Design and Construction of Reinforced Concrete Chimneys (ACI 307-98)

Reported by ACI Committee 307

This standard gives material, construction, and design requirements for cast-in-place and precast reinforced concrete chimneys. It sets forth minimum loadings for design and contains methods for determining the concrete and reinforcement required as a result of these loadings. The method of analysis applies primarily to circular chimney shells; however, a general procedure for analysis of noncircular shapes is included.

This standard is written in explicit, mandatory language, and as such, is intended for reference in project specifications.

Equations are provided for determining the temperature gradient through the concrete resulting from the difference in temperature of the gases inside the chimney and the surrounding atmosphere. Methods for combining the effects of dead and wind (or earthquake) loads with temperature both vertically and circumferentially are included in the standard. These methods permit the designer to establish minimum concrete and reinforcement requirements.

This standard refers extensively to “Building Code Requirements for Structural Concrete” (ACI 318); construction requirements are generally in accordance with ACI 318; and notation is in accordance with ACI 104.

Keywords: chimneys; compressive strength; concrete construction; earthquake-resistant structures; formwork (construction); foundations; high temperature; linings; loads (forces); moments; openings; precast concrete; quality control; reinforced concrete; reinforcing steels; specifications; static loads; strength; structural analysis; structural design; temperature; thermal gradient; wind pressure.

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CHAPTER 1—GENERAL

1.1—Scope
This standard covers the design and construction of circular cast-in-place or precast reinforced concrete chimney shells. If other shapes are used, their design shall be substantiated in accordance with the principles used here. The standard does not include the design of linings, but includes the effects of linings on the concrete shell.

A precast chimney shell is defined as a shell constructed wholly from precast reinforced concrete sections, assembled one atop another, to form a freestanding, self-supporting cantilever. Vertical reinforcement and grout are placed in cores as the precast sections are erected to provide structural continuity and stability. The use of precast panels as stay-in-place forms is considered cast-in-place construction.

1.2—Drawings
Drawings of the chimney shall be prepared showing all features of the work, including the design strength of the concrete, the thickness of the concrete chimney shell, the size and position of reinforcing steel, details and dimensions of the chimney lining, and information on chimney accessories.

1.3—Regulations

1.3.1 The design and construction of the chimney shall meet the requirements of all ordinances and regulations of authorities having jurisdiction, except that where such requirements are less conservative than the comparable requirements of this standard, this standard shall govern.

1.3.2 Consideration shall be given to the recommendations of the Federal Aviation Administration with respect to chimney heights and aviation obstruction lighting and marking, and the standards of the Underwriters Laboratories regarding lightning protection and grounding.

1.4—Reference standards
Standards of the American Concrete Institute, the American Society of Civil Engineers, and the American Society for Testing and Materials referred to in this standard are listed in the following with their serial designations, including the year of adoption or revision, and are declared to be a part of this standard as if fully set forth here.

ACI 104-71 Preparation of Notation for Concrete
(Revised 1982) (Reapproved 1987)
ACI 318-95 Building Code Requirements for Reinforced Concrete
ASCE 7-95 Minimum Design Loads for Buildings and Other Structures
ASTM A 615-95c Standard Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement
ASTM A 617-96 Standard Specification for Axle-Steel Deformed and Plain Bars for Concrete Reinforcement
ASTM A 706-96 Standard Specification for Low-Alloy Steel Deformed Bars for Concrete Reinforcement
ASTM C 33-93 Standard Specification for Concrete Aggregates
ASTM C 150-95 Standard Specification for Portland Cement
ASTM C 309-95 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
ASTM C 595-95 Standard Specification for Blended Hydraulic Cement

CHAPTER 2—MATERIALS

2.1—General
All materials and material tests shall conform to ACI 318, except as otherwise specified here.

2.2—Cement
The same brand and type of cement shall be used throughout the construction of the chimney. The cement used shall conform to the requirements for Type I, Type II, Type III, or Type V of ASTM C 150, or Type IS or Type IP of ASTM C 595.

2.3—Aggregates

2.3.1 Concrete aggregates shall conform to ASTM C 33.

2.3.2 The maximum size of coarse aggregate shall be not larger than 1/8 of the narrowest dimension between forms nor larger than 1/2 the minimum clear distance between reinforcing bars.

2.4—Reinforcement
Reinforcement shall conform to ASTM A 615, A 617, or A 706. Deformed reinforcement with a specified yield stress $f_y$ exceeding 60,000 psi (414.0 MPa) shall be permitted provided the ultimate tensile strain shall equal or exceed 0.07.

CHAPTER 3—CONSTRUCTION REQUIREMENTS

3.1—General
Concrete quality, methods of determining strength of concrete, field tests, concrete proportions and consistency, mixing and placing, and formwork and details of reinforcement shall be in accordance with ACI 318, except as stated otherwise here.

3.2—Concrete quality
The specified concrete compressive strength shall not be less than 3000 psi (20.7 MPa) at 28 days.

3.3—Strength tests
The 28-day compressive strength of the concrete shall be determined from a minimum of two sets of cylinders (consisting of three specimens each) per 8-hr shift (slipform) or per lift (jump form). For precast sections, a minimum of two sets shall be taken from each class of concrete cast each day and from each 100 yd$^3$ (76.5 m$^3$) of concrete placed each day.
3.4—Forms
3.4.1 Forms for the chimney shell shall be made of metal, wood, or other suitable materials. If unlined wooden forms are used, they shall be of selected material with tongue-and-groove joints and shall be kept continuously wet to prevent shrinking and warping due to exposure to the elements. A nonstaining form oil shall be permitted to be used. Form oil shall not be used unless it is a nonstaining type and it has been established that specified protective coatings or paint can be applied to concrete exposed to form oil.
3.4.2 Forms shall be sufficiently tight to prevent leakage of mortar.
3.4.3 No construction load shall be supported upon any part of the structure under construction until that portion of the structure has attained sufficient strength to safely support its weight and the loads placed thereon.
3.4.4 Forms shall be removed in such manner as to ensure the safety of the structure. Forms shall be permitted to be removed after concrete has hardened to sufficient strength to maintain its shape without damage and to safely support all loads on it, including temporary construction loads.
3.4.5 Ties between inner and outer chimney shell forms shall not be permitted.
3.4.6 Construction joints shall be properly prepared to facilitate bonding. As a minimum, all laitance and loose material shall be removed.

3.5—Reinforcement placement
3.5.1 Circumferential reinforcement shall be placed around the exterior of, and secured to, the vertical bars. All reinforcing bars shall be tied at intervals of not more than 2 ft (0.60 m). Particular attention shall be paid to placing and securing the circumferential reinforcement so that it cannot bulge or be displaced during the placing and working of the concrete so as to result in less than the required concrete cover over this circumferential reinforcement.
3.5.2 Vertical reinforcement projecting above the forms for the chimney shell or cores of precast sections shall be so supported as to prevent the breaking of the bond with the freshly placed concrete.
3.5.3 Not more than 50 percent of bars shall be spliced along any plane unless specifically permitted and approved by the responsible engineer.
3.5.4 The concrete cover over the circumferential reinforcement shall be a minimum of 2 in. (50 mm) for cast-in-place chimneys and 1 1/2 in. (38 mm) for precast units manufactured under plant control conditions.

3.6—Concrete placement
No vertical construction joints shall be used for cast-in-place chimney shells. Horizontal construction joints for jump-form and precast construction shall be maintained at approximately uniform spacing throughout the height of the chimney. Concrete shall be deposited in approximately level layers no greater than 16 in. (400 mm) deep. Particular care shall be exercised when casting concrete in thin wall sections and when casting cores of precast sections. Grout used to seat precast sections shall have a compressive strength at least equal to the design strength of the shell.

3.7—Concrete curing
3.7.1 Immediately after the forms have been removed all necessary finishing of concrete shall be done.
3.7.2 As soon as finishing has been completed, both faces of concrete shall be cured by coating with a membrane curing compound or other method approved by the engineer. The curing compound shall comply with ASTM C 309 and shall be applied in strict accordance with the manufacturer’s recommendations. If coatings are to be applied to the concrete, the curing compound shall be of a type compatible with these coatings.

