

**Code Requirements for Reinforced
Concrete Chimneys (ACI 307-08)
and Commentary**

An ACI Standard

Reported by ACI Committee 307



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Code Requirements for Reinforced Concrete Chimneys and Commentary

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An ACI Standard

Reported by ACI Committee 307

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The committee acknowledges the late Milton Harstein for his contribution to the development of these code requirements.

This code 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.

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 this code. These methods permit the licensed design professional to establish minimum concrete and reinforcement requirements.

The Commentary discusses some of the background and considerations of Committee 307 in developing the provisions contained in "Code Requirements for Reinforced Concrete Chimneys (ACI 307-08)." Two appendixes provide the derivation of the equations for nominal strength and temperature stresses. Commentary provisions begin with an "R," such as "R1.1.1," and are shown in italics.

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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R0—INTRODUCTION

As industry expanded in the years immediately following World War I and, as a result of the development of large pulverized coal-fired boilers for the electric power-generating utilities in the 1920s, a number of large reinforced concrete chimneys were constructed to accommodate these new facilities. A group of interested engineers who foresaw the potential need for many more such chimneys, and who were members of the American Concrete Institute, embarked on an effort to develop rational design criteria for these structures. The group was organized into ACI Committee 505 (predecessor to the present Committee 307) to develop such criteria in the early 1930s.

Committee 505 submitted a "Proposed Standard Specification for the Design and Construction of Reinforced Concrete Chimneys," an outline of which was published in the ACI JOURNAL (ACI Committee 505 1934). This specification was adopted as a tentative standard in February 1936. Although this tentative standard was never accepted by ACI as an official standard, it was used as the basis for the design of many chimneys. As these chimneys aged, inspections revealed considerable cracking. When the industrial expansion began following World War II, other engineers recognized the need for developing an improved design specification for reinforced concrete chimneys.

In May 1949, Committee 505 was reactivated to revise the tentative standard specification, embodying modifications that were found desirable during the years it had been in use. The section dealing with the temperature gradient through the

chimney lining and the chimney shell was completely revised and extended to cover different types and thicknesses of linings and both unventilated and ventilated air spaces between the lining and the concrete shell. In 1954, this specification was approved as ACI 505-54 (ACI Committee 505 1954).

The rapid increase in the size and height of concrete chimneys being built in the mid-1950s raised further questions about the adequacy of the 1954 version of the specification, especially in relation to earthquake forces and the effects of wind.

In May 1959, the ACI Board of Direction reactivated Committee 505 (renamed Committee 307) to review the standard and to update portions with the latest design techniques and the then-current knowledge of the severity of the operating conditions that prevailed in large steam plants. The material in the standard was reorganized, charts were added, and the methods for determining loads due to wind and earthquakes were revised. The information on design and construction of various types of linings was amplified and incorporated in an appendix. That version included criteria for working stress design. It was planned to add ultimate strength criteria in a future revision.

In preparing the earthquake design recommendations for ACI 307-69 (ACI Committee 307 1969), the committee incorporated the results of theoretical studies by adapting them to existing United States codes. The primary problems in this endeavor stemmed from the uncertainties still inherent in the definition of earthquake forces and from the difficulty of selecting the proper safety and serviceability levels that might be desirable for various classes of construction. Committee investigations revealed that with some modifications (such as the K factor), the base shear equations developed by the Seismology Committee of the Structural Engineers' Association of California (SEAOC) could be applied to chimneys. Similarly, the shape of the force, shear, and moment distributions, as revised in their 1967 report, were also suitable for chimneys. A use factor (U factor) ranging from 1.3 to 2.0 was introduced in the specification, and it was emphasized that the requirements of Section 4.5 of ACI 307-69 that related to seismic design could be superseded by a rational analysis based on evaluation of the seismicity of the site and modal response calculations. The modifications were approved in ACI 307-69. In that version, the commentary and derivation of equations were published separately as a supplement to ACI 307-69.

In 1970, the document was reissued with corrections of typographical errors. This issue of ACI 307-69 was also designated ANSI A158.1-1970. At the time, as a result of numerous requests, the commentary and derivation of equations were bound together with the specification.

