Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials (ACI 313-97)

Reported by ACI Committee 313

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This ACI standard practice gives material, design, and construction requirements for concrete silos, stave silos, and stacking tubes for storing granular materials. It includes design and construction recommendations for cast-in-place or precast and conventionally reinforced or post-tensioned silos.

Silos and stacking tubes are special structures, posing special problems not encountered in normal building design. While this standard refers to Building Code Requirements for Structural Concrete (ACI 318) *for many requirements, it puts forth special requirements for the unique cases of static and dynamic loading from funnel flow, mass flow, concentric flow, and asymmetric flow in silos, and the special loadings on stacking tubes. The standard includes requirements for seismic design and hopper bottom design.*

Keywords: asymmetric flow; bins; circumferential bending; concrete; concrete construction; dead loads; dynamic loads: earthquake resistant structures; formwork (construction); funnel flow; granular materials; hoppers; jumpforms; lateral loads: loads (forces); lowering tubes; mass flow; overpressure; quality control; reinforced concrete; reinforcing steels; silos; slipform construction; stacking tubes; stave silos; stresses; structural analysis; structural design; thermal stresses; walls.

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This standard was submitted to letter ballot of the committee and was approved in accordance with Institute standardization procedures.

ACI 313-97 was adopted as a standard of the American Concrete Institute on January 7, 1997, to supersede ACI 313-91, in accordance with the Institute's standardization procedure.

CHAPTER 1—GENERAL

1.1—Introduction

This document, which covers design and construction of concrete silos and stacking tubes for storing granular materials, replaced the 1968 ACI Committee 313 Report 65-37 and was adopted as an ACI Standard in March 1977 as ACI 313-77. It was subsequently revised in 1983 and 1991. The current revision reflects the most recent state-of-the-art in structural design, detail, and construction of concrete silos and stacking tubes.

Static pressures are exerted by the stored material at rest and shall be computed by methods presented. Flow pressures that differ from static pressures are exerted by the stored material during flow and also shall be computed by the methods presented.

Design of the structures shall consider both static and flow loading.

Applicable sections of ACI 318 shall apply.

1.2—Definitions

The term “silo,” as used herein, applies to any upright container for storing bulk granular material.

Alternate names such as “bins” and “bunkers” are used in different localities, but for purposes of this Standard, all such structures are considered to be silos.

“Stacking tubes” or “lowering tubes” are relatively slender, free-standing, tubular concrete structures used to stack conical piles of granular materials. See Commentary Section 7.2.

“Slipformed” silos are constructed using a typically 4 ft. (1.2 m) high continuously moving form.

“Jumpformed” silos are constructed using three typically 4 ft. (1.2 m) high fixed forms. The bottom lift is jumped to the top position after the concrete hardens sufficiently.

A “hopper” is the sloping, walled portion at the bottom of a silo.

“Stave silos” are silos assembled from small precast concrete units called “staves,” usually tongued and grooved, and held together by exterior adjustable steel hoops.

Other special terms are defined in the Commentary.

1.3—Scope

This Standard covers the design and construction of concrete silos and stacking tubes for storing granular materials. Silos for storing of ensilage have different requirements and are not included. However, industrial stave silos for storage of granular materials are included.

Coverage of precast concrete is limited to that for industrial stave silos.

The Standard is based on the strength design method. Provisions for the effect of hot stored material are included. Explanations of requirements of the Standard, additional design information, and typical details are found in the Commentary.

1.4—Drawings, specifications, and calculations

1.4.1 Project drawings and project specifications for silos shall be prepared under the direct supervision of and bear the seal of the engineer.

1.4.2 Project drawings and project specifications shall show all features of the work, naming the stored materials assumed in the design and stating their properties, and including the size and position of all structural components, connections and reinforcing steel, the required concrete strength, and the required strength or grade of reinforcing and structural steel.

CHAPTER 2—MATERIALS

2.1—General

All materials and tests of materials shall conform to ACI 301, except as otherwise specified.

2.2—Cements

Cement shall conform to ASTM C 150 (Types I, IA, II, IIAA, III and IIIA), ASTM C 595 (excluding Types S, SA, IS and IS-A), or ASTM C 845.

2.3—Aggregates

The nominal maximum size of aggregate for slipformed concrete shall not be larger than one-eighth of the narrowest dimension between sides of wall forms, nor larger than three-eighths of the minimum clear spacing between individual reinforcing bars or vertical bundles of bars.

2.4—Water

Water for concrete shall be potable, free from injurious amounts of substances that may be harmful to concrete or steel. Non-potable water may be used only if it produces mortar cubes, prepared according to ASTM C 109, having 7- and 28-day strengths equal to at least the strength of similar specimens made with potable water.

2.5—Admixtures

2.5.1 Air-entraining, water reducing, retarding or accelerating admixtures that may be required for specific construction conditions shall be submitted to the engineer for approval prior to their use.

2.6—Metal

2.6.1 Hoop post-tensioning rods shall be hot-dip galvanized or otherwise protected from corrosion. 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 A 123.

2.6.2 Malleable iron castings shall conform to ASTM A 47.

2.7—Precast concrete staves

2.7.1 Materials for staves manufactured by the dry-pack vibratory method shall conform to ASTM C 55.

2.7.2 Before a stave is used in a silo, drying shrinkage shall have caused the stave to come within 90 percent of its equilibrium weight and length as defined by ASTM C 426.

2.8—Tests of materials

2.8.1 Tests of materials used in concrete construction shall be made as required by the applicable building codes and the engineer. All material tests shall be by an agency acceptable to the engineer.

2.8.2 Tests of materials shall be made 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 engineer or owner for at least 2 years after completion of the construction.

2.8.3 *Silo stave tests*—The results of mechanical tests of silo staves and stave assemblies shall be used as criteria for structural design of stave silos. The application of the test results is given in Chapter 5. Example methods of performing the necessary tests are given in the Commentary.

CHAPTER 3—CONSTRUCTION REQUIREMENTS

3.1—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.

3.2—Concrete quality

3.2.1 The compressive strength specified for cast-in-place concrete shall be not less than 4000 psi (28 MPa) at 28 days. The compressive strength specified for concrete used in precast units shall be not less than 4000 psi (28 MPa) at 28 days. The acceptance strength shall conform to ACI 301.

3.2.2 Exterior concrete in silo or stacking tube walls that will be exposed to cycles of freezing and thawing shall be air entrained.

3.3—Sampling and testing concrete

3.3.1 For strength tests, at least one set of three specimens shall be made and tested of the concrete placed during each 8 hrs or fraction thereof.

3.3.2 Accelerated curing and testing of concrete cylinders shall conform to ASTM C 684.

3.4—Details and placement of reinforcement

3.4.1 Horizontal tensile reinforcement in silo and hopper walls shall not be bundled.

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

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

3.4.4 The minimum concrete cover provided for reinforcement shall conform to ACI 318 for cast-in-place concrete (non-prestressed), except as noted in Section 4.3.10.

3.5—Forms

3.5.1 The design, fabrication, erection and operation of a slipform or jumpform system for a silo or stacking tube wall shall meet the appropriate requirements of ACI 347.

3.5.2 Forms shall be tight and rigid to maintain the finished concrete wall thickness within the specified dimensional tolerances given in Section 3.9.

3.5.3 Slipform systems shall include an approved means of determining and controlling level at each jack unit.

3.6—Concrete placing and finishing

3.6.1 Construction joints in silos shall not be permitted unless shown on the project drawings or specifically approved by the engineer.

3.6.2 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.

3.6.3 As soon as forms have been raised (or removed), vertical wall surfaces shall be finished by filling voids with mortar made from the same materials (cement, sand and water) as used in the wall and by applying a "smooth rubbed finish" in accordance with Section 10.3.1 of ACI 301.

3.7—Concrete protection and curing

3.7.1 Cold weather concreting may begin when temperature is 24°F (-4°C) and rising, provided that the protection method will allow 500 psi (4 MPa) compressive strength gain before the concrete temperature drops below 32°F (0°C). For cold weather concreting, ACI 306R recommendations shall be used where applicable.

3.7.2 In hot weather, measures shall be taken to prevent drying of the concrete before application of a curing compound. For hot weather concreting, ACI 305R recommendations shall be used where applicable.

3.7.3 Where the wall surfaces will remain moist naturally for 5 days, no curing measures are required. Otherwise, curing measures conforming to ACI 308 shall be used.

3.7.4 Where curing measures are required, they shall be provided before the exposed exterior surfaces begin to dry, but after the patching and finishing have been completed. Wall surfaces shall be protected against damage from rain, running water or freezing.

3.7.5 Curing compounds shall not be used on the inside surfaces of silos unless required by the project drawings or project specifications, or unless specifically approved by the engineer. When curing of interior surfaces is required, non-toxic compounds and ventilation or other methods of assuring worker safety shall be used.

3.7.6 Curing compound shall be a non-staining, resin base type complying with ASTM C 309, Type 2, and shall be applied in strict accordance with the manufacturer's instructions. Waxbase curing compounds shall not be permitted. If a curing compound is used on the interior surfaces of silos to be used for storing materials for food, the compound shall be non-toxic, non-flaking and otherwise non-deleterious.

3.8—Lining and coating

3.8.1 Linings or coatings used to protect the structure from wear and abrasion, or used to enhance flowability, shall be composed of materials that are non-contaminating to the stored material.