3.8—Construction tolerances
3.8.1 The chimney shell shall be constructed within the tolerance limits set forth here.
3.8.1.1 Vertical alignment of centerpoint—The centerpoint of the shell shall not vary from its vertical axis by more than 0.001 times the height of the shell at the time of measurement, or 1 in. (25 mm), whichever is greater. Locally, the centerpoint of the shell shall not be changed by more than 1 in. per 10 ft (25 mm per 3.05 m).
3.8.1.2 Diameter—The measured outside shell diameter at any section shall not vary from the specified diameter by more than 1 in. (25 mm) plus 0.01 times the specified or theoretical diameter.
3.8.1.3 Wall thickness—The measured wall thickness shall not vary from the specified wall thickness by more than –1/4 in. (–6 mm), +1/2 in. (+13 mm) for walls 10 in. (250 mm) thick or less, or by more than –1/2 in. (–13 mm), +1 in. (+25 mm) for walls greater than 10 in. (250 mm) thick. A single wall thickness measurement is defined as the average of at least four measurements taken over a 60 deg arc.
3.8.2 Openings and embedments—Tolerances on the size and location of openings and embedments in the shell cannot be uniformly established due to the varying degrees of accuracy required depending on the nature of their use. Appropriate tolerances for opening and embedment sizes and locations shall be established for each chimney.

3.9—Precast erection
3.9.1 The precast sections shall be erected in a manner and at a rate that ensures that sufficient strength has been attained in grout, core concrete, and all connecting components to safely support construction and applicable design loads.
3.9.2 Precast sections shall be keyed if necessary to transfer shear and grouted to level and seal joints.

CHAPTER 4—SERVICE LOADS AND GENERAL DESIGN CRITERIA
4.1—General
4.1.1 The chimney shell shall be designed for the effects of gravity, temperature, wind, and earthquake in accordance with ACI 318, except as stated otherwise here.
4.1.2 The chimney shell shall be designed for load combinations in accordance with the provisions of Chapter 5, Design of chimney shell: Strength method.

4.1.3

4.1.3.1 The chimney shell shall not be less than 8 in. (200 mm) thick when cast in place, or less than 7 in. (180 mm) thick when composed of precast sections.

4.1.3.2 The chimney shell thickness, through openings, shall not be less than 1/4 the height of the opening.

The thickened shell shall extend at least 1/2 the height of the opening above and below the opening. Properly designed buttresses or other means of lateral restraint may be used in place of this requirement; however, the buttresses shall be ignored when calculating vertical strength.

4.1.3.3 When the internal diameter of the shell exceeds 28 ft (8.5 m), the minimum thickness shall be increased 1/6 in. for each 1 ft (10.4 mm per 1 m) increase in internal diameter.

4.1.4 A chimney shell that supports lining loads shall comply with the requirements of this standard with the lining in place. The interaction of the liner with the shell shall be considered.

4.1.5 Consideration shall be given to loadings during the construction phase.

4.1.6 If required during construction, temporary access openings may be provided in the concrete shell. For the design of the shell, these openings shall be designed as permanent openings.

4.1.7

4.1.7.1 The maximum foundation bearing pressure shall be established using unfactored chimney loads.

4.1.7.2 The foundation shall be designed by the strength method in accordance with the procedures of ACI 318. The foundation design shall be based on a pseudo-bearing pressure method in accordance with the procedures of ACI 318. The maximum foundation bearing pressure shall not be less than 1/24 the height of the opening.

4.1.7.3 The minimum factor of safety against overturning shall be 1.50 using unfactored loads.

4.1.7.4 Consideration shall be given to the effects of radiant heat of gases on any part of the foundation, including the foundation floor area which is exposed within the liner and also concrete floors supported from the concrete shell.

4.2—Wind loads

4.2.1 General—Reinforced concrete chimneys shall be designed to resist the wind forces in both the along-wind and across-wind directions. In addition, the hollow circular cross section shall be designed to resist the loads caused by the circumferential pressure distribution.

The reference design wind speed in mph (km/h), which shall be denoted as VR, shall be the “3-sec gust” wind speed at 33 ft (10 m) over open terrain where VR = (I)0.5 V. This speed V and importance factor I shall be as specified by ASCE 7. All chimneys shall be classified as Category IV structures as defined in ASCE 7-95. Terrain effects referenced in Section 6.5.5 of ASCE 7-95 are omitted.

At a height z ft (z m) above ground, the mean hourly design speed \( V(z) \) in ft/sec (or for \( V(z) \) in m/s) shall be computed from

\[
\overline{V}(z) = (1.47)V_R \left( \frac{z}{33} \right)^{0.154} \left( \frac{0.65}{10} \right)
\]

for metric units:

\[
\overline{V}(z) = 0.2784V_R \left( \frac{z}{10} \right)^{0.154} \left( \frac{0.65}{10} \right)
\]

with \( V_R \) in km/hr.

The provisions with respect to wind load take account of dynamic action but are simplified and lead to equivalent static loads. A properly substantiated dynamic analysis may be used in place of these provisions.

4.2.2 Along-wind load: Circular shapes—The along-wind load, \( w(z) \) per unit length at any height \( z \) ft, shall be the sum of the mean load \( w(z) \) and the fluctuating load \( w'(z) \).

The mean load \( w(z) \) in lb/ft (w(z) in N/m) shall be computed from Eq. (4-2)

\[
w(z) = C_{dr}(z) \cdot d(z) \cdot p(z)
\]

where

\[
C_{dr}(z) = 0.65 \quad \text{for } z < h - 1.5d(h)
\]

\[
C_{dr}(z) = 1.0 \quad \text{for } z \geq h - 1.5d(h)
\]

\[
p(z) = 0.0013 \cdot [\overline{V}(z)]^2
\]

for metric units, \( p(z) \) in Pa:

\[
p(z) = 0.67[\overline{V}(z)]^2
\]

\[
d(z) = \text{outside diameter at height } z, \text{ ft (or } d(z) \text{ in m})
\]

\[
h = \text{chimney height above ground level, ft (or } h \text{ in m})
\]

\[
d(h) = \text{top outside diameter, ft (or } d(h) \text{ in m})
\]

The fluctuating load \( w'(z) \), lb/ft, \( w'(z) \) in N/m shall be taken equal to

\[
w'(z) = \frac{3.0z \cdot G_{w'} \cdot M_w(b)}{h^3}
\]

where \( M_w(b) \) = base bending moment, lb-ft (N-m), due to \( \overline{V}(z) \) and

\[
G_{w'} = 0.30 + \frac{11.0[T_1 \cdot V(33)]^{0.47}}{(h + 16)^{0.86}}
\]

for metric units, \( \overline{V}(z) \) in N/m:
where \( V(33) \) is determined from Eq. (4-1) for \( z = 33 \) ft (10 m).

For preliminary design and evaluation of the critical wind speed \( V_{cr} \), as described in Section 4.2.3.1, the natural period of an unlined chimney \( T_1 \), in seconds per cycle, may be approximated using Eq. (4-7). However, for final design, the period shall be computed by dynamic analysis

\[
T_1 = \frac{5}{G_{w'}} \frac{h^2}{d_b} \left[ \frac{\rho_{ck}}{E_{ck}} \right]^{0.3} \left[ \frac{t(h)}{t(b)} \right]^{0.3} \tag{4-7}
\]

for metric units:

\[
T_1 = 5.32808 \frac{h^2}{d_b} \left[ \frac{\rho_{ck}}{E_{ck}} \right]^{0.3} \left[ \frac{t(h)}{t(b)} \right]^{0.3} \tag{4-7}
\]

where

- \( h \) = chimney height above base, ft (m)
- \( t(h) \) = thickness at top, ft (m)
- \( t(b) \) = thickness at bottom, ft (m)
- \( d_b \) = mean diameter at bottom, ft (m)
- \( \rho_{ck} \) = mass density of concrete, kip-sec²/ft⁴ (mg-sec²/m⁴)
- \( E_{ck} \) = modulus of elasticity of concrete, kip/ft² (MPa)

If the lining is supported in any manner by the shell, the effect of the lining on the period shall be investigated.

### 4.2.3 Across-wind load: Circular shapes

**4.2.3.1 General**—Across-wind loads due to vortex shedding in the first and second modes shall be considered in the design of all chimney shells when the critical wind speed \( V_{cr} \) is between 0.50 and 1.30 \( V(z_{cr}) \) as defined here. Across-wind loads need not be considered outside this range.

