An ACI Standard

Design Specification for Concrete Silos and Stacking Tubes for Storing Granular Materials (ACI 313-16) and Commentary

Reported by ACI Committee 313
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Shahriar Shahriar, Chair

William D. Arockiasamy  Timothy A. Harvey  John E. Sadler
William H. Bokhoven  F. Thomas Johnston  Michael D. Simpson
Patrick B. Ebner  David C. Mattes  Bill J. Socha
Stephen G. Frankosky  Rodney M. Nohr  Consulting Members

This Design Specification provides material, design, and construction requirements for concrete silos, stave silos, and stacking tubes for storing granular materials, including design and construction requirements for cast-in-place or precast and conventionally reinforced or post-tensioned silos.

Silos and stacking tubes require design considerations not encountered in building structures. While this Design Specification refers to ACI 318 for several requirements, static and dynamic loading from funnel, mass, concentric, and asymmetric flow in silos; special loadings on stacking tubes; and seismic and hopper bottom design are also included.

Keywords: asymmetric flow; bins; funnel flow; granular materials; hoppers; mass flow; silos.
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**SPECIFICATION**

**COMMENTARY**

**Introduction**

This commentary presents considerations and assumptions in developing provisions of the Design Specification. Initial filling (static) pressures are exerted by the stored material at rest. Flow pressures differ from initial filling pressures, and are exerted by the stored material during flow.

Comments on specific provisions of the Design Specification are made using corresponding chapter and section numbers of the Design Specification. References cited in the commentary are listed in Chapter R10.
1.1—Scope
This Design Specification covers the design and construction of concrete silos, stave silos, and stacking tubes for storing granular materials.

For the design of these structures, initial filling and flow loading shall be considered. This Design Specification is supplemental to ACI 318-11 for design and ACI 301-10 for construction, where indicated.

1.1.1 Specific inclusions—Industrial stave silos for storage of granular materials are included in these specifications. The application to precast concrete is limited to industrial stave silos. Effect of hot stored material is included in this Design Specification.

1.1.2 Specific exclusions—Silos for storing silage are not included in this Design Specification. This Design Specification does not consider any chemical reaction between the silo reinforced concrete and the stored granular material. Three-dimensional dome structures are not included in this Design Specification.

1.1.3 Hierarchy of standards—Whenever the requirements of this Design Specification are more stringent than the requirements of ACI 318-11, the requirements of this Design Specification shall govern.

1.2—Documentation
1.2.1 Project drawings and specifications for silos shall be prepared under the direct supervision of and bear the seal of the licensed design professional.

1.2.2 Contract documents shall show all features of the work, naming the stored materials assumed in the design and stating their properties, including the size and position of all structural components, connections, and reinforcing steel; the specified concrete strength; and the specified strength or grade of reinforcement and structural steel.

R1.1—Scope
Silo failures have alerted licensed design professionals to the inadequacy of designing silos for only static pressures due to stored material at rest. Those failures motivated researchers to study the variations of pressures and flow of materials. Research has established that pressures during withdrawal can be significantly higher (Turitzin 1963; Pieper and Wenzel 1964; Reimbert and Reimbert 1980, 1987) or significantly lower than those present when the material is at rest. The excess (above static pressure) is called overpressure, and the shortfall is called underpressure. One of the causes of overpressure is the switch from active to passive conditions that occurs during material withdrawal (Jenike et al. 1972). Underpressures can occur at a flow channel, and overpressures can occur away from the flow channel at the same level (Colijn and Peschl 1981; Homes 1972; Bernache 1987). Underpressures concurrent with overpressures cause circumferential bending in the silo wall. Impact during filling can cause the total pressure to exceed the static pressure. Whereas overpressures and underpressures are generally important in deeper silos, impact loading is usually significant for shallow bins (bunkers) in which large volumes of material are dumped suddenly. Some stored granular materials have sufficient cohesion and unconfined compressive strength to form large arches or cavities during discharge. The collapse of these arches and cavities can develop significant impact loads when the material above strikes the wall or floor. This document does not provide methods for calculation of such loads.

The probability of forming arches and cavities can be reduced by using hopper and discharge equipment designs that reflect results from flowability testing of the stored material.

Overpressure, underpressure, or impact should be considered in the structural design of silos if present. Initial filling (static) pressures are exerted by the stored material at rest. Flow pressures differ from initial filling pressures, and are exerted by the stored material during flow.

R1.2—Documentation
Silos and stacking tubes are unusual structures. Many licensed design professionals are unfamiliar with computation of their design loads and with their design and detail requirements. Design computations and the preparation of project drawings and project specifications for silos, bunkers, and stacking tubes should be done under the supervision of a licensed design professional experienced in the design of such structures.

If possible, the properties of the stored materials to be used in the design should be obtained from tests of the actual materials to be stored or from records of tests of similar materials previously stored. Properties assumed in the design should be stated in the contract documents.
1.3—Regulations/Inspections

1.3.1 This Design Specification supplements legally adopted building codes in all matters pertaining to concrete silo and stacking tubes for storing granular materials.

1.3.2 Construction shall be inspected throughout the various work stages by or under the supervision of a licensed design professional or a qualified inspector.

R1.3—Regulations/Inspections

Investigations of silo damage and deterioration failures frequently reveal omitted or mislocated reinforcement, inadequate or misaligned reinforcement splices, and inadequate reinforcement cover.

The quality and performance of slipformed concrete silo structures depend on construction workmanship. The best materials and design will not be effective unless the construction is in accordance with project documents. For example, during slipform operations, the proper placement of reinforcement is a critical task. In addition, horizontal lifts, buckled jackrods, and concrete delaminations can occur if the concrete sets too rapidly, the slipform is improperly battered, or jackrods are overloaded. Similar considerations are associated with the quality and performance of jumpformed concrete silos.

Continuous field inspection of construction activity helps ensure conformance with the project requirements. The committee recommends that field inspection of construction activity be performed by or under the supervision of a licensed design professional. Field inspection of construction activity does not relieve the contractor of the responsibility to conform to project requirements.
CHAPTER R2—NOTATION AND DEFINITIONS

R2.1—Commentary notation

The following additional terms are used in the Commentary, but are not used in the Design Specification.

\[ A_s' = \text{compression steel area, in.}^2 \text{ (mm}^2) \]
\[ d = \text{effective depth of flexural member, in.} \text{ (mm)} \]
\[ d', d'' = \text{distances from face of wall to center of reinforcement nearest that face, in.} \text{ (mm)} \]
\[ EI = \text{flexural stiffness of wall, lb-in.}^2 \text{ (N-mm}^2) \]
\[ e, e', e'' = \text{eccentricities, in.} \text{ (mm)} \]
\[ F = \text{radial force on the wall that results from the stressing (jacking) of the tendon, lb (N)} \]
\[ K_t = \text{thermal resistance of wall, °F/in.} \text{ (°C/mm)} \]
\[ M_{max} = \text{maximum vertical bending moment per unit width of wall} \]
\[ M_s = \text{required flexural strength per unit height of wall, ft-lb (m-N)} \]
\[ M_i = \text{vertical bending moment per unit width caused by force } F \text{ on the wall, ft-lb (m-N)} \]
\[ T_i = \text{temperature inside mass of stored material,} °\text{F (°C)} \]
\[ T_o = \text{exterior dry-bulb temperature, °F (°C)} \]
\[ V_{hy} = \text{shear per unit width caused by a force } F \text{ on the wall, lb (N)} \]
\[ V_{max} = \text{maximum shear force per unit width of wall, lb (N)} \]
\[ y = \text{distance above and below tendon location, in.} \text{ (mm)} \]
\[ \beta_p = \text{factor relating to Poisson’s ratio, silo diameter, and wall thickness} \]
\[ \theta_1, \theta_p = \text{angle of conical or plane flow hopper with vertical, deg} \]
\[ \theta_f = \text{angle of flow channel with vertical, deg} \]
\[ \theta_t = \text{angle of flow channel axis with vertical, deg} \]
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\( h_h = \) height of hopper from apex to top of hopper, ft (m)
\( h_i = \) height of sloping top surface (repose volume) of stored material, ft (m)
\( h_{st} = \) height of stave specimen for compression test, in. (mm)
\( h_y = \) depth below top of hopper to point in question, ft (m)
\( h_l = \) core wall thickness, in. (mm).
\( k = \) ratio of \( p \) to \( q \)
\( L_w = \) length of design flow channel perimeter in contact with wall, ft (m)
\( l_{stg} = \) amount of vertical stagger between horizontal stave joints, ft (m)
\( M_{neg} = \) negative (tension outside face) circumferential bending moments caused by asymmetric filling or emptying under service load conditions, ft-lb (m-N) per unit height
\( M_{pos} = \) positive (tension inside face) circumferential bending moment caused by asymmetric filling or emptying under service load conditions, ft-lb (m-N) per unit height
\( M_t = \) thermal bending moment per unit width of height of wall (consistent units), ft-lb/ft (m-N/m)
\( M_0 = \) circumferential bending strength for an assembled circular group of silo staves, ft-lb (m-N) per unit height; the statical moment or sum of absolute values of \( M_{0,pos} \) and \( M_{0,neg} \)
\( M_{0,neg} = \) calculated bending strength in the negative moment zone (tension on the outside face), ft-lb (m-N) per unit height
\( M_{0,pos} = \) calculated bending strength in the positive moment zone (tension on the inside face), ft-lb (m-N) per unit height
\( n = \) constant used to compute \( q_y \)
\( P_f = \) perimeter of flow channel, ft (m)
\( P_{nw} = \) nominal axial load strength of cast in place silo walls per unit area, psi (MPa), or hollow stave silo walls per unit perimeter, lb/ft (N/m)
\( P_{nw,buckling} = \) nominal axial load strength of the stave wall per unit perimeter as limited by buckling, lb/ft (N/m)
\( P_{nw,joint} = \) nominal axial load strength of the stave wall per unit perimeter as limited by the stave joint, lb/ft (N/m)
\( P_{nw,stave} = \) nominal axial load strength of the stave wall per unit perimeter as limited by the shape of the stave, lb/ft (N/m)
\( p = \) initial (filling) horizontal pressure due to stored material, lb/ft\(^2\) (N/m\(^2\))
\( p_f = \) horizontal design pressure in a flow channel, lb/ft\(^2\) (N/m\(^2\))
\( p_n = \) pressure normal to hopper surface at a depth below top of hopper, lb/ft\(^2\) (N/m\(^2\))
\( p_s = \) horizontal pressure within static material around flow channel(s), lb/ft\(^2\) (N/m\(^2\))
\( q = \) initial (filling) vertical pressure due to stored material, lb/ft\(^2\) (N/m\(^2\))
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- $q_f$ = vertical design pressure in the nonconverging section of the flow channel, lb/ft$^2$ (N/m$^2$)
- $q_o$ = initial vertical pressure at top of hopper, lb/ft$^2$ (N/m$^2$)
- $q_s$ = vertical pressure within static material around flow channels(s), lb/ft$^2$ (N/m$^2$)
- $q_y$ = vertical pressure at a distance $h_y$ below top of hopper, lb/ft$^2$ (N/m$^2$)
- $R_H$ = ratio of area to perimeter of horizontal cross section of storage space, ft (m)
- $R_f$ = ratio of area to perimeter for a flow channel, ft (m)
- $r$ = silo inside radius, ft (m)
- $s$ = bar spacing, in. (mm)
- $V$ = total vertical frictional force on a unit length of wall perimeter above the section in question, lb (N)
- $v_n$ = initial friction force per unit area between stored material and hopper surface, lb (N)
- $W$ = wind load, or related internal moments and forces, lb/ft$^2$ (N/m$^2$)
- $W_t$ = tension force per stave from wind overturning moment, lb (N)
- $w$ = design crack width, in. (mm)
- $w_s$ = width of stave specimen for compression test, in. (mm)
- $w_{p}$ = strength level wind pressure, lb/ft$^2$ (N/m$^2$)
- $Y$ = depth from the effective depth of the repose volume to point in question, ft (m)
- $Y_f$ = diameter of flow channel, ft (m)
- $Y_{EFF}$ = vertical distance from the top of the discharge opening to the effective depth of the repose volume, ft (m)
- $y$ = depth below top surface of a flow channel, ft (m)
- $\alpha$ = angle of hopper from the horizontal
- $\alpha_c$ = thermal coefficient of expansion of concrete, in./in. per °F (mm/mm per °C)
- $\beta$ = constant used to compute $B$
- $\delta$ = effective angle of internal friction, deg
- $\gamma$ = weight per unit volume for stored material, lb/ft$^3$ (kg/m$^3$)
- $\phi$ = strength reduction factor or angle of internal friction, deg
- $\phi'$ = angle of friction between material and wall and hopper surface, deg
- $\mu'$ = coefficient of friction between stored material and wall or hopper surface
- $\mu''$ = coefficient of friction of flowing material
- $\nu$ = Poisson's ratio for concrete, assumed to be 0.2
- $\theta$ = angle of hopper from vertical, degrees
- $\theta_f$ = angle of flow channel with vertical, deg
- $\rho$ = angle of repose, deg
- $\Delta T$ = temperature difference between inside face and outside face of wall, °F (°C)
2.2—Definitions

The following terms are defined for general use in this Design Specification. Specialized definitions appear in individual chapters.

**aeration pressures**—air pressures caused by injection of air for mixing or homogenizing, or for initiating flow near discharge openings.

**asymmetric flow**—flow pattern in which the flow channel is not centrally located.

**concentric flow**—flow pattern in which the flow channel has a vertical axis of symmetry coinciding with that of the silo and discharge outlet.

**discharging**—process of emptying the material by gravity from the silo.

**effective angle of internal friction** ($\delta$)—a measure of combined friction and cohesion of material; approximately equal to the angle of internal friction for free-flowing or coarse materials, but significantly higher for cohesive materials.

**expanded flow**—flow pattern in which a mass flow hopper is used directly over the outlet to expand the flow channel diameter beyond the maximum stable rathole diameter.

**expanded flow silo**—silo equipped with a self-cleaning hopper section above a mass flow hopper section.

**filling**—the process of loading the material by gravity into the silo.

**flow channel**—channel of moving material that forms above a discharge opening.

**flow pressures**—stored material pressures during flow.

**funnel flow**—flow pattern in which the flow channel forms within the material; material surrounding the flow channel remains at rest during discharge.

**hopper**—converging portion at the bottom of a silo making the transition from a silo to one or more outlets.

**initial filling pressure**—pressures during filling and settling of material, but before discharge has started.

**jackrod**—vertical steel pipe or solid rod embedded in a silo wall, used in slipform silo construction; slipform lifting jacks are supported by and ride up the jackrods, advancing the wall forms vertically.

**jumpformed silo**—silo constructed typically using three segments of fixed forms; the bottom segment is moved to the top position after the concrete at bottom level gains adequate strength.

**mass flow**—flow pattern in which all material is in motion whenever any of it is withdrawn.

**overpressure factor**—multiplier applied to the initial filling pressure to provide for pressure increases that occur during discharge.