3.8.2 Lining materials installed in sheet form shall be fastened to the structure with top edges and side seams sealed to prevent entrance of stored material behind the lining.

3.8.3 Coatings used as barriers against moisture or as barriers against chemical attack shall conform to ACI 515.1R.

3.9—Tolerances for slipformed and jumpformed structures

3.9.1 Translation of silo centerline or rotational (spiral) of wall:

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)

3.9.2 Inside diameter or distance between walls:

Per 10 ft. (3 m) of diameter or distance. . . . 1/2 in. (12 mm)
but not more than. . . . . 3 in. (75 mm)

3.9.3 Cross-sectional dimensions of:

Walls. . . . . +1 in. (25 mm)
or. . . . . -3/8 in. (10 mm)

3.9.4 Location of openings, embedded plates or anchors:

Vertical. . . . . $\pm$3 in. (75 mm)
Horizontal. . . . . $\pm$1 in. (25 mm)

3.9.5 Other tolerances to meet ACI 117.

CHAPTER 4—DESIGN

4.1—Notation

Consistent units must be used in all equations. Except where noted, units may be either all U.S. Customary or all metric (SI).

A = effective tension area of concrete surrounding the tension reinforcement and having the same centroid as that reinforcement, divided by the number of bars. When the reinforcement consists of different bar sizes, the number of bars shall be computed as the total area of reinforcement divided by the area of the largest bar used. See Fig. 4-3.

D = dead load or dead load effect, or diameter

E_c = modulus of elasticity for concrete

L = live load or live load effect

M_t = thermal bending moment per unit width or height of wall (consistent units)

P_{nw} = nominal axial load strength of wall per unit perimeter

R = ratio of area to perimeter of horizontal cross-section of storage space

T = temperature or temperature effect

ΔT = temperature difference between inside face and outside face of wall

U = required strength

V = total vertical frictional force on a unit length of wall perimeter above the section in question

Y = depth from the equivalent surface of stored material to point in question. See Fig. 4-2.

d_c = thickness of concrete cover taken equal to 2.5 bar diameters, or less. See Fig. 4-3.

e = base of natural logarithms

f_c' = compressive strength of concrete

f_s = calculated stress in reinforcement at initial (filling) pressures

h = wall thickness

h_h = height of hopper from apex to top of hopper. See Fig. 4-2.

h_s = height of sloping top surface of stored material. See Fig. 4-2.

h_y = depth below top of hopper to point in question. See Fig. 4-2.

k = p/q

p = initial (filling) horizontal pressure due to stored material

p_n = pressure normal to hopper surface at a depth h_y below top of hopper. See Fig. 4-2.

q = initial (filling) vertical pressure due to stored material
q_o = initial vertical pressure at top of hopper
q_y = vertical pressure at a distance h_y below top of hopper. See Fig. 4-2.
s = bar spacing, in. See Fig. 4-3.
v_n = initial friction force per unit area between stored material and hopper surface calculated from Eq. (4-8) or (4-9)
w = design crack width, in. or lateral wind pressure
α = angle of hopper from horizontal. See Fig. 4-2.
α_c = thermal coefficient of expansion of concrete
γ = weight per unit volume for stored material
θ = angle of hopper from vertical. See Fig. 4-2.
μ' = coefficient of friction between stored material and wall or hopper surface
ν = Poisson's ratio for concrete, assumed to be 0.2
ϕ = strength reduction factor or angle of internal friction
ϕ' = angle of friction between material and wall and hopper surface
ρ = angle of repose. See Fig. 4-2.

4.2—General

4.2.1 Silos and stacking tubes shall be designed to resist all applicable loads, including:

(a) Dead load: Weight of the structure and attached items including equipment dead load supported by the structure.

(b) Live load: Forces from stored material (including overpressures and underpressures from flow), floor and roof live loads, snow, equipment loads, positive and negative air pressure, either wind or seismic load (whichever controls), and forces from earth or from materials stored against the outside of the silo or stacking tube (see also Section 4.8).

(c) Thermal loads, including those due to temperature differences between inside and outside faces of wall.

(d) Forces due to differential settlement of foundations.

4.2.2 Structural members shall be proportioned for adequate strength and stiffness. Stresses shall be calculated and combined using methods provided in Chapter 4 for silos and Chapter 7 for stacking tubes. Design methods for reinforced or prestressed concrete members such as foundations, floors, roofs, and similar structures not covered herein shall be in accordance with ACI 318.

4.2.3 The thickness of silo or stacking tube walls shall be not less than 6 in. (150 mm) for cast-in-place concrete, nor less than 2 in. (50 mm) for precast concrete.

4.2.4 ***Load factors and strength reduction factors***

4.2.4.1 Load factors for silo or stacking tube design shall conform to those specified in ACI 318. The weight of and pressures due to stored material shall be considered as live load.

4.2.4.2 For concrete cast in stationary forms, strength reduction factors, ϕ, shall be as given in ACI 318. For slipforming, unless continuous inspection is provided, strength reduction factors given in ACI 318 shall be multiplied by 0.95.

4.2.5 *Pressure zone*—The pressure zone shall be the part of the wall that is required to resist forces from stored material, hopper, or hopper forming fill.

4.3—Details and placement of reinforcement

4.3.1 Where slipforming is to be used, reinforcement arrangement and details shall be as simple as practical to facilitate placing and inspection during construction.

4.3.2 Reinforcement shall be provided to resist all bending moments, including those due to continuity at wall intersections, alone or in combination with axial and shear forces.

4.3.3 Horizontal ties shall be provided as required to resist forces that tend to separate adjoining silos of monolithically cast silo groups.

4.3.4 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. In no case shall the total horizontal reinforcement area be less than 0.0025 times the gross concrete area per unit height of wall.

4.3.5 Vertical reinforcement in the silo wall shall be #4 (#10M diameter) bars or larger, and the minimum ratio of vertical reinforcement to gross concrete area shall be not less than 0.0020. Horizontal spacing of vertical bars shall not exceed 18 in. (450 mm) for exterior walls nor 24 in. (600 mm) for interior walls of monolithically cast silo groups.

Vertical steel shall be provided to resist wall bending moment at the junction of walls with silo roofs and bottoms. In slipform construction, jackrods, to the extent bond strength can be developed, may be considered as vertical reinforcement when left in place.

4.3.6 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 (if needed to resist wind or seismic forces or forces from material stored against the bottom of the wall) at the bottom of walls.

4.3.7 Lap splices of reinforcing bars, both horizontal and vertical, shall be staggered in circular silos. Adjacent hoop reinforcing lap splices in the pressure zone shall be staggered horizontally by not less than one lap length nor 3 ft. (1 m), and shall not coincide in vertical array more frequently than every third bar. Lap splices of vertical and, whenever possible, horizontal reinforcing bars shall be staggered in non-circular silos.

4.3.8 ***Reinforcement at wall openings***

4.3.8.1 *Openings in pressure zone*

(a) Unless all areas of stress concentration are analyzed and evaluated and reinforcement provided accordingly, horizontal reinforcement interrupted by an opening shall be replaced by adding at least 1.2 times the area of the interrupted horizontal reinforcement, one-half above the opening and one-half below (see also Section 4.3.8.3).

(b) Unless determined otherwise by analysis, additional vertical reinforcement shall be added to the wall on each side of the opening. The added reinforcement shall be calculated by assuming a narrow strip of wall, $4h$ in width on each side of the opening, to act as a column, unsupported within the opening height and carrying its own share of the vertical load

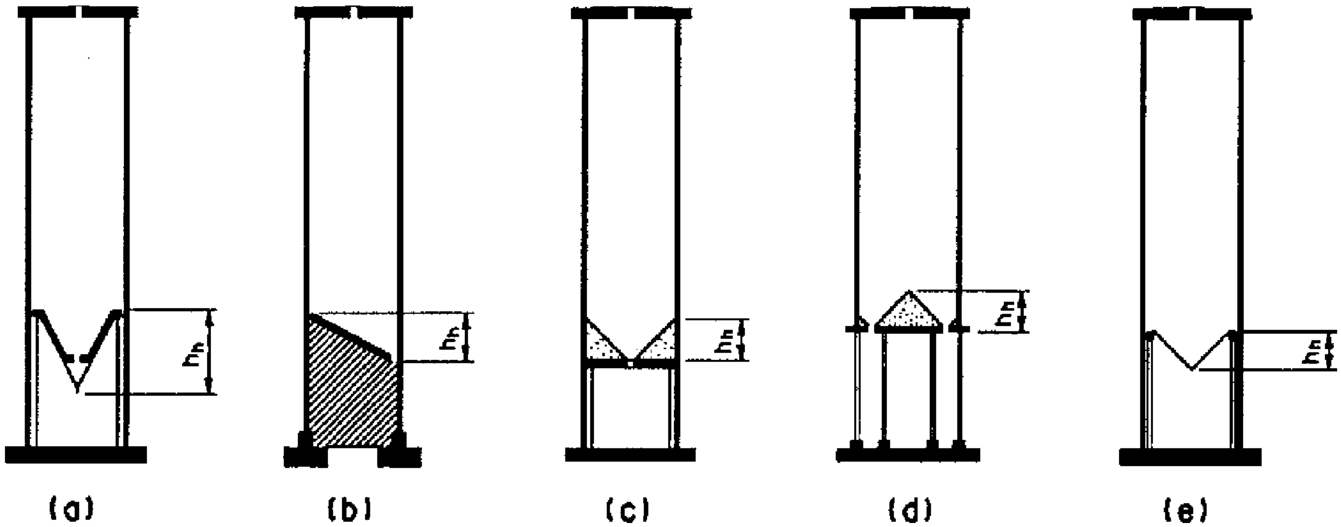

Fig. 4-1—Vertical cross-sections of silos

plus one-half of the loads occurring over the wall opening within a height equal to the opening width. The added reinforcement area for each side shall not be less than one-half of the reinforcement area eliminated by the opening.