**4.2.3.2 Analysis**—When the outside shell diameter at \( \frac{1}{3}h \) is less than 1.6 times the top outside diameter, across-wind loads shall be calculated using Eq. (4-8) which defines the peak base moment \( M_a \):

\[
M_a = \frac{G_{w'}}{S_l} C_L C_L 0.243 - 5.648 i 18.182 i 2 - \frac{h}{d(u)} \cdot \pi \left[ \frac{4(\beta_s + \beta_a)}{} \right]^{1/2} \cdot S_p \left[ \frac{2L}{h} \right]^{1/2} \tag{4-8}
\]

for metric units, \( M_a \) in m-N:

\[
M_a = G S_L C_L 0.243 - 5.648 i 18.182 i 2 - \frac{h}{d(u)} \cdot \pi \left[ \frac{4(\beta_s + \beta_a)}{} \right]^{1/2} \cdot S_p \left[ \frac{2L}{h} \right]^{1/2} \tag{4-8}
\]

Eq. (4-8) defines the peak base moment \( M_a \) for values of \( V \), where \( V \) is evaluated between 0.5 and 1.30 \( V(z_{cr}) \). When \( V \geq V(z_{cr}) \), \( M_a \) shall be multiplied by

\[
\left[ 1.0 - 0.95 \left( \frac{V - V(z_{cr})}{V(z_{cr})} \right) \right] \tag{4-8a}
\]

where

- \( V(z_{cr}) \) = the mean design wind speed at \( z_{cr} \), \( z_{cr} = 5/6 \) \( h \), ft/sec (m/sec)
- \( g \) = acceleration due to gravity = 32.2 ft/sec²
- \( G \) = peak factor = 4.0
- \( S_s \) = mode shape factor = 0.57 for first mode, 0.18 for second mode

\[
C_L = C_{Lo} F_1(B) \tag{4-9}
\]

where

\[
C_{Lo} = -0.243 + 5.648 i - 18.182 i 2 \tag{4-10}
\]

but not \( > 1.0 \) or \( < 0.20 \).

- \( \rho_a \) = density of air = 0.075 lb/ft³ (1.2 kg/m³)
- \( V_{cr} \) = critical speed at \( 5/6h \), ft/sec (m/sec)

\[
V_{cr} = \frac{f d(u)}{S_l} \tag{4-13}
\]

where

- \( f \) = first-mode frequency, Hz
- \( S_s \) = Strouhal number

\[
S_s = 0.25 F_1(A) \tag{4-14}
\]

where

\[
F_1(A) = 0.333 + 0.206 \log_e \frac{h}{d(u)} \tag{4-15}
\]
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The period \( T_2 \) in seconds per cycle for an unlined shell may be estimated by Eq. (4-24). For final design, \( T_2 \) shall be calculated by dynamic analysis

\[
T_2 = 0.82 \frac{h^2}{\bar{d}(b)} \left[ \frac{\overline{\rho}_{ck}}{E_{ck}} \right]^{0.09} \left[ \frac{\bar{d}(h)}{\bar{d}(b)} \right]^{-0.22}
\]

for metric units:

\[
T_2 = 0.82 \times 3.2808 \frac{h^2}{\bar{d}(b)} \left[ \frac{\overline{\rho}_{ck}}{E_{ck} \times 1099.2} \right]^{0.09} \left[ \frac{\bar{d}(h)}{\bar{d}(b)} \right]^{-0.22}
\]

where \( \bar{t}(h) \) and \( \bar{t}(b) \) are the thicknesses at the top and bottom, respectively, and \( \bar{d}(h) \) and \( \bar{d}(b) \) are the mean diameters at the top and bottom, respectively.

The effect of a shell-supported liner on the period of the second mode shall also be investigated.

Any method using the modal characteristics of the chimney shall be used to estimate the across-wind response in the second mode.

**4.2.3.4 Grouped chimneys**—When two identical chimneys are in close proximity, the across-wind load shall be increased to account for the potential increase in vortex-induced motions. In such cases, the lift coefficient \( C_L \) in Eq. (4-9) shall be modified as follows

\[ a) \text{ if } s/d(z_{cr}) > 12.75, \ C_L \text{ is unaltered} \]
\[ b) \text{ if } 3 < s/d(z_{cr}) < 12.75, \ C_L \text{ shall be multiplied by:} \]
\[ [0.26 - 0.015 s/d(z_{cr})] + [2 - s/12 d(z_{cr})] \]

where
\[ s = \text{center-to-center spacing of chimneys, ft (m)} \]
\[ d(z_{cr}) = \text{outside diameter of chimney at critical height } z_{cr}, \text{ ft (m)} \]

For chimneys that are not identical and for identical chimneys where \( s/d(z_{cr}) < 3 \), the value of \( C_L \) shall be established by reference to model tests or observations or test reports of similar arrangements.

**4.2.3.5 Combination of across-wind and along-wind loads**—Across-wind loads shall be combined with the coexisting along-wind loads. The combined design moment \( M_u(z) \) at any section shall be taken as

\[
M_u(z) = \left\{ \left[ M_{u}(z) \right]^2 + \left[ M_{l}(z) \right]^2 \right\}^{0.5}
\]

where
\[ M_{u}(z) = \text{moment induced by across-wind loads} \]
\[ M_{l}(z) = \text{moment induced by the mean} \]
along-wind load \( w_l(z) \)

where

\[
    w_l(z) = \bar{w}(z) \left[ \frac{V}{V(z_{cr})} \right]^2
    \quad (4-26)
\]

except that \( w_l(z) \) shall not exceed \( w(z) \).

4.2.4 Circumferential bending — The maximum circumferential bending moments due to the radial wind pressure distribution shall be computed by Eq. (4-27) and (4-28)

\[
    M_i(z) = 0.31pr(z) [r(z)]^2, \text{ ft-lb/ft (tension on inside)} \quad (4-27)
\]

for metric units:

\[
    M_i(z) = 0.31pr(z) [r(z)]^2, \text{ N-m/m}
\]

\[
    M_o(z) = 0.27pr(z) [r(z)]^2, \text{ ft-lb/ft (tension on outside)} \quad (4-28)
\]

for metric units:

\[
    M_o(z) = 0.27pr(z) [r(z)]^2, \text{ N-m/m}
\]

where

\( r(z) = \text{mean radius at height } z, \text{ ft (m)} \)

\[
    pr(z) = 0.0013[V(z)]^2 \cdot G_r(z), \text{ lb/ft}^2 \quad (4-29)
\]

for metric units:

\[
    pr(z) = 0.67[V(z)]^2 \cdot G_r(z), \text{ Pa}
\]

\[
    G_r(z) = 4.0 - 0.8\log_{10} z, \text{ except } G_r(z) = 4 \text{ for } z \leq 1.0 \quad (4-30)
\]

for metric units:

\[
    G_r(z) = 4.0 - 0.8\log_{10} (3.2808 \cdot z), \text{ except } G_r(z) = 4 \text{ for } z < 1.0
\]

The pressure \( pr(z) \) shall be increased by 50 percent for a distance 1.5\( d(h) \) from the top.

4.2.5 Wind loads: Noncircular shapes — The provisions of ASCE 7 shall be followed including force coefficients and gust response factors. Unusual cross-sectional shapes not covered in ASCE 7 shall require wind tunnel testing or other similar documentation to verify along- or across-wind loads, or both. Similarly, horizontal bending due to wind pressure distributions shall also require wind tunnel testing or other documentation from reliable sources.

4.3—Earthquake loads

4.3.1 General — Reinforced concrete chimneys in earthquake areas shall be designed and constructed to resist the earthquake effects in accordance with the requirements of this section. Applicable effective peak velocity-related accelerations \( A_v \) shall be in accordance with the ASCE 7 maps for the site.

Chimneys shall be designed for earthquakes by means of the dynamic response spectrum analysis method given in Section 4.3.2. In place of the dynamic spectrum analysis method, time history analysis based on accellograms representative of the locality may be used.

The effects due to the vertical component of earthquakes are generally small and can be ignored in the earthquake design of chimneys. The horizontal earthquake force shall be assumed to act alone in any lateral direction.

4.3.2 Dynamic response spectrum analysis method — The shears, moments, and deflections of a chimney due to earthquake shall be determined by using a site-specific response spectrum and the elastic modal method. The site-specific response spectrum shall be based on a 90 percent probability

| Table 4.3.2(a)— Special values for maximum ground acceleration of 1.0g* |
|---|---|---|---|
| Frequency, Hz | Displacement spectrum, in. | Velocity spectrum, in/sec | Acceleration spectrum, g |
| \( f \leq 0.25 \) | 50.7 | 318.6f | 5.186f^2 |
| \( 0.25 \leq f \leq 2.5 \) | 10.39 \( f 1.1436 \) | 65.26 \( f 0.1436 \) | 1.062f^0.8564 |
| \( 2.5 \leq f \leq 9 \) | \( 25.32 f 2.1158 \) | \( 159.1 f 1.1158 \) | \( 2.589 f 0.1158 \) |
| \( 9 \leq f \leq 33 \) | \( 63.87 f 2.5369 \) | \( 401.3 f 1.5369 \) | \( 6.533 f 0.5369 \) |
| \( f > 33 \) | \( 9.768 f 2 \) | \( 6.37 f \) | 1.00 |

* Damping ratio = 0.05. (Convert to comparable units. No metric conversion is presented.)

| Table 4.3.2(b)—Response spectrum scaling ratio versus \( A_v \) |
|---|---|
| \( A_v \) effective peak velocity-related accelerations | Scaling ratio |
| 0.05 | 0.04 |
| 0.08 | 0.06 |
| 0.15 | 0.11 |
| 0.20 | 0.15 |
| 0.30 | 0.23 |
| 0.40 | 0.30 |

Linear interpolation may be used in between \( A_v \) coefficients not given.
of not being exceeded in 50 years with 5 percent damping. If a site-specific response spectrum is unavailable, the design response spectrum for the site shall be obtained by scaling down the normalized 1.0g peak ground acceleration spectrum for 5 percent damping shown in Fig. 4.3.2 or Table 4.3.2(a) by the scaling ratios given in Table 4.3.2(b) for the $A_v$ of the site.