**plane flow hopper**—hopper with two flat sloping sides and two vertical ends.

**pressure zone**—that zone within the silo subjected either directly or indirectly to pressure from stored material.

**pyramidal hopper**—hopper with polygonal flat sloping sides.
rathole—flow channel configuration that, when formed in surrounding static material, remains stable after the contents of the flow channel have been discharged.

self-cleaning hopper—hopper that is sloped steeply enough to cause material, which has remained static during funnel flow, to slide off of it when the silo is completely discharged.

stable arch dimension—maximum dimension up to which a material arch can form and remain stable.

silo—any upright enclosed concrete structure with a bulk granular material stored against vertical walls.

slipformed silo—silo constructed using a continuously moving form.

stacking tube—relatively slender, free-standing tubular concrete structure used to lower material in a controlled fashion from a conveyor to a storage pile.

stave silo—silo assembled from small precast concrete units called staves, usually having tongue-and-groove joints, and held together by exterior adjustable steel hoops.

tilted hopper—hopper that has its axis tilted from the vertical.

transition hopper—hopper with flat and curved surfaces.

silo—the term “silo” includes both deep bins and shallow bins; the latter are sometimes called bunkers. Wherever the term “silo” is used in the Design Specification, it should be interpreted as meaning a silo, bin, or bunker of any proportion, shallow or deep.

stave silo—stave silos are used principally in agriculture for storing chopped silage, but are used for storing granular materials in other industries. The Design Specification covers industrial stave silos, but does not cover silos storing silage. The methods of computing pressures due to granular material are the same for industrial stave silos as for other silos. Design of stave silos, however, relies heavily on strength and stiffness tests; consequently, the Design Specification includes several design requirements that are peculiar to stave silos only.
CHAPTER 3—REFERENCE STANDARDS

**American Concrete Institute**
- ACI 117-10(15)—Specification for Tolerances for Concrete Construction and Materials and Commentary
- ACI 301-10—Specifications for Structural Concrete
- ACI 318-11—Building Code Requirements for Structural Concrete and Commentary
- ACI 305.1-14—Guide to Hot Weather Concreting
- ACI 306.1-90(02)—Guide to Cold Weather Concreting
- ACI 308.1-11—Standard Specification for Curing Concrete

**American Society of Civil Engineers**
- ASCE/SEI 7-10—Minimum Design Loads for Buildings and Other Structures

**ASTM International**
- ASTM A153/A153M-16—Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware
- ASTM C55-14—Standard Specification for Concrete Building Brick
- ASTM C309-11—Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
- ASTM C426-15—Standard Test Method for Linear Drying Shrinkage of Concrete Masonry Units

**Post-Tensioning Institute**
- PTI M55.1-12—Specification for Grouting of Post-Tensioned Structures
4.1—General
All materials and tests of materials shall conform to the ASTM standards specified in ACI 301. For materials that are not specifically provided for, the design strength and permissible stress shall be established by tests.

4.2—Cement and concrete
4.2.1 Cement shall conform to the requirements of ACI 301-10, 4.2.

4.2.2 The minimum specified concrete compressive strength shall be 4000 psi (28 MPa) at 28 days.

4.2.3 Concrete that will be exposed to cycles of freezing and thawing shall be air entrained. Air content shall not exceed that required by ACI 301-10, 4.2.2.4.

4.3—Aggregates
The nominal maximum dimension of aggregate for slipformed silo walls shall not exceed one-eighth of the narrowest dimension between sides of wall forms, or exceed three-fourths of the minimum clear distance between individual reinforcing bars or vertical bundles of bars.

4.4—Water
Water used in mixing concrete shall conform to the requirements of ACI 301-10, 4.2.1.3.

4.5—Admixtures
Admixtures used in concrete shall conform to the requirements of ACI 301-10, 4.2.2.5, and shall be subject to prior approval by the licensed design professional.

R4.2—Cement and concrete
R4.2.1 To minimize variations in concrete color, cement for exposed parts of silos or bunkers should be of one particular type and brand of cement.

In general, the types of cement permitted by ACI 318-11, 3.2, are permitted herein, except as noted. There is some variation in the physical properties of each type of cement. Type I cement that is very finely ground (a fineness modulus greater than 2000) can act in the same manner as Type III and cause placing difficulties by accelerating the initial set during a slipform operation.

Types IS and IP are not recommended for use in slipform or jumpform concrete because of long initial setting time and low strength at an early age.

R4.2.2 Performance and design requirements for concrete mixtures should meet the requirements of ACI 301-10. Concrete mixtures should be proportioned to produce a required average compressive strength determined in accordance with ACI 301-10.

Historically, concrete mixtures with a slump of 4 in. (100 mm) have been used successfully for construction of slipformed silo walls under a variety of field conditions. High-range water-reducing admixtures have been successfully used to increase slump without adversely affecting the water-cement ratio (w/c) or strength.

R4.2.3 Concrete is considered exposed to freezing and thawing when, in a cold climate, the concrete is in almost continuous contact with moisture before freezing. Entrained air in concrete will provide some protection against damage from freezing.

R4.5—Admixtures
The use of admixtures in concrete silo walls is a common method of controlling the initial set of concrete and, therefore, the rate at which slipforms or jumpforms may be raised.
4.6—Reinforcement

4.6.1 Hoop post-tensioning rods shall be hot-dip galvanized or otherwise protected from corrosion. Post-tensioning connectors, nuts, and lugs shall either be hot-dip galvanized or made from corrosion-resistant castings or corrosion-resistant steel. Galvanizing shall conform to ASTM A123/A123M or ASTM A153/A153M.

4.6.2 Malleable iron castings shall conform to ASTM A47/A47M.

4.6.3 Steel reinforcement shall conform to the requirements of ACI 301.

4.7—Precast concrete staves

4.7.1 Materials for staves manufactured by the dry-pack vibratory method shall conform to ASTM C55.

4.7.2 Before a stave is used in a silo, drying shrinkage shall have caused the stave to come within 10 percent of its equilibrium weight and length as defined by ASTM C426.

4.8—Tests of materials

4.8.1 Tests of materials used in construction shall be specified by the licensed design professional.

4.8.2 Tests of materials shall be in accordance with the applicable ASTM standards. The complete record of such tests shall be available for inspection during the progress of the work, and a complete set of these documents shall be preserved by the licensed design professional for at least 2 years after completion of the construction.

4.8.3 All material tests shall be performed by an accredited testing agency.

4.8.4 The results of mechanical tests of silo staves and stave assemblies shall be used as criteria for structural design of stave silos. Application of the test results is given in Chapter 7.

During the construction operation, the amount of admixture can be adjusted in the field to suit the ambient conditions and so maintain a constant rate of rise for the forms.

Concrete that includes accelerators or retarders should be placed in uniform depths in the slipform or jumpforms to maintain a consistent time of initial set at any wall elevation.

When using admixtures, trial batches should be made and evaluated for potential problems with set and for adverse effects on the slipform operation.

Similarly, admixtures are commonly used in mortar, parge coatings, protective coatings, and grout for post-tensioning ducts. Trial batches should be made and evaluated when required to substantiate mixture designs.
5.1—General
Concrete quality control, methods of determining concrete strength, field tests, concrete proportions and consistency, mixing and placing, formwork, details of reinforcement, and structural members shall conform to ACI 301, except as specified otherwise herein.

5.2—Sampling and testing concrete
Concrete shall be evaluated and tested in accordance with ACI 301-10, 1.6.

5.3—Details and placement of reinforcement
Horizontal reinforcement shall be accurately placed and adequately supported prior to placing concrete. It shall be physically secured to vertical reinforcement or other adequate supports to prevent displacement during movement of forms or placement of concrete.

5.4—Forms
5.4.1 Calculations and drawings for the design, fabrication, and erection of a slipform or jumpform system for a silo or stacking tube wall shall bear the registration stamp of an engineer licensed to practice in the location where the silo or stacking tube wall is to be constructed.

5.5—Concrete placing and finishing
5.5.1 Construction joints in slipform silo walls shall not be permitted unless shown on the contract documents or specifically approved by the licensed design professional responsible for the wall design. Construction joints in jumpform silo walls shall be constructed as shown on the contract documents or as required by the licensed design professional responsible for the wall design. Prior to the start of silo construction, the licensed design professional and contractor shall agree on construction details to be used in case of an unplanned construction joint. In the event of an interruption in slipform wall construction, the licensed design professional shall be notified immediately.

5.5.2 Concrete shall be deposited within 5 ft (1.5 m) of its final position in a way that will prevent segregation and shall not be worked or vibrated a distance of more than 5 ft (1.5 m) from the point of initial deposit.
5.5.3 Wall surface voids shall be filled where required in accordance with ACI 301-10, 5.3.3.3, with mortar made from the same materials (cement, sand, and water) as used in the wall. For slipform construction, wall surface voids shall be filled within 2 hours after forms have been raised or removed. For jumpform construction, wall surface voids shall be filled when required by the contract documents, or as required by the licensed design professional responsible for the wall design.

5.5.4 Surface finish shall be specified in the contract documents.

5.5.5 Surface fins and protrusions in jumpform walls shall be removed where they exceed the Class D Formed Surface Irregularities provision, as defined by ACI 117-10, 4.8.3, or as required by the licensed design professional responsible for the wall design.

5.6—Concrete protection and curing

5.6.1 Cold weather concrete placement shall comply with ACI 306.1. The requirements of ACI 306.1 govern over those of ACI 301.

5.6.2 Hot weather concrete placement shall comply with ACI 305.1. The requirements of ACI 305.1 govern over those of ACI 301.

5.6.3 Curing methods shall comply with ACI 308.1.

5.6.4 For slipform construction, curing measures shall be provided before the exposed exterior wall surfaces begin to dry, but after the patching and finishing are completed. For

R5.5.4 Slipformed walls are typically finished as the bottom of the moving slipform is raised, exposing newly placed concrete. Jumpform wall surfaces are typically not exposed until several hours or days after the concrete is poured. Jumpform wall surfaces typically have an as-cast finish, as described by ACI 117.

R5.5.5 Small surface fins or protrusions are typically removed from jumpform walls only when they interfere with form placement or they constitute a hazard. The Class D irregularity provisions of ACI 117-10, 4.8.3, allow irregularities of approximately 1 in. (25 mm) size.

R5.6—Concrete protection and curing

R5.6.1 A guide to cold weather concreting is presented in ACI 306R.

R5.6.2 A guide to hot weather concreting is presented in ACI 305R.

R5.6.3 Procedures for curing of concrete are presented in ACI 308.1-11. Curing compounds, where required, are applied to walls after any surface voids are addressed. In some cases, atmospheric conditions are such that excess water from bleeding of concrete as placed in the forms is sufficient to keep the surface of the newly formed walls moist for several days, and no additional provisions for curing are needed. Where deck forms or other enclosures retain the atmosphere in a highly humid condition, no additional curing measures are needed. Construction during moderate to high relative humidity and low to moderate winds will typically not require additional curing methods. These conditions are very often true of the inside face of silo wall construction. When the aforementioned conditions cannot be met, a curing compound may be used or a water spray or mist applied to keep the wall surface continuously moist. The amount of water should be carefully regulated to avoid damage to the concrete by erosion. If a curing compound is not used, the concrete should not be allowed to have a dry surface for at least 5 days.
jumpform construction, curing shall be provided as soon as possible after forms are advanced and any incidental patching is completed. Wall surfaces shall be protected against damage from rain, running water, or freezing.

5.6.5 Curing compound shall not be used on the inside surfaces of silos, unless required by the contract documents, or unless specified by the licensed design professional. When curing of interior surfaces is required, nontoxic compounds and ventilation or other methods of ensuring worker safety shall be used.

5.6.6 Curing compound shall be a nonstaining, resin-base type conforming to ASTM C309 and shall be applied in accordance with the manufacturer’s instructions. Wax-based curing compounds shall not be permitted. If a curing compound is used on the interior surfaces of a silo to be used for storing materials for food, the compound shall be nontoxic, nonflaking, and otherwise nondeleterious.

5.7—Lining and coating

5.7.1 Lining or coating material used to protect the structure from wear and abrasion, or used to enhance flowability, shall be noncontaminating to the stored material.

5.7.2 Lining materials installed in sheet form shall be fastened to the structure with all seams sealed to prevent entrance of stored material behind the lining.

5.8—Tolerances for slipformed and jumpformed structures

5.8.1 Translation of silo centerline or spiraling of the silo wall about the vertical axis of the silo (lateral departure from the nominal centerline):
   - For heights 100 ft (30 m) or less: ±3 in. (75 mm)
   - For heights greater than 100 ft (30 m): 1/400 times the height, but not more than ±4 in. (100 mm)

5.8.2 Inside diameter or distance between walls:
   - For each 10 ft (3 m) of diameter or distance: ±1/2 in. (12 mm) but not more than ±3 in. (75 mm)

5.8.3 Cross-sectional dimensions of:
   - Walls: ±1 in. (25 mm), −3/8 in. (10 mm)

5.8.4 Deviation from the specified locations of openings, embedded plates, or anchors:
   - Vertical: ±3 in. (75 mm)
   - Horizontal: ±1 in. (25 mm)

5.8.5 Other tolerances shall be in accordance with ACI 117. Plus (+) tolerance increases the amount or dimension to which it applies, or raises a deviation from level. Minus (−) tolerance decreases the amount or dimension to which it applies, or lowers a deviation from level. Where only one signed tolerance is specified (+ or −), there is no tolerance in the opposing direction.

R5.6.5 Curing compound may be undesirable on the interior surfaces that are in contact with the stored material. As the curing compound is abraded, it contaminates the stored material. Such compound, if present, modifies the friction between the interior wall surface and the stored material.
6.1—General

6.1.1 Silos (Fig. 6.1.1) and stacking tubes shall be designed to resist all applicable forces, including:

(a) Dead loads: weight of the structure and attached items including equipment dead loads supported by the structure

(b) Live loads: granular material loads including those from flow, floor, and roof live loads; equipment loads; positive and negative air pressure; and forces from earth or from materials stored against the outside of the silo or stacking tube

(c) Wind, snow, and seismic loads

(d) Thermal forces, including those due to temperature differences between inside and outside faces of wall

(e) Forces due to differential settlement of foundations

Fig. 6.1.1—Examples of vertical cross sections of silos used to determine the height of the hopper. Other configurations are possible.
6.1.2 Structural members shall be proportioned for adequate strength and stiffness. Pressures and forces shall be calculated and combined using methods provided in Chapter 6 for silos and Chapter 9 for stacking tubes. Design of reinforced or prestressed concrete members, such as foundations, floors, and roofs not covered herein shall be in accordance with ACI 318-11.

6.1.3 The thickness of silo or stacking tube walls shall not be less than 6 in. (150 mm) for reinforced cast-in-place and precast concrete. The thickness of precast staves used in externally reinforced stave silo walls shall not be less than 2 in. (50 mm).

6.1.4 Load factors shall conform to ACI 318-11, 9.2, and this section. Strength reduction factors shall conform to ACI 318-11, 9.3.

6.1.4.1 The load factor for granular material shall be:
(a) 1.6 for load combinations with dead and live loads that do not include wind (W) or seismic (E) loads
(b) 1.2 for load combinations that include wind (W) or seismic (E) loads, where the wind (W) or seismic (E) loads are additive to the gravity loads
(c) 0.9 for load combinations that include seismic (E) loads, where the seismic (E) loads counteract gravity loads

6.2—Details and placement of reinforcement
6.2.1 In slipformed concrete structures, the reinforcement size, spacing, configuration, dimensions, and lap splice details shall be such that the placement of reinforcement is achieved without any omission and without any interference with the slipform operation.

R6.1.3 Experience has shown that slipformed walls thinner than 6 in. (150 mm) are difficult to construct. When slipforming thin walls, concrete can more easily be lifted by friction between the forms and the freshly-placed concrete, causing horizontal and vertical planes of weakness or actual separation.

R6.2—Details and placement of reinforcement
R6.2.1 Figures R6.2.1a and R6.2.1b illustrate typical reinforcing patterns at wall intersections, ring beams, and wall openings. The illustrated details are not mandatory, but are examples to aid the licensed design professional.