ACI 307-79 (ACI Committee 307 1979) updated its requirements to agree with the then-accepted standard practices in the design and construction of reinforced concrete chimneys. The major changes included the requirement that two layers of reinforcing steel be used in the walls of all chimneys (previously, this only applied to chimney walls thicker than 18 in.) and the requirement that horizontal sections through the chimney wall be designed for the wind pressure distribution around the chimney. Formulas

were included to compute the stresses under these conditions. Many revisions of less importance were included to bring the specification up to date.

The editions of the specifications before 1979 included appendixes on the subjects of chimney linings and accessories. In 1971, Committee 307 learned of buckling problems in steel chimney liners. The committee also noted that, in modern power plant and process chimneys, environmental regulations required treatment of the effluent gases that could result in extremely variable and aggressively corrosive conditions in the chimneys. These facts led the committee to agree that the task of keeping the chimney liner recommendations current was not a responsibility of an ACI committee and could be misleading to licensed design professionals using the chimney specification. By committee consensus, the reference to chimney liner construction was dropped from future editions of the specification. Committee 307 then made a recommendation to the Brick Manufacturers' Association and the American Society of Civil Engineers that each appoint a task force or a committee for the development of design criteria for brick and steel liners, respectively. The Power Division of ASCE took up the recommendation and appointed a task committee that developed and published a design guide in 1975 titled "Design and Construction of Steel Chimney Liners" (ASCE Task Committee on Steel Chimney Liners 1975). ASTM established two task forces for chimney liners: one for brick and one for fiberglass-reinforced plastic.

The committee had extensive discussion on the question of including strength design in the 1979 specification. The decision to exclude it was based on the lack of experimental data on hollow concrete cylinders to substantiate this form of analysis for concrete chimneys. The committee continued, however, to consider strength design, and encouraged experiments in this area.

Shortly after ACI 307-79 was issued, the committee decided to incorporate strength design provisions and update the wind and earthquake design requirements.

ACI 307-88 (ACI Committee 307 1988) incorporated significant changes in the procedures for calculating wind forces as well as requiring strength design rather than working stress. The effects of these and other revisions resulted in designs with relatively thin walls governed mainly by steel area and, in many instances, across-wind forces.

The subject of across-wind loads dominated the attention of the committee between 1988 and 1995, and ACI 307-95 (ACI Committee 307 1995) introduced modified procedures to reflect more recent information and thinking.

Precast chimney design and construction techniques were introduced as this type of design became more prevalent for chimneys as tall as 300 ft.

The subject of noncircular shapes was also introduced in ACI 307-95. Due to the infinite array of possible configurations, however, only broadly defined procedures were presented.

Because of dissimilarities between the load factors required by ACI 307 and 318, the committee added guidelines for determining bearing pressures and loads to size and design chimney foundations.

The major changes incorporated into the ACI 307-95 were:

- Modified procedures for calculating across-wind loads;
- Added requirements for precast concrete chimney columns;
- Added procedures for calculating loads and for designing noncircular chimney columns;
- Deleted exemptions previously granted to smaller chimneys regarding reinforcement and wall thickness; and
- Deleted static equivalent procedures for calculating earthquake forces.

For the ACI 307-98 (ACI Committee 307 1998), revisions to the ASCE 7-95 relating to wind and seismic forces required several changes to be made to the ACI 307-95. The changes incorporated into the ACI 307-98 were:

- Site-specific wind loads were calculated using a 3-second gust speed determined from Fig. 6-1 in ASCE 7-95, instead of the previously used fastest-mile speed;
- Site-specific earthquake forces were calculated using the effective peak velocity-related acceleration contours determined from Contour Map 9-2 in ASCE 7-95 instead of previously designated zonal intensity;
- The vertical load factor for along-wind forces was reduced from 1.7 to 1.3;
- The vertical load factor for seismic forces was reduced from 1.87 to 1.43;
- The load factor for across-wind forces was reduced from 1.40 to 1.20; and
- The vertical strength reduction factor ϕ was reduced from 0.80 to 0.70.

The reduced load factors should be used in concert with the revised strength reduction factor and the wind and seismic loads specified in ASCE 7-95.