4.3.8.2 *Openings not in pressure zone*—Unless all areas of stress concentration are analyzed and evaluated, and reinforcement provided accordingly, the amount of added horizontal reinforcement above and below the opening shall each be not less than the normal horizontal reinforcement area for a height of wall equal to one-half the opening height.

Vertical reinforcement adjacent to openings below the pressure zone shall be determined in the manner given for openings in the pressure zone [Section 4.3.8.1 (b)].

4.3.8.3 *Reinforcement development at openings*—Added reinforcement to replace load-carrying reinforcement that is interrupted by an opening shall extend in each direction beyond the opening. The extension each way shall be:

(a) Sufficient to develop specified yield strength of the reinforcement through bond;

(b) Not less than 24 in. (600 mm); and,

(c) Not less than one-half the opening dimension in a direction perpendicular to the reinforcement bars in question, unless determined otherwise by analysis.

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

4.3.9 The clear vertical spacing between horizontal bars shall be not less than 2 in. (50 mm). The center-to-center spacing of such bars shall be not less than 5 bar diameters. In addition, the vertical spacing of horizontal bars in slipformed walls shall be large enough to allow time for placing and tying of bars during slipform movement.

4.3.10 The lap length of horizontal reinforcement of silo walls shall be not less than:

(a) The lap length specified by ACI 318 for Class B splices for non-circular silos with unstaggered splices.

(b) The lap length specified by ACI 318 for Class B splices plus 6 in. (150 mm) for circular silos (or any cell with circular reinforcing).

In determining the lap length, horizontal bars in jumpformed structures shall be assumed as top bars. Concrete thickness covering the reinforcement at lap splices shall be at least that specified in ACI 318 for that particular splice, but not less than 1 in. (25 mm). In addition, the horizontal distance from the center of the bars to the face of wall shall be not less than 2.5 bar diameters.

Lap splices shall not be used in zones where the concrete is in tension perpendicular to the lap, unless adequate reinforcement is provided to resist tension perpendicular to the lap.

4.3.11 In singly-reinforced walls, the reinforcement to resist thermal bending moment shall be added to the main reinforcement.

In walls with two-layer reinforcement, the reinforcement to resist thermal bending moment shall be added to the layer nearest the colder surface.

4.3.12 In singly-reinforced circular walls, the main hoop reinforcement shall be placed nearer the outer face. Walls shall not be singly-reinforced, unless such reinforcement is designed and positioned to resist all bending moments in addition to hoop tension.

4.4—Loads

4.4.1 ***Stored material pressures and loads***

4.4.1.1 Stored material pressures, and loads against silo walls and hoppers, shall be determined using the provisions given in Sections 4.4.2 through 4.4.4. Pressures to be considered shall include initial (filling) pressures, air pressures and pressure increases or decreases caused by withdrawal of material from concentric or eccentric outlets. For monolithically cast silo groups, the condition of some silos full and some silos empty shall be considered.

4.4.1.2 Any method of pressure computation may be used that gives horizontal and vertical design pressures and frictional design forces comparable to those given by Sections 4.4.2 and 4.4.3.

4.4.1.3 Where properties of stored materials vary, pressures shall be computed using combinations of properties given in Section 4.4.2.1(e).

4.4.2 ***Pressures and loads for walls***

4.4.2.1 Pressures due to initial filling shall be computed by Janssen's method.

(a) The initial vertical pressure at depth ***Y*** below the surface of the stored material shall be computed by

$$q = \frac{\gamma R}{\mu' k}[1 - e^{-\mu' k Y/R}] \qquad (4\text{-}1)$$

(b) The initial horizontal pressure at depth ***Y*** below the surface of the stored material shall be computed by

$$p = kq \qquad (4\text{-}2)$$

(c) The lateral pressure ratio ***k*** shall be computed by

$$k = 1 - \sin\phi \qquad (4\text{-}3)$$

where ϕ is the angle of internal friction.

(d) The vertical friction load per unit length of wall perimeter at depth ***Y*** below the surface of the material shall be computed by

$$V = (\gamma Y - q)R \qquad (4\text{-}4)$$

(e) Where γ, μ' and ***k*** vary, the following combinations shall be used with maximum γ:

(1) Minimum μ' and minimum ***k*** for maximum vertical pressure ***q***.

(2) Minimum μ' and maximum ***k*** for maximum lateral pressure ***p***.

(3) Maximum μ' and maximum ***k*** for maximum vertical friction force ***V***.

4.4.2.2 *Concentric flow*—The horizontal wall design pressure above the hopper for concentric flow patterns shall be obtained by multiplying the initial filling pressure computed according to Eq. (4-2) by a minimum overpressure factor of 1.5. Lower overpressure factors may be used for particular cases where it can be shown that such a lower factor is satisfactory. In no case shall the overpressure factor be less than 1.35.

4.4.2.3 *Asymmetric flow*—Pressures due to asymmetric flow from concentric or eccentric discharge openings shall be considered.

4.4.3 *Pressures and loads for hoppers*

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

(a) The initial vertical pressure at depth h_y below top of hopper shall be computed by

$$q_y = q_o + \gamma h_y \qquad (4\text{-}5)$$

where q_o is the initial vertical pressure at the top of the hopper computed by Eq. (4-1).

(b) The initial pressure normal to the hopper surface at a depth h_y below top of hopper shall be the larger of

$$P_n = \frac{q_y \tan\theta}{\tan\theta + \tan\phi'} \qquad (4\text{-}6)$$

or

$$P_n = q_y(\sin^2\theta + k\cos^2\theta) \qquad (4\text{-}7)$$

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

$$\nu_n = p_n \tan\phi' \qquad (4\text{-}8)$$

when Eq. (4-6) is used to determine p_n and by

$$\nu_n = q_y(1 - k)\sin\theta\cos\theta \qquad (4\text{-}9)$$

when Eq. (4-7) is used to determine p_n.

4.4.3.2 *Funnel flow hoppers*—Design pressures at and below the top of a funnel flow hopper shall be computed using Eq. (4-5) through (4-9) with q_o multiplied by an overpressure factor of 1.35 for concrete hoppers and 1.50 for steel hoppers. The vertical design pressure at the top of the hopper need not exceed γY.

4.4.3.3 *Mass flow hoppers*—Design pressures at and below the top of mass flow hoppers shall be considered. In no case shall the design pressure be less than computed by Section 4.4.3.2.

4.4.3.4 In multiple outlet hoppers, the condition that initial pressures exist above some outlets and design pressures exist above others shall be considered.

4.4.4 *Pressures for flat bottoms*

4.4.4.1 Initial filling pressures on flat bottoms shall be computed by Eq. (4-1) with ***Y*** taken as the distance from the top of the floor to the top of the material.

4.4.4.2 Vertical design pressures on flat bottoms shall be obtained by multiplying the initial filling pressures computed according to Section 4.4.4.1 by an overpressure factor of 1.35 for concrete bottoms and 1.50 for steel bottoms. The vertical design pressure need not exceed γY.

4.4.5 Design pressures in homogenizing silos shall be taken as the larger of:

(a) Pressures computed according to Sections 4.4.2 and 4.4.3 neglecting air pressure.

(b) Pressures computed by

$$p = q = 0.6\gamma Y \qquad (4\text{-}10)$$

where γ is the unaerated weight per unit volume of the material.

4.4.6 The pressures and forces calculated as prescribed in Sections 4.4.1 through 4.4.5 are due only to stored material. The effects of dead, floor and roof live loads, snow, thermal, either wind or seismic loads, internal air pressure and forces from earth or materials stored against the outside of the silo shall also be considered in combination with stored material loads.

4.4.7 *Wind forces*—Wind forces on silos shall be considered generated by positive and negative pressures acting concurrently. The pressures shall be not less than 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.

4.4.8 *Earthquake forces*—Silos to be located in earthquake zones shall be designed and constructed to withstand lateral seismic forces calculated using the provisions of the Uniform Building Code, except that the effective weight of the stored material shall be taken as 80 percent of the actual weight. The centroid of the effective weight shall coincide with the centroid of the actual volume. The fundamental period of vibration of the silo shall be estimated by any rational method.

4.4.9 *Thermal loads*—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 computed by

$$M_t = E_c h^2 \alpha_c \Delta T / 12(1 - \nu) \qquad (4\text{-}11)$$

E_c may be reduced to reflect the development of a cracked moment of inertia if such assumptions are compatible with the planned performance of the silo wall at service loads.

4.5—Wall design

4.5.1 *General*—Silo walls shall be designed for all tensile, compressive, shear and other loads and bending moments to which they may be subjected. Minimum wall thickness for all silos shall be as prescribed in Section 4.2.3. Required wall thickness for stave silos shall be determined by the methods of Chapter 5. Minimum wall reinforcement for cast-in-place silos shall be as prescribed in Section 4.3.