Fig. R6.2.1a—Reinforcement pattern at intersecting walls.
6.2.2 Provide reinforcement to resist axial forces, tension forces due to bending moments, and shear forces, taking into consideration the effect of the connection of the wall to the roof, silo bottom, and adjoining walls in silo groups.

R6.2.2 The licensed design professional should be aware that bending moments may occur in silos of any shape. Bending moments will be present in walls of silo groups, especially when some cells are full and some are empty (Safarian and Harris 1984; Stalnaker and Harris 1992). They may also occur when flow patterns change or when some cells are subjected to initial (filling) pressures whereas others are subjected to design (flow) pressures (Jenike 1977).

The walls of interstices and pocket bins will have axial forces, bending moments, and shear forces, and may cause axial forces, bending moments, and shear forces in the silo walls to which they are attached.

Wall bending moments in a circular silo are difficult to evaluate accurately, but do exist. They result from non-uniform pressures around the circumference during discharge, especially eccentric discharge. They can also result from temperature differential, structural continuity, and materials stored against the outside of the silo.

6.2.3 Provide horizontal ties to resist forces that tend to separate adjoining silos of monolithically constructed silo groups.

R6.2.3 Forces that tend to separate silos of monolithically constructed silo groups can occur when some cells are full and some empty (Safarian and Harris 1984), such as four empty cells with a full interstice. They can also result from non-uniform pressure around the circumference, thermal expansion, seismic loading, or differential foundation settlement.
6.2.4 The minimum ratio of horizontal reinforcement area to gross concrete area of the wall shall be 0.0025. Horizontal reinforcement shall not be spaced farther apart than three times the wall thickness, or farther apart than 18 in. (450 mm). Unless determined otherwise by analysis, horizontal reinforcement at the bottom of the pressure zone shall be continued at the same size and spacing for a distance below the pressure zone equal to at least four times the thickness \( h \) of the wall above.

R6.2.4 Horizontal hoop tension (or tension plus shear and bending moment) does not cease abruptly at the bottom of the pressure zone. The portion of the wall below the pressure zone has strains and displacements comparable with those of the wall at the bottom of the pressure zone. Therefore, the pattern of main horizontal reinforcement should be continued downward from the bottom of the pressure zone for a distance equal to four times the thickness \( h \) of the wall above. Because the wall below the pressure zone frequently has sizeable openings, that wall may need to be designed (usually as a deep beam) to span those openings. In this case, reinforcement areas should be adequate for deep beam action.

6.2.5 The minimum ratio of vertical reinforcement area to gross concrete area of the wall shall be 0.0020. The minimum vertical reinforcing bar size in the silo wall shall be No. 4 (No. 13). The maximum horizontal spacing of vertical bars shall be 18 in. (450 mm) for exterior walls and interior walls of monolithically cast silo groups. Jack rods left in place during slipform construction shall not be considered as vertical reinforcement.

R6.2.5 Vertical reinforcement in silo walls helps distribute lateral load irregularities vertically to successive layers of horizontal reinforcement. In addition, it resists vertical bending and tension due to the following causes:

1. Temperature changes in the walls when the wall is restrained or not free to move in the vertical direction
2. Wall restraint at roof, floor, or foundation
3. Eccentric loads, such as those from hopper edges or ancillary structures
4. Concentrated loads at the transition between the cylindrical and converging section of a flow channel
5. Temperature differentials between inside and outside wall surfaces or between silos (Safarian and Harris 1970)
6. Splitting action from bond stresses at lapped splices of hoop bars

To provide access for concrete buggies in slipform construction, vertical reinforcement may be spaced farther apart at specified access locations. Vertical reinforcement should not be omitted for this purpose; only the spacing should be affected, larger than specified at the access location, and smaller than specified on each side. Buggy pathway locations and widths should be specified on the drawings.

6.2.6 Dowels shall be provided at the bottom of columns and pilasters and also at portions of walls serving as columns. Dowels shall also be provided as needed to resist wind or seismic forces at the bottom of walls. Dowel spacing, size, and quantity shall be determined by analysis. Dowels shall be developed on both sides of the shear plane in accordance with shear-friction provisions of ACI 318-11, 11.6.4.

R6.2.7 The possibility of bond failure, with subsequent splitting, is greater where bars are closely spaced, as at lap splices (Ferguson and Krishbaswamy 1971). Staggering of lap splices increases the average bar spacing. With adjacent splices, one splice failure can trigger another. With staggered splices, this possibility is less likely.

6.2.7 In circular silo walls, lap splices of horizontal and vertical reinforcement shall be staggered. In circular silos, adjacent horizontal and vertical reinforcement lap splices shall be staggered by a distance not less than one lap length or 3 ft (0.9 m). Adjacent hoop reinforcement lap splices shall not coincide in vertical array more frequently than every third bar. In noncircular silos, lap splices need not be staggered. Reinforcement splices in circular and noncircular silos shall be checked for conformance to development and anchorage requirements of ACI 318-11 Chapter 12.
**SPECIFICATION**

6.2.8 Reinforcement at wall openings

6.2.8.1 Openings in pressure zone—Stress concentrations at openings shall be analyzed and adequate reinforcement shall be designed and provided accordingly.

6.2.8.2 Unless determined otherwise by analysis, horizontal reinforcement interrupted by an opening shall be replaced by adding a minimum of 1.2 times the area of the interrupted horizontal reinforcement, one-half above the opening and one-half below.

Unless determined otherwise by analysis, additional vertical reinforcement shall be added to the wall on each side of the opening. The added vertical reinforcement shall be calculated by assuming that a strip of wall, $4h$ in width on each side of the opening, is an unsupported column within the opening height. This column supports its own share of the vertical load plus one-half of the load acting over the wall opening within a height equal to the opening width. The minimum added vertical reinforcement area for each side shall be one-half of the reinforcement area eliminated by the opening.

6.2.8.3 Reinforcement development at openings—Unless determined otherwise by analysis, the reinforcement provided to replace the interrupted reinforcement at an opening shall extend in each direction beyond the opening. The minimum extension each way shall be the greater of (a), (b), and (c):

(a) The development length of the reinforcement per ACI 318-11 Section 12.2
(b) 24 in. (600 mm)
(c) One-half the opening dimension in a direction perpendicular to the reinforcing bars being considered

6.2.8.4 Narrow vertical walls between openings—Unless determined otherwise by analysis, wall sections $8h$ in width or less between openings shall be designed as columns.

6.2.9 The minimum center-to-center spacing of adjacent specified rows of horizontal or hoop reinforcement shall be five bar diameters. Replacement or additional hoop reinforcement placed at wall openings are allowed to be placed closer than five bar diameters, but must meet the bar spacing requirements of ACI 318.

6.2.10 The lap length of horizontal and vertical reinforcement in silo walls shall be not less than the lap length specified by ACI 318-11, 12.15, for Class B splices.

The length of circular reinforcing bars in slipformed silos shall be increased by 6 in. (150 mm) to facilitate assurance of the minimum required lap length.

In determining the lap length, horizontal bars in jump-formed structures shall be assumed as top bars.

**COMMENTARY**

R6.2.8 Reinforcement at wall openings

R6.2.8.1 Reinforcement at openings consists of vertical bars, horizontal bars, diagonal bars, and shear reinforcement. The area of added reinforcement should be determined by analysis, including deep beam action (tension, flexure, and shear) when applicable (Safarian and Harris 1974).

R6.2.8.2 The required area of horizontal reinforcement should be determined by analysis. The 20 percent minimum increase in the area of horizontal reinforcement is to limit cracking at stress concentrations next to the opening. Bar spacing and clearances frequently become critical where such extra reinforcement is added.

R6.2.8.3 Reinforcement development at openings—The distance that reinforcement should be extended to replace the strength that would otherwise be lost at the opening depends not only on development length, but also on the proportions of the opening. Horizontal extension should be longer for deep openings than for shallow openings. Similarly, vertical extension should be longer for wide openings than for narrow openings. In each case, the extension length depends on the opening dimension perpendicular to the bar direction.

R6.2.9 The five-bar diameter minimum spacing of specified horizontal bar rows ensures more concrete between bars and helps prevent possible brittle bond failures.

R6.2.10 Additional bar length is specified for hoop bars in walls of slipformed silos because bars may easily be misplaced longitudinally, leading to reduced lap at one end of the bars. Note that it is not the intent to increase the required lap length by 6 in. (150 mm). The intent is to provide increased bar length that will result in increased field placement tolerance. This provision to increase reinforcing bar length does not apply to vertical bars. For rectan-
Concrete thickness covering the reinforcement at lap splices shall be at least that specified in ACI 318-11, 12.2, for that particular splice, but not less than 1 in. (25 mm). The horizontal distance from the center of the bars to the face of wall shall be not less than two-and-a-half bar diameters.

**6.2.11** Silo walls that are 9 in. (230 mm) or more in thickness shall have two layers of horizontal and vertical reinforcement.

**6.2.12** In walls with a single layer of reinforcement, reinforcement to resist thermal bending moments shall be placed within that layer.

In walls with two layers of reinforcement, reinforcement to resist thermal bending moments shall be added to the layer nearer to the colder face.

**6.2.13** In singly-reinforced circular walls, the main hoop reinforcement shall be placed closer to the outer face.

**6.2.14** Reinforcement in silo and stacking tube walls shall not be bundled. Reinforcement that is to be field bent shall be clearly identified on the drawings and shall be bent in accordance with ACI 301-10, 3.2.2.

**6.2.15** The minimum concrete cover provided for reinforcement shall conform to ACI 318-11, 7.7, for cast-in-place concrete (nonprestressed), except as noted in 6.2.10 herein.

**6.3—Loads**

**6.3.1** Stored material pressures and loads

**6.3.1.1** Stored material pressures and loads against silo walls and hoppers shall be determined in accordance with 6.3.2 through 6.3.5. Pressures shall include initial (filling) pressures, air pressures, and pressure increases or decreases caused by withdrawal of material from concentric or eccentric outlets.

**6.3.1.2** Any method of pressure computation for determining the horizontal and vertical pressures and frictional pressures is to use Janssen’s (1885) formula (Eq. (6.3.2.1a)).

**R6.2.11** Caution should be exercised in selecting walls thinner than 9 in. (230 mm), because such walls will not generally accommodate two curtains of reinforcement. Two-face reinforcement substantially improves performance of a wall subjected to both tension and bending forces.

**R6.2.12** Both horizontal and vertical thermal tensile stress will occur on the colder side of the wall. Where thermal stress adds significantly to stress due to stored material, additional reinforcement is required by 6.3.9.

Better crack-width control on the outside face is possible when the horizontal reinforcement is near the outer face. Also, because this is frequently the colder face, reinforcement so placed is in a better position to resist thermal stress.

Care should be taken to ensure adequate concrete cover over the bars on the outside surface to prevent bond splitting failures and reinforcement corrosion.

Crack-width control and concrete cover on the inside face are also important to lessen the effects of abrasion due to flow and to reduce the possibility that corrosive elements from the stored material may damage the reinforcement.

**R6.2.13** Singly reinforced circular walls, with the reinforcement placed near the outside face, may not effectively resist bending moments that cause tension on the inside face of the wall.

**R6.2.14** Because no reinforcing bars can project beyond the face of a slipform silo wall, dowels that project into abutting walls, slabs, or silo bottoms are frequently field bent. If reinforcing bars are welded or have items welded to them, it is essential to know the carbon content of the bars to select the proper procedure and materials for the weld.

**R6.2.15** The minimum cover for reinforcing bars placed on the inside face of silo walls should be 1 in. (25 mm). Additional cover should be provided where required by 6.2.10.
design forces within the silo shall be permitted, provided such methods are either based on generally accepted principles or methods that have been verified empirically or by test.

6.3.1.3 Properties of stored materials vary. Pressures shall be calculated using combinations of properties given in 6.3.2.1(e).

R6.3.1.3 To compute pressures, certain properties of the stored material should be known or assumed. There are many tables in the technical literature listing such properties as silo design parameters. In using those parameters for structural analysis, however, the designer should be aware that they are, at best, a guide. Unquestioned use may lead to an unsafe design. This situation exists because of a long-maintained effort to associate design parameters with the generic name of the material to be stored, neglecting the wide range of properties that such a name may cover. The usual design parameters, density, internal friction angle, and wall friction angle, all used in computing pressures, are affected by:
(a) Conditions of the material—moisture content, particle size, gradation, and angularity of particles
(b) Operating conditions—consolidation pressure, time in storage, temperature, rate of filling, and amount of aeration

The licensed design professional should use physical and flow properties of the stored material from reliable sources. Table R6.3.1.3 provides examples of physical properties for various materials. Actual physical properties of specific materials may vary from the properties shown in the table. Upper and lower bounds of properties should be determined by testing the material in question. If the actual material to be stored is unavailable, the bounds should be determined by testing or by examining representative materials from other similar installations.

Note that the physical properties noted in Table R6.3.1.3 for some materials show a wide range of values, demonstrating the variability in the properties that affect pressures and flow in silos. Values shown in the table should be used with caution.
6.3.2 Pressures and loads for walls

6.3.2.1 Pressures due to initial filling (Fig. 6.3.2.1) shall be calculated by the following:

(a) With reference to Fig. 6.3.2.1, the initial (filling) vertical pressure at depth \( Y \) of the stored material shall be calculated by

\[
q = \frac{\gamma R_H}{\mu'k} \left[1 - e^{-\mu'\gamma Y/\delta} \right] \quad (6.3.2.1a)
\]

(b) The initial (filling) horizontal pressure at depth \( Y \) in Fig. 6.3.2.1 shall be calculated by

\[
p = kq \quad (6.3.2.1b)
\]

(c) The lateral pressure ratio \( k \) shall be calculated by

\[
k = 1 - \sin \phi \quad (6.3.2.1c)
\]

where \( \phi \) is the angle of internal friction

(d) The vertical friction load per unit length of wall perimeter at depth \( Y \) in Fig. 6.3.2.1 shall be calculated by

\[
V = (\gamma Y - q)R_H \quad (6.3.2.1d)
\]
During initial filling and during discharge, even when both are concentric, overpressures occur because of imperfections in the cylindrical shape of the silo, non-uniformity in the distribution of particle sizes, and convergence at the top of hoppers or in flow channels.

A minimum overpressure factor of 1.6 is recommended for concentric flow silos, even when they are of a mass flow configuration. The recommended factor recognizes that even though higher and lower point pressures are measured in full-size silos, they are distributed vertically through the stiffness of the silo wall and can be averaged over larger areas for structural design. The 1.6 overpressure factor \( C_d \) is in addition to the load factor required by 6.1.4 (design pressure = load factor \( \times C_d \times \) initial filling pressure).

Licensed design professionals are cautioned that the overpressure factor provided in 6.3.2.2 is for concentric flow and is not intended for asymmetric flow.
6.3.2.3 Asymmetric flow—Pressures due to asymmetric flow from concentric or eccentric discharge openings shall be considered in design of silo walls. Refer to 6.4.4.2 through 6.4.4.7.

The effect of asymmetric flow on design pressures, and the method used to design the silo wall shall be determined by the licensed design professional based on silo geometry; flow characteristics; material properties; material and surface finish of the hopper; and position, type, and configuration of the silo discharge.

6.3.3 Pressures and loads for hoppers

6.3.3.1 Initial (filling) pressures below the top of the hopper:

(a) The initial vertical pressure at depth \( h \) below top of hopper shall be calculated by

\[
q_v = q_o + \gamma h_v
\]

(6.3.3.1a)

where \( q_o \) is the initial vertical pressure at the top of the hopper calculated by Eq. (6.3.2.1a).