Revisions to ASCE 7 again caused Committee 307 to revisit and revise ACI 307-98. The changes incorporate applicable ASCE 7-02 wind and seismic load factors and methods. The changes to the ACI 307-98 were:

- Included procedure in Section 4.3, Earthquake load, compatible with ASCE 7-02 and the ASCE 7 seismic risk maps;
- Updated the load factors and load combinations to be more in line with ASCE 7-02 values and presentation; and
- Changed the vertical strength reduction factor ϕ back to 0.80.

As stated previously, the current methods in this document can only be used in conjunction with the ASCE 7-02.

CHAPTER 1—GENERAL

1.1—Scope

This code covers the minimum design and construction requirements 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 herein. This code does not include the design of linings, but does include 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 on top of another, to form a freestanding, self-supporting cantilever. Vertical reinforcement and grout are placed in cores as the precast section are erected to provide structural

continuity and stability. The use of precast panels as stay-in-place forms is considered cast-in-place construction.

RI.1 For this revision, ACI 307-98 was updated to an ACI code. ACI 307, "Code Requirements for Reinforced Concrete Chimneys," is written for new construction. The committee acknowledges that the general analytical procedures and requirements contained in ACI 307 are appropriate for the investigation and retrofitting of existing chimneys. The committee recognizes, however, that not all code requirements, such as Section 4.4, will be feasible or appropriate when retrofitting existing chimneys.

The scope of ACI 307-95 was expanded to include precast chimney shells. Additional information can be found in PCI manuals (PCI 1977, 1985). Warnes (1992) provides further guidelines on connection details for precast structures. Additional information is given in ACI 550R.

1.2—Drawings

Drawings of the chimney shall be prepared showing 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 This code supplements local building regulations and shall govern in all matters pertaining to reinforced concrete chimney design and construction.

1.3.2 Consideration shall be given to the regulations of the Federal Aviation Administration with respect to chimney heights and aviation obstruction lighting and marking (AC70-7460-1K), and the standards of the Underwriters Laboratories (UL 96A) regarding lightning protection and grounding.

1.4—Notation

A_s	=	area of reinforcing steel at top and bottom of opening, in. ² (Chapter 4)
B	=	band-width parameter (Chapter 4)
C_b	=	coefficient of thermal conductivity of chimney's uninsulated lining or insulation around steel liner, Btu·in./(h·ft ² ·°F) of thickness/h/°F difference in temperature (Chapter 6)
C_c	=	coefficient of thermal conductivity of concrete of chimney shell, Btu·in./(h·ft ² ·°F) of thickness/h/°F difference in temperature (12 for normalweight concrete) (Chapter 6)
C_{dr}	=	drag coefficient for along-wind load (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·in./(h·ft ² ·°F) of thickness/h/°F difference in temperature (3 for lightweight concrete) (Chapter 6)
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)

