

Commentary on 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 Commentary presents some of the considerations and assumptions of ACI Committee 313 in developing the provisions of the Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials. It also provides suggested methods for calculating crack width and through-the-wall temperature gradient due to hot stored materials.

Comments on specific provisions of the Standard practice are made using the corresponding chapter and section numbers of the Standard practice. A list of selected references is given at the end of the Commentary. Notations, not defined herein, are defined in Appendix A of the Standard.

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 silo; stresses; structural analysis; structural design; thermal stresses; thickness; walls.

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CHAPTER 1—GENERAL

R1.1—Introduction

Silo failures have alerted design engineers to the danger of designing silos for only static pressures due to stored material at rest. Those failures have inspired wide-spread research into the variations of pressures and flow of materials. The research thus far has established beyond doubt that pressures during withdrawal may be significantly higher¹⁻⁴ 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 which occurs during material withdrawal.⁵ Underpressures may occur at a flow channel in contact with the wall and overpressures may occur away from the flow channel at the same level.⁶⁻⁸ Underpressures concurrent with overpressures cause circumferential bending in the wall. Impact during filling may cause total pressure to exceed the static. While overpressures and underpressures are generally important in deeper silos, impact is usually critical only for shallow ones (bunkers) in which large volumes are dumped suddenly.

Obviously, to design with disregard for either overpressure, underpressure or impact could be dangerous.

R1.2—Definitions

The term “silo” used here includes both deep bins and shallow bins, the latter sometimes referred to as “bunkers.” Where

ever the term “silo” is used, it should be interpreted as meaning a silo, bin or bunker of any proportion, shallow or deep.

Stave silos are used principally in agriculture for storing chopped “silage,” but are finding increasing use in other industry for storing granular materials. This Standard covers the industrial stave silo, but is not to be used as a standard for farm silos. The methods of computing pressures due to granular material are the same for industrial stave silos as for other silos (Chapter 4). However, design of stave silos relies heavily on strength and stiffness tests; consequently, this Standard includes several design requirements that are peculiar to stave silos only.

R1.4—Drawings, specifications, and calculations

Silos and bunkers are unusual structures, and many engineers are unfamiliar with computation of their design loads and with other design and detail requirements. It is important that the design and the preparation of project drawings and project specifications for silos and bunkers be done under the supervision of an engineer with specialized knowledge and experience in 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 on the project drawings.

CHAPTER 2—MATERIALS

R2.2—Cements

Cement for exposed parts of silos or bunkers should be of one particular type and brand if it is desired to prevent variations in color of the concrete.

In general, the types of cement permitted by ACI 318 are permitted under the recommended practice, except as noted. Experience has shown that there can be 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 on the Wagner scale) can act in the same manner as Type III and cause difficulties by accelerating the initial set during a slipform operation.

Type 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.

R2.3—Aggregates

Aggregates for exposed parts of silos or bunkers should be the same type and source if it is desired to avoid variations in appearance of the completed work.

R2.5—Admixtures

R2.5.1 The use of admixtures in concrete silo walls is a common construction method of controlling the initial set of concrete and, therefore, the rate at which slipforms and/or jumpforms may be raised. During the actual construction operation, the amount of admixture may be adjusted in the field to suit the ambient conditions and to maintain a constant rate of rise for the forms.

Concrete which 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.

It should be recognized that while potlives of up to 1½ hours are available, some superplasticizer (high range water reducer) admixtures have a relatively short useful life (30-35 minutes) after being added to a concrete mixture. This can create problems during placement of stiff mixtures of high strength concrete or mixtures using special cements such as Type K, M and S of ASTM C 845.

CHAPTER 3—CONSTRUCTION REQUIREMENTS

R3.1—Notation

The following additional term is used in the Commentary for Chapter 3, but is not used in the Standard.

f_{cr} = Required average compressive strength of concrete

R3.2—Concrete quality

R3.2.1 The committee recommends a statistical basis to establish an average strength, f_{cr} , to assure attainment of the design strength, f'_c .

ACI Committee 214 has noted that, with general construction having fair control standards, the required f'_c should be attained in over 90 percent of field molded compression specimens provided f_{cr} is not less than 4000 psi (28 MPa). Fair control standards, indicating a 20 percent coefficient of variation, were assumed to establish the relation between the design and average strength.

It can be shown that lower coefficients of variation may reduce the average strength requirements and, consequently, larger water-cement ratios than permitted in ACI 301 should be possible. However, in the interest of durability, ratios larger than the maximums given in ACI 301 should not be used.