(b) The initial pressure normal to the hopper surface at a depth \( h \) below top of hopper shall be the larger of Eq. (6.3.3.1b) and (6.3.3.1c)

\[
p_n = \frac{q_o \tan \theta}{\tan \theta + \tan \phi'}
\]

(6.3.3.1b)

or

\[
p_n = q_o (\sin^2 \theta + k \cos^2 \theta)
\]

(6.3.3.1c)

(c) The initial friction force per unit area of hopper wall surface shall be calculated by

\[
v_n = p_n \tan \phi'
\]

(6.3.3.1d)

when Eq. (6.3.3.1b) is used to determine \( p_n \) and by

\[
v_n = q_o (1 - k) \sin \theta \cos \theta
\]

(6.3.3.1e)

when Eq. (6.3.3.1c) is used to determine \( p_n \)

6.3.3.2 Funnel flow hoppers—Design pressures at and below the top of a funnel flow hopper shall be calculated using Eq. (6.3.3.1a) through (6.3.3.1e), with \( q_o \) multiplied by an overpressure factor \( C_y \) of 1.45 for concrete hoppers and 1.60 for steel hoppers. The vertical design pressure at the top of the hopper need not exceed \( \gamma Y \), where \( Y \) is the effective depth of the stored material from the top of the hopper.

R6.3.2.3 Asymmetric flow can result from the presence of one or more eccentric outlets, from non-uniform distribution of material over a concentric outlet, or even from non-uniform flow through a center outlet.

R6.3.3 Pressures and loads for hoppers

R6.3.3.1 Hopper pressures are more complex to predict than wall pressures. The pressure distribution will be more sensitive to the variables discussed in R6.3.1.3. There is a significant diversity within the technical literature with regard to hopper pressures (Walker 1966; DIN 1055 1987; ISO 11697:1995; Standards Association of Australia 1989). Equations (6.3.3.1a) through (6.3.3.1e), which are based on Walker’s (1966) method, provide a generally acceptable method to estimate initial pressures in hoppers. Equation (6.3.3.1a) reflects Walker’s assumption of an incompressible material and, therefore, yields conservative pressures near the outlets of steep hoppers. Some pressure measurements reported in the technical literature (Clague and Wright 1973; Blight 1988), however, are not significantly lower than those predicted by Eq. (6.3.3.1a) in the lower part of the hopper.

Equations (6.3.3.1b) and (6.3.3.1d) generally control for steep smooth hoppers where the friction along the material-hopper interface is fully developed. Equations (6.3.3.1c) and (6.3.3.1e) generally control for shallow hoppers where the friction along the material-hopper interface is not fully developed. The value of \( k \) to be used in Eq. (6.3.3.1c) should be conservatively calculated by Eq. (6.3.2.1c). Because of the uncertainty inherent in hopper pressure estimates, the engineer should check Eq. (6.3.3.1b) and (6.3.3.1c), and use the equation that yields the larger \( p_n \).

While lower hopper pressures may be justified, a hopper failure can result in significant damage or total collapse of a silo; therefore, the use of the slightly conservative procedure of Eq. (6.3.3.1a) through (6.3.3.1e) is recommended. Pressures on gates and feeders at hopper outlets are usually lower than the pressures calculated using Eq. (6.3.3.1a).

R6.3.3.2 Funnel flow occurs only when the outlet is large enough for the material to flow without forming a stable arch or ratheole, and the hopper walls are not sufficiently smooth or sufficiently steep to develop a mass flow pattern. To obtain a self-cleaning condition, the hopper slope should be steep enough to cause the material to slide off of it when the silo is discharged completely. Jenike (1964) suggests \( \alpha \geq \phi' + 25 \) degrees. Some designers select \( \alpha \) such that \( \tan \alpha > 1.5 \tan \phi' \) for hoppers having flat surfaces and \( 1.5 \sqrt{2} \tan \phi' \) for conical hoppers or the valley of pyramidal hoppers. The
slope of a funnel flow hopper should be selected to avoid the possibility of mass flow that is discussed further in R6.3.3.3. The recommended overpressure factors for hoppers and flat bottoms are intended to cover dynamic loads that normally occur during funnel flow. Collapse of large arches and ratholes can subject the silo to severe shock loads that can cause structural damage. Such loading requires additional analysis and design that is not covered herein. Selection of silo and hopper configurations and flow control devices that minimize the potential for forming stable arches and ratholes is highly recommended. A common approach is to select an expanded flow pattern. An expanded flow pattern is typically a two-slope hopper, with a lower mass flow section and an upper self-cleaning section. The boundary between the mass flow and self-cleaning sections should be chosen to minimize the potential for forming stable arches and ratholes.

6.3.3.3 Mass flow hoppers—Design pressures at and below the top of mass flow hoppers shall be calculated by 6.3.3.3(a) through 6.3.3.3(d).

(a) The vertical pressure at depth \( h_y \) below the top of the hopper shall be calculated by

\[
q_v = \frac{\gamma}{n-1} (h_y - h_h) \left[ 1 - \left( \frac{h_h - h_y}{h_h} \right)^{n-1} \right]
\]

(6.3.3.3a)

where \( q_o \) (the initial vertical pressure at the top of the hopper) is calculated by Eq. (6.3.2.1a), and for circular cones

\[
n = \frac{2B}{\tan \theta} \quad \text{(but not less than 1.0)}
\]

(6.3.3.3b)

for plane flow hoppers

\[
n = \frac{B}{\tan \theta} \quad \text{(but not less than 1.0)}
\]

(6.3.3.3c)

where

\[
B = \frac{\sin \delta \sin 2(\theta + \beta)}{1 - \sin \delta \cos 2(\theta + \beta)}
\]

(6.3.3.3d)

and

\[
\beta = \frac{1}{2} \left[ \phi' + \arcsin \left( \frac{\sin \phi'}{\sin \delta} \right) \right]
\]

(6.3.3.3e)

(b) The pressure normal to the hopper surface at a depth \( h_y \) below the top of the hopper shall be calculated by

R6.3.3.3 Mass flow occurs only when the outlet is large enough for the material to flow without arching, the flow control device permits flow through the entire outlet, and the hopper walls are smooth enough and steep enough to allow material to slide.

Jenike (1964, 1967) provides design information in graph form for selecting the slopes of two common shapes of hoppers (conical and plane flow). Approximate slopes necessary for mass flow to occur may be estimated using Fig. R6.3.3.3a. The occurrence of mass flow or funnel flow depends on the hopper slope angles \( \theta_c \) and \( \theta_p \) and the hopper wall friction angle \( \phi' \). The region labeled uncertain on the graphs of Fig. R6.3.3.3a indicates conditions for which flow may shift abruptly between funnel flow and mass flow, with large masses of material being in unsteady flow and the consequent development of shock loads (Carson and Johanson 1977). Such flow conditions will also lead to nonsymmetric flow patterns and, hence, to nonsymmetric loads on the silo. Selecting hopper slopes in the uncertain region should be avoided.

Other hopper configurations include pyramidal and transition hoppers. For mass flow to develop in a pyramidal hopper, the slope of the hopper valleys should be steeper than \( \theta_c \). For transition hoppers, the side slope should be steeper than \( \theta_p \), and the slope of the curved end walls should be steeper than \( \theta_c \). For tilted hoppers with one vertical side, mass flow will develop when the included angle is greater than 1.25\( \theta_c \) or 1.25\( \theta_p \).

Figure R6.3.3.3b is a flowchart showing a recommended procedure for selecting a silo hopper configuration. Detailed procedures for computing hopper slopes and outlet sizes are given by Jenike (1964).

Mass flow results in high pressures at the top of the hopper (at and directly below the transition). Methods for computing mass flow pressures are given by Jenike (1967, 1977) and Walker (1966). The two methods result in slightly different pressure distributions, with Jenike yielding peak pressures at the transition higher than Walker. Comprehensive reviews
of hopper pressures are given in Gaylord and Gaylord (1984), Rotter (1990), and Ooi and Rotter (1991). Equations (6.3.3.3e) through (6.4.8) are based on Walker (1966).

Pressures in mass flow tilted hoppers, where the angle between the hopper axis and the vertical does not exceed $\theta_c$ or $\theta_p$, may be calculated using 6.3.3.3, with $\theta$ taken as the angle between the hopper axis and the hopper surface.

(c) The unit friction load between the stored material and hopper surface is calculated by Eq. (6.3.3.1d), with $p_v$ calculated by Eq. (6.3.3.3f).

(d) In no case shall the design pressure in a mass flow hopper be taken less than the design pressure calculated by 6.3.3.2.
6.3.3.4 In multiple outlet hoppers, the condition that initial pressures exist above some outlets and design pressures exist above others shall be considered in the design of the hoppers and supporting structures.

6.3.4 Pressures for flat bottoms

6.3.4.1 Initial filling pressures on flat bottoms shall be calculated per 6.3.2.1, with \( Y \) taken as the effective depth of the stored material from the top of the flat bottom.

6.3.4.2 Vertical design pressures on flat bottoms shall be obtained by multiplying the initial filling pressures calculated according to 6.3.4.1 by an overpressure factor \( C_d \) of 1.45 for concrete bottoms and 1.60 for steel bottoms. The vertical design pressure need not exceed \( \gamma Y \).

R6.3.3.4 In multiple-outlet hoppers, flow may occur over some outlets, whereas initial filling pressures exist over others. The differential lateral pressures on hopper segments between outlets can be substantial.

R6.3.4 Pressures for flat bottoms

R6.3.4.1 Equation (6.3.2.1a) assumes a uniform vertical pressure distribution across the diameter of the silo. Vertical pressures may be lower at the wall and higher at the center of the silo, particularly if the silo height-diameter ratio is low. Such pressure variations should be considered in the design of flat bottom floors.
**SPECIFICATION**

6.3.5 Design pressures in homogenizing silos shall be taken as the larger of (a) and (b):

(a) When air pressure is not present, compute pressures according to 6.3.2 and 6.3.3.

(b) When air pressure and volume are sufficient to fluidize the total depth of stored material, compute pressures by

\[ p = q = 0.6\gamma Y \]  

(6.3.5)

where \( \gamma \) is the non-aerated weight per unit volume of the stored material.

6.3.6 The pressures and forces calculated in accordance with 6.3.1 through 6.3.5 are due only to stored material. The effects of dead load; floor and roof live load; and snow, ice, thermal, wind, seismic force, internal air pressure, and forces from earth or materials stored against the outside of the silo shall be considered in combination with stored material loads.

6.3.7 Wind force—Wind force on silos shall be considered generated by positive and negative pressure acting concurrently. The pressure shall be not less than that required by the local building code for the locality and height zone in question. Wind pressure distributions shall take into account adjacent silos or structures. Circumferential bending due to wind on the empty silo shall be considered.

6.3.8 Seismic forces—Silos and stacking tubes shall be designed to withstand the seismic forces in accordance with ASCE/SEI 7. The design shall consider the full range of material loading, from empty to full. It shall be permitted to consider the interaction between the silo and the stored material using an appropriate structural analysis procedure found in ASCE/SEI 7. Unless otherwise determined by analysis, the effective density of the stored material, used to compute seismic forces in accordance with ASCE/SEI 7-10, shall be equal to \( \gamma \). Provisions of ACI 318 shall be satisfied for seismic design of concrete silos.

6.3.9 Thermal effects—The thermal effects of hot or cold stored materials and hot or cold air shall be considered. For circular walls or wall areas with total restraint to warping (as at corners of rectangular silos), the thermal bending moment per unit of wall height or width shall be calculated by

\[ M_t = E_c h^2 \alpha_c \Delta T/12(1 - \nu) \]  

(6.3.9)

where \( \alpha_c \) is the thermal coefficient of expansion of concrete. It shall be permitted to reduce \( E_c \) or \( h \) to reflect the development of a cracked moment of inertia if such assumptions are

**COMMENTARY**

R6.3.5 Pressures in homogenizing silos—Homogenizing silos are those in which air pressure is used to mix dust-like materials. The material being mixed may behave as a fluid; thus, the possibility of hydrostatic pressures should be considered. The factor 0.6 reflects the fact that the suspended particles are not in contact, and the average density is less than for the material at rest. Partially aerated silos may experience aeration pressure directly additive to nonaerated inter-granular pressures (Anderson 1985). Refer to 6.3.2.3 for computing design pressures in partially fluidized silos. Some homogenizing silos are aerated in sequential sectors. The walls of such silos can be subjected to large pressure differentials between aerated and non-aerated sectors. Such pressure differentials can lead to significant vertical and horizontal bending moments.

R6.3.8 The determination of seismic forces and moments on a stacking tube due to a surrounding pile of granular material should consider the relative stiffness of the tube and the material. Large shear forces and moments may result, especially for tall stacking tubes, in areas of high seismic risk.

R6.3.9 Thermal effects—Computation of bending moments due to thermal effects requires determining the temperature differential through the wall. To determine this differential, the licensed design professional should consider the rates at which heat flows from the hot material to the inside surface of the wall, through the wall thickness, and from the wall to the atmosphere. There are two distinct and different conditions to be analyzed.

1. The worst thermal condition is usually found in the wall above the hot material surface, where the air is maintained at a high temperature while fresh hot material is fed into
the silo. In that portion of the wall, high thermal loads will coexist with wall dead load and no material loads.

2. A less severe condition exists below the hot material surface, where temperatures fall as heat flows through the wall to the outside and a temperature gradient develops through some thickness of the granular material (Bohm 1956). In that portion of the wall, material loads will coexist with reduced thermal loads.

The temperature differential may be estimated by (Safarian and Harris 1970)

\[ \Delta T = (T_i - T_o - 80°F)K_i \text{ (U.S. customary)} \]
\[ \Delta T = (T_i - T_o - 45°C)K_i \text{ (SI)} \]

where \( K_i \) for cement is given by Fig. R6.3.9.

Other methods for computing bending moments due to thermal effects are available (Turitzin 1963; Theimer 1969; Broersma 1972; Jenkyn 1994).

The licensed design professional should also recognize that structural steel items such as roof beams inside a concrete silo will expand and contract more rapidly than the concrete and cause an overstress at contact areas if space for expansion is not provided. Provision should also be provided for vertical thermal expansion at roof beam bearings.

The bending moments induced in a silo wall are affected by the stiffness of the wall. An adjustment to \( E_i \) or \( h \) may be made to account for the reduced stiffness of a cracked wall, where appropriate. It is recommended that the stiffness used for analysis should not be lower than that provided in ACI 318 for cracked walls in compression.

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**Fig. R6.3.9—Determination of \( K_i \) for a wall of a cement storage silo.**

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1. Resistance of 8 in. (203 mm) cement (considered to act as insulating material) = 3.92
2. Resistance of 1 in. (25.4 mm) thick concrete = 0.08
3. Resistance of outer surface film = 0.17

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6.4—Wall design

6.4.1 Minimum wall thickness for silos shall be in accordance with 6.1.3. Minimum wall reinforcement for cast-in-place silos shall be in accordance with 6.2. The wall thickness for stave silos shall be in accordance with 7.4.2.

6.4.2 Walls shall have design strengths at all sections at least equal to the required strength calculated for the factored forces, moments, and shears in accordance with 6.1.4.

6.4.3 Design of walls subject to axial load or to combined flexure and axial load shall be in accordance with ACI 318-11 Chapter 10. Design of walls subject to shear shall be in accordance with ACI 318-11 Chapter 11.

R6.4—Wall design

R6.4.2 Storage of hot materials can cause appreciable thermal stresses in the walls of silos. Thermal stresses may or may not occur concurrently with the maximum hoop forces.