D	=	dead load (Chapter 5)
d	=	diameter of chimney, ft (Chapter 4)
d_b	=	mean diameter of uninsulated lining or insulation around liner, ft (Chapter 6)
d_{bi}	=	inside diameter of uninsulated lining or insulation around liner, ft (Chapter 6)
d_c	=	mean diameter of concrete chimney shell, ft (Chapter 6)
d_{ci}	=	inside diameter of concrete chimney shell, ft (Chapter 6)
d_{co}	=	outside diameter of concrete chimney shell, ft (Chapter 6)
d_s	=	mean diameter of space between lining and shell, ft (Chapter 6)
$d(b)$	=	bottom outside diameter of chimney, ft (Chapter 4)
$\bar{d}(b)$	=	mean diameter at bottom of chimney, ft (Chapter 4)
$d(h)$	=	top outside diameter of chimney, ft (Chapter 4)
$\bar{d}(h)$	=	mean diameter at top of chimney, ft (Chapter 4)
$d(u)$	=	mean outside diameter of upper third of chimney, ft (Chapter 4)
$d(z)$	=	outside diameter of chimney at height z , ft (Chapter 4)
$d(z_{cr})$	=	outside diameter of chimney at critical height z_{cr} , ft (Chapter 4)
E	=	earthquake loads or forces (Chapter 5)
E_c	=	modulus of elasticity of concrete, psi (Chapter 6)
E_{ck}	=	modulus of elasticity of concrete, kip/ft ² (Chapter 4)
E_s	=	modulus of elasticity of reinforcement, psi (Chapters 5 and 6)
F_a	=	acceleration-based site coefficient at 0.2-second period (Section 4.3)
F_V	=	velocity-based site coefficient at 1.0-second period (Section 4.3)
F_{1A}	=	strouhal number parameter (Chapter 4)
F_{1B}	=	lift coefficient parameter (Chapter 4)
f	=	frequency, Hz (Chapter 4)
f'_c	=	specified compressive strength of concrete, psi (Chapter 4)
$f'_c(c)$	=	f'_c modified for temperature effects, circumferential, psi (Chapter 5)
$f'_c(v)$	=	f'_c modified for temperature effects, vertical, psi (Chapter 5)
f''_{CTC}	=	maximum circumferential stress in concrete due to temperature inside chimney shell, psi (Chapters 5 and 6)
f''_{CTV}	=	maximum vertical stress in concrete inside chimney shell due to temperature, psi (Chapters 5 and 6)
f_{STC}	=	maximum stress in outside circumferential reinforcement due to temperature, psi (Chapters 5 and 6)
f_{STV}	=	maximum stress in outside vertical reinforcement due to temperature, psi (Chapters 5 and 6)
f''_{STV}	=	maximum stress in inside vertical reinforcement due to temperature, psi (Chapters 5 and 6)
f_y	=	specified yield strength of reinforcing steel, psi (Chapters 4 and 5)
$f'_y(c)$	=	f_y modified for temperature effects, circumferential

	psi (Chapter 5)		outside, ft-lb/ft (Chapter 4)
$f'_y(v)$	f_y modified for temperature effects, vertical, psi (Chapter 5)	M_u	factored moment at section, ft-lb (Chapter 5 and Appendix A)
G	across-wind peaking factor (Chapter 4)	$M_w(b)$	bending moment at base due to mean along-wind load, ft-lb (Chapter 4)
$G_r(z)$	gust factor for radial wind pressure at height z (Chapter 4)	$M_w(z)$	combined design moment at height z for across-wind and along-wind loads, ft-lb (Chapter 4)
$G_{w'}$	gust factor for along-wind fluctuating load (Chapter 4)	n	modular ratio of elasticity, E_s/E_c (Chapter 6)
g	acceleration due to gravity, 32.2 ft/s ² (Chapter 4)	n_1	number of openings entirely in compression zone (Chapter 5 and Appendix A)
h	chimney height above ground level, ft (Chapter 4)	P_{cr}	pressure due to wind at critical speed, lb/ft ² (Chapter 4)
I	importance factor for wind design (Chapter 4)	P_u	factored vertical load, lb (Chapter 5 and Appendix A)
I_E	occupancy importance factor from Section 4.3.2 (Chapter 4)	$\bar{p}(z)$	pressure due to mean hourly design wind speed at height z , lb/ft ² (Chapter 4)