It is important when determining slump for slipformed concrete, that the proposed mix include the same proportions of materials that will actually be used, including admixtures such as accelerators, retarders, air-entraining agents and water-reducing plasticizers.

Historically, concrete mixtures with a slump of 4 in. (100 mm) have been used successfully for construction of slipformed concrete silo and stacking tube walls under a wide variety of field conditions.

R3.2.2 Concrete is considered exposed to freezing and thawing when, in a cold climate, the concrete is in almost continuous contact with moisture prior to freezing.

Entrained air in concrete will provide some protection against damage from freezing against the effects of de-icer chemicals.

R3.3—Sampling and testing concrete

Non-destructive testing of in-place concrete may be used to determine the approximate strength or quality, or to forecast the approximate 28-day strength. Some of these methods of testing are ultrasonic pulse, pulse echo, radioactive measurement of the absorption or scatter of x-rays or gamma radiation, and surface hardness (rebound or probe penetration).

R3.3.2 ASTM C 684 describes three different procedures for the accelerated curing of test cylinders: Warm Water Method, Boiling Water Method and Autogenous Method.

The first two methods permit testing the cylinders at 24 and 28½ hours respectively, while the third requires hours (± 15 min). ACI 214.1R *Use of Accelerated Strength Testing* provides guidance for interpretation of these test results.

R3.4—Details and placement of reinforcement

R3.4.2 Bars not tied can be moved during vibration or even initially mislocated in slipforming. Failures have occurred because of incorrect spacing of horizontal steel. A positive means of controlling location is essential.

Because no reinforcing bars can project beyond the face of a slipform silo wall, dowels that project into abutting walls, slabs or silo bottoms must frequently be field bent. See ACI 318-95 Commentary **Section 7.3** for discussion on cold bending and bending by preheating.

If reinforcing bars are to be welded or to have items attached to them, it is essential to know the carbon content of the bars in order to select the proper procedure and materials for the weld.

R3.4.3 Designers should be cautious about selecting walls thinner than 9 in. (230 mm) since such will not generally accommodate two curtains of reinforcement. Two-face reinforcement substantially improves performance of the wall when the wall is subjected to both tension and bending forces.

R3.4.4 In general, the minimum cover for reinforcing bars placed on the inside face of silo walls should be 1 in. Additional cover should be provided where conditions of wear, chemical attack or moisture can occur.

R3.5—Forms

Slipform and/or jumpform systems should be designed, constructed and operated by or under the supervision of persons experienced in this type of construction. ACI Special Publication No. 4, *Formwork for Concrete*, and References 9 and 10 contain a general description of the vertical slipform process.

The rate of advancement of the slipform system shall be slow enough that concrete exposed below the bottom of the forms will be capable of supporting itself and the concrete placed above it, but rapid enough to prevent concrete from bonding to the forms.

The advancement of the jumpform system shall be slow enough that hardened concrete in contact with the forms is capable of supporting the jumpform system, the construction loads and the fresh concrete placed above it.

R3.6—Concrete placing and finishing

During the construction of slipformed silo or stacking tube walls, it is possible that the concrete placing operation must be interrupted due to unforeseen or unavoidable field conditions and an unplanned construction joint will occur. In this event, the engineer should be notified and concrete placement recommended only upon the engineer's approval.

R3.7—Concrete protection and curing

R3.7.3 In many 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 5 days and no additional provisions for curing need be made. Where deck forms or other enclosures retain the atmosphere in a highly humid condition, no additional curing measures are needed.

Where the above 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 being carefully regulated to avoid damage by erosion. At no time should the concrete be allowed to have a dry surface until it has reached an age of at least 5 days.

R3.7.5 Curing compound is undesirable on interior surfaces which are to be in contact with the stored material. Such compound, if present, would modify the effect of the friction between the interior surface and the stored material. As the curing compound is abraded, it contaminates the stored material.

CHAPTER 4—DESIGN

R4.1—Notation

The following additional terms are used in the Commentary for Chapter 4, but are not used in the Standard.

A'_s	=	compression steel area. See Fig. 4-F.
B	=	constant calculated from Eq. (4D)
K_t	=	thermal resistance of wall. See Fig. 4-E.
M_u	=	required flexural strength per unit height of wall
T_i	=	temperature inside mass of stored material
T_o	=	exterior dry-bulb temperature
d	=	effective depth of flexural member. See Fig. 4-F.
d', d''	=	distances from face of wall to center of reinforcement nearest that face. See Fig. 4-F.
e, e', e''	=	eccentricities. See Fig. 4-F.
n	=	constant calculated from Eq. (4B) or Eq. (4C).
β	=	constant calculated from Eq. (4E)
δ	=	effective angle of internal friction
θ_c, θ_p	=	angle of conical or plane flow hopper with vertical. See Fig. 4-C.