The normalized design response spectrum given in Fig. 4.3.2 or Table 4.3.2(a) is suitable for firm soil conditions. The response spectrum shall be modified for soft and shallow soil conditions by any method that is properly substantiated and complies with the basic principles herein.

The analytical model of a chimney used in the dynamic response spectrum analysis shall be sufficiently refined to represent variations of chimney and liner masses, variations of stiffness, and the foundation support condition. A minimum of 10 elements shall be included. The total dynamic response of the chimneys in terms of shear and moment shall be computed using the SRSS over a minimum of five normal modal responses. SRSS means taking the square root of the sum of the squares of modal maxima. The use of the CQC method (complete quadratic combination) is also permitted.

### 4.4—Special design considerations and requirements

#### 4.4.1 Two layers of vertical and circumferential reinforcement are required. The total vertical reinforcement shall be not less than 0.25 percent of the concrete area. The outside vertical reinforcement shall be not less than 50 percent of the total reinforcement. Outside-face vertical bars shall not be smaller than No. 4, nor shall they be spaced more than 12 in. (No. 13 M bars at 300 mm) on centers. Inside-face vertical bars shall not be smaller than No. 4, nor shall they be spaced more than 24 in. (No. 13 M bars at 600 mm) on centers.

#### 4.4.2 The total circumferential reinforcement shall not be less than 0.20 percent of the concrete area. The circumferential reinforcement in each face shall be not less than 0.1 percent of the concrete area at the section.

Spacing of outer face circumferential reinforcement shall not exceed the wall thickness or 12 in. (300 mm). Spacing of circumferential reinforcement on the inner face shall not exceed 12 in. (300 mm). The minimum size of circumferential reinforcing bars shall be No. 3 (No. 10 M).

#### 4.4.3 The circumferential reinforcement for a distance of 0.2$d(h)$ from the top of the chimney or 7.5 ft (2.3 m), whichever

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**Fig. 4.3.2—Normalized horizontal elastic seismic response spectra. (Convert to comparable units. No metric conversion is presented.)**
is greater, shall be at least twice the amount required by Section 5.7.

4.4.4 Where a segment between openings is critical as related to the height of the openings, this segment shall be investigated as a beam-column. Where more than two openings occur at the same elevation, appropriate design methods consistent with the cases shown by Fig. 5.5.1(a), (b), and (c) shall be used.

4.4.5 In addition to the reinforcement determined by design, extra reinforcement shall be provided at the sides, top, bottom, and corners of these openings as hereinafter specified. This extra reinforcement shall be placed near the outside surface of the chimney shell as close to the opening as proper spacing of bars will permit. Unless otherwise specified, all extra reinforcement shall extend past the opening a minimum of the development length.

4.4.6 At each side of the opening, the additional vertical reinforcement shall have an area at least equal to the design steel ratio times one-half the area of the opening. The extra reinforcement shall be placed within a distance not exceeding twice the wall thickness unless otherwise determined by a detailed analysis.

4.4.7 At both the top and bottom of each opening, additional reinforcement shall be placed having an area at least equal to one-half the established design circumferential reinforcement interrupted by the opening, but the area of this additional steel at the top and also at the bottom shall be not less than that given by Eq. (4-31), unless otherwise determined by a detailed analysis

\[ A_s = \frac{0.06 f'_c t l}{f_y} \text{ (in}^2 \text{ or mm}^2) \]  

(4-31)

where

- \( f'_c \) = specified compressive strength of concrete, psi (MPa)
- \( t \) = concrete thickness at opening, in. (mm)
- \( l \) = width of opening, in. (mm)
- \( f_y \) = specified yield strength of reinforcing steel, psi (MPa)

One-half of this extra reinforcement shall extend completely around the circumference of the chimney, and the other half shall extend beyond the opening a sufficient distance to develop the bars in bond. This steel shall be placed as close to the opening as practicable, but within a height not to exceed three times the thickness \( t \).

4.4.8 For openings larger than 2 ft (600 mm) wide, diagonal reinforcing bars with a total cross-sectional area in square inches (mm²) of not less than \( 1/6 \) (5.08) of the shell thickness in inches (mm) shall be placed at each corner of the opening. For openings 2-ft (600 mm) wide or smaller, a minimum of two No. 5 (No. 16 M) reinforcing bars shall be placed diagonally at each corner of the opening.

4.5—Deflection criteria

The maximum lateral deflection of the top of a chimney under all service conditions prior to the application of load factors shall not exceed the limits set forth by Eq. (4-32)

\[ Y_{max} = 0.04h \]  

or

\[ Y_{max} = 3.33h \]  

for metric units:

where

- \( Y_{max} \) = maximum lateral deflection, in. (mm)
- \( h \) = chimney height, ft (m)

CHAPTER 5—DESIGN OF CHIMNEY SHELLS: STRENGTH METHOD

5.1—General

5.1.1 Except as modified herein, design assumptions shall be in accordance with ACI 318, Chapter 10. The chimney shell shall be designed by the strength method.

5.1.2 The equivalent rectangular concrete stress distribution described in Section 10.2.7 of ACI 318 and as modified herein shall be used. For vertical strength the maximum strain on the concrete is assumed to be 0.003 and the maximum strain in the steel is assumed to be 0.07. Whichever value is reached first shall be taken as the limiting value.

In place of the equivalent rectangular concrete compressive stress distribution used in this chapter, any other relationship between concrete compressive stress and strain may be assumed that results in prediction of the strength of hollow circular sections in substantial agreement with results of comprehensive tests.

5.1.3 The design and detailing of precast chimney shells shall emulate the design of cast-in-place chimney shells unless specifically stated otherwise herein. Particular attention should be given to the spacing and reinforcement of cast-in-place cores and closures joining precast units to ensure that the requirements of this and other applicable standards are met.

5.1.4 Refer to Section 5.7 for design procedures of noncircular shells.

5.2—Design loads

5.2.1 Dead loads and wind or earthquake forces at service conditions prior to the application of load factors, shall be in accordance with Chapter 4 of this standard. Thermal effects at service conditions shall be in accordance with Chapter 6.

5.3—Required strength

5.3.1 Required vertical strength \( U_v \) to resist dead load \( D \), or wind load \( W \) and normal temperature \( T \), shall be the largest of the following

\[ U_v = 1.4D \]  

(5-1a)

\[ U_v = 1.1D + 1.4T + 1.3W^\alpha \]  

(5-1b)
Fig. 5.5.1(a)—Stress diagram.

Fig. 5.5.1(b)—Two openings in compression zone.

Fig. 5.5.1(c)—Two symmetric openings partly in compression zone.
and

\[ U_v = 0.9D + 1.4T + 1.3W^* \]  

(5-1c)

*The load factor 1.3 shall be used for the along-wind loads of Section 4.2.2. For the across-wind loading combined with the along-wind loading (Section 4.2.3.5), a load factor of 1.2 shall be used.

5.3.2 For earthquake loads or forces \( E \), the load combinations of Section 5.3.1 shall apply except that 1.1 \( E \) shall be substituted for \( W \).

5.3.3 Required circumferential strength \( U_c \) to resist wind load \( W \) and normal temperature load \( T \) shall be

\[ U_c = 1.05T + 1.3W \]  

(5-1d)

5.4—Design strength

5.4.1 Design strength of a section in terms of moment shall be taken as the nominal moment strength calculated in accordance with the requirements of this standard multiplied by a strength reduction factor \( \phi \) equal to 0.70 for vertical strength and 0.90 for circumferential strength.