i	local turbulence parameter (Chapter 4)	$p_r(z)$	radial wind pressure at height z , lb/ft ² (Chapter 4)
K	parameter for nominal moment strength (Chapter 5)	Q	stress level correction parameter (Chapter 5)
K_1	parameter for nominal moment strength (Chapter 5)	Q'	parameter for nominal moment strength (Chapter 5)
K_2	parameter for nominal moment strength (Chapter 5)	Q_1	parameter for nominal moment strength (Chapter 5)
K_3	parameter for nominal moment strength (Chapter 5)	Q_2	parameter for nominal moment strength (Chapter 5)
K_d	wind directionality factor (Chapter 4)	Q_3	parameter for nominal moment strength (Chapter 5)
K_e	E_s/f_y (Chapter 5 and Appendix E)	R	response modification factor for concrete chimney from Section 4.3.2 (Chapter 4)
K_i	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 /h/°F difference in temperature (Chapter 6)	$\bar{R}$	parameter for nominal moment strength (Chapter 5)
K_o	coefficient of heat transmission from outside surface of chimney shell to surrounding air, Btu/ft ² /h/°F difference in temperature (Chapter 6)	R_L	response modification factor for liner (Chapter 4)
K_r	coefficient of heat transfer by radiation between outside surface of lining and inside surface of concrete chimney shell, Btu/ft ² /h/°F difference in temperature (Chapter 6)	r	average radius of section, ft (Chapter 5)
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 /h/°F difference in temperature (Chapter 6)	r_q	ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces (Chapter 6)
k	ratio of wind speed $\bar{V}$ to critical wind speed V_{cr} (Chapter 4)	$r(z)$	mean radius at height z , ft (Chapter 4)
k_a	aerodynamic damping parameter (Chapter 4)	S_1	mapped maximum considered earthquake, 5% damped, spectral response acceleration at a period of 1 second (Section 4.3)
k_{ao}	mass damping parameter of small amplitudes (Chapter 4)	S_a	design spectral response acceleration (Section 4.3)
k_s	equivalent sand-grained surface roughness factor (Chapter 4)	S_{aM}	the maximum spectral response acceleration for site-specific procedures (Section 4.3)
L	correlation length coefficient (Chapter 4)	S_{D1}	the design spectral response acceleration at a period of 1 second (Section 4.3)
l	width of opening in concrete chimney shell, in. (Chapter 4)	S_{DS}	the design spectral response acceleration at short periods (Section 4.3)
M_a	peak base moment, ft-lb (Chapter 4)	S_{M1}	the maximum considered earthquake, 5% damped, spectral response acceleration at a period of 1 second adjusted for site class effects (Section 4.3)
$M_a(z)$	moment induced at height z by across-wind loads, ft-lb (Chapter 4)	S_{MS}	the maximum considered earthquake, 5% damped, spectral response acceleration at short periods adjusted for site class effects (Section 4.3)
$M_i(z)$	maximum circumferential bending moment due to radial wind pressure, at height z , tension on inside, ft-lb/ft (Chapter 4)	S_p	spectral parameter (Chapter 4)
$M_l(z)$	moment induced at height z by mean along-wind load, ft-lb (Chapter 4)	S_{sv}	mode shape factor (Section 4.2)
M_n	nominal moment strength at section, ft-lb (Chapter 5 and Appendix A)	S_s	mapped maximum considered earthquake, 5% damped, spectral response acceleration at short periods (Section 4.3)
$M_o(z)$	maximum circumferential bending moment due to radial wind pressure, at height z , tension on	S_t	strouhal number (Chapter 4)
		s	center-to-center spacing of chimneys, ft (Chapter 4)
		T	normal temperature effect, °F (Chapter 6)
		T	period of structure (Section 4.3)
		T_1	fundamental period of vibration for unlined shell