R4.2—General

R4.2.3 Walls thinner than 6 in. (150 mm) are difficult to construct. When slipforming thinner walls, concrete can be more easily “lifted,” causing horizontal and vertical planes of weakness or actual separation. Thin walls are subject to honeycomb.

R4.2.4 Load and Strength Reduction Factors

R4.2.4.1 The load factors of 1.7 for live load and 1.4 for dead load are consistent with ACI 318. ACI 318 requires a higher factor for live load than for dead load since live load cannot normally be estimated or controlled as accurately as dead load. In ordinary structures, a frequent cause of overload is increased depth or decreased spacing of stored materials. In silos, this problem cannot occur, since design is always for a full silo, and extra material can never be added. Pressures in the silo, however, are sensitive to minor changes in the stored material’s properties and overload may occur as a result of these changes. Thus, a live load factor of 1.7 is specified. Larger variations in properties are possible between dry and wet stored materials. In such cases, use the combination of properties that creates the highest pressures.

The weight per unit volume, γ , can vary significantly even for the same material. The purpose of the load factor is not to permit a silo that is designed for one material to be used for storing another (e.g. clean coal versus raw coal). If different

materials are stored, consider each material, noting that one material may control for lateral pressure, while another may control for vertical pressure.

R4.2.4.2 The lower strength reduction factor for slip-formed concrete without continuous inspection recognizes the greater difficulty of controlling reinforcement location.

R4.3—Details and placement of reinforcement

R4.3.1 Fig. 4-A and 4-B illustrate typical reinforcing patterns at wall intersections, ring beams and wall openings. The illustrated details are not mandatory, but are examples to aid the designer.

R4.3.2 The designer 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 empty.^{11,12} They may also occur when flow patterns change or when some cells are subjected to initial (filling) pressures while others are subjected to design (flow) pressures.¹³

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 accurately evaluate, but do exist. They result from non-uniform pressures around the circumference during discharge, especially eccentric discharge. They can also result from temperature differential, from structural continuity and from materials stored against the outside of the silo.

R4.3.3 Forces tending to separate silos of monolithically cast silo groups may occur when some cells are full and some empty¹¹ (such as four empty cells with a full interstice). They may also result from non-uniform pressure around the circumference, thermal expansion, seismic loading or differential foundation settlement.

R4.3.4 Horizontal hoop tension (or tension plus shear and bending moment) does not cease abruptly at the bottom of the pressure zone. The upper portion of the wall below has strains and displacements compatible with those of the wall above. Therefore, the pattern of main horizontal reinforcement is continued downward from the bottom of the pressure zone for a distance equal to four times the thickness h of the wall above.

Since the wall below the pressure zone frequently has sizeable openings, it is often necessary to design that wall (usually as a deep beam) to span those openings. In this case, reinforcement areas must be adequate for deep beam action.

R4.3.5 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.