The reinforcement added for thermal bending moments should be placed near the cooler (usually outside) face of the wall. In singly reinforced walls, it should be added to the main hoop reinforcement, which should be near the outside face. In walls with two-layer reinforcement, the entire amount should be added to the outer layer. For simplicity, an equal amount is often added to the inner layer to avoid having bar sizes or spacings differ from one layer to the other.

Horizontal and vertical thermal moments will be present in the wall above the hot material surface, and should be considered in the design. Where the vertical dead load compressive stress is low, added vertical temperature reinforcement may be required.

R6.4.3 Strength design of walls subject to combined axial tension and flexure should be based on the stress and strain compatibility assumptions of ACI 318-11 Chapter 10, and on the equilibrium between the forces acting on the cross section at nominal strength. For small eccentricity (Fig. R6.4.3) \( e = M_u / F_u < h/2 - d'' \), the required tensile reinforcement area per unit height may be calculated by

\[
A_s = \frac{F_u e'}{\phi_f (d - d')} \quad \text{(R6.4.3a)}
\]

on the side nearest to force \( F_u \), and

\[
A'_s = \frac{F_u e''}{\phi_f (d - d')} \quad \text{(R6.4.3b)}
\]

on the opposite side. The variables \( A_s \) and \( A'_s \) are both in tension. For large eccentricity \( e = M_u / F_u > h/2 - d'' \), refer to Safarian and Harris (1974).

Fig. R6.4.3—Axial tension and flexure with small eccentricity.
**SPECIFICATION**

6.4.4 Circular walls in pressure zone

6.4.4.1 For concentric flow, circular silo walls shall be designed for hoop tension due to horizontal pressures computed in accordance with 6.3.2.2. The minimum wall hoop reinforcement shall be in accordance with 6.2.4.

6.4.4.2 For asymmetric flow, circular silo walls shall be designed for the effect of combined axial tension, bending moments, and shear forces due to non-uniform pressures using either the Flow Channel Method of 6.4.4.3 through 6.4.4.6 or the Eccentricity Method of 6.4.4.7. Asymmetric loading in homogenizing silos shall conform to 6.4.4.8.

The choice of design method shall be made by the licensed design professional taking into account the stored material properties and flow characteristics; the configuration, construction, material, and surface finish of the silo bottom or hopper; and the industry’s experience with similar full-size silos.

The Eccentricity Method of design shall not be used for silos containing materials with an effective angle of internal friction, δ, of more than 40 degrees.

The Eccentricity Method of design shall not be used for asymmetric loading in homogenizing silos.

The minimum wall hoop reinforcement shall be as required by 6.4.4.1.

6.4.4.3 Design pressures for asymmetric flow patterns shall be determined by selecting design flow channel(s) that come in contact with the silo wall over an appropriate height of the wall and by computing pressures in static and flowing materials after flow begins in accordance with 6.4.4.4 through 6.4.4.6. The design pressures shall be used to determine silo wall tensions, moments, and shears in the silo wall.

In determining tensions, moments, and shears, any method of structural analysis shall be acceptable that results in a realistic approximation of the behavior of the wall and considers the following:

a) Restraint or fixity provided by common walls of adjacent silos, interstices, or both

b) Interaction between the silo wall and the stored material; the stiffness of the material within the flow channel boundary shall be taken as not more than 10 percent of the stiffness of the static material

c) Effect of wall cracking

**COMMENTARY**

R6.4.4 Circular walls in pressure zone

R6.4.4.1 Even though circular walls of concentric flow silos are analyzed as being subject to hoop tension only, bending moments can occur due to temperature differentials, wind, seismic, or differential settlement effects. The hoop tensions, bending moments, and shear forces should be combined according to 6.4.2 and the wall thickness and hoop reinforcement determined according to 6.4.3.

R6.4.4.2 Although the Flow Channel Method is applicable to all silos, it is more commonly used for silos storing stronger, higher δ materials where definitive flow channels occur. The method calculates variation in pressure around the perimeter of the silo based on design flow channel(s). The circumferential moments, radial shears, and tensions resulting from these variations are then determined by structural analysis and used to select the wall thickness and reinforcement. Sadler et al. (1995) provides general guidelines for designing silo walls based on flow channel considerations.

The Eccentricity Method is commonly used for silos storing weaker, lower δ materials where flow channel boundaries may not be easily definable. The method increases the normal amount of hoop tension reinforcement by a calculated percentage based on the offset of an eccentric discharge point when compared with the silo diameter. The resulting increased hoop reinforcement increases the ability of the wall to resist forces resulting from asymmetric flow.

The Eccentricity Method is not to be used in cases when the effective angle of internal friction of the material, δ, under service conditions of moisture, gradation, and compaction, exceeds 40 degrees.

The two methods may or may not yield comparable results. The overpressure factor, Cδ, in 6.3.2.2 is not intended to cover asymmetric flow situations.

R6.4.4.3 Any rational method of structural analysis that recognizes the stiffness and passive resistance of the static material may be used to estimate bending moments. Finite element models with differential pressures on their shell elements that exclude the stiffness of stored materials can provide unreasonably large bending moments and shear forces.

Figure R6.4.4.3 from Sadler et al. (1995) is a design aid used to estimate moments for D/h and different Lw/D. The figure provides moment coefficients for a single flow channel and for two diametrically opposed flow channels, based on the ratio of the silo diameter D to the silo wall thickness h.

The design aid is based on a linear elastic finite element model of a slice of unit height of the silo wall and static material. For monolithically constructed silo groups and silos with unusual configurations, a three-dimensional finite element model, as opposed to a slice model, may be required.

Compared with an uncracked wall analysis, a cracked wall analysis results in lower bending moments. A reduced wall thickness to simulate the effect of a cracked wall moment of
Redistribution of bending moments from negative moment ($M_{OF}$) zones to positive moment ($M_{IF}$) zones shall be permitted in accordance with ACI 318-11, 8.4.

Reductions to shear capacity of the wall caused by axial hoop tension shall be considered. Shear reinforcement to supplement wall shear strength shall be in accordance with ACI 318-11 Chapter 11.

If the difference between $p_s$ and $p_f$ is known, the coefficients $C_1$ and $C_2$ can be used to determine $M_{TOTAL}$ and the wall moments $M_{OF}$ and $M_{IF}$. The higher negative moments ($M_{OF}$) at the edges of flow channels may be redistributed to the lower positive moment ($M_{IF}$) zone at the center channel, to help equalize the area of reinforcement between the inside and outside faces of the wall. Using the same bar size and spacing in both faces simplifies placement, especially for slipformed walls.

Reinforcement for bending should typically be carried around the entire perimeter of the silo to cover flow channels that might meander laterally away from the outlet and over the height of the silo wall.

Although analysis may show hoop tension varying around the silo circumference, maximum hoop tension is recommended at all locations for design.
The design flow channel configuration(s) shall be specified by the licensed design professional based on experience and field observations of flow in silos with comparable configurations and stored materials. Configuration of the assumed design flow channel(s) shall be shown on the project drawings.

Unless otherwise determined by analysis or field observation, the design flow channel shall be assumed to contact the silo wall from the top of the hopper to the top of the material, and the flow channel diameter shall be estimated using Fig. 6.4.4.4. The selected flow angle $\theta_f$ and channel diameter $\bar{Y}$ shall be representative of actual flow channels normally found in the type of silo considered.

In case of a side discharge, where the outlet is in the silo wall, the flow channel shall be assumed to contact the wall from the bottom of the outlet to the top of the material.

Stored material variability; variations in flow channel location or configuration; and silo wall serviceability, such as crack width under cyclic loading, shall be addressed.

Selection of a design flow channel should be based on an understanding of material flow and experience with asymmetric flow in comparable silos storing comparable materials. Flow channels that form over outlet openings are often observed in the field from silo roof openings; sizes, locations, and limits can be defined by scouring or abrasion marks on the silo walls.

Figure 6.4.4.4 (Giunta 1968) is a useful analytical starting point for estimating $\theta_f$ and $\bar{Y}$ based on $\delta$. Whereas $\delta$ is a good measure of the ability of the material to form definitive flow channels, $\delta$ as measured in shear strength tests on small samples may not be representative of the complete range of particle sizes in the silo. Therefore, when selecting design flow channel configuration(s) based on $\delta$, the licensed design professional should place more reliance on observed behavior in full-size silos than on shear test results and Fig. 6.4.4.4.

The channel should rarely be assumed to be plumb, but should be tilted toward the nearest wall where coarse material accumulates from segregation during filling, as shown in Fig. R6.4.4.4. The channel should be assumed to increase in size at the included angle $2\theta_f$ from its apex until it reaches diameter $\bar{Y}$, after which it continues without further expansion. The tilt angle $\theta_t$ should be taken not less than $\theta_f$ and may be conservatively set equal to $\theta_f$, making the flow channel start at the top of the hopper.

Actual flow channels that develop in silos will most likely differ from the design flow channel assumed; therefore, a reasonably full range of variations in size and locations should be explored.
Fig. R6.4.4.4—Tilted design flow channel.
6.4.4.5 Vertical design pressure in the flow channel at depth $y$ below the top surface of the flow channel shall be calculated by

$$q_f = \frac{\gamma R_f}{\mu' k} \left[ 1 - e^{-\mu' y/R_f} \right]$$

(6.4.4.5a)

Horizontal design pressure in the flow channel at depth $y$ below the surface of the stored material shall be calculated as

$$p_f = k q_f$$

(6.4.4.5b)

where $C_d = 1.0$ for both flow and static pressures.

6.4.4.6 Vertical design pressure in the static material at any depth $y$ below the surface of the stored material shall be calculated by

$$q_s = \frac{A_{silo} q - \sum A_f q_f}{A_{silo} - \sum A_f}$$

(6.4.4.6a)

where $\sum A_f$ is the summation of the plan areas of all flow channels that are active at depth $y$.

The horizontal design pressure in the static material at any depth $y$ below the surface of the stored material shall be calculated by

$$p_s = k q_s$$

(6.4.4.6b)

6.4.4.7 The Eccentricity Method of design shall be used only on silos containing material with an effective angle of internal friction of 40 degrees or less.

For the Eccentricity Method of design, the horizontal wall design pressure above the hopper calculated in accordance with 6.3.2.2 shall be increased. The calculated increase shall be 25 percent of the static pressure when the discharge opening eccentricity $E_{CC}$ equals the silo radius ($D/2$). In cases where the discharge is less than fully eccentric, the calculated increase shall be $E_{CC} / (D/2)$ times 25 percent of the static pressure.

The material effective depth $Y_{EFF}$ shall be taken as the vertical distance from the top of the discharge opening to

R6.4.4.5 Vertical and horizontal pressures exerted by the flowing material, which are less than the pressures exerted by the static or nonflowing material, result in circular flexing of the silo wall. In applications where the converging portion of the flow channel is in contact with the wall, $R_f$, $A_f$, and $L_w$ decrease with depth and an incremental (layer by layer) solution of Eq. (6.4.4.5a) and (6.4.4.5b) is required. The generalized form of Eq. (R6.4.4.5) is useful for this purpose.

$$q_f = \frac{\gamma R_f}{\mu' k} \left[ 1 - e^{-\mu' y/R_f} \right] + q_s e^{-\mu' y/R_f}$$

(R6.4.4.5)

where $q_s$ is the vertical flow pressure on the top of the layer being considered.

Alternatively, the material pressures within the converging portion of the flow channel may be calculated using mass flow pressure formulas in 6.3.3.3, but substituting $q_f$ for $q_0$ in Eq. (6.3.3.3a), $\theta_f$ for $\theta$ in Eq. (6.3.3.3b) and (6.3.3.3d), $\phi$ for $\phi'$ in Eq. (6.3.3.3e), and $2\theta_f$ for $\theta$ in Eq. (6.3.3.3f). Recognize that the reduced flow pressure is applied over a linearly decreasing $L_w$. Such formulas will result in a less conservative design (a smaller difference between $p_f$ and $p$) at and below the transition. The opposite will be true near the outlet.

In Eq. (6.4.4.5a), $\mu'$ may be conservatively taken equal to $\tan \phi$. Alternatively, a weighted average for $\mu'$ following the procedure given in Sadler et al. (1995) may be used.

R6.4.4.6 Geometry dictates that as the number and size of flow channels of a multiple-outlet silo increase, the pressures in the static material and the resulting moments increase significantly. Therefore, it is important to consider realistic combinations of flow channels and not arbitrarily assume all discharge feeders will be interlocked and operated together.

R6.4.4.7 The eccentricity method described herein was introduced in 4.4.2.4 of the ACI 313-77 Commentary. Even though it was not retained in subsequent updates of ACI 313, it has been used with success in the grain industry.

The Eccentricity Method is not appropriate for design of silos with small or zero eccentricities if the flow channel can deviate laterally above the opening and contact the wall as shown in Fig. R6.4.4.4.
the effective depth of the repose volume. For silos where the ratio of $Y_{EFF}$ to diameter is 2 or less, the pressure increase shall be considered constant from the top of the discharge to a height of $1.0D$, and then reduce linearly to zero at the top of the stored material.

For silos where the ratio of $Y_{EFF}$ to diameter is greater than 2, the pressure increase shall be considered constant from the top of the discharge to a height of $1.5D$, and then reduce linearly to zero at the top of the stored material. The increased design pressures shall be uniformly applied around the circumference of the silo.

**6.4.4.8** For homogenizing silos, circular silo walls shall be designed for hoop tension due to horizontal pressures calculated in accordance with 6.3.5. For partially fluidized silos, circular silo walls shall be designed for combined hoop tensions, bending moments and shear forces due to non-uniform horizontal pressures computed in accordance with 6.4.4.2. The minimum wall hoop reinforcement shall be in accordance with 6.2.4.

**6.4.5** Walls in the pressure zone of square, rectangular, or polygonal silos shall be designed for combined axial tension, bending moments, and shear forces due to horizontal pressure from stored material.

**6.4.6** Walls below the pressure zone shall be designed as walls subjected to vertical load and applicable lateral loads.

**6.4.7** Design axial strength per unit area, $\phi P_{nw}$, for walls in which buckling, including local buckling, does not control, shall be calculated by Eq. (6.4.7)

$$\phi P_{nw} = 0.55\phi f'_c$$  \hspace{1cm} (6.4.7)

in which the strength reduction factor $\phi$ is 0.65.

**6.4.8** For walls in the pressure zone, wall thickness and reinforcement shall be so proportioned that, under initial (filling) pressures, the calculated crack width at 2.5 bar diameters from the center of bar ($d_0 = 2.5$ bar diameters) shall not exceed 0.010 in. (0.25 mm) (Fig. 6.4.8). The crack width (in. [mm]) shall be calculated by

$$w = 1.0 \times 10^{-7} f'_c \sqrt{d_0} A$$  \hspace{1cm} (6.4.8)

**R6.4.4.8** Aeration systems that fluidize only portions of the silo subject silo walls to non-uniform horizontal pressure. Design pressures should be computed by 6.3.2.3. Hoop tensions, bending moments, and shear forces should be computed by 6.4.4.2.

**R6.4.5** Suggested procedures for the analysis and design of noncircular silo walls are given in Safarian and Harris (1984).

**R6.4.7** Equation (6.4.7) is obtained from ACI 318-11, Eq. (14-1), for walls. Proportions of cast-in-place circular silo walls are such that buckling due to vertical compression ordinarily does not control, and the axial load compressive strength given by Eq. (6.4.7) need not be reduced for slenderness effects.

For silos of unusual proportions and for some silo walls next to openings, however, the design vertical compressive strength may be less than given by Eq. (6.4.7). Suggested formulas for such conditions are given in Safarian and Harris (1984) and Baker et al. (1981).