5.5—Nominal moment strength: Circular shells

5.5.1 The following equations apply [refer to Fig. 5.5.1(a), and 5.5.1(b)]

\[ P_u/\rho_t f'c’ = K_1 = 1.7Q\lambda + 2\varepsilon_m K_c \omega_1 Q_1 + 2\omega_1 \lambda_1 \]  

(5-2)

where

\[ P_u = \text{factored vertical load} \]

\[ r = \text{average radius of section} \]

\[ t = \text{thickness of section} \]

\[ \lambda = \tau - n_1\beta \]  

(radians)  

(5-3)

\[ Q_1 = \frac{\sin \psi - \sin \mu - (\psi - \mu)\cos \alpha}{1 - \cos \alpha} \]  

(5-4)

\[ \lambda_1 = \mu + \psi - \pi \]  

(radians)  

(5-5)

\( \mu, \tau, \psi = \text{angles shown in Fig. 5.5.1(a).} \)

\[ \cos \tau = 1 - \beta_1(1 - \cos \alpha) \]  

(5-6)

\[ \cos \psi = \cos \alpha - \left(1 - \cos \alpha\right) \left(\frac{f_y}{E_s}\right) \geq -1.0 \]  

(5-7)

\[ \cos \mu = \cos \alpha + \left(1 - \cos \alpha\right) \left(\frac{f_y}{E_s}\right) \leq 1.0 \]  

(5-8)

where

\[ \alpha = \text{one-half the central angle subtended} \]

by neutral axis

\[ \beta = \text{one-half opening angle} \]

\[ \beta_1 = 0.85 \text{ for } f'c’ \leq 4000 \text{ psi (27.6 MPa)} \]

\[ = 0.85 - 0.05(f'c’ - 4000)/1000 \geq 0.65, \text{ for } f'c’ > 4000 \text{ psi} \]

for metric units:

\[ \beta_1 = 0.85 - 0.05 \left(\frac{f'c’}{27.6}\right) \geq 0.65, \text{ for } f'c’ \leq 27.6 \text{ MPa} \]

\[ = 0.85 - 0.05 \left(\frac{f'c’}{6.9}\right) \geq 0.65, \text{ for } f'c’ > 27.6 \text{ MPa} \]

\[ K_e = \frac{E_s}{f_y} \]

\[ \omega_t = \frac{\rho_t f_y}{f'c’} \]

\[ \rho_t = \text{ratio of total vertical reinforcement to total area of concrete} \]

\[ n_1 = \text{number of openings entirely in compression zone (maximum 2)} \]

\[ \varepsilon_m = 0.07(1 - \cos \alpha)/(1 + \cos \alpha) \leq 0.003 \]

(5-9)

\[ M_n/P_u r = K_3 = \cos \alpha + K_2/K_1, M_n = P_u r K_3 \]  

(5-10)

\[ K_2 = 1.7QR + \varepsilon_m K_c \omega_1 \omega_2 + 2\omega_1 K \]  

(5-11)

For \( \alpha \leq 5 \text{ deg} \)

\[ Q = (-0.523 + 0.181 \alpha - 0.0154\alpha^2) \]

\[ + (41.3 - 13.2\alpha + 1.32\alpha^2)(t/r) \]  

(5-12a)

For 5 deg < \( \alpha \leq 10 \text{ deg} \)

\[ Q = (-0.154 + 0.01773\alpha + 0.00249\alpha^2) \]

\[ + (16.42 - 1.980\alpha + 0.0674\alpha^2)(t/r) \]  

(5-12b)

For 10 deg < \( \alpha \leq 17 \text{ deg} \)

\[ Q = (-0.488 + 0.076\alpha) + (9.758 - 0.640\alpha)(t/r) \]  

(5-12c)

For 17 deg < \( \alpha \leq 25 \text{ deg} \)

\[ Q = (-1.345 + 0.2018\alpha - 0.004434\alpha^2) \]

\[ + (15.83 - 1.676\alpha + 0.03994\alpha^2)(t/r) \]  

(5-12d)

For 25 deg < \( \alpha \leq 35 \text{ deg} \)

\[ Q = (0.993 - 0.00258\alpha) + (-3.27 + 0.0862\alpha)(t/r) \]  

(5-12e)

For \( \alpha > 35 \text{ deg} \)

\[ Q = 0.89 \]  

(5-12f)

where

\[ M_n = \text{nominal moment strength of section} \]
By trial and error, find the value of
Step 2.

\[
Q_2 = \left[ \frac{(\psi - \mu)(1 + 2\cos^2 \alpha) + (1/2)(4\sin 2\alpha + \sin 2\psi - \sin 2\mu)}{1 - \cos \alpha} \right]
\]

\[K = \sin \psi + \sin \mu + (\pi - \psi - \mu) \cos \alpha\]  

(5-13)

\[R = \sin \tau - (\tau - n_1 \beta) \cos \alpha - (n_1/2)[\sin(\gamma + \beta) - \sin(\gamma - \beta)]\]  

(5-15a)

\[\gamma = \frac{1}{2} \text{ angle between center lines of two openings and for no openings, } n_1 = \gamma = \beta = 0; \text{ for one opening in compression zone, } n_1 = 1, \gamma = 0; \text{ for two openings in compression zone, } n_1 = 2\]

5.5.2 Two symmetric openings partly in compression zone—Refer to Fig. 5.5.1(c). This condition exists when \(\gamma + \beta > \tau\) and \(\gamma - \beta < \tau\). For this case, let \(\delta = \gamma - \beta\). Then in Eq. (5-2), \(\lambda = \delta\).

And in Eq. (5-11)

\[R = \sin \delta - \delta \cos \alpha\]  

(5-15b)

5.5.3 Openings in tension zone—Openings in the tension zone are ignored since the tensile strength of the concrete is neglected and the bars cut by the openings are replaced at the sides of the openings.

5.5.4 Openings in compression zone—In calculations of the forces in the compression reinforcement only, openings in the compression zone are ignored since the cut bars are replaced at the sides of the openings.

5.5.5 Limitation—The one-half opening angle \(\beta\) shall not exceed 30 deg.

5.5.6 Calculation procedure—Given \(r, t, f'_c, \beta, \gamma, P_u, M_u\), and the number of openings (where \(P_u\) and \(M_u\) are the factored vertical load and the factored moment, respectively), use the following procedure:

Step 1. Assume a value for the total vertical steel ratio \(\rho_v\).

Step 2. By trial and error, find the value of \(\alpha\) that satisfies Eq. (5-2).

Step 3. Substitute this value of \(\alpha\) in Eq. (5-10) and calculate \(M_w\).

Step 4. If \(\phi M_n < M_w\) increase \(\rho_v\); if \(\phi M_n > M_w\) decrease \(\rho_v\).

Step 5. Repeat Step 2 through Step 4 until \(\phi M_n = M_w\).

5.5.7 For load combinations with temperature effects, modify \(f'_y\) and \(f'_c\) using Eq. (5-16a) and (5-17a).

Replace \(f'_y\) with

\[f'_y'(v) = f'_y \cdot \frac{1.4}{1 + y_1} \left(\frac{f'_{STV} - \gamma_1 f''_{STV}}{f'_{STV}}\right)\]  

(5-16a)

Replace \(f'_c\) with

\[f''_c(v) = f'_c - 1.40 f''_{CTV}\]  

(5-17a)

Fig. 5.6—Stress-strain curve for concrete.

where \(\gamma_1, f'_{STV}, f''_{STV}\), and \(f''_{CTV}\) are as defined in Chapter 6.

5.6—Noncircular shapes

5.6.1 General—All applicable sections of this Standard shall be followed, including horizontal bending and temperature effects.

5.6.2 Design assumptions—Strain in reinforcement and concrete shall be assumed directly proportional to the distance from the neutral axis.

For vertical strength, the maximum strain in the concrete is assumed to be 0.003 and the maximum strain in the steel is assumed to be 0.07. Whichever value is reached first shall be taken as the limiting value.

Stress in reinforcement below the specified yield strength \(f'_y\) for grade of reinforcement used shall be taken as \(E_s\) times steel strain. For strains greater than that corresponding to \(f'_y\), stress in reinforcement shall be assumed equal to \(f'_y\).

Tensile strength of concrete shall be neglected.

Relationship of concrete compressive stress and concrete strain shall be assumed in accordance with stress-strain curve as shown in Fig. 5.6.

5.6.3 Calculation procedure—For a given geometry and given \(P_u\) and \(M_u\) (where \(P_u\) is the factored vertical load and \(M_u\) is the factored moment), use the following procedure:

Step 1. Assume a value for the total vertical steel ratio \(\rho_v\).

Step 2. By trial and error, find the location of the neutral axis which makes the total vertical force in the section equal and opposite to \(P_u\).

Step 3. With this location of the neutral axis, calculate \(M_n\), the nominal moment strength of the section.

Step 4. If \(\phi M_n < M_u\) increase \(\rho_v\).
If $\phi M_n > M_u$, decrease $\rho$.

**Step 5.** Repeat Step 2 through Step 5 until $\phi M_n = M_u$.

### 5.6.4 Horizontal bending—Design for horizontal bending

shall comply with the requirements of Section 5.7.

#### 5.7—Design for circumferential bending

#### 5.7.1 Any horizontal strip of the concrete column shall be designed as a horizontal beam resisting circumferential bending moments as given in Section 4.2.4 and thermal effects described in Section 6.3.