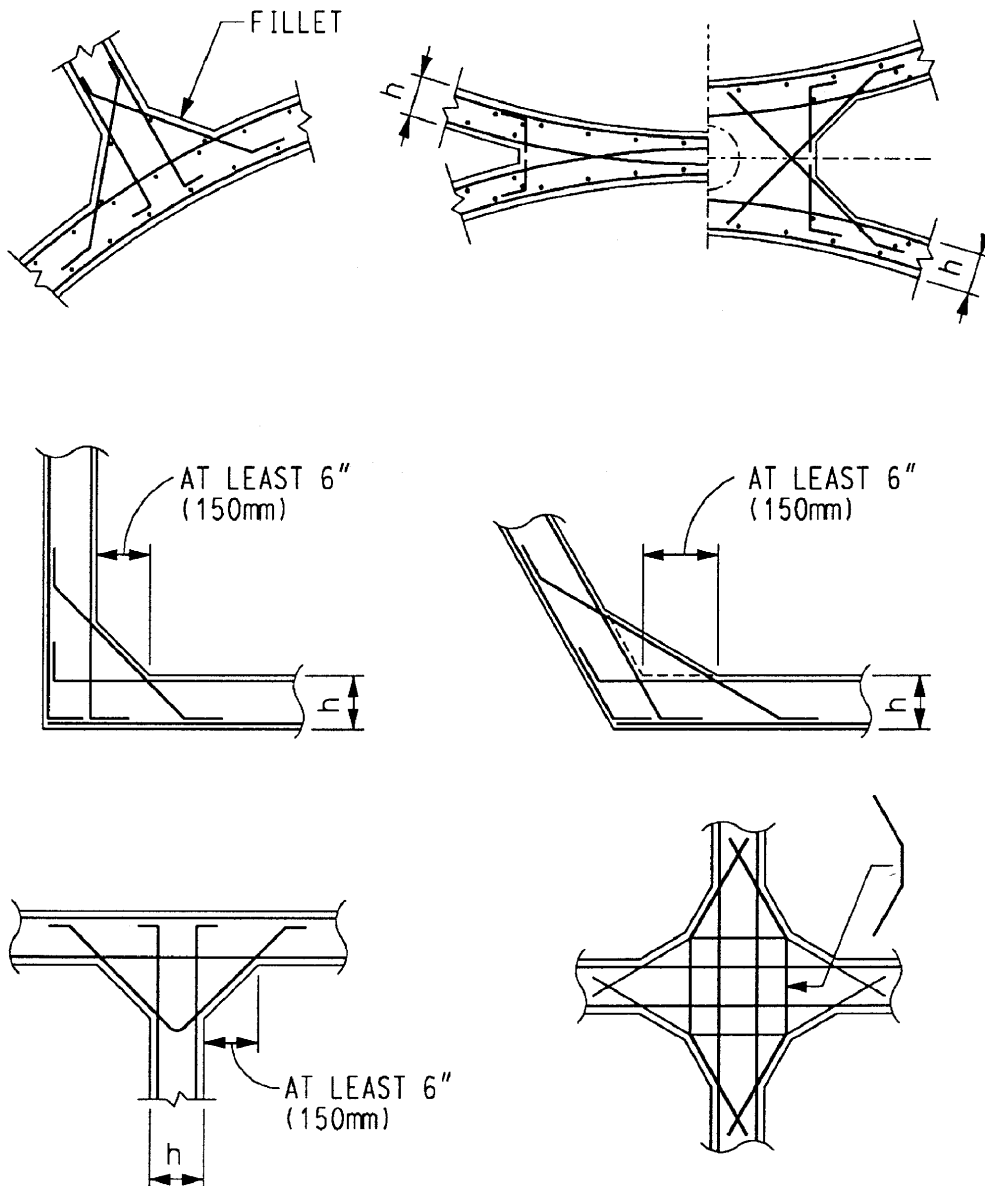


Fig. 4-A—Reinforcement pattern at intersecting walls

5. Temperature differentials between inside and outside wall surfaces or between silos.¹⁴

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. Reinforcement should not be omitted for this purpose; only the spacing should be affected, larger than normal at the access location and smaller than normal on each side.

R4.3.7 The possibility of bond failure, with subsequent splitting, is greater where bars are closely spaced, as at lap splices.¹⁵ 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.

R4.3.8 Reinforcement at Wall Openings

R4.3.8.1 Openings in pressure zone

(a) This requirement for added horizontal reinforcement is based on the assumption that the silo strength to resist

horizontal design pressures from the stored materials should not be reduced by the opening. The 20 percent increase is for stress concentrations next to the opening. Bar spacing and clearances frequently become critical where such extra reinforcement is added.¹⁶

R4.3.8.2 Openings not in pressure zone

For narrow openings, this method provides a simple rule of thumb by which to provide reinforcement for a lintel-type action above and below the openings. Reinforcement for beam action below the opening is important since the wall below will usually have vertical compressive stress. For large openings, a deep beam analysis should be considered.

R4.3.8.3 All openings, bar extension

(a) The distance that reinforcement must be extended to replace the strength that would otherwise be lost at the opening depends not merely on bond strength, but also on the proportions of the opening. Horizontal extension must be more for deep openings than for shallow. Similarly, vertical extension should be more for wide openings than for narrow.