	seconds per cycle (Chapter 4)		liner, ft (Chapter 4)
T_2	= second mode period of vibration for unlined shell, seconds per cycle (Chapter 4)	Z_c	= exposure length, ft (Chapter 4)
T_i	= maximum specified design temperature of gas inside chimney, °F (Chapter 6)	z	= height above ground, ft (Chapter 4)
T_o	= minimum temperature of outside air surrounding chimney, °F (Chapter 6)	z_{cr}	= height corresponding to V_{cr} , ft (Chapter 4)
T_o	= seismic parameter (Section 4.3)	α	= on chimney cross section, one-half of the central angle subtended by neutral axis, radians (Chapter 5)
T_x	= temperature drop across concrete shell, °F (Chapter 6)	α_{te}	= thermal coefficient of expansion of concrete and of reinforcing steel, 0.0000065 per °F (Chapter 6)
t	= thickness of concrete shell, in. (Chapters 5 and 6)	β	= one-half of the central angle subtended by an opening on the chimney cross section, radians (Chapter 5 and Appendix A)
t	= concrete thickness at opening, in. (Chapter 4)	β_1	= factor in Section 10.2.7.3 of ACI 318 (Chapters 5 and 6)
t_b	= thickness of uninsulated lining or insulation around steel liner, in. (Chapter 6)	β_a	= aerodynamic damping factor (Chapter 4)
t_s	= thickness of air space or insulation filling the space between lining and shell, in. (Chapter 6)	β_s	= fraction of critical damping for across-wind load (Chapter 4)
$t(b)$	= thickness of concrete shell at bottom, ft (Chapter 4)	γ	= one-half of the central angle subtended by the centerlines of two openings on chimney cross section, radians (Chapter 5 and Appendix A)
$t(h)$	= thickness of concrete shell at top, ft (Chapter 4)	γ_1	= ratio of inside face vertical reinforcement area (Chapter 6)
U_c	= required circumferential strength (Chapter 5)	γ_2	= ratio of distance between inner surface of chimney shell and outside face vertical reinforcement to total shell thickness (Chapter 6)
U_v	= required vertical strength (Chapter 5)	γ_1'	= ratio of inside face circumferential reinforcement area to outside face circumferential reinforcement area (Chapter 6)
V	= basic wind speed, mph (Chapter 4)	γ_2'	= ratio of distance between inner surface of chimney shell and outside face circumferential reinforcement to total shell thickness (Chapter 6)
V_{cr}	= critical wind speed for across-wind loads, corresponding to fundamental mode, ft/s (Chapter 4)	γ_d	= $d(h)/d(b)$ (Chapter 4)
V_{cr2}	= critical wind speed for across-wind loads corresponding to second mode, ft/s (Chapter 4)	δ	= $\gamma - \beta$ for two symmetric openings partly in compression zone, radians (Chapter 5)
V_r	= $V(I^{0.5})$, mph (Chapter 4)	ε_m	= maximum concrete compressive strain (Chapter 5 and Appendix A)
$\bar{V}$	= mean hourly wind speed at $(5/6)h$ varying over range of 0.50 and $1.30V(z_{cr})$, ft/s (Chapter 4)	λ	= $\tau - n_1\beta$, radians (Chapter 5)
$\bar{V}(33)$	= mean hourly wind speed at height of 33 ft, ft/s (Chapter 4)	λ_1	= $\mu + \psi - \pi$, radians (Chapter 5)
$\bar{V}(h)$	= mean hourly wind speed at top of chimney, ft/s (Chapter 4)	μ	= angle shown on Fig. 5.1(a), radians (Chapter 5 and Appendix A)
$\bar{V}(z)$	= mean hourly design wind speed at height z , ft/s (Chapter 4)	τ	= angle shown on Fig. 5.1(a), radians (Chapter 5 and Appendix A)
$\bar{V}(z_{cr})$	= mean hourly design wind speed at $(5/6)h$, ft/s (Chapter 4)	ψ	= angle shown on Fig. 5.1(a), radians (Chapter 5 and Appendix A)
W	= wind load (Chapter 5)	π	= 3.1416 (Chapter 5)
$w(z)$	= total along-wind load per unit length at height z , lb/ft (Chapter 4)	ρ	= ratio of area of vertical outside face reinforcement to total area of concrete shell (Chapter 6)
$\bar{w}(z)$	= mean along-wind load per unit length at height z , lb/ft (Chapter 4)	ρ'	= ratio of area of circumferential outside face reinforcement per unit of height to total area of concrete shell per unit of height (Chapter 6)
$w'(h)$	= fluctuating along-wind load per unit length at top of chimney, lb/ft (Chapter 4)	ρ_a	= specific weight of air, 0.0765 lb/ft ³ (Chapter 4)
$w'(z)$	= fluctuating along-wind load per unit length at height z , lb/ft (Chapter 4)	ρ_{ck}	= mass density of concrete, kip-s ² /ft ⁴ (Chapter 4)
$w_1(z)$	= mean along-wind load per unit length as given by Eq. (4-27), lb/ft (Chapter 4)	ρ_t	= ratio of total area of vertical reinforcement to total area of concrete shell cross section (Chapter 5)
$w_a(h)$	= across-wind load per unit length at top of chimney, lb/ft (Chapter 4)	ϕ	= strength reduction factor (Chapter 5 and Appendix A)
$w_a(z)$	= across-wind load per unit length at height z , lb/ft (Chapter 4)	ω_t	= $\rho_t f_y f_c'$ (Chapter 5)
$wt(u)$	= average weight per unit length for top third of chimney, lb/ft (Chapter 4)		
Y_{max}	= maximum lateral deflection of top of chimney, ft (Chapter 4)		
y	= total (SRSS or CQC) lateral displacement of concrete chimney, ft (Chapter 4)		
y_L	= total (SRSS or CQC) lateral displacement of		