#### 5.7.2 For loads combined with temperature effects, modify $f_y$ and $f_y$' using Eq. (5-16b) and (5-17b).

Replace $f_y$ with $f_y'(c) = f_y - 1.05f_{STC}$ (5-16b)

Replace $f_y'$ with $f_y''(c) = f_y' - 1.05f''_{CTC}$ (5-17b)

where $f_{STC}$ and $f''_{CTC}$ are as defined in Chapter 6.

### CHAPTER 6—THERMAL STRESSES

#### 6.1—General

The equations for temperature stresses given in this chapter are based on working stress procedures and shall be considered in the calculation of the nominal moment strength in Chapter 5.

#### 6.2—Vertical temperature stresses

#### 6.2.1 The maximum vertical stresses in the concrete and steel, in psi (MPa), occurring at the inside of the chimney shell due to temperature $f''_{CTV}$ and $f''_{STV}$, respectively, shall be computed by Eq. (6-1a) and (6-1b)

$$ f''_{CTV} = \alpha_{te} \cdot c \cdot T_x \cdot E_c \quad (6-1a) $$

$$ f''_{STV} = \alpha_{te} \cdot (c - 1 + \gamma_2) \cdot T_x nE_c \quad (6-1b) $$

where

- $\alpha_{te}$ = thermal coefficient of expansion of concrete and of reinforcing steel, to be taken as 0.0000065 (0.0000117 per C)
- $E_c$ = modulus of elasticity of concrete, psi (MPa)
- $c = -\rho n(\gamma_1 + 1) + \sqrt{\rho n(\gamma_1 + 1)^2 + 2\rho n(\gamma_2 + \gamma_1(1 - \gamma_2))} \quad (6-2)$
- $\rho$ = ratio of total area of vertical outside face reinforcement to total area of concrete chimney shell at section under consideration
- $\gamma_1$ = ratio of inside face vertical reinforcement area to outside face vertical reinforcement area
- $\gamma_2$ = ratio of distance between inner surface of chimney shell and center line of outer face vertical reinforcement to total shell thickness
- $n = E_s/E_c$

$T_x$, the temperature gradient across the concrete shell, shall be computed by Eq. (6-3a), (6-3b), (6-3c), (6-3d), or by a complete heat balance study for all operating conditions.

a) For unlined chimneys

$$ T_x = \frac{td_{ci}}{C_c d_e} \left( \frac{T_i - T_o}{K_i + \frac{td_{ci}}{C_c d_e} + \frac{d_{ci}}{K_o d_{co}}} \right) \quad (6-3a) $$

b) For lined chimneys with insulation completely filling the space between the lining and shell

$$ T_x = \frac{td_{bi}}{C_c d_e} \left( \frac{T_i - T_o}{K_i + \frac{td_{bi}}{C_b d_b} + \frac{d_{bi}}{K_o d_{co}}} \right) \quad (6-3b) $$

c) For lined chimneys with unventilated air space between the lining and shell

$$ T_x = \frac{td_{bi}}{C_c d_e} \left( \frac{T_i - T_o}{r_q K_i + \frac{td_{bi}}{r_q C_b d_b} + \frac{d_{bi}}{r_q K_o d_{co}}} \right) \quad (6-3c) $$

d) For lined chimneys with a ventilated air space between the lining and shell

$$ T_x = \frac{td_{bi}}{C_c d_e} \left( \frac{T_i - T_o}{r_q K_i + \frac{td_{bi}}{r_q C_b d_b} + \frac{d_{bi}}{r_q K_o d_{co}}} \right) \quad (6-3d) $$

where

- $r_q$ = ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces
- $t$ = thickness of concrete shell, in. (m)
- $t_b$ = thickness of uninsulated lining or insulation around steel liner, in. (m)
- $t_s$ = thickness of air space or insulation filling the space between the lining and shell, in. (m)
- $T_i$ = maximum specified design temperature of gas inside chimney, F (C)
- $T_o$ = minimum temperature of outside air surrounding chimney, F (C)
- $C_b$ = coefficient of thermal conductivity of chimney uninsulated lining or insulation around steel liner, Btu/ft²/in. of thickness/hr/F difference in temperature (watt/(meter Kelvin))
- $C_c$ = coefficient of thermal conductivity of the concrete of chimney shell, Btu/ft²/in. of thickness/hr/F difference in temperature (watt/(meter Kelvin))
- $C_s$ = coefficient of thermal conductivity of insulation
filling in space between lining and shell, Btu/ft²/in. of thickness/hr/F difference in temperature (watt/meter Kelvin and 0.43 watt/meter Kelvin for lightweight concrete) (3 for lightweight concrete)

\[ K_i = \text{coefficient of heat transmission from gas to inner surface of chimney lining when chimney is lined, or to inner surface of chimney shell when chimney is unlined, Btu/(ft}^2 \cdot \text{hr} \cdot \text{F}) [\text{watt/(m}^2 \cdot \text{Kelvin})] \text{ difference in temperature} \]

\[ K_o = \text{coefficient of heat transmission from outside surface of chimney shell to surrounding air, Btu/(ft}^2 \cdot \text{hr} \cdot \text{F}) [\text{watt/(m}^2 \cdot \text{Kelvin})] \text{ difference in temperature} \]

\[ K_r = \text{coefficient of heat transfer by radiation between outside surface of lining and inside surface of concrete chimney shell, Btu/(ft}^2 \cdot \text{hr} \cdot \text{F}) [\text{watt/(m}^2 \cdot \text{Kelvin})] \text{ difference in temperature} \]

\[ K_s = \text{coefficient of heat transfer between outside surface of lining, and inside surface of shell for chimneys with ventilated air spaces, Btu/(ft}^2 \cdot \text{hr} \cdot \text{F}) [\text{watt/(m}^2 \cdot \text{Kelvin})] \text{ difference in temperature} \]

\[ d_{bi} = \text{inside diameter of uninsulated lining or insulation around liner, ft (m)} \]

\[ d_b = \text{mean diameter of uninsulated lining or insulation around liner, ft (m)} \]

\[ d_s = \text{mean diameter of space between lining and shell, ft (m)} \]

\[ d_c = \text{mean diameter of concrete chimney shell, ft (m)} \]

\[ d_{co} = \text{outside diameter of concrete chimney shell, ft (m)} \]

6.2.2 Unless complete heat balance studies are made for the particular chimney, it is permissible to use the approximate values given below. These constants when entered into equations for temperature differential through the chimney shell \( T_i \) will give values of accuracy in keeping with the basic design assumptions.

\[ r_q = 0.5 \]

\[ C_c = 12 \text{ (or 1.73 watt/(meter Kelvin))} \]

\[ C_s = \text{to be obtained from the manufacturer of the materials used} \]

\[ C_b = \text{to be obtained from the manufacturer of the materials used} \]

\[ K_i = \text{to be determined from curves in Fig. 6.2.2} \]

\[ K_o = 12 \text{ Btu/(ft}^2 \cdot \text{hr} \cdot \text{F}) [68 \text{ watts/(m}^2 \cdot \text{Kelvin})] \]

\[ K_r = T_i/120 \text{ (or } T_i/9.75 \text{ in metric)} \]

\[ K_s = T_i/150 \text{ (or } T_i/9.75 \text{ in metric)} \]

The value of \( r_q = 0.5 \) shall apply only where the distance between the lining and the chimney shell is not less than 4 in. throughout the entire height of the lining and air inlet and outlet openings are provided at the bottom and top of the chimney shell. The area of the inlet and outlet openings in square feet shall numerically equal two-thirds the inside diameter in feet of the chimney shell at the top of the lining. Local obstructions in the air space between the lining and the chimney shell shall not restrict the area of the air space at any horizontal section to less than that specified for air inlet or outlet.
6.2.3 The maximum stress in the vertical steel \( f_{STV} \) in psi (or MPa), occurring at the outside face of the chimney shell due to temperature, shall be computed by Eq. (6-4)

\[
f_{STV} = \alpha_{ts} \cdot (\gamma_2 - c) \cdot T_x \cdot E_s \quad (6-4)
\]

where

\[
E_s = \text{modulus of elasticity of the reinforcement, psi (MPa)}
\]

6.3—Circumferential temperature stresses

6.3.1 The maximum circumferential stress in psi (or MPa) in the concrete due to temperature \( f''_{CTC} \) occurring at the inside of the chimney shell shall be computed by Eq. (6-5)

\[
f''_{CTC} = \alpha_{ts} \cdot c' \cdot T_x \cdot E_c \quad (6-5)
\]

where

\[
c' = -\rho' n(\gamma_1' + 1) + \sqrt{[\rho' n(\gamma_1' + 1)]^2 + 2\rho' n[\gamma_2' + \gamma_1'(1 - \gamma_2')]} \quad (6-6)
\]

and

\[
T_x = \text{value determined for vertical temperature stresses}
\]

\[
\rho' = \text{ratio of cross-sectional area of circumferential outside face reinforcing steel per unit of height to cross-sectional area of chimney shell per unit of height}
\]

\[
\gamma_1' = \text{ratio of inside face circumferential reinforcing steel area to outside circumferential reinforcing steel area}
\]

\[
\gamma_2' = \text{ratio of distance between inner surface of chimney shell and circumferential outside face reinforcing steel to total thickness} \ t
\]

All other notations are the same as for vertical temperature stresses.