4.5.2 Walls shall be designed to have design strengths at all sections at least equal to the required strength calculated for the factored loads and forces in such combinations as are stipulated in ACI 318 and prescribed herein.

Where the effects of thermal loads $\boldsymbol{T}$ are to be included in design, the required strength $\boldsymbol{U}$ shall be at least equal to

$$U = 1.4D + 1.4T + 1.7L \qquad (4\text{-}12)$$

4.5.3 Design of walls subject to axial load or to combined flexure and axial load shall be as prescribed in ACI 318.

4.5.4 ***Circular walls in pressure zone***

4.5.4.1 For concentric flow, circular silo walls shall be considered in direct hoop tension due to horizontal pressures computed according to Section 4.4.2.2.

4.5.4.2 For asymmetric flow, circular silo walls shall be considered in combined tension and bending due to non-uniform pressures. In no case shall the wall hoop reinforcement be less than required by Section 4.5.4.1.

4.5.4.3 For homogenizing silos, circular silo walls shall be considered in direct hoop tension due to horizontal pressures computed according to Section 4.4.5. In partially fluidized silos, bending moments due to non-uniform pressures

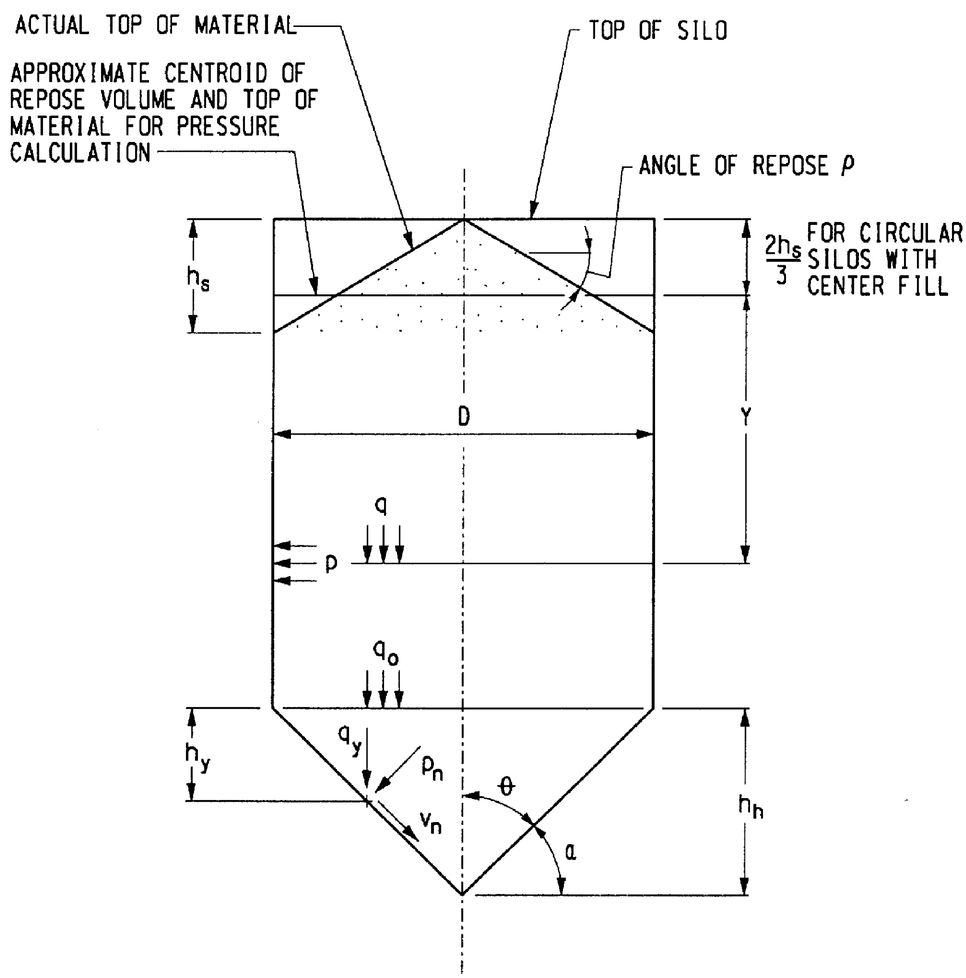

Fig. 4-2—Silo dimensions for use in calculation of pressures and loads for walls and hoppers

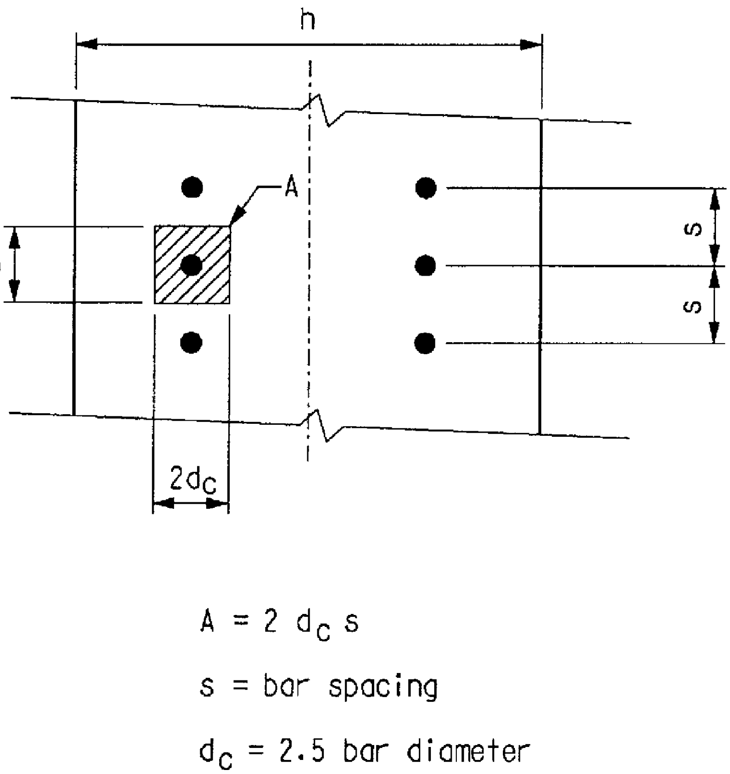

Fig. 4-3—Effective tension area "A" for crack width computation

shall be considered. In no case shall the wall hoop reinforcement be less than required by Section 4.5.4.1.

4.5.5 Walls in the pressure zone of square, rectangular, or polygonal silos shall be considered in combined tension, flexure and shear due to horizontal pressure from stored material.

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

4.5.7 The compressive axial load strength per unit area for walls in which buckling (including local buckling) does not control shall be computed by

$$P_{nw} = 0.55\phi f_c' \tag{4-13}$$

in which strength reduction factor ϕ is 0.70.

4.5.8 For walls in the pressure zone, wall thickness and reinforcing shall be so proportioned that, under initial (filling) pressures, the design crack width computed at 2.5 bar diameter from the center of bar ($\boldsymbol{d_c}$ = 2.5 bar diameter) shall not exceed 0.010 in. (0.25 mm). The design crack width (inch) shall be computed by

$$w = 0.0001 f_s \sqrt[3]{d_c A} \tag{4-14}$$

4.5.9 The continuity between a wall and suspended hopper shall be considered in the wall design.

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

4.5.11 Walls at each side of opening shall be designed as columns, the column width being limited to no more than four times the wall thickness.

4.6—Hopper design

4.6.1 *Loads*—Silo hoppers shall be designed to withstand loading from stored materials computed according to Section 4.4.3 and other loads. Earthquake loads, if any, shall be determined using provisions of Section 4.4.8. Thermal stresses, if any, due to stored material shall also be considered.

4.6.2 ***Suspended hoppers***

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

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

4.6.2.3 The design crack width of reinforced concrete suspended hoppers shall meet the requirements of Section 4.5.8.

4.6.2.4 Wall thickness of suspended reinforced concrete hoppers shall not be less than 5 in. (125 mm).

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

4.6.3 ***Flat bottoms***

4.6.3.1 For horizontal bottom slabs, the design loads are dead load, vertical design pressure (from stored material) computed at the top of the slab according to Section 4.4.4.2, and the thermal loading (if any) from stored material. If hopper forming fill is present, the weight of the fill shall be considered as dead load.

4.7—Column design

The area of vertical reinforcement in columns supporting silos or silo bottoms shall not exceed 0.02 times gross area of column.

4.8—Foundation design

4.8.1 Except as prescribed below, silo foundations shall be designed in accordance with ACI 318.

4.8.2 It shall be permissible to neglect the effect of overpressure from stored material in the design of silo foundations.

4.8.3 Unsymmetrical loading of silo groups and the effect of lateral loads shall be considered in foundation design.

4.8.4 Differential settlement of silos within a group shall be considered in foundation, wall, and roof design.

CHAPTER 5—CONCRETE STAVE INDUSTRIAL SILOS

5.1—Notation

Consistent units must be used in all equations. Except where noted, units may be either all U.S. Customary or all metric (SI).