CHAPTER 2—MATERIALS

2.1—General

All materials and material tests shall conform to ACI 318, except as otherwise specified herein.

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 Types I, II, III, or V of ASTM C150, or Type IS or IP of ASTM C595.

2.3—Aggregates

2.3.1 Concrete aggregates shall conform to ASTM C33.

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

R2.3.2 *This requirement differs from the ACI 318 because most walls are 8 in. thick, and 3/4 or 1 in. aggregate works best with 8 ft forms.*

2.4—Reinforcement

Reinforcement shall conform to ASTM A615/A615M, A996/A996M, or A706/A706M. Other deformed reinforcement with a specified minimum yield strength f_y exceeding 60,000 psi shall be permitted provided that the ultimate tensile strain shall equal or exceed 0.07.

R2.4 *Refer to R5.1.2 for explanation of ultimate tensile strain limits.*

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.

3.2—Concrete strength

The specified concrete compressive strength shall not be less than 3000 psi at 28 days.

3.3—Strength tests

The 28-day compressive strength of the concrete shall be determined from a minimum of two strength tests (consisting of the average of two cylinders per each test) per 8-hour 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 yd³ of concrete placed each day.

R3.3 *Requirements for testing precast concrete units were added in ACI 307-95.*

3.4—Forms

R3.4 *Shear transfer within precast concrete shells should be considered in design, especially if the structure has vertical as well as horizontal construction joints.*

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. 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 Load shall not be placed on the concrete structure 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 the concrete has hardened to a 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 requirement, all laitance and loose material shall be removed.

3.5—Reinforcement placement

R3.5 *The size, spacing, and location of vertical cores within precast concrete chimney shells will be determined by geometry and steel area requirements. It is important that the design of precast chimneys complies with the minimum spacing requirements of ACI 318 when arranging reinforcement within the cores to permit proper bar splicing and concrete placement.*

3.5.1 Circumferential reinforcement shall be placed around the exterior of, and secured to, the vertical reinforcement bars. All reinforcing bars shall be tied at intervals of not more than 2 ft. Bars shall be secured against displacement within the tolerances of the ACI 318.

R3.5.1 *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 temporarily supported so as to prevent the breaking of the bond with the freshly placed concrete.

R3.5.2 *It is important to protect the early bond set. Vertical bars are subjected to movement due to wind forces. Vertical bars should be tied together or braced to prevent damaging the bond.*

3.5.3 Not more than 50% of bars shall be spliced along any horizontal or vertical plane unless specifically permitted and approved by the licensed design professional.

3.5.4 For reinforcement in cast-in-place chimneys, the minimum concrete cover shall be 2 in. For reinforcement in precast units manufactured under plant-controlled conditions, the minimum concrete cover shall be 1.5 in.

3.6—Concrete placement

Cast-in-place concrete placement shall conform to ACI 318, and shall be placed in layers no greater than 16 in. Vertical construction joints for cast-in-place chimney shells shall not be used. Where used, horizontal construction joints for cast-in-place and precast concrete shall be approximately evenly spaced throughout the height of the chimney shell. Grout for setting precast sections shall have a specified compressive strength equal to or greater than the specified compressive strength of the set precast sections.

3.7—Concrete curing

3.7.1 Immediately after the forms have been removed, all necessary finishing of concrete shall commence.

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 licensed design professional. The curing compound shall comply with ASTM C309, 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

R3.8 A quality control program should be established to measure, document, and verify compliance with the construction tolerance requirements of this code. The program should identify the type, number, and frequency of the measurements required to document each of the areas specified in this code.

3.8.1 The chimney shell shall be constructed within the tolerance limits set forth herein.

3.8.1.1 Vertical alignment of centerpoint—The actual centerpoint of the shell shall not vary from its theoretical axis by more than 0.001 times the height of the shell, or 1 in., whichever is greater. Locally, the actual centerpoint of the shell shall not change horizontally by more than 1 in. for any 10 ft of vertical rise.

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. 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., $+1/2$ in. for walls 10 in. thick or less, or by more than $-1/2$ in., $+1$ in. for walls greater than 10 in. thick. A single wall thickness measurement is defined as the average of at least four measurements taken at a uniform spacing over a 60-degree arc. A negative tolerance decreases the overall thickness, and a positive tolerance increases the overall thickness.