6.3.2 The maximum stress in psi in the outside circumferential reinforcement \( f_{STC} \) due to temperature shall be computed by Eq. (6-7)

\[
f_{STC} = \alpha_{ts} \cdot (\gamma_2' - c') \cdot T_x \cdot E_s \quad (6-7)
\]

APPENDIX A—NOTATION

\( A_s \) = area of reinforcing steel at top and bottom of opening, in.\(^2\) (mm\(^2\)) (Chapter 4)
\( B \) = band width parameter (Chapter 4)
\( c \) = ratio of distance from extreme compression fiber to neutral axis for vertical stresses to total thickness \( t \) (Chapter 6)
\( c' \) = \( c \) for circumferential stresses (Chapter 6)
\( C_b \) = coefficient of thermal conductivity of chimney uninsulated lining or insulation around steel liner, Btu \( \cdot \) ft/(hr \( \cdot \) ft\(^2\) \( \cdot \) F) of thickness/hr/F (watt/ [meter Kelvin]) difference in temperature (Chapter 6)
\( C_c \) = coefficient of thermal conductivity of concrete of chimney shell, Btu \( \cdot \) ft/(hr \( \cdot \) ft\(^2\) \( \cdot \) F) of thickness/hr/F (watt/[meter Kelvin]) difference in temperature (12 for normal weight concrete) or 1.73 watt/meter Kelvin (Chapter 6)
\( C_{dr} \) = drag coefficient for along-wind load (Chapter 4 and Commentary Chapter 4)
\( C_E \) = end effect factor (Chapter 4)
\( C_L \) = rms lift coefficient (Chapter 4)
\( C_{Lo} \) = rms lift coefficient modified for local turbulence (Chapter 4)
\( C_s \) = coefficient of thermal conductivity of insulation filling in space between lining and shell, Btu \( \cdot \) ft/(hr \( \cdot \) ft\(^2\) \( \cdot \) F) of thickness/hr/F (watt/meter Kelvin) difference in temperature (3 for lightweight concrete) or 0.43 watt/meter Kelvin (Chapter 6)
\( d \) = diameter of chimney (Commentary Chapter 4)
\( d_b \) = mean diameter of uninsulated lining or insulation around liner, ft (m) (Chapter 6)
\( d_{bi} \) = inside diameter of uninsulated lining or insulation around liner, ft (m) (Chapter 6)
\( d_c \) = mean diameter of concrete chimney shell, ft (m) (Chapter 6)
\( d_{ci} \) = inside diameter of concrete chimney shell, ft (m) (Chapter 6)
\( d_{co} \) = outside diameter of concrete chimney shell, ft (m) (Chapter 6)
\( d_s \) = mean diameter of space between lining and shell, ft (or m) (Chapter 6)
\( d(b) \) = bottom outside diameter of chimney, ft (m) (Chapter 4)
\( d(b) \) = mean diameter at bottom of chimney, ft (m) (Chapter 4)
\( d(h) \) = top outside diameter of chimney, ft (m) (Chapter 4 and Commentary Chapter 4)
\( d(h) \) = mean diameter at top of chimney, ft (m) (Chapter 4)
\( d(u) \) = mean outside diameter of upper third of chimney, ft (m) (Chapter 4)
\( d(z) \) = outside diameter of chimney at height \( z \), ft (m) (Chapter 4 and Commentary Chapter 4)
\( d(z_{cr}) \) = outside diameter of chimney at critical height \( z_{cr} \), ft (m) (Chapter 4)
\( D \) = dead load (Chapter 5)
\( E \) = earthquake loads or forces (Chapter 5)
\( E_c \) = modulus of elasticity of concrete, psi (MPa) (Chapter 6)
$E_{ck} =$ modulus of elasticity of concrete, kip/ft$^2$ (MPa) (Chapter 4)

$E_s =$ modulus of elasticity of reinforcement, psi (MPa) (Chapters 5 and 6)

$EPV =$ effective peak velocity (Commentary Chapter 4)

$f =$ frequency, Hz (Chapter 4)

$f_c' =$ specified compressive strength of concrete, psi (MPa) (Chapter 4)

$f_c''(c) =$ $f_c'$ modified for temperature effects, circumferential, psi (MPa) (Chapter 5)

$f_c''(v) =$ $f_c'$ modified for temperature effects, vertical, psi (MPa) (Chapter 5)

$f_{CTC}'' =$ maximum circumferential stress in concrete due to temperature at inside of chimney shell, psi (MPa) (Chapters 5 and 6)

$f_{CTV}'' =$ maximum vertical stress in concrete at inside of chimney shell due to temperature, psi (MPa) (Chapters 5 and 6)

$f_{STC} =$ maximum stress in outside circumferential reinforcement due to temperature, psi (MPa) (Chapters 5 and 6)

$f_{STV} =$ maximum stress in outside vertical reinforcement due to temperature, psi (MPa) (Chapters 5 and 6)

$f_{STV}'' =$ maximum stress in inside vertical reinforcement due to temperature, psi (MPa) (Chapters 5 and 6)

$f_y =$ specified yield strength of reinforcing steel, psi (MPa) (Chapters 4 and 5)

$f_y'(c) =$ $f_y$ modified for temperature effects, circumferential, psi (MPa) (Chapter 5)

$f_y'(v) =$ $f_y$ modified for temperature effects, vertical, psi (MPa) (Chapter 5)

$F_{IA} =$ strouhal number parameter (Chapter 4)

$F_{LB} =$ lift coefficient parameter (Chapter 4)

$g =$ acceleration due to gravity, 32.2 ft/sec$^2$ (9.8 m/sec$^2$) (Chapter 4 and Commentary Chapter 4)

$G =$ across-wind peaking factor (Chapter 4)

$G_f(z) =$ gust factor for radial wind pressure at height $z$ (Chapter 4 and Commentary Chapter 4)

$G_{w_r} =$ gust factor for along-wind fluctuating load (Chapter 4 and Commentary Chapter 4)

$h =$ chimney height above ground level, ft (m) (Chapter 4 and Commentary Chapter 4)

$i =$ local turbulence parameter (Chapter 4)

$I =$ importance factor for wind design in Chapter 4 and ASCE 7

$k =$ ratio of wind speed ($\bar{V}$) to critical wind speed ($V_{cr}$)

$k_a =$ aerodynamic damping parameter (Chapter 4)

$k_{ao} =$ mass damping parameter of small amplitudes (Chapter 4)

$k_s =$ equivalent sand-grained surface roughness factor (Commentary Chapter 4)

$K =$ parameter for nominal moment strength in Chapter 5 or horizontal force factor for earthquake design in Commentary Introduction

$K_r =$ coefficient of heat transmission from gas to inner surface of chimney lining when chimney is lined, or to inner surface of chimney shell when chimney is unlined, Btu/ft$^2$/hr/F ($\text{watt/}[\text{m}^2\text{Kelvin}]$) difference in temperature (Chapter 6)

$K_t =$ coefficient of heat transfer by radiation between outside surface of lining and inside surface of concrete chimney shell, Btu/ft$^2$/hr/F ($\text{watt/}[\text{m}^2\text{Kelvin}]$) difference in temperature (Chapter 6)

$K_s =$ coefficient of heat transfer between outside surface of lining and inside surface of shell for chimneys with ventilated air spaces, Btu/ft$^2$/hr/F ($\text{watt/}[\text{m}^2\text{Kelvin}]$) difference in temperature (Chapter 6)

$K_{1}, K_{2}, K_{3} =$ parameters for nominal moment strength (Chapter 5)

$l =$ width of opening in concrete chimney shell, in. (mm) (Chapter 4)

$L =$ length coefficient (Chapter 4)

$M_{a(z)} =$ moment induced at height $z$ by across-wind loads, ft-lb (m-N) (Chapter 4)

$M_{cl}(z) =$ maximum circumferential bending moment due to radial wind pressure, at height $z$, tension on inside, ft-lb/ft (m-N/m) (Chapter 4)

$M_f(z) =$ moment induced at height $z$ by mean along-wind load, ft-lb (m-N) (Chapter 4)

$M_n =$ nominal moment strength at section (Chapter 5)