**R6.4.8** The primary concern of crack control is to minimize crack width. In terms of protecting the reinforcement from corrosion, however, surface crack width appears to be relatively less important than previously believed. Therefore, it is usually preferable to provide a greater thickness of concrete cover, even though this will lead to wider surface cracks. Construction practices directed toward minimizing drying shrinkage will have significant impact on crack control. Additional information on this subject is found in ACI 318-11 Section 10.6 and in ACI 224R.

Similarly, to protect against splitting of the concrete around the reinforcement, the minimum center-to-center spacing and the minimum concrete cover of the reinforcement should be limited to those prescribed by 6.2.9 and 6.2.10, even though this may also lead to wider surface cracks.
6.4.9 The continuity between a wall and a suspended hopper shall be considered in the wall design.

6.4.10 Walls shall be reinforced to resist forces and moments due to continuity of walls in monolithically constructed silo groups. The effects of load patterns of both full and empty cells shall be considered.

6.4.11 Unless determined otherwise by analysis, walls at each side of an opening shall be designed as columns. The column width shall not exceed four times the wall thickness.

6.5—Hopper design

6.5.1 Loads—Silo hoppers shall be designed to withstand forces from stored materials calculated according to 6.3.3 and other loads such as mechanical equipment and support platforms. Seismic forces shall be determined using provisions of 6.3.8. Thermal effects due to stored material shall also be considered.

6.5.2 Suspended hoppers

6.5.2.1 Suspended conical hopper shells shall be considered subject to circumferential and meridional (parallel to hopper slope) tension membrane forces.

6.5.2.2 Suspended pyramidal hopper walls shall be considered subject to combined tension membrane forces, flexure, and shear.

R6.5—Hopper design

R6.5.1 Loads—Hoppers should be designed to withstand flow pressures in accordance with 6.3.3.2 and 6.3.3.3, in addition to other loads described in this chapter.

R6.5.2 Formulas for computing stresses in hoppers are found in Safarian and Harris (1984), Gaylord and Gaylord (1984), Rotter (1990), and Ooi and Rotter (1991). The design of structural steel hoppers should be in accordance the requirements of the American Institute of Steel Construction, Inc. (2010).
The design of hopper supports should consider potential differential horizontal and vertical movements between the hopper support and silo walls. Such movements may induce forces and moments not otherwise anticipated.

Under sustained compressive load, creep in a reinforced concrete column causes the concrete stress to reduce, transferring load to the steel reinforcement. With subsequent sudden unloading, the concrete may be in tension and develop horizontal cracks. This condition is more pronounced in columns with large ratios of reinforcement-to-concrete area (DiPasquale 1981).

The problem of such cracking is seldom experienced in normal building structures because dead load exceeds vertical live load and extreme unloading cannot occur. In storage silos, however, live load (stored materials) usually accounts for the major portion of the load, and can be quickly removed. Thus, the horizontal cracking of heavily reinforced silo support columns can be severe.

Such cracking will be serious if it is accompanied by vertical cracking, as could occur with high bond stress during unloading. This latter condition can be dangerous, and can be prevented by the following:

a) If lateral forces are not a problem, the vertical reinforcement ratio should be kept low to prevent horizontal cracking upon unloading.

b) If lateral forces have to be resisted, larger columns with a low reinforcement ratio should be used.

The maximum area of vertical reinforcement in columns supporting silos or silo bottoms shall be 0.02 times the gross area of the column.

The maximum calculated crack width of reinforced concrete suspended hoppers shall meet the requirements of 6.4.8.

The minimum wall thickness of suspended reinforced concrete hoppers shall be 5 in. (125 mm).

Hopper supports shall have adequate strength to resist the hopper reactions.

For horizontal bottom slabs, the design shall consider the dead load; the vertical design pressure (from stored material) calculated at the top of the slab according to 6.3.4.2; and the thermal effects, if any, from stored material. If hopper forming fill is present, the weight of the fill shall be considered as dead load.

The maximum area of vertical reinforcement in columns supporting silos or silo bottoms shall be 0.02 times the gross area of the column.

Except as prescribed, silo foundations shall be designed in accordance with ACI 318-11 Chapter 15.

The overpressure effects from stored material, as defined in 6.3.2.2, 6.3.3.2, and 6.3.4.2, shall be neglected in the design of silo foundations.

Unsymmetrical loading of silo groups and the effect of lateral loads shall be considered in foundation design.
6.7.4 Differential settlement of silo walls and floor support columns, and silos within a group shall be considered in foundation, wall, and roof design. Estimations of differential settlement, creep, shrinkage, or temperature changes shall be based on a realistic assessment of such effects occurring in service.

**COMMENTARY**

R6.7.3 Unsymmetrical loading should be considered for its effect on stability (against overturning), soil pressures, and structural design of the foundation.

R6.7.4 Differential settlement of the silo foundation resulting from soil-structure interaction should be considered.
CHAPTER 7—CONCRETE STAVE INDUSTRIAL SILOS

7.1—Scope
This chapter applies to precast concrete stave silos that are used only for storing granular bulk material. It does not apply to farm silos for storage of silage.

7.2—Coatings
7.2.1 Interior and exterior coatings shall be applied to the staves where specified.

R7.2—Coatings
Coatings are often specified for the inside face, outside face, or both, of stave silo walls to protect the stored material from moisture infiltration, to protect the staves from hazardous stored materials, or to protect the staves and stave hoops from weathering. The coating material, where required, should be chosen to be consistent with the properties of the stored material, the stave concrete, and the steel hoops.

Interior coatings, where specified, typically consist of a single-operation, three-coat plaster (parge) application of fine sand and cement worked into the stave surface and joints in such a manner as to become an integral part of the wall. The final finish is typically steel-troweled smooth.

Exterior coatings, where specified, typically consist of thick cement slurry brushed or otherwise worked into the surface and joints of the staves to provide maximum joint rigidity and watertightness.

7.3—Erection tolerances
7.3.1 For vertical alignment of the center point, the actual center point of the silo shall not vary from its theoretical axis:
Per 10 ft (3 m) of height: ±1 in. (25 mm)

7.3.2 Rotational (spiral) of the vertical stave joint:
Per 10 ft (3 m) of height: ±1 in. (25 mm)

7.3.3 Bulging of stave wall:
For any 10 ft (3 m) of height: 1 in. (25 mm)
For entire height: 3 in. (75 mm)

7.3.4 The measured inside shell diameter at any section shall not vary from the specified diameter by more than 1 in. (25 mm) or 0.1 times the specified diameter (ft [m]), whichever is greater.

7.3.5 Hoops—In no case shall a lower quantity of hoops be placed than specified in the design. The vertical spacing requirement shall not deviate from specified design by:
Hoop vertical spacing: ±1 in. (25 mm)

R7.3—Erection tolerances
A quality control program should be established to measure, document, and verify compliance with the construction tolerance requirements of this document. The program should identify the type, number, and frequency of the measurements required to document each of the areas specified in this document.

R7.3.2 Spiraling results when staves are tilted slightly so that, even though their outer faces are vertical, their edges are inclined. Such misplacement causes vertical joint lines to be long-pitch spirals rather than plumb lines. The resulting assembly appears to spiral.

R7.3.3 A bulge is the vertical out-of-plane deviation of a stave wall as measured from a straightedge or string and should be measured over a 10 ft (3 m) section of wall height.

R7.3.4 The measured inside shell diameter should be taken at regular intervals as established by the quality control program. The diameter of the silo is measured in feet (meters) for the tolerance calculation.
### 7.4—Wall design

#### 7.4.1 Loads, design pressures, and forces—Loads, design pressures, and vertical forces for stave silo design shall be determined as specified in Chapter 6. Overpressure or impact, the effects of eccentric discharge openings; and wind, snow, thermal effects, and seismic forces shall all be considered. Strength requirements shall be satisfied in accordance with 7.4 through 7.6 and referenced tests in 7.6.

#### 7.4.2 Wall thickness—The required stave silo wall thickness shall be determined considering circular bending, compression, tension, and buckling, but shall in no case be less than 2 in. (50 mm).

#### 7.4.3 Circular bending—Unless a more detailed analysis is performed, the circumferential bending strength $M_0$ shall satisfy (a) and (b):

(a) In the case of wind acting on an unbraced wall or an empty silo

$$M_0 \geq D^2 w_p/8 \quad (7.4.3a)$$

where $w_p$ is strength-level wind pressure. Where wind pressure $w_p$ has not been reduced by a directionality factor, 0.8$w_p$ must be used in place of $w_p$ in Eq. (7.4.3a).

(b) In the case of unequal interior pressures from asymmetric filling or emptying

$$M_0 = 1.6(M_{\text{pos}} + |M_{\text{neg}}|) \quad (7.4.3b)$$

$$M_{0,\text{pos}} \geq 1.0M_{\text{pos}} \quad (7.4.3c)$$

where 1.6 and 1.0 are load factors, and $M_{\text{pos}} + M_{\text{neg}}$ are determined by the Flow Channel Method in accordance with 6.4.4.2 through 6.4.4.7.

The following strength relationships shall be satisfied

$$0.875(\phi A f_y - F_u)h \geq M_0 \quad (7.4.3d)$$

$$0.375(\phi A f_y - F_u)h \geq M_{0,\text{pos}} \quad (7.4.3e)$$

(If Eq. (7.4.3d) and (7.4.3e) are not satisfied, a complete circular assembly of staves, such as described in Fig. R7.6b, shall be tested to prove satisfactory strength.)

### COMMENTARY

#### R7.4—Wall design

**R7.4.1** The pressure formulas in Chapter 6 are not applicable to silos storing silage. Guidance for farm silo design is given in International Silo Association (1981).

**R7.4.2** Stave silo strength depends not so much on the strength of any one component as on the way these components and their connections act when assembled. Therefore, stave assembly tests are needed to determine joint shear strength (tension) and vertical compressive strength, as well as vertical and horizontal wall stiffness and bending strength. Recommended tests are given in R7.6.

**R7.4.3** Because of thin walls and a multitude of vertical joints, stave silos have less circular rigidity than monolithic silos. If joints are not shaped so they can be pointed with grout after erection, they are free to rotate and allow the silo to assume an oval shape. Decreased circular strength also results from the placement of steel hoops on the exterior surface. When the curvature of the wall increases, the hoops add to circular strength; however, when the curvature decreases, the hoops add minimal strength. While a stave wall has the undesirable tendency to go out-of-round if it is not stiff enough, it also has the desirable ability to redistribute circumferential bending moments from weaker positive moment (tension inside face) zones to stronger negative moment zones (tension outside face).

The circular strength and stiffness of a stave silo can be increased by additional hoops, thicker staves, or better vertical joint details. The strength of any particular stave design is difficult to determine without testing full-scale stave assemblies. It can be estimated, however, that the total statical moment strength is typically not more than 0.875($\phi A f_y - F_u$)h and that the positive moment strength is typically not more than 0.375($\phi A f_y - F_u$)h.

Equation (7.4.3b) requires the total statical moment strength to be 1.6 times the total moment acting on the wall. Equation (7.4.3c) requires the positive moment strength to be 1.0 times the positive moment acting on the wall. It is assumed a portion of the positive moments will redistribute to the negative moment zones and the factor of safety against total failure will be maintained, even though there may be some cracking on the inside face in the positive moment zones.

Equations (7.4.3d) and (7.4.3e) simply restate Eq. (7.4.3b) and (7.4.3c) in terms of the actual wall thickness and hoops supplied. The term ($\phi A f_y - F_u$) represents the excess hoop capacity supplied for bending. The quantity 0.875$h$ in Eq. (7.4.3d) represents the approximate distance between the tension force in the hoops (assumed 1/2 in. [12 mm] diameter) and the compression block. The quantity 0.375$h$ in Eq. (7.4.3e) represents the approximate distance between the
7.4.4 Compression and buckling—The design axial load strength per unit perimeter, \( \phi P_{nw} \), shall be taken as the smaller of that calculated by Eq. (7.4.4a) through (7.4.4c)

\[
\phi P_{nw} = 0.50\phi P_{nw,\text{stave}} \quad (7.4.4a)
\]

\[
\phi P_{nw} = 0.55\phi P_{nw,\text{joint}} \quad (7.4.4b)
\]

\[
\phi P_{nw} = 0.55\phi P_{nw,\text{buckling}} \quad (7.4.4c)
\]

where \( \phi \) is 0.65, and \( P_{nw,\text{stave}}, P_{nw,\text{joint}}, \) and \( P_{nw,\text{buckling}} \) are determined by computation of properties, or proven by tests of stave assemblies such as described by Fig. R7.6a. The variable \( P_{nw,\text{buckling}} \) shall take into account the maximum eccentricities from out-of-plane deviations allowed in 7.3.

The wall thickness shall be such that \( P_{nw} \) shall not be exceeded by any appropriate combination of applicable forces as specified in 6.1.

R7.4.4 Deformation from asymmetric flow, particularly over a side withdrawal, can reduce the wall curvature and increase the possibility of the wall buckling under vertical loads.

The \( P_{nw,\text{stave}} \) in Eq. (7.4.4a) is the nominal axial load strength obtained from tests illustrated by Fig. R7.4.4a or Fig. R7.4.4b. The \( P_{nw,\text{joint}} \) in Eq. (7.4.4b) is the strength from tests illustrated by Fig. R7.4.4b, and is typically lower. The \( P_{nw,\text{buckling}} \) in Eq. (7.4.4c) is obtained by test, or by a combination of test results and published methods of computing critical buckling strength, and should take into account the sometimes large out-of-plane deviations found in stave silo walls.
7.4.5 Forces due to overturning—The empty silo shall have a factor of safety not less than 1.33 against wind or earthquake overturning forces. Computation shall be based on a shape factor for rough-surfaced cylinders for wind loads and not more than 0.9 times the calculated dead load of structure. If anchorage is necessary, the following shall be satisfied where anchors attach to the stave wall

\[ 5\phi A_w \sqrt{f'_c} \geq 2(W \text{ or } E) \] (7.4.5a)

and

\[ \phi_0.1(A_d f_y - F_u) \text{ lap} \geq 2(W \text{ or } E) \] (7.4.5b)

where \( \phi \) is 0.65; the force \((A_d f_y - F_u)\) is per unit length of wall height; \( \text{lap} \) is the amount of vertical stagger, in feet (m), between horizontal stave joints; and \( W \) is the strength-level wind uplift. The limitations of Eq. (7.4.5b) shall be imposed unless tests, such as described by Fig. R7.4.4a, indicate greater strength.

7.4.6 Wall openings—Wall openings in stave silos shall be framed in such a way that the vertical and horizontal bending and tensile strengths of the wall are not reduced by the opening.

R7.4.5 Silo walls are subjected to vertical tension when the silo has insufficient self-weight to resist overturning from wind or earthquake overturning. In such cases, anchor straps secured to the foundation are extended up the silo wall an appropriate distance and secured to the hoops. Where the straps are discontinued, the wall should resist the remaining tension. Tension failure of the wall can occur if the stave breaks in tension or if the stave slips out of the lapped position depicted in Fig. R7.4.4b. Compliance with Eq. (7.4.5a), which assumes the tensile strength of concrete is \( 5\sqrt{f'_c} \) (0.42\( \sqrt{f'_c} \)), will prevent a tension failure of the concrete in the stave. Compliance with Eq. (7.4.5b), which assumes the coefficient of sliding friction of concrete on concrete is 0.1, will prevent slipping of the stave from the lapped position. The force \( W \) or \( E \) in Eq. (7.4.5a) and (7.4.5b) is doubled because only half of the staves are continuous at any horizontal joint.
7.5—Hoops for stave silos

7.5.1 Size and spacing—Except as noted, the size and spacing of external hoops for stave silos shall be calculated in the same manner as horizontal reinforcement of circular, cast-in-place silos. In computing the hoop reinforcement, it is permitted to use an average design pressure over a wall height equal to 30 times its thickness. Hoops shall be 1/2 in. (12 mm) minimum in diameter. The maximum spacing shall not exceed the stave height or 10 times the wall thickness.