A_s =area of hoop reinforcement, per unit height
A_w =effective cross-sectional area (horizontal projection) of an individual stave
D =dead load or dead load effect, or diameter
E =modulus of elasticity
F_u =required hoop or horizontal tensile strength, per unit height of wall
L =live load or live load effect
M =stored material load stress
M_{pos}, M_{neg} =positive (tension inside face) and negative (tension outside face) circumferential bending moments, respectively, caused by asymmetric filling or emptying under service load conditions
M_θ =circular bending strength for an assembled circular group of silo staves, per unit height; the statical moment or sum of absolute values of $M_{\theta,pos}$ and $M_{\theta,neg}$
$M_{\theta,pos}$, $M_{\theta,neg}$ =the measured or computed bending strengths in the positive moment zone and negative moment zone, respectively
P_{nw} =nominal axial load strength of wall per unit perimeter
$P_{nw,buckling}$ =strength of the stave wall as limited by buckling
$P_{nw,joint}$ =strength of the stave wall as limited by the stave joint
$P_{nw,stave}$ =strength of the stave wall as limited by the shape of the stave
W =tension force per stave from wind over-turning moment
f_y =specified yield strength of non-prestressed reinforcement
h =wall thickness
h_{st} =height of stave specimen for compression test. See Figs. 5-1 and 5-2.
w =design crack width, in., or lateral wind pressure
ϕ =strength reduction factor or angle of internal friction

5.2—Scope

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

5.3—Coatings

5.3.1 Interior coatings, where specified, shall consist of a single operation, three-coat plaster (parge) application of fine sand and cement worked into the stave surface and joints to become an integral part of the wall. Final finish shall be steel troweled smooth.

5.3.2 Exterior coatings, where specified, shall consist of a thick cement slurry brushed or otherwise worked into the surface and joints of the staves to provide maximum joint rigidity and water-tightness.

5.4—Erection tolerances

5.4.1 Translation of silo centerline or rotation (spiral) of vertical stave joints:

Per 10 ft. (3 m) of height. . . . . 1 in. (25 mm)

5.4.2 Bulging of stave wall:

For any 10 ft. (3 m) of height. . . . . 1 in. (25 mm)

For entire height. .3 in. (75 mm)

5.4.3 Inside diameter of silo:

Per 10 ft. (3 m) of diameter. . . . . $\pm$1 in. (25 mm)

5.4.4 Hoops:

Number of hoop. 0

Spacing of hoop. . . . .$\pm$1 in. (25 mm)

5.5—Wall design

5.5.1 *Loads, design pressures, and forces*—Loads, design pressures and vertical forces for stave silo design shall be determined as specified in Chapter 4. Overpressure or impact (whichever controls), and the effects of eccentric discharge openings, wind, thermal stress (if any), and seismic action shall all be considered.

5.5.2 *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 given in Section 4.2.3.

5.5.3 *Circular bending*—Unless a more detailed analysis is performed, the circular bending strength M_θ for a given stave design shall satisfy the following:

a) In the case of wind acting on an unbraced wall:

$$M_\theta \geq 0.75(1.7)D^2 w/8 \quad (5\text{-}1)$$

where the product 0.75 (1.7) is the load factor.

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

$$M_\theta \geq 1.7(M_{pos} + |M_{neg}|) \quad (5\text{-}2)$$

$$M_{\theta,pos} \geq 1.0 M_{pos} \quad (5\text{-}3)$$

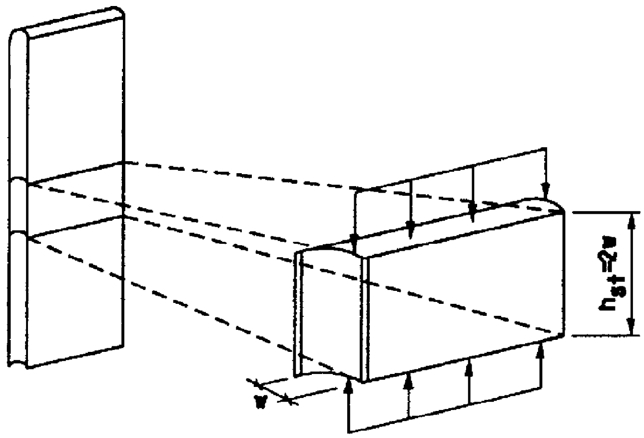

Fig. 5-1—Solid stave

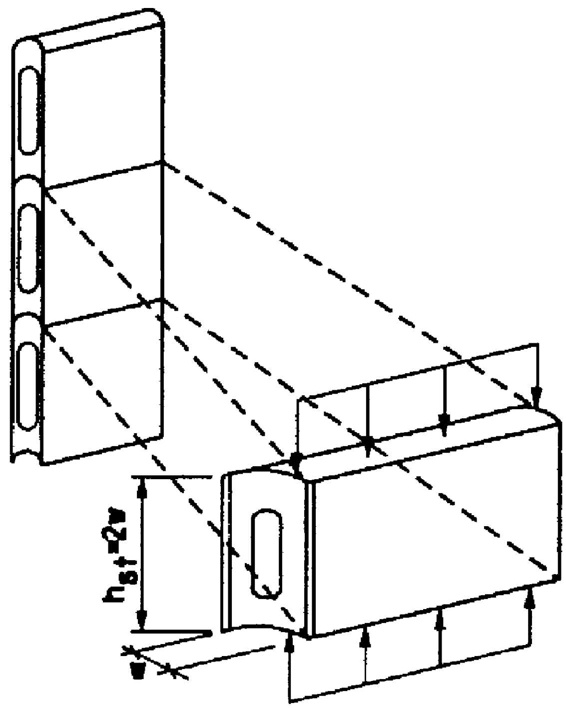

Fig. 5-2—Hollow stave

where 1.7 and 1.0 are load factors (see Commentary), and M_{pos} + M_{neg} are determined from the methods of Chapter 4 or other published methods.

The following strength relationships shall be satisfied also:

$$0.875(\phi A_s f_y - F_u)h \geq M_\theta \tag{5-4}$$

$$0.375(\phi A_s f_y - F_u)h \geq M_{\theta,pos} \tag{5-5}$$

Unless Eq. (5-4) and Eq. (5-5) are satisfied, a complete circular assembly of staves (Commentary Fig. 5-D) shall be tested to prove satisfactory strength.

5.5.4 *Compression and buckling*—The nominal axial load strength per unit perimeter, P_{nw} shall be taken as the smaller of:

$$P_{nw} = 0.50\phi P_{nw,\,stave} \tag{5-6}$$

$$P_{nw} = 0.55\phi P_{nw,\,joint} \tag{5-7}$$

$$P_{nw} = 0.55\phi P_{nw,\,buckling} \tag{5-8}$$

In the above, ϕ is 0.7, and $P_{nw,stave}$ and $P_{nw,\,joint}$ are determined by computation and/or tests (Commentary Fig. 5-C) of stave assemblies, after taking into account the maximum eccentricities from out-of-plane deviations allowed in Section 5.4.

The wall thickness shall be such that P_{nw} is not exceeded by any of the following combinations:

$$0.75(1.4D + 1.7L + 1.7W) \tag{5-9}$$

$$(1.4D + 1.7M + 1.7L) \tag{5-10}$$

$$0.75(1.4D + 1.7M + 1.7 \times 1.1E) \tag{5-11}$$

where D is dead load, L is live load, W is wind load, M is stored material load, and E is earthquake load.

5.5.5 *Tension and shear*—The empty silo shall have a factor of safety not less than 1.33 against wind overturning. Calculations shall be based on a shape factor for rough surfaced cylinders and not more than 0.9 times the computed dead load of structure. If anchorage is necessary, the following shall be satisfied where anchors attach to the stave wall,

$$\phi A_w 5\sqrt{f'_c} \geq 1.7(2W) \qquad (5\text{-}12)$$

and, unless results of tests (Commentary Fig. 5-A) indicate greater strength,

$$\phi 0.1(A_s f_y - F_u) lap \geq 1.7(2W) \qquad (5\text{-}13)$$

In the above, ϕ is 0.65, the force $(A_s f_y - F_u)$ is per foot of wall height, lap is the amount of vertical stagger in feet between horizontal stave joints and 1.7 is the load factor.

5.5.6 *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.

5.6—Hoops for stave silos

5.6.1 *Size and spacing*—Except as noted below, the size and spacing of external hoops for stave silos shall be computed in the same manner as for horizontal reinforcing of circular, cast-in-place silos. In computing the hoop reinforcing, an average design pressure over a wall height equaling 30 times the effective thickness may be used. Hoops shall be not less than $^1/_2$ in. (12.7 mm) in diameter. Spacing shall be not more than the stave height nor ten times the effective wall thickness.

5.6.2 *Calculating steel area*—When calculating the required size and spacing of stave silo hoops, the hoop net area shall be used and shall be taken as the smaller of: (a) the area of the rod, or (b) the root area of the thread. Appropriate restrictions in the available strength of the hoop/lug assembly shall be considered if lugs or mechanical fasteners induce bending deformations or strains in the hoop that reduce the yield strength of the hoop.

5.6.3 *Tensioning*—Stave silo hoops shall be tensioned such that enough stress remains after all losses from shrinkage, creep, elastic shortening and temperature changes to maintain the required vertical and circular strength, and stiffness of the stave assembly.

5.7—Concrete stave testing

The following procedure shall be used for testing concrete staves to determine compressive strengths:

5.7.1 A given test section shall consist of the full width of a solid stave with the height of this section being twice the thickness of the stave (see Fig. 5-1). The stave shall 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.

5.7.2 When testing a cored stave, a section shall be cut with a height twice the thickness of the stave (Fig. 5-2). The maximum depth, however, shall include only one complete core, and no portion of a core shall be present on either top or bottom of the test specimen.

5.7.3 The selection and required number of test sections and the procedures for capping and testing the test sections shall conform to ASTM C 140.