$M_{n}(z) =$ maximum circumferential bending moment due to radial wind pressure, at height $z$, tension on outside, ft-lb/ft (m-N/m) (Chapter 4)

$M_{n}(b) =$ factored moment at section (Chapter 5)

$M_{w}(z) =$ bending moment at base due to mean along-wind load, ft-lb (m-N) (Chapter 4)

$M_{w}(z) =$ combined design moment at height $z$ for across-wind and along-wind loads (Chapter 4)

$n =$ modular ratio of elasticity $E_s/E_c$ (Chapter 6)

$n_1 =$ number of openings entirely in compression zone (Chapter 5)

$\bar{p}(z) =$ pressure due to mean hourly design wind speed at height $z$, lb/ft$^2$ (Pa) (Chapter 4)
\[ p_z(z) = \text{radial wind pressure at height } z, \text{ lb/ft}^2 (\text{Pa}) \]

(Chapter 4 and Commentary Chapter 4)

\[ P_{cr} = \text{pressure due to wind at critical speed} \]

(Chapter 4)

\[ P_r = \text{actored vertical load} \]

(Chapter 5)

\[ Q = \text{stress level correction parameter} \]

(Chapter 5 and Commentary Chapter 5)

\[ Q', Q_1, Q_2, Q_3 = \text{parameters for nominal moment strength} \]

(Chapter 5)

\[ r = \text{average radius of section} \]

(Chapter 5)

\[ r_q = \text{ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces} \]

(Chapter 6)

\[ r(z) = \text{mean radius at height } z, \text{ ft (m)} \]

(Chapter 4)

\[ R = \text{parameter for nominal moment strength} \]

(Chapter 5)

\[ S_p = \text{spectral parameter} \]

(Chapter 4)

\[ S_r = \text{mode shape factor} \]

(Chapter 4)

\[ S_t = \text{strouhal number} \]

(Chapter 4)

\[ t = \text{thickness of concrete shell (m)} \]

(Chapters 5 and 6)

\[ t_b = \text{thickness of uninsulated lining or insulation filling the space between lining and shell, in. (m)} \]

(Chapter 6)

\[ t(h) = \text{thickness of concrete shell at top, ft (m)} \]

(Chapter 4)

\[ T = \text{normal temperature effect, F (C)} \]

(Chapter 6)

\[ T_i = \text{maximum specified design temperature of gas inside chimney, F (C)} \]

(Chapter 6)

\[ T_o = \text{minimum temperature of outside air surrounding chimney, F (C)} \]

(Chapter 6)

\[ T_s = \text{temperature drop across concrete shell, F (C)} \]

(Chapter 6)

\[ T_1 = \text{fundamental period of vibration for unlined shell, sec per cycle} \]

(Chapter 4 and Commentary Chapter 4)

\[ T_2 = \text{second mode period of vibration for unlined shell, sec per cycle} \]

(Chapter 4 and Commentary Chapter 4)

\[ U_c = \text{required circumferential strength} \]

(Chapter 5)

\[ U_r = \text{required vertical strength} \]

(Chapter 5)

\[ V = \text{basic wind speed, mph (km/hr)} \]

(ASCE 7 and Chapter 4)

\[ V_{cr} = \text{critical wind speed for across-wind loads, corresponding to fundamental mode ft/sec (m/sec)} \]

(Chapter 4)

\[ V_{cr2} = \text{critical wind speed for across-wind loads corresponding to second mode} \]

(Chapter 4 and Commentary Chapter 4)

\[ V_r = V(t^{0.5}), \text{mph (km/hr)} \]

(Chapter 4)

\[ \bar{V} = \text{mean hourly wind speed at 5/6h varying over a range of 0.50 and 1.30 } \bar{V}(z_{cr}), \text{ ft/sec (m/sec)} \]

(Chapter 4)

\[ \bar{V}(h) = \text{mean hourly wind speed at top of chimney, ft/sec (m/sec)} \]

(Chapter 4)

\[ \bar{V}(z) = \text{mean hourly design wind speed at height } z, \text{ ft/sec (m/sec)} \]

(Chapter 4)

\[ \bar{V}(z_{cr}) = \text{mean hourly design wind speed at 5/6h, ft/sec (m/sec)} \]

(Chapter 4)

\[ \bar{V}(33) = \text{mean hourly wind speed at a height of 33 ft, ft/sec (m/sec)} \]

(Chapter 4)

\[ w(z) = \text{total along-wind load per unit length at height } z, \text{ lb/ft (N/m)} \]

(Chapter 4)

\[ \bar{w}(z) = \text{mean along-wind load per unit length at height } z, \text{ lb/ft (N/m)} \]

(Chapter 4 and Commentary Chapter 4)

\[ w'(h) = \text{fluctuating along-wind load per unit length at top of chimney, lb/ft (N/m)} \]

(Commentary Chapter 4)

\[ w'(z) = \text{fluctuating along-wind load per unit length at height } z, \text{ lb/ft (N/m)} \]

(Chapter 4)

\[ w_a(h) = \text{across-wind load per unit length at top of chimney, lb/ft (N/m)} \]

(Chapter 4)

\[ w_a(z) = \text{across-wind load per unit length at height } z, \text{ lb/ft (N/m)} \]

(Chapter 4)

\[ w_t(u) = \text{average weight per unit length for top third of chimney, lb/ft (N/m)} \]

(Chapter 4)

\[ w_1(z) = \text{mean along-wind load per unit length as given by Eq. (4-27), lb/ft (N/m)} \]

(Chapter 4)

\[ W = \text{wind load} \]

(Chapter 5)

\[ Y_{max} = \text{maximum lateral deflection of top of chimney, in. (mm)} \]

(Chapter 4)

\[ z = \text{height above ground, ft (m)} \]

(Chapter 4 and Commentary Chapter 4)

\[ z_{cr} = \text{height corresponding to } V_{cr}, \text{ (Chapter 4)} \]

\[ Z_c = \text{exposure length factor} \]

(Chapter 4)

\[ \alpha = \text{on chimney cross section, one-half the central angle subtended by neutral axis} \]

(Chapter 5 and Commentary Chapter 5)

\[ \alpha_{te} = \text{thermal coefficient of expansion of concrete and of reinforcing steel, 0.0000065 per F (0.0000117 per C)} \]

(Chapter 6)

\[ \beta = \text{on the chimney cross section, one-half central angle subtended by an opening} \]

(Chapter 5 and Commentary Chapter 5)

\[ \beta_a = \text{aerodynamic damping factor} \]

(Chapter 4)

\[ \beta_s = \text{fraction of critical damping for across-wind load} \]

(Chapter 4)

\[ \beta_f = \text{factor defined in Section 10.2.7.3 of ACI 318} \]

(Chapter 6)

\[ \gamma = \text{on chimney cross section, one-half central angle subtended by the center lines of two openings} \]

(Chapter 5)

\[ \gamma_d = \frac{d(h)/d(b)} \]

(Chapter 4)
\( \gamma_1 = \) ratio of inside face vertical reinforcement area (Chapter 6)

\( \gamma_2 = \) ratio of distance between inner surface of chimney shell and outside face vertical reinforcement to total shell thickness (Chapter 6)

\( \gamma_1' = \) ratio of inside face circumferential reinforcement area to outside face circumferential reinforcement area (Chapter 6)

\( \gamma_2' = \) ratio of distance between inner surface of chimney shell and outside face circumferential reinforcement to total shell thickness (Chapter 6)

\( \delta = \gamma - \beta \) for two symmetric openings partly in compression zone (Chapter 5)

\( \varepsilon_m = \) maximum concrete compressive strain (Chapter 5 and Commentary Chapter 5)

\( \lambda = \tau - n_1 \beta \) (Chapter 5)

\( \lambda_1 = \mu + \psi - \pi \) (radians) (Chapter 5)

\( \mu, \tau, \psi = \) angles shown on Fig. 5.5.1(a) (Chapter 5)

\( \phi = \) strength reduction factor (Chapter 5 and Commentary Chapter 5)

\( \omega = \rho_t f_y / f'_c \) (Chapter 5)

\( \pi = 3.1416 \) (Chapter 5)

\( \rho = \) ratio of area of vertical outside face reinforcement to total area of concrete shell (Chapter 6)

\( \rho' = \) ratio of area of circumferential outside face reinforcement per unit of height to total area of concrete shell per unit of height (Chapter 6)

\( \rho_a = \) specific weight of air, 0.075 lb/ft\(^3\) (1.2 kg/m\(^3\)) (Chapter 4)

\( \rho_{ck} = \) mass density of concrete, kip-sec\(^2\)/ft\(^4\) (mg-sec\(^2\)/m\(^4\)) (Chapter 4)

\( \rho_t = \) ratio of total area of vertical reinforcement to total area of concrete shell cross section (Chapter 5)