7.5.2 Calculating steel area—When calculating the required size and spacing of stave silo hoops, the hoop net area shall be used and taken as the lesser of (a) and (b):

(a) The area of the rod
(b) The root area of the thread

If lugs or mechanical fasteners induce bending deformations or strains in the hoop that reduce the yield strength of the hoop, appropriate restrictions in the available strength of the hoop/lug assembly shall be considered.

7.5.3 Tensioning—Initial stave silo hoop tension shall be such that, after all losses from shrinkage, creep, elastic shortening, and temperature changes, the required vertical and circular strength and stiffness of the stave assembly is maintained.

7.6—Concrete stave and stave assembly testing

7.6.1 Compressive strength of the concrete staves shall conform to the requirements of the contract documents. Concrete design strength shall not be taken less than 4000 psi (28 MPa).

R7.5—Hoops for stave silos

R7.5.1 Hoops are typically of galvanized steel. The exterior cement paste coating, when used, is typically applied over top of the stave hoops, providing additional protection.

R7.5.2 Typical hoop connector lugs are configured to allow the connected hoop ends to splice by offsetting and overlapping. As the hoops are tightened, the lugs through which the hoops pass rotate slightly because of the offset. This causes the hoops to bend slightly where they enter the lug.

R7.5.3 Hoops generally consist of three or more rods connected by lugs of malleable iron or pressed steel. Even though tightening is done only at the lug, within a short time the hoop stress will be uniform along the entire hoop length.

R7.6—Concrete stave and stave assembly tests

The compressive strength of concrete staves should be in accordance with the following.

A test section should consist of the full width of a solid stave with the height of this section being twice the thickness of the stave shown in Fig. 7.6c. The stave should be tested in a conventional compression testing machine, being loaded by the machine in the same manner as it is loaded in the silo wall.

When testing a cored stave, a section should be cut with a height twice the thickness of the stave shown in Fig. 7.6d. The maximum depth, however, should include only one complete core, and no portion of a core should be present on either top or bottom of the test specimen.

The selection and required number of test sections and the procedures for capping and testing the test sections should conform to ASTM C140/C140M.

The average minimum compressive strength on the effective cross-sectional area, \( A_{wc} \), should be at least 4000 psi (28 MPa) at 28 days. The average of any five consecutive stave strength tests should be equal to or greater than the specified concrete strength and not more than 20 percent of the tests should have a compressive strength value less than the specified strength.

The following are tests of individual staves:

(a) Compressive strength tests to determine \( P_{nc, stave} \) have been defined previously. Compressive test samples should be cut from five or more randomly selected staves. The specimens shown in Fig. R7.4.4a and R7.4.4b are full stave width with height equal to twice the stave thickness. The
compressive load is vertical, with the specimen positioned as for use in the silo wall.

(b) Flexural strength measures concrete quality and can be used instead of the compressive strength test. Bending specimens are cut from five or more randomly selected staves. The specimen length is sufficient to permit testing on a 24 in. (600 mm) simple span with concentrated midspan load. End reactions and midspan load are distributed across the full width of the specimen and are applied through padded bearing plates 2 in. (50 mm) wide. The span direction is parallel to the vertical direction of the stave in the silo. Test speed is not over 0.05 in. (0.13 mm) per minute. The bending strength is calculated as the bending modulus of rupture.

The following are tests of stave assemblies that may be used to establish properties and prove strength of assembled staves:

(a) Joint shear strength (tension)—that is, resistance to sliding—can be determined by testing a group of three staves as shown in Fig. R7.4.4a. Lateral confining forces simulate the forces applied by hoop prestress in the unloaded actual silo. The test measures the vertical pull necessary to cause the center stave to slide with respect to the two adjacent staves. The word “tension” describes this test because such joint shear and sliding result from vertical wall tension from wind load on the empty silo.

(b) Figure R7.4.4b shows a test for stave joint compressive strength $P_{nw,joint}$. It measures the compressive force that can be transferred from stave to stave across a horizontal joint. Joints and surfaces should be grouted, coated, or both, in the manner that will be used in the actual silo.

(c) Figure R7.6a is a test for determining vertical stiffness. An assembly four staves high by four wide is coated in the manner that will be used in the actual silo. Confining forces are applied to the assembly in a manner that simulates the prestress force (after losses) of the hoop rods. Lateral load is applied and deflections measured. From loads and deflections, the value of effective $EI$, and then effective wall thickness, can be calculated for use in obtaining $P_{nw,buckling}$.

(d) Figure R7.6b is a test for horizontal strength and stiffness. The assembled staves are coated similarly to how they will be used in the actual silo. Deflection and load values are measured. The effective $EI$ and wall thickness are then calculated from test results for use in silo design.

When the Fig. R7.6b test is used to determine circular bending strength for purposes of checking resistance to bending from asymmetric pressures, the hoops should be loosened an appropriate amount to simulate the loss of compression across the vertical joints that would occur from the internal pressure of the stored material.

There are no standards for the tests of stave assemblies described in R7.6. The tests are not to be considered proof tests used to assure that a certain strength specified by a designer or code authority has been met. They are rather to provide guidance to a contractor and the licensed design professional in determining what strengths might reasonably be relied upon with their particular assembly of staves and in their particular application.
Fig. R7.6a—Stave assembly test for vertical stiffness.

Fig. R7.6b—Stave assembly test for horizontal stiffness.
**Fig. R7.6c**—Solid stave.

**Fig. R7.6d**—Hollow stave.
CHAPTER 8—POST-TENSIONED CONCRETE SILOS

8.1—Scope

8.1.1 Provisions in this chapter apply to cast-in-place concrete silo walls post-tensioned with high-strength steel strands meeting the requirements of ACI 318-11 Chapter 18. Pretensioned systems, where the reinforcement is stressed before the concrete is cast, are not covered herein.

8.1.2 Requirements of Chapters 1, 4, 5, and 6 (where not in conflict with this chapter) shall apply to post-tensioned concrete silos, unless specifically stated otherwise.

8.1.3 Provide sufficient prestressed and nonprestressed reinforcement to resist all hoop tensile forces and bending moments.

8.2—Post-tensioning systems

8.2.1 Permitted post-tensioning systems for silos shall be bonded internal tendons in embedded ducts, or unbonded external strands with protective cover.

8.2.2 Internal tendons consist of strands or bars inside ducts embedded in the concrete. The embedded ducts shall be grouted after tensioning of the strands.

8.2.3 Unbonded external strands use high-strength strands that are placed around the silo and post-tensioned individually. The strands and splices shall be protected from the environment.

8.3—Tendon systems

8.3.1 Wall thickness $h$ for silos with tendons in embedded ducts shall not be less than 10 in. (250 mm). The wall thickness shall be sufficient to prevent the compression stress from exceeding $0.55f_{ci}$ at the time of initial stressing.

8.3.2 The center-to-center spacing of tendons shall not exceed three times the wall thickness $h$ or $h_1$, as applicable, but no more than 42 in. (1 m).

8.3.3 The clear spacing between embedded tendon ducts shall be at least the greatest of (a), (b), and (c):

(a) Three times the duct diameter
**SPECIFICATION**

8.3.4 The minimum clear spacing between unbonded external tendon ducts shall be at least the greatest of (a), (b), and (c):

(a) The duct diameter
(b) 3/4 in. (20 mm)
(c) The clear spacing required for external strand splicing hardware

8.3.5 Horizontal embedded tendon ducts shall be located interior to the exterior vertical nonprestressed reinforcement.

8.3.6 Stressing points shall be located at vertical pilasters on the outside of the walls, at wall intersections, or at blockouts. In determining the number of stressing locations, friction loss and local concentrations of the post-tensioning force shall be considered. Blockout sizes and locations shall be such that, at the time of initial stressing, the compressive stress in the net concrete wall area shall not exceed 0.55f’c.

**COMMENTARY**

R8.3.4 In slipform construction, embedded tendon ducts are normally placed near the center of the wall.

R8.3.5 Jacking locations should be spaced uniformly around the circumference of the silo to avoid unnecessary concentrations of stresses. Wall pilasters should be located and proportioned to avoid reverse curvature of the tendons. Radial forces from reverse curvature should be considered in the design of the pilaster and its web reinforcement. Spiral reinforcement should be placed at trumpet locations to control bursting forces.

R8.3.6 Horizontal tie reinforcement should be provided in pilasters to prevent radial forces from continuing tendons and forces from anchored tendons from splitting the wall. Ties to resist splitting forces should be provided at pilasters common to two silos, as at wall intersections shown in Fig. R8.3.6.

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![Fig. R8.3.6—Circumferential post-tensioning anchorage details.](image-url)
**SPECIFICATION**

**8.3.7** Reinforcement shall be provided at stressing locations to resist forces created by the post-tensioning operation.

**8.3.8** Tendon ducts shall be supported to maintain location within vertical and horizontal tolerances.

**8.3.9** Tendon anchor locations shall be staggered such that stressing locations do not coincide in vertical array more often than every second tendon.

**8.3.10** After stressing is completed, anchorage and end fittings shall be permanently protected against corrosion. Where protective plastic fittings are exposed to sunlight, they shall be resistant to ultraviolet light. Blockouts and pockets shall be filled with a nonshrink grout that will bond to and develop the strength of the adjacent concrete.

**8.4—Bonded tendons**

**8.4.1** Anchorages and couplers for bonded tendons shall meet the requirements of ACI 318-11, 18.21.

**8.4.2** Grout materials, proportioning, mixing, and pumping grout shall conform to ACI 318-11, 18.18, or PTI M55.1-12.

**8.5—Unbonded tendons**

**8.5.1** Anchorages and couplers for unbonded tendons shall develop 100 percent of $f_{pu}$ without exceeding the anticipated set.

**8.5.2** External, ungalvanized, unbonded tendons shall be coated with a protective lubricant and encased in protective ducts to provide protection from corrosion and ultraviolet radiation for the intended useful life of the structure. The ducts shall be continuous over the entire zone to be unbonded and shall prevent intrusion of cement paste, water, or both, and the loss of coating materials during concrete placement. The anchorage and end fittings shall be protected as specified in 8.3.9.

**8.6—Post-tensioning ducts**

**8.6.1** Tendon ducts shall be mortar-tight and nonreactive with concrete, tendons, or the grout. The minimum metal duct wall thickness shall be 0.012 in. (0.30 mm). Metal ducts shall be prebent to conform to the intended circular shape and intended radial position. Metal ducts shall be spliced at each joint. Duct splices shall be staggered and ducts shall be installed free of kinks or unspecified curvature changes. Plastic ducts shall not be spliced and shall be connected to trumpets at the anchorage points. Ducts shall be supported at intervals as necessary to meet tolerances specified in 8.13.2.

**COMMENTARY**

**R8.3.7** Horizontal (radial) tie reinforcement, shown in Fig. R8.3.6, is provided in walls between pilasters and between inner and outer main horizontal bars to resist radial tensile stresses.

**R8.3.9** Dry-packed mortar consisting of one part shrinkage-compensating cement and two parts sand is recommended for filling blockouts and pockets.

**R8.4—Bonded tendons**

**R8.4.2** Any anchorage encasement material in contact with the grout and exposed to the environment should be resistant to degradation from sunlight and have an effective life equivalent to that of the concrete.

**R8.5—Unbonded tendons**

**R8.5.1** Cyclic loading and unloading of the silo that might lead to fatigue failure of anchorages or couplers should be considered in the selection of anchorages. A discussion of the factors to consider in cases of cyclic loading that might lead to premature fatigue failures are found in ACI 215R.

**R8.6—Post-tensioning ducts**

Semi-rigid metal tendon ducts are usually available in 20 ft (6 m) lengths. Flexible plastic ducts are usually available in 400 ft (120 m) rolls. Metal ducts are typically corrugated and prebent to conform to the intended circular shape and radial position. Metal ducts require splices at approximately 20 ft (6 m) intervals.

Because plastic ducts come in 400 ft (120 m) lengths, splices are needed only at points where the ducts terminate and are connected to trumpets at anchorage points.
8.6.2 Ducts for grouted single wire, strand, or bar tendons shall have an inside diameter at least 1/4 in. (6 mm) larger than tendon diameter.

8.6.3 Ducts for grouted multiple wire, strand, or bar tendons shall have an inside cross-sectional area at least two times the net area of tendons.

8.6.4 In addition to meeting the requirements of 8.6.2 and 8.6.3, duct diameter shall be compatible with tendon installation requirements, taking into consideration curvature of wall, duct length, potential blockage, and silo configuration.

8.6.5 Ducts shall be kept clean and free of water. Grouting shall be performed as soon after post-tensioning as possible. When grouting is delayed, the exposed elements of the system shall be protected against intrusion of water or any foreign material that is detrimental to the system.

8.6.6 Ducts for grouted tendons shall be capable of transferring bond between tendons and grout to the surrounding concrete.

8.7—Details and location of nonprestressed reinforcement

8.7.1 Vertical nonprestressed reinforcement shall be provided to withstand bending moments due to post-tensioning, banding of post-tensioning reinforcement at openings, stored material loads (partially full and full), temperature, and other loading conditions to which the walls are subjected. The minimum area of vertical nonprestressed reinforcement provided shall be as required by Chapter 6.

8.7.2 Horizontal nonprestressed reinforcement shall be provided to resist bending moments in accordance with 8.10.5. Bending due to differential temperature, non-uniform pressures of stored material, asymmetric flow of material, and shrinkage and temperature effects during the period between completion of wall construction and start of post-tensioning shall be considered. The minimum total area of such reinforcement shall meet the requirements of Chapter 6.

8.8—Wall openings

8.8.1 Nonprestressed reinforcement at wall openings shall meet the requirements of 6.2.8. Axial forces, bending moments, and shear forces due to flaring of post-tensioned tendons shall be considered in the design of such reinforcement.

Plastic ducts, however, should be tied for support at more frequent intervals than semi-rigid ducts to prevent sag and shifting during concrete placement and vibration.

Concrete placing and compacting should be completed carefully to avoid punching holes in the duct, which allows concrete to fill it. In the event ducts are punctured, concrete should be removed and holes patched while the concrete is still workable.

R8.6.3 Post-tensioning suppliers typically recommend the necessary duct diameter for a given tendon profile based on anchorage, installation, and grouting requirements.
8.8.2 Where post-tensioning reinforcement would cross wall openings in pressure zones, the post-tensioning reinforcement shall be flared to pass immediately above and below the opening. The length of flare, measured from the center of the opening, shall be not more than the silo diameter or less than six times the opening height. Horizontal and vertical stress concentrations resulting from flaring of tendons around openings shall be considered for cases of both full and empty silos. Minimum spacing requirements shall be observed at all locations.

8.9—Stressing records

8.9.1 Stressing procedures and results shall be documented and the records submitted to the licensed design professional and preserved for the period specified on the project drawings and project specifications, but not less than 2 years. Records shall include type, size, and source of strand or bars; date of stressing; jacking pressures; sequence of stressing; elongation before and after anchor set; any deviations from expected response from jacking; and name of the inspector.

8.10—Design

8.10.1 Design shall satisfy both strength requirements and concrete stresses at service conditions. All critical load stages during the life of the structure from the time post-tensioning stress is first applied shall be considered.