5.7.4 The average minimum compressive strength on the net area shall be at least 4000 psi (28 MPa) at 28 days. The average of any five consecutive stave strength tests shall be equal to or greater than the specified ultimate strength of the concrete, and not more than 20 percent of the tests shall have a value less than the specified strength.

CHAPTER 6—POST-TENSIONED CONCRETE SILOS

6.1—Notation

Consistent units must be used in all equations. Except where noted, units may be either all U.S. Customary or all metric (SI).

D	=dead load or dead load effect, or diameter
E	=modulus of elasticity
f_{ci}	=compressive strength of concrete at time of initial stressing
f_{pu}	=specified tensile strength of post-tensioning tendons, wires or strands
f_{py}	=specified yield strength of post-tensioning tendons, wires or strands
f_{se}	=effective stress in post-tensioning reinforcement (after allowance for all losses)
f_y	=specified yield strength of non-prestressed reinforcement
h	=wall thickness, including protective cover, if any, over post-tensioning steel
h_1	=core wall thickness

6.2—Scope

6.2.1 Provisions in this chapter apply to cast-in-place concrete silo walls fully or partially post-tensioned with high-strength steel meeting the requirements of Section 3.5.5 of ACI 318. Prestressed systems, where the reinforcement is stressed before the concrete is cast, are not covered herein.

6.2.2 Provisions of other chapters of this Standard and of ACI 318 that do not conflict with provisions of this chapter shall apply.

6.3—Post-tensioning systems

6.3.1 The two most widely used post-tensioning systems for silos are tendon systems and wrapped systems.

6.3.2 Tendon systems use strands, wires or bars inside of ducts. The tendons can be either left unbonded or can be bonded after tensioning by pressure grouting the open space inside the duct. The ducts can be either embedded in the concrete wall or placed on the exterior of the wall. Exterior ducts can be left exposed if constructed of suitable materials. Ducts that cannot be left exposed are protected, usually with shotcrete.

6.3.3 Wrapped systems use high strength wires or strands that are tensioned as they are installed or wrapped around the completed core wall. The wires or strands are protected, usually with shotcrete.

Table 6.1—Maximum permissible stresses in concrete (at service loads, after allowance for all losses)

	Fully post-tensioned	Partially post-tensioned
Axial compression	$0.30 f_c'$	$0.225 f_c'$
Combined axial and bending compression-extreme fiber	$0.45 f_c'$	$0.45 f_c'$
Axial tension	0	$6\sqrt{f_c'}$ psi
	(0)	($0.5\sqrt{f_c'}$ MPa)
Combined axial and bending tension-extreme fiber	$6\sqrt{f_c'}$ psi	$12\sqrt{f_c'}$ psi
	($0.5\sqrt{f_c'}$ MPa)	($1.0\sqrt{f_c'}$ MPa)

6.4—Tendon systems

6.4.1 Wall thickness, $\boldsymbol{h}$, for silos with tendons in embedded ducts shall be not less than 10 in. (250 mm), nor less than the sum of $\boldsymbol{h_1}$ (as determined from Section 6.8.1), the duct diameter, and the concrete cover.

6.4.2 The center-to-center spacing of tendons shall not exceed three times the wall thickness $\boldsymbol{h}$ or $\boldsymbol{h_1}$, nor, in the case of horizontal tendons, 42 in. (1.07 m).

6.4.3 The clear spacing between embedded tendon ducts shall be not less than three times the duct diameter or 6 in. (150 mm), whichever is larger. The clear spacing between non-embedded tendon ducts shall be not less than the duct diameter or $^3/_4$ in. (20 mm), whichever is larger.

6.4.4 Horizontal embedded tendons shall be placed inside the outside face vertical wall reinforcement.

6.4.5 Stressing points may be located at vertical pilasters on the outside of the walls, at wall intersections or at blockouts. In determining the number of stressing points, consideration shall be given in design to friction loss and local concentrations of the post-tensioning force. Blockout sizes and locations shall be such that, at the time of initial stressing, the stress in the net concrete wall area remaining shall not exceed 0.55 $\boldsymbol{f_{ci}}$ during the post-tensioning procedure.

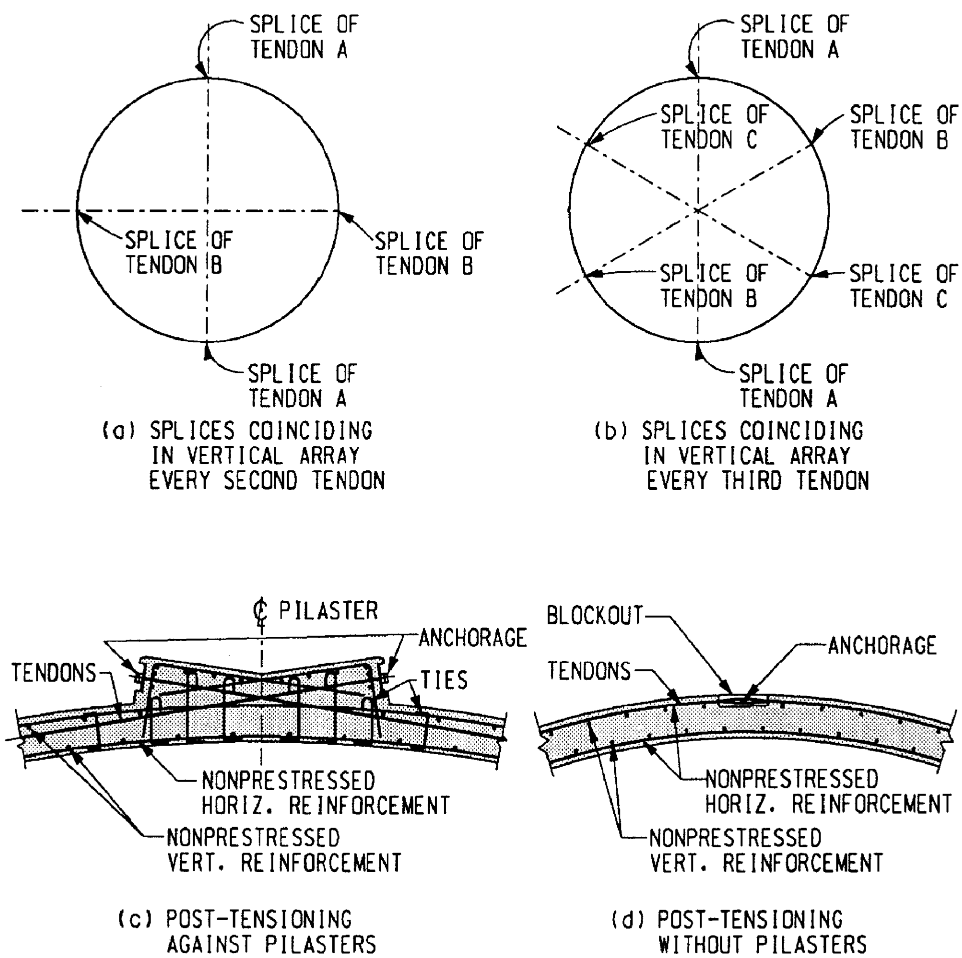

Fig. 6-1—Circumferential prestressing details

Table 7.1—Load combinations

Types of load acting on tube	Loading cases						
	1	2	3	4	5	6	7
Vertical load (7.3.1) caused by:							
a) Conveyor and headhouse dead load	+1.4	+1.4	+1.4	+1.4	+0.9	+0.9	+0.9
b) Conveyor and headhouse live load	+1.7	+1.7	+1.7	+1.7			
Horizontal load (7.3.2.1) caused by:							
a) Wind on conveyor and headhouse			+1.7			-1.7	
b) Seismic on conveyor and headhouse				+1.87			-1.87
Longitudinal load (7.3.2.2) caused by:							
a) Belt pull of conveyor		+1.7	+1.7	+1.7	-1.7	-1.7	-1.7
b) Thermal changes of conveyor		+1.4	+1.4	+1.4	-1.4	-1.4	-1.4
Tube vertical load (7.3.3) caused by:							
a) Dead load of tube	+1.4	+1.4	+1.4	+1.4	+0.9	+0.9	+0.9
b) Material inside tube, if any	+1.7	+1.7	+1.7	+1.7	+0.9	+0.9	+0.9
c) Complete pile outside tube	+1.7						
d) Partial pile outside tube		+1.7	+1.7	+1.7	+0.9	+0.9	+0.9
Tube horizontal load (7.3.4) caused by:							
a) Wind on exposed portion of tube			+1.7			-1.7	
b) Seismic on tube mass				+1.87			+1.87
c) Unbalanced loads from partial pile		+1.7	+1.7	+1.87	-1.7	-1.7	-1.7
d) Seismic on material in tube, if any				+1.87			-1.87
e) Seismic on partial pile outside				+1.87			-1.87
Multiplier	1.00	1.00	0.75	0.75	1.00	0.75	0.75

Methods of staggering pilaster and blackout stressing points are shown in Fig. 6-1.

6.4.6 Reinforcement shall be provided at vertical pilasters as required to resist forces created by the post-tensioning system during and after the stressing operation. Fig. 6-1 shows one possible arrangement.

6.4.7 Embedded tendon ducts shall have a concrete cover of not less than $1^1/_2$ in. (40 mm). Tendon ducts shall be supported to maintain location within vertical and horizontal tolerances.