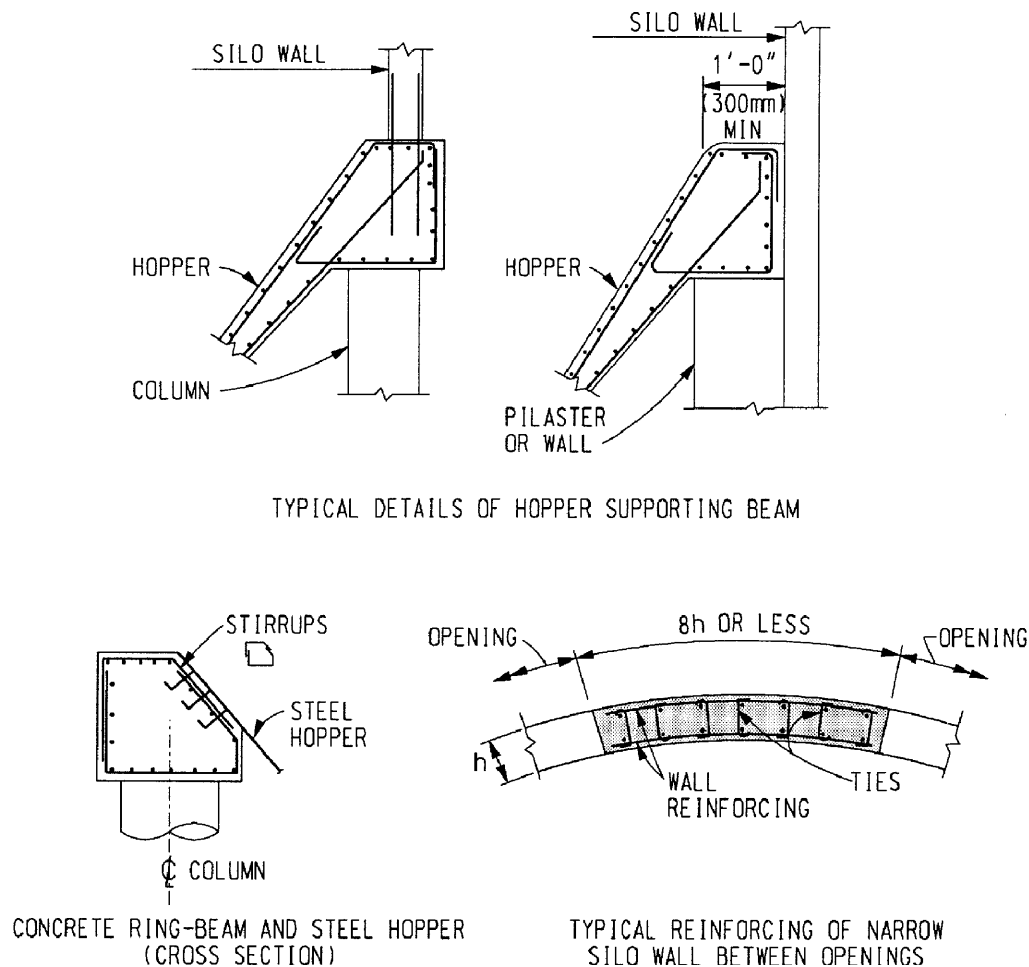


Fig. 4-B—Miscellaneous details

In each case, extension length depends on the opening dimension perpendicular to the bar direction.

R4.3.9 For walls, the suggested spacing of horizontal bars is not less than 4 in. (100 mm) for walls with two-layer reinforcing nor less than 3 in. (75 mm) for singly reinforced walls. The use of lesser spacing makes it difficult to locate and tie bars.

Since internal splitting of the concrete and complete loss of bond or lap strength can be catastrophic in a silo wall, it is mandatory to select reinforcement patterns which will force strength to be controlled by tensile failure of the horizontal reinforcement rather than by splitting of the concrete.

The 5-bar diameter minimum spacing of horizontal bars assures more concrete between bars and helps prevent brittle bond failures.

R4.3.10 Additional lap length is specified for hoop bars in walls of slipformed silos since bars may easily be misplaced longitudinally, leading to less lap at one end of the bars and more at the other. For rectangular or polygonal silos, where the shape of the bar prevents longitudinal misplacement of horizontal bars at a splice, the additional lap length may not be required.

R4.3.11 Both horizontal and vertical thermal tensile stresses will occur on the colder side of the wall. Where these stresses add significantly to those due to stored material pressures, additional reinforcement is required. (See Section 4.4.9.)

Better crack width control on the outside face is possible when the horizontal reinforcement is near the outer face. Also, since 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.

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 any corrosive elements from the stored material might damage the reinforcement.

R4.3.12 Singly-reinforced circular walls, with the reinforcement placed near the outside face may not effectively resist bending moments which cause tension on the inside face of the wall.

R4.4—Loads

R4.4.1.1 Material pressures against silo walls and hoppers depend on the initial (filling) conditions and on the flow patterns which develop in the silo upon discharge. The procedure for pressure calculations requires definition of the following terms:

(a) *Filling*—The process of loading the material by gravity into the silo.

(b) *Discharging*—The process of emptying the material by gravity from the silo.