8.10.2 Silo walls shall be designed to resist all applicable loads as specified in Chapter 6, plus the effect of post-tensioning forces during and after tensioning. Stress concentrations and edge restraint at wall junctions with silo roof, bottom, and wall intersections or other intersecting structural members, such as hopper supports, shall be considered.

8.10.3 Concrete stress shall not exceed the values provided in Chapter 6 and in ACI 318-11, 18.4, except as provided in Table 8.10.3 herein.

Table 8.10.3—Maximum permissible stresses in concrete*

<table>
<thead>
<tr>
<th>Stress Condition</th>
<th>Maximum Permissible Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial compression</td>
<td>0.225f′c</td>
</tr>
<tr>
<td>Combined axial compression and bending: extreme fiber</td>
<td>0.45f′c</td>
</tr>
<tr>
<td>Axial tension, psi (MPa)</td>
<td>6f′c (0.5f′c)</td>
</tr>
<tr>
<td>Combined axial tension and bending: extreme fiber, psi (MPa)</td>
<td>12f′c (1.0f′c)</td>
</tr>
</tbody>
</table>

*R8.10—Design

8.10.4 Tensile stress in strands or bars of tendon systems shall not exceed (a) or (b):

(a) During jacking: 0.80f′pu or 0.94f′py—whichever is smaller, but not more than maximum value recommended by the manufacturer of tendons or anchorages

(b) Immediately after anchoring: 0.70f′pu

Average stress in strands or bars of tendon systems shall not exceed (c) or (d):

R8.10.3 In post-tensioned silos, a residual compressive stress in the silo wall of approximately 40 psi (0.28 MPa) should be maintained under service load of 1.5 times initial filling pressures plus thermal loads to minimize the likelihood of open cracks (Safarian and Harris 1995).

A careful evaluation should be made of the expected cracking and the effects such cracking can have on protection of the post-tensioning tendons from weather or abrasion (Johnston 1990).
SPECIFICATION

(c) Immediately after stressing: $0.70f_{pu}$
(d) After all losses: $0.55f_{pu}$

8.10.5 *Required area of reinforcement*—The amount of post-tensioned reinforcement furnished shall be as required to resist the hoop tension due to horizontal pressures calculated according to 6.3.2.2. In silo walls subjected to combined hoop tension and bending, resistance to bending shall be provided by non-post-tensioned reinforcement.

8.10.6 Unless more accurate information is available from the manufacturer or by independent test data, the following values shall be used for the modulus of elasticity $E_p$:
- Bars: $29 \times 10^6$ psi ($200 \times 10^3$ MPa)
- Strands: $28.5 \times 10^6$ psi ($197 \times 10^3$ MPa)

8.10.7 *Nonprestressed reinforcement*

8.10.7.1 The amount of nonprestressed reinforcement shall be determined by the strength design method as required in ACI 318-11. The minimum amount of nonprestressed reinforcement provided shall be as required by 8.7 and 8.8.

8.10.7.2 Design shall not be based on a yield strength of reinforcement, $f_y$, in excess of that permitted by ACI 318-11, 9.4.

8.10.7.3 The modulus of elasticity, $E_s$, of nonprestressed reinforcement shall be taken as $29 \times 10^6$ psi ($200 \times 10^3$ MPa).

8.10.8 Where a circular wall is post-tensioned within a distance of 10 wall thicknesses of a roof, silo bottom, foundation, or other intersecting structural member, the minimum initial concrete circumferential compression stress, for a height of wall extending from $0.4\sqrt{Dh}$ to $1.1\sqrt{Dh}$, shall be:
- Edges unrestrained: 280 psi (2.0 MPa)
- Edges restrained: 140 psi (1.0 MPa)

8.10.9 *Losses*—Prestress losses that are used to establish the effective stress $f_{se}$ shall be determined using the provisions of ACI 318-11, 18.6.

8.11—*Vertical bending moment and shear due to post-tensioning*

Nonprestressed vertical reinforcement shall be provided to resist vertical bending moments and shear forces due to post-tensioning.

**COMMENTARY**

R8.10.2 ACI 318-11, 9.4, does not permit designs based on a yield strength $f_y$ in excess of 80,000 psi (550 MPa), except for prestressing steel. In addition to the upper limit of 80,000 psi (550 MPa) for yield strength of nonprestressed reinforcement, there are other limitations on the yield strength in ACI 318-11, 9.4.

R8.10.8 The height limits given in 8.10.8 for the transition zone have been obtained by shell analysis. Specified minimum levels of initial compressive stress are lower than recommended by ACI 372R because some cracking can be tolerated, whereas cracking in liquid storage tanks cannot be tolerated.

R8.10.9 Formulas for estimating losses from anchorage set and tendon elongation within the jack and for calculation of the length influenced by anchor set are found in Post-Tensioning Institute (2006) and 2014 AASHTO LRFD Bridge Design Specifications. Methods of estimating prestress losses due to elastic shortening and time-dependent losses are found in the Post-Tensioning Institute (2006), 2014 AASHTO LRFD Bridge Design Specifications, Prestressed Concrete Institute (2010), and Zia et al. (1979).

R8.11—*Vertical bending moment and shear due to post-tensioning*

Vertical bending moment will be caused whenever a tendon is tensioned due to inward movement of the wall at the tendon location, whereas the wall at some distance
8.12—Tolerances

8.12.1 The tolerance for placement of ducts at support points, relative to position shown on the project drawings, shall be ±1 in. (25 mm) vertically or horizontally.

8.12.2 The tolerance for duct vertical sag or horizontal displacement between support points shall be ±1/2 in. (13 mm).

above and below that tendon is relatively unaffected. During prestressing, vertical bending moment is also caused by the restraint to inward movement of the wall offered by the foundation, nonsliding roofs, and silo bottom slabs. These bending moments should be considered in design (ACI Committee 344 1980). Bending moments may be calculated using finite element methods or estimated using approximate methods (ACI Committee 344 1980; Timoshenko and Woinowsky-Krieger 1959; Beyer 1948; Girkmann 1959; Flugge 1957; Born 1960).
CHAPTER 9—CONCRETE STACKING TUBES

9.1—Scope
This chapter covers the design and construction of reinforced concrete stacking tubes. Requirements of Chapters 1 through 6 shall be applicable to stacking tubes unless specifically stated otherwise.

9.2—General layout
The inside diameter of a stacking tube shall be sufficient to prevent arching across the tube. Wall discharge openings shall be sufficient to prevent arching across the openings and allow free flow of material from the stacking tube.

Discharge openings over the height of the tube shall be located as to minimize the effects of circumferential bending from uneven loads. Where a concentric discharge is provided inside the tube through the reclaim tunnel roof at the bottom of the stacking tube, it shall be sufficient to prevent arching across the opening and prevent the formation of a stable rathole in the tube.

SPECIFICATION

CHAPTER R9—CONCRETE STACKING TUBES

R9.2—General layout
Stacking tubes, also known as lowering tubes, are free-standing tubular structures used to stack conical piles of granular bulk materials, similar to Fig. R9.2a. They are used to reduce dust emissions and support the stacking conveyor and headhouse. Concrete stacking tubes typically vary in diameter from 10 to 16 ft (3 to 5 m) and in wall thickness from 6 to 16 in. (150 to 400 mm). Stacking tubes typically have a round cross section, but square stacking tubes have also been constructed.

The bulk material is discharged into the top of the tube, and as material builds up in the bottom, it spills out through the wall openings to form a conical pile. Openings are generally equipped with hinged dust flaps and arranged in symmetric 90- or 180-degree patterns. The materials segregate during the stockpiling process. The less flowable fines collect in and adjacent to the tube. The coarse material collects at the foot of the pile.

Stacking tubes are frequently built directly over conveyor-equipped tunnels that reclaim material by gravity from the pile above. Typically, tunnel reclaim openings are furnished on either side of the tube. Sometimes openings are furnished directly under the tube, similar to Fig. R9.2b. Even though the latter location is less effective in reclaiming from the pile, it does inhibit plugging of the tube.

Operators of stacking tube systems frequently work on top of the piles with bulldozers to push materials toward and away from the tube during stockpiling and reclaiming. Bulldozers create additional fines and compact the material into a denser state. This action, added to densification of fines from accumulating weight, frequently causes flow problems in the tube vicinity. Such problems include:

a) Equipment and workers falling into ratholes when the material around or over a rathole collapses. A stable rathole forms when the stockpiled material gains sufficient cohesion and internal strength to arch horizontally around a flow channel and remain stable even after the flowing material is gone. Stable ratholes have been observed from 5 to 20 ft (1 m to 6 m) in width.

b) Walls of dense material that can collapse while reclaiming the material
c) Arches that prevent material from flowing into or out of the stacking tube openings
d) Arches in the upper portions of tubes with cavities below; collapse of the arches when cleaning from below can injure personnel and structurally damage the tube
e) Structural damage to tube walls and dust flaps by dozer operators reclaiming material close to the tube
f) Failure of open dust-flaps from entrapment and settlement of the surrounding pile

Stacking tube diameters, outlet opening sizes, wall thicknesses, reclaim opening configurations, and dust-flap designs that will minimize potential problems should be chosen.

Fig. R9.2a—Stacking tube elevation.

Fig. R9.2b—Reclaim tunnel under stacking tube.
**SPECIFICATION**

**R9.3—Loads**

The design of the stacking tube (Safarian and Harris 1985a,b; Wu 1975; Reimbert and Reimbert 1974) should consider the most severe probable loading condition the tube might experience from operation of the stockpiling and reclaiming system. Many loading combinations should be considered in the analysis and design of a stacking tube. The licensed design professional should consider all possible combinations of operational and environmental loads as well as stockpile loads that result from a bulldozed pile sloping down to the tube, or a full conical pile, a partially drawn down pile, or from no pile at all.

Reclaim hoppers large enough to prevent stable ratholes should be used if possible; if they are not, the tube design should consider the uneven lateral loading that might result from a pile that is complete, except for a stable rathole on one side of the tube. The design should also consider all likely configurations of bulldozed and excavated material.

Stockpiling conveyor system loads are usually transmitted to the top of the stacking tube through a headhouse structure. Eccentricity between the applied loads and tube should be considered in the design.

Stiffness of the tube relative to the conveyor structure should be assessed when analyzing longitudinal loads from the conveyor.

**9.3—Loads**

All vertical and lateral loads that are inside or outside the stacking tube shall be considered. The following loads shall be considered for the design of stacking tubes.

**9.3.1 Vertical loads at top of tube**

(a) The vertical reaction from the weight of the conveyor and headhouse structure

(b) The vertical reaction from the walkway live load, headhouse floor live load, and the weight of material carried by the conveyor

**9.3.2 Horizontal loads at top of tube**

(a) The horizontal reaction from wind on the conveyor and headhouse

(b) The horizontal reaction from seismic force on the conveyor and headhouse

**9.3.3 Vertical loads over height of tube**

(a) The weight of the tube

(b) The vertical drag force from the material stored inside the tube

(c) The vertical drag force from a complete pile of material stored outside the tube

(d) The vertical drag force from a partial pile of material stored outside the tube

**9.3.4 Horizontal loads over height of tube**

(a) Wind action on the exposed portion of the tube

(b) Seismic action on the mass of the tube

(c) Unbalanced forces acting on the tube as a result of a partial pile of material stored around the tube

(d) Seismic action on the material stored inside the tube

(e) Seismic action on the pile stored on the outside of the tube

**9.4—Load factors and strength reduction factors**

**9.4.1** Load factors, load combinations, and strength reduction factors shall be in accordance with 6.1.4.

**COMMENTARY**

**R9.4—Load factors and strength reduction factors**

Load factors used in the analysis and design of a stacking tube should be chosen to reflect the likelihood of them occurring simultaneously. Conveying equipment is often designed for large motor startup or upset condition loadings. The licensed design professional should determine which conditions are most probable during routine operations.
9.5—Tube wall design

9.5.1 The stacking tube shall be designed as a cantilevered beam fixed at the top of the foundation or reclaim tunnel roof. The minimum concrete wall strength shall be as required by the most severe combination of loads at the base of the tube and at every level.

9.5.2 The stacking tube wall shall be reinforced vertically and horizontally. For wall thicknesses of 9 in. (230 mm) or more, reinforcement shall be provided on each face. The vertical reinforcement shall resist the maximum tension resulting from the combination of vertical loads and overturning moments. In addition, the vertical reinforcement adjacent to the openings shall resist the forces and moments resulting from the bending action of the wall between the openings. The minimum ratio of vertical reinforcement to gross concrete area shall be 0.0025.

9.5.3 Horizontal reinforcement shall resist circumferential forces and moments and horizontal tension caused by the redistribution of vertical loads around the openings. Horizontal reinforcement that is discontinuous at openings shall be replaced by adding not less than 60 percent of the interrupted reinforcement above the top and 60 percent below the bottom of the opening. The minimum ratio of horizontal reinforcement to gross concrete area shall be 0.0025.

9.6—Foundation or reclaim tunnel

The foundation and reclaim tunnel shall support all horizontal and vertical loads imposed on them by the tube or by the material above and adjacent to the tube and reclaim tunnel.

R9.6—Foundation or reclaim tunnel

Stacking tubes are often supported by the reclaim tunnel for the stored material. The reclaim tunnel structure design should consider the combined loads of the stacking tube and the stored material pile.

The vertical loads (Wu 1975) that the bulk material pile imparts on the stacking tube, reclaim tunnel, and foundation should be carefully considered if the pile is supported on compressible soils while the tube is supported on rigid foundations. In this case, the stacking tube and other associated rigid structures can be subjected to extremely large negative skin friction loads as the pile settles relative to the tube, tunnel, and foundation.

Careful consideration should also be given to the effect of differential foundation settlement.
CHAPTER R10—COMMENTARY REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

**American Concrete Institute**
- ACI 117-10(15)—Specification for Tolerances for Concrete Construction and Materials and Commentary
- ACI 215R-92(97)—Considerations for Design of Concrete Structures Subjected to Fatigue Loading
- ACI 224R-01(08)—Control of Cracking in Concrete Structures
- ACI 301-16—Specifications for Structural Concrete
- ACI 305R-10—Guide to Hot Weather Concreting
- ACI 306R-10—Guide to Cold Weather Concreting
- ACI 318-14—Building Code Requirements for Structural Concrete and Commentary
- ACI 347-04—Guide to Formwork for Concrete

**ASTM International**
- ASTM C140/C140M-15—Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units

**American Association of State Highway and Transportation Officials**
- AASHTO 2014 LRFD Bridge Design Specifications

**International Organization for Standardization**

**Authored documents**


Ferguson, P. M., and Krishbaswamy, C. M., 1971, “Tensile Lap Splices, Part 2; Design Recommendations for Retaining Wall Splices and Larger Bar Splices,” Center for Highway Research, University of Texas, Austin, TX.


Hurd, M. K., 2005, Formwork for Concrete, SP-4, seventh edition, American Concrete Institute, Farmington Hills, MI, 500 pp.

International Silo Association, 1981, “Recommended Practice for Design and Construction of: Top Unloading Monolithic Farm Silos; Bottom Unloading Monolithic Farm Silos; Top Unloading Concrete Stave Farm Silos; and Bottom Unloading Concrete Stave Farm Silos,” V. 1-4, Luxemburg, WI.


Prestressed Concrete Institute, 2010, Design Handbook, seventh edition, Chicago, IL.


SPECIFICATION


As ACI begins its second century of advancing concrete knowledge, its original chartered purpose remains “to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading knowledge.” In keeping with this purpose, ACI supports the following activities:

- Technical committees that produce consensus reports, guides, specifications, and codes.
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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org
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