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

6.4.9 After stressing is completed, anchorage and end fittings shall be permanently protected against corrosion. Blockouts and pockets shall be filled with a non-shrink material that will bond to and develop the strength of the adjacent concrete.

6.5—Bonded tendons

6.5.1 Anchorages and couplers for bonded tendons shall meet the requirements of ACI 318-95. Tests of anchorages and couplers shall be performed on unbonded specimens.

6.5.2 Grout for bonded tendons shall consist of portland cement and water, or portland cement, fine aggregate and water.

6.5.3 Grout shall have at least 2500 psi (17 MPa) compressive strength at 7 days based on 2 in. (50 mm) cubes, molded, cured and tested in accordance with ASTM C 1019.

6.5.4 Proportions of grouting materials shall be based on results of fresh and hardened grout tests made prior to beginning work. Water content shall be the minimum necessary for proper placement, but in no case more than 0.45 times the content of cement by weight.

6.5.5 Grout shall be mixed and placed by equipment capable of providing a continuous flow of grout at a rate and pressure that will uniformly distribute the grout and fill the voids in the duct. Grout shall be continuously agitated and placed as quickly as possible after mixing. Grout shall be filtered through a screen to remove lumps and coarse material that would plug the grout tubes and ducts. Grout shall be allowed to flow from the vents to ensure that free water is expelled from the duct. After full flow is obtained, vents shall be closed, pumping stopped and the system checked for leaks while pressure is maintained.

6.5.6 The temperature of the members at the time of grouting shall be above 35°F (2°C) and shall be maintained above this temperature until job-cured 2 in. (50 mm) cubes of grout tested as defined by ASTM C 1019 reach a minimum compressive strength of 800 psi (6 MPa). Grout temperature shall be not greater than 90°F (32°C) during mixing and injection. Grout shall be cooled during hot weather to avoid quick setting and blockage.

6.6—Unbonded tendons

6.6.1 Anchorages and couplers for unbonded tendons shall develop 100 percent of f_{pu} without exceeding the anticipated set. Cyclic loading and unloading of the silo that might lead to fatigue failure of anchorages or couplers shall be considered in the selection of anchorages.

6.6.2 External and internal unbonded tendons shall be coated with a protective lubricant and encased in a protective duct or wrapping to provide long-term corrosion protection. The tendon duct or wrapping shall be continuous over the entire zone to be unbonded. It shall prevent intrusion of cement paste or water (or both) and the loss of coating materials during concrete placement. The anchorage and end fittings shall be protected as specified in Section 6.4.9.

6.7—Post-tensioning ducts

6.7.1 Ducts for grouted or unbonded tendons shall be mortar-tight and non-reactive with concrete, tendons or the grout. Metal duct walls shall be no thinner than 0.012 in. (0.3 mm). Duct splices shall be staggered and ducts shall be installed free of kinks or unspecified curvature changes.

6.7.2 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.

6.7.3 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.

6.7.4 In addition to meeting the requirements of Sections 6.7.2 and 6.7.3, duct diameter shall be compatible with tendon installation requirements, taking into consideration curvature of wall, duct length, potential blockage and silo configuration.

6.7.5 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 may be detrimental to the system.

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

6.8—Wrapped systems

6.8.1 Core wall thickness, h_1, for silos with wires or strands wound around the outside face of the core wall shall be not less than 6 in. (150 mm) nor less than that required to prevent the stress on the core wall from exceeding 0.55 f_{ci} at the time of initial stressing.

6.8.2 Large voids or other defects in the core wall shall be chipped down to sound concrete and repaired before post-tensioning commences. Dust, efflorescence, oil, and other foreign material shall be removed. Concrete core walls shall have a bondable surface and may require sandblasting.

6.8.3 Procedures used for post-tensioning by wrapping shall be as approved by the engineer.

6.8.4 Pitch of high-tensile wire in spiral wrapping and simultaneous stressing is to be determined by requirements of the tensile forces caused by stored material lateral pressures. A clear distance of at least 1/4 in. (6 mm), but not less than one wire diameter, shall be left between successive turns of wire.

6.8.5 If multiple-layer wrapping is used, the layers shall be separated by shotcrete, conforming to ACI 506.2.

6.8.6 The outside post-tensioning wires or strand shall be coated by two or more layers of shotcrete. The total coating thickness over the wires or strand shall be not less than 1 in. (25 mm). Shotcrete coating shall conform to requirements of ACI 506.2.

6.9—Details and placement of non-prestressed reinforcement

6.9.1 Vertical non-prestressed reinforcement shall be provided to withstand bending moments resulting from 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 area of vertical non-prestressed reinforcement provided shall be not less than that required by Chapter 4.

6.9.2 Horizontal non-prestressed reinforcement shall be provided to withstand bending moments from all causes and to control shrinkage and temperature-induced cracking during the period between completion of wall construction and start of post-tensioning. In any case, the total area of such reinforcement shall be not less than 0.0025 times the area of the wall. The spacing of horizontal non-prestressed reinforcement provided shall be not more than 18 in. (450 mm).

6.9.3 Number 4 (10M) stirrups at 2.5 ft. (0.75m) c/c each way shall be provided in post-tensioned walls.

6.10—Wall openings

6.10.1 For wall openings not within pressure zone, see Section 4.3.8.2.

6.10.2 For wall openings in pressure zones, post-tensioning elements that would cross an opening 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 nor 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.

6.10.3 Vertical reinforcement at each side of the opening shall be not less than the minimum required by Section 4.3.8, nor less than that calculated for the vertical bending moments or forces due to flaring the post-tensioning elements.

6.11—Stressing records

6.11.1 Stressing procedures shall be documented and the records submitted to the engineer 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 wire, 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 inspector.

6.12—Design

6.12.1 Design shall be based on the strength method and on behavior at service conditions at all load stages that may be critical during the life of the structure from the time post-tensioning stress is first applied.

6.12.2 Silo walls shall be designed to resist all applicable loads as specified in Chapter 4, plus the effect of post-tensioning forces during and after tensioning, including stress concentration and conditions of edge restraint at wall junctions with silo roof, bottom and wall intersections.

6.12.3 Stresses in concrete shall not exceed the values provided in Chapter 4 and in Section 18.4 of ACI 318, except as provided in Table 6.1.

6.12.4 Tensile stresses in strands, wires or bars of tendon systems shall not exceed the following:

(a) During jacking. . . . . 0.85 f_{pu} or 0.94 f_{py}

whichever is smaller, but not more than maximum value recommended by the manufacturer of tendons or anchorages.

(b) Immediately after anchoring. . . . . 0.70 f_{pu}

Average stresses in wires or strands used in wrapped systems shall not exceed the following:

(a) Immediately after stressing. . . . . 0.70 f_{pu}

(b) After all losses. . . . . 0.55 f_{pu}

6.12.5 *Required area of post-tensioning reinforcement*—Prestressed reinforcement or a combination of prestressed and non-prestressed reinforcement shall be provided to resist the hoop tension due to horizontal pressures computed according to Section 4.4.2.2. In silo walls subjected to combined hoop tension and bending, resistance to bending shall be provided by non-prestressed reinforcement.

When post-tensioned reinforcement and non-prestressed reinforcement are considered to act together to provide the required resistance to axial tension or to combined axial tension and bending in the wall, the assumed stresses in each type of reinforcement shall be determined based on stress-strain compatibility relationships.

6.12.6 The modulus of elasticity, E, of post-tensioning reinforcement shall be based on data supplied by the manufacturer or shall be determined by independent tests. Unless more accurate information is available, the following values shall be used:

Bars. . . . . 29 x 10^6 psi (200 x 10^3 MPa)

Strands. . . . . 28.5 x 10^6 psi (197 x 10^3 MPa)

Wires. 29 x 10^6 psi (200 x 10^3 MPa)

6.12.7 ***Non-prestressed reinforcement***

6.12.7.1 Amount of non-prestressed reinforcement shall be determined by the strength design method as specified in ACI 318. The amount of non-prestressed reinforcement provided, however, shall be not less than required by Sections 6.9 and 6.10.

6.12.7.2 Yield strength (f_y) of non-prestressed reinforcement shall not be taken in excess of 60,000 psi (414 MPa).

6.12.7.3 The modulus of elasticity of non-prestressed reinforcement shall be taken as 29 x 10^6 psi (200 x 10^3 MPa).

6.12.8 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 not less than:

Edges unrestrained. . . . . 280 psi (2.0 MPa)

Edges restrained. . . . . 140 psi (1.0 MPa)

6.12.9 *Losses*—Stress losses that are used to establish the effective stress, f_{se}, shall be determined using the provisions of ACI 318, Section 18.6.

6.13—Vertical bending moment and shear due to post-tensioning

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

6.14—Tolerances

6.14.1 Tolerances for placement of ducts at support points, relative to position shown on the project drawings, shall not exceed 1 in. (25 mm) vertically or horizontally.

6.14.2 The vertical sag or horizontal displacement between support points shall be not greater than 1/2 in. (13 mm).

CHAPTER 7—STACKING TUBES

7.1—Scope

This chapter covers the design and construction of reinforced concrete stacking tubes. Unless specifically stated otherwise, all general requirements in Chapters 1, 2, 3, and 4 (where not in conflict with this chapter), are applicable to stacking tubes.

