In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary and specified by the licensed design professional. The applicable requirements for concrete based on exposure categories in 19.3.1.1 of ACI 318 shall be satisfied, or other protection shall be provided.

5.1.4.2 For prestressed concrete members classified as Class T or C in 24.5.2.1 of ACI 318 and exposed to corrosive environments or other severe exposure categories such as those defined in 19.3.1.1 of ACI 318, the specified concrete cover shall be at least 1.5 times the cover for prestressed reinforcement required by 5.1.2 for cast-in-place prestressed concrete members and 5.1.3 for precast concrete members.

5.1.4.3 The increased cover requirement of 5.1.4.2 need not be satisfied if the precompressed tension zone is not in tension under sustained loads.

5.1.5 *Concrete surface exposed to earth or weather*

5.1.5.1 If concrete surface is exposed to earth or weather, concrete cover provisions shall be in accordance with 20.6.1 of ACI 318.

CHAPTER 6—REINFORCEMENT REQUIREMENTS

6.1—Shell reinforcement

6.1.1 Shell reinforcement shall be provided to resist tensile stresses from internal membrane forces, to resist tension from bending and twisting moments, to limit shrinkage and temperature crack width and spacing, and as reinforcement at shell boundaries, load attachments, and shell openings.

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R6—REINFORCEMENT REQUIREMENTS

R6.1—Shell reinforcement

R6.1.1 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. The 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 the associated transverse shears. Limiting membrane crack width and spacing due to shrinkage,

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temperature, and service load conditions are a major design consideration.

6.1.2 Tensile 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 in ACI 318.

R6.1.2 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, magnitudes, and combinations of the various applied loads.

The magnitude of the internal membrane forces, acting at any point due to a specific load, is generally calculated on the basis of an elastic theory in which the shell is assumed to be uncracked. The calculation of the required amount of reinforcement to resist the internal 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 the design. Achieving this may require a working stress design for reinforcement selection.

Where reinforcement is not placed in the direction of the principal tensile forces and where cracks at the service load level are objectionable, the 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. Thus, equilibrium is attained by equating tensile-resisting forces in reinforcement and compressive-resisting forces in concrete.

The 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 is not necessary to calculate principal stresses if the alternative approach is used.

6.1.3 The minimum area of shell reinforcement at any section as measured in two orthogonal directions shall be at least 0.0018 times the gross area of the section for Grade 60 reinforcement or 0.0020 for Grade 40 reinforcement.

R6.1.3 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.

6.1.4 Reinforcement for shear and bending moments about axes in the plane of the shell slab shall be calculated in accordance with the analysis requirements of ACI 318.

6.1.5 The area of shell tension reinforcement shall be limited so that the reinforcement will yield before either crushing of concrete in compression or shell buckling can take place.

R6.1.5 The requirement that the tensile reinforcement yields before the concrete crushes anywhere is consistent with ACI 318. Such crushing can also occur in regions near supports and, for some shells, where the principal membrane forces are approximately equal and opposite in sign.

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

R6.1.6 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

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trajectories. For such cases, orthogonal component reinforcement is allowed.

6.1.7 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.

R6.1.7 When the directions of reinforcement deviate significantly (more than 10 degrees) from the directions of the principal membrane stresses, higher strains in the shell occur to develop the reinforcement. This might lead to the development of unacceptable crack widths. Crack widths should be estimated and limited if necessary.

Permissible crack widths for service loads under different environmental conditions are given in ACI 224R. 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.

6.1.8 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 where it can be shown that this provides a safe basis for design. The ratio of shell reinforcement in any portion of the tensile zone shall be at least 0.0035 based on the overall thickness of the shell.

R6.1.8 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 for domes. The requirement of providing the minimum reinforcement in the remaining tensile zones is intended to limit the width and spacing of cracks.

6.1.9 Reinforcement required to resist shell bending moments shall be proportioned with due regard to the simultaneous action of membrane axial forces at the same location. Where shell reinforcement is required in only one face to resist bending moments, equal amounts shall be placed near both surfaces of the shell even though a reversal of bending moments is not indicated by the analysis.

R6.1.9 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). The sign of bending moments may change rapidly from point to point of a shell. For this reason, reinforcement to resist bending, where required, is to be placed near both outer surfaces of the shell. 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.

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

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

R6.1.11 and R6.1.12 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. ACI 318 requires extra length to achieve the required lap splice and development lengths on curved surfaces.

6.1.12 Lap splice lengths of shell reinforcement shall be at least the greater of $1.2\ell_d$ and 18 in. The number of principal tensile reinforcement splices shall be kept to a practical minimum. Where lap splices are necessary, they shall be staggered at least ℓ_d with not more than one-third of the reinforcement spliced at any section.

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CHAPTER 7—CONSTRUCTION REQUIREMENTS

7.1—Construction

7.1.1 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, used shall be determined from flexural tests of field-cured beam specimens. The number of test specimens, the dimensions of beam test specimens, and test procedures shall be specified by the licensed design professional.

7.1.2 The licensed design professional shall specify in the construction documents the tolerances for the shape of the shell. 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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R7—CONSTRUCTION REQUIREMENTS

R7.1—Construction

R7.1.1 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 be obtained from a flexural test of field-cured specimens. It is not sufficient to determine the modulus from the formula in ACI 318 even if the compressive strength of concrete is determined for the field-cured specimen.

R7.1.2 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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