7.2—General layout

The inside dimension shall be large enough to prevent arching across the tube. Wall discharge openings shall be large enough to prevent arching across the openings and allow free flow of material from the stacking tube. The discharge openings shall be symmetrically arranged in sets of two and 180° apart with alternate sets located at 90° to each other.

The wall between the foundation and the bottom of the first set of openings shall be sufficient to provide the necessary strength to resist the internal pressures as well as the external uneven pile loads. Discharge openings shall be located over the height of the tube in such a way as to minimize the effects of ring bending from uneven loads. If a concentric discharge is provided inside the tube through the reclaim tunnel roof at the bottom of the stacking tube, it shall be large enough to prevent arching across the opening and prevent the formation of a stable rathole in the tube.

7.3—Loads

The following loads shall be considered for the design of stacking tubes:

7.3.1 ***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.

7.3.2 ***Horizontal loads at top of tube***

7.3.2.1 Acting perpendicular to the conveyor:

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

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

7.3.2.2 Acting parallel to the conveyor:

a) The horizontal reaction due to the belt pull, including tension from start-up.

b) The horizontal reaction due to thermal expansion or contraction of the conveyor support structure. Such force shall be taken as not less than 10 percent of the total (dead plus live) vertical reaction of the conveyor system on the top of the tube, unless provision is made to reduce the loads with rollers or rockers.

7.3.3 ***Vertical loads over the height of the 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.

7.3.4 ***Horizontal loads over the height of the 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. Such forces shall be computed assuming that the conical pile is missing a radial sector and that the tube has reduced lateral support from stored material on the open side.

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

e) Seismic action on the partial pile stored on the outside of the tube.

7.4—Load combinations

Unless it can be shown that a particular specified load combination does not apply, the required strength of the stacking tube shall be not less than that indicated for each of the loading cases of Table 7.1. The required strength is obtained by summing the loads in each column and multiplying by the multiplier at the bottom of the column.

Each of the loading cases in Table 7.1 shall be investigated to determine the critical design force at the base of the tube.

1. Maximum downward considering vertical loads only.
2. Maximum downward considering vertical and horizontal loads.
3. Maximum downward considering vertical, horizontal and wind loads.
4. Maximum downward considering vertical, horizontal and seismic loads.
5. Maximum upward considering vertical and horizontal loads.
6. Maximum upward considering vertical, horizontal and wind loads.
7. Maximum upward considering vertical, horizontal and seismic loads.

Where tubes are in close proximity to each other, consideration shall be given to possible increases in horizontal loads due to horizontal arching of the stacked material between tubes.

7.5—Tube wall design

7.5.1 The stacking tube shall be designed as a cantilevered beam fixed at the top of the foundation or reclaim tunnel roof. The concrete wall thickness and reinforcing shall be such that its strength will not be less than required by the most severe combination of loads of Table 7.1 at the base of the tube and at each level of discharge opening above.

7.5.2 The stacking tube wall shall be reinforced vertically and horizontally. For wall thicknesses of 9 in. (225 mm) or more, reinforcing shall be provided on each face. The vertical reinforcement shall be designed to resist the maximum tensile stresses resulting from the combination of vertical loads and overturning moments. In addition, the vertical reinforcing adjacent to the openings shall be designed to resist the bending and shear stresses resulting from the bending action of the wall between the openings. The ratio of vertical reinforcement to gross concrete area shall not be less than 0.0025.

7.5.3 Horizontal reinforcement shall be designed to resist hoop and circumferential bending stresses 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 ratio of horizontal reinforcement to gross concrete area shall not be less than 0.0025.

7.6—Foundation or reclaim tunnel

The foundation or reclaim tunnel shall be designed to support all horizontal and vertical loads on the tube and to be stable against the overturning moments. In addition, the foundation or reclaim tunnel shall be designed to support the material above and adjacent to the tube and the tunnel.

CHAPTER 8—SPECIFIED AND RECOMMENDED REFERENCES

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Concrete Institute

117	Standard Tolerances for Concrete Construction and Materials
214	Recommended Practice for Evaluation of Strength Test Results of Concrete
214.1R	Use of Accelerated Strength Testing
215R	Considerations for Design of Concrete Structures Subjected to Fatigue Loading
301	Specifications for Structural Concrete for Buildings
305R	Hot Weather Concreting
306R	Cold Weather Concreting
308	Standard Practice for Curing Concrete
318	Building Code Requirements for Structural Concrete
344R-W	Design and Construction of Circular Wire and Strand Wrapped Prestressed Concrete Structures
347R	Guide to Formwork for Concrete
506.2	Specification for Materials, Proportioning and Application of Shotcrete
515.1R	Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete

American Society for Testing and Materials

A 47	Specification for Ferritic Malleable Iron Castings
A 123	Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products
C 55	Standard Specification for Concrete Building Brick
C 109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2 in. or 50 mm Cube Specimens)

C 140	Standard Methods of Sampling and Testing Concrete Masonry Units
C 150	Standard Specification for Portland Cement
C 309	Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 426	Standard Test Method for Drying Shrinkage of Concrete Block
C 595	Standard Specification for Blended Hydraulic Cements
C 684	Standard Test Method of Making, Accelerated Curing and Testing of Concrete Compression Test Specimens
C 845	Standard Specification for Expansive Hydraulic Cement
C 1019	Standard Test Method of Sampling and Testing Grout

International Conference of Building Officials
1994 Edition Uniform Building Code

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094

ASTM
100 Bar Harbor Dr.
West Conshohocken, Pa. 19428-2959

International Conference of Building Officials
5360 South Workman Mill Rd.
Whittier, Calif. 90601

APPENDIX A—NOTATION

Consistent units must be used in all equations. Except where noted, units may be either all U.S. Customary or all metric (SI).

A = effective tension area of concrete surrounding the tension reinforcement and having the same centroid as that reinforcement, divided by the number of bars. When the reinforcement consists of different bar sizes, the number of bars shall be computed as the total area of reinforcement divided by the area of the largest bar used. See Fig. 4-3.
A_s = area of hoop or tension reinforcement, per unit height
A_w = effective cross-sectional area (horizontal projection) of an individual stave
D = dead load or dead load effect, or diameter
E = modulus of elasticity
E_c = modulus of elasticity for concrete
F_u = required hoop or horizontal tensile strength, per unit height of wall
L = live load or live load effect
M = stored material load stress
M_{pos} M_{neg} = positive (tension inside face) and negative (tension outside face) circumferential bending moments, respectively, caused by asymmetric filling or emptying under service load conditions
M_θ = circular bending strength for an assembled circular group of silo staves, per unit height; the statical moment or sum of absolute values of $M_{\theta,pos}$ and $M_{\theta,neg}$
$M_{\theta,pos}$ $M_{\theta,neg}$ = the measured or computed bending strengths in the positive moment zone and negative moment zone, respectively
M_t = thermal bending moment per unit width of height of wall (consistent units)
P_{nw} = nominal axial load strength of wall per unit perimeter
$P_{nw,buckling}$ = strength of the stave wall as limited by buckling
$P_{nw,joint}$ = strength of the stave wall as limited by the stave joint
$P_{nw,stave}$ = strength of the stave wall as limited by the shape of the stave
R = ratio of area to perimeter of horizontal cross-section of storage space
T = temperature or temperature effect
ΔT = temperature difference between inside face and outside face of wall
U = required strength
V = total vertical frictional force on a unit length of wall perimeter above the section in question
W = tension force per stave from wind overturning moment
Y = depth from the equivalent surface of stored material to point in question. See Fig. 4-2.
d_c = thickness of concrete cover taken equal to 2.5 bar diameters, or less. See Fig. 4-3.
e = base of natural logarithms
f'_c = compressive strength of concrete
f_{ci} = compressive strength of concrete at time of initial stressing
f_{pu} = specified tensile strength of post-tensioning tendons, wires or strands
f_{py} = specified yield strength of post-tensioning tendons, wires or strands
f_s = calculated stress in reinforcement at initial (filling) pressures
f_{se} = effective stress in post-tensioning reinforcement (after allowance for all losses)
f_y = specified yield strength of non-prestressed reinforcement
h = wall thickness
h_h = height of hopper from apex to top of hopper. See Fig. 4-2.
h_s = height of sloping top surface of stored material. See Fig. 4-2.
h_{st} = height of stave specimen for compression test. See Figs. 5-1 and 5-2.
h_y = depth below top of hopper to point in question. See Fig. 4-2.

h_1 = core wall thickness
k = p/q
p = initial (filling) horizontal pressure due to stored material
p_n = pressure normal to hopper surface at a depth h_y below top of hopper. See Fig. 4-2.
q = initial (filling) vertical pressure due to stored material
q_o = initial vertical pressure at top of hopper
q_y = vertical pressure at a distance h_y below top of hopper. See Fig. 4-2.
s = bar spacing, in. See Fig. 4-3.
v_n = initial friction force per unit area between stored material and hopper surface calculated from Eq. (4-8) or (4-9)
w = design crack width, in. or lateral wind pressure
α = angle of hopper from horizontal. See Fig. 4-2.
α_c = thermal coefficient of expansion of concrete
γ = weight per unit volume for stored material
θ = angle of hopper from vertical. See Fig. 4-2.
μ' = coefficient of friction between stored material and wall or hopper surface
ν = Poisson's ratio for concrete, assumed to be 0.2
ϕ = strength reduction factor or angle of internal friction
ϕ' = angle of friction between material and wall and hopper surface
ρ = angle of repose. See Fig. 4-2.