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 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 grouted to level, and joints shall be sealed. Shear keys shall be installed if required by the licensed design professional.

CHAPTER 4—LOADS AND GENERAL DESIGN CRITERIA

4.1—General

R4.1 For the 1995 edition, the Committee re-evaluated the previous exemptions regarding two-face reinforcement and minimum wall thickness for chimneys 300 ft or less in height and less than 20 ft in diameter. Recent information has indicated that two-face circumferential reinforcement is necessary to minimize vertical cracking due to radial wind pressures and reverse thermal gradients due to the effects of solar heating. Reverse thermal gradients due to solar heating may be more pronounced when the air space between the column and lining is purged by pressurization fans and gas temperatures are low. Further, the current committee believes that two-face reinforcement should be required in all chimney columns, regardless of size, considering the aggressive environment surrounding chimneys.

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.

4.1.2 The chimney shell shall be designed for load combinations in accordance with the provisions of Chapter 5.

4.1.3 Minimum shell thickness

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

R4.1.3.1 A minimum wall thickness of 8 in. (7 in. if precast) is required to provide for proper concrete placement within and around two curtains of reinforcement.

4.1.3.2 The chimney shell thickness, through openings, shall not be less than $1/24$ times the height of the opening over a vertical distance extending from $1/2$ the height of the opening below the sill of the opening to $1/2$ the height of the opening above the top of the opening. Properly designed buttresses or other means of lateral restraint may be permitted in place of this requirement. However, the buttresses or other means of lateral restraint shall not be included when calculating vertical strength.

R4.1.3.2 The committee expressed concern regarding edge buckling of relatively thin walls through regions where tall openings are present. The simplified procedure given in this section will give approximately the same results as the procedures of Section 10.10 of ACI 318-02 (ACI Committee 318 2002).

The committee defines a buttress to be rectangular or square in shape and can project either inside or outside (or both) the chimney wall. A buttress provides additional stability to the thin wall design.

If jamb buttresses are used, they should be placed homogeneously with the section or adequately tied to ensure composite action.

4.1.3.3 When the inside diameter of the shell exceeds 28 ft, the minimum thickness shall be increased 1/8 in. for each 1 ft increase in inside diameter.

4.1.4 Shell and liner interaction—A chimney shell that supports lining loads shall comply with the requirements of this standard with the lining in place. The loads on the concrete shell shall include any lining loads resulting from dead load, thermal, wind, or seismic loads.

4.1.5 Design for temporary construction loads—When temporary access openings are used during construction, they shall be designed as permanent openings.

4.1.6 Foundation considerations

4.1.6.1 The maximum foundation bearing pressure shall be established using service chimney loads.

R4.1.6.1 Service loads are defined in Section 2.4 of ASCE 7-02.

4.1.6.2 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 distribution, or pile loads, using the loading combinations given in Section 5.3.1.

R4.1.6.2 Foundation design—The pseudo-bearing pressure/pile loads should be computed by multiplying the unfactored dead and axial bending loads by their appropriate load factor from Sections 5.3.1.

4.1.6.3 The minimum factor of safety against overturning shall be 1.50 using service loads.

4.1.6.4 Design shall include the effects of radiant heat of gases on any part of the foundation, including the foundation floor area that is exposed within the liner and 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, which shall be denoted as V_r , shall be the 3-second gust wind speed at 33 ft over open terrain, where $V_r = (I)^{0.5}V$. This speed V shall be as specified by ASCE 7-02. The importance factor I for all chimneys shall be 1.15. Topographic effects referenced in Section 6.5.7.1 of ASCE 7-02 are omitted.

At a height z ft above ground, the mean hourly design speed $\bar{V}(z)$ in ft/s shall be computed from Eq. (4-1)

$$\bar{V}(z) = (1.47)V_r \left(\frac{z}{33} \right)^{0.154} \times (0.65) \quad (4-1)$$

The provisions with respect to wind load take into account dynamic action, but are simplified and result in equivalent static loads. A properly substantiated dynamic analysis shall be permitted in place of these provisions.

R4.2.1 The basic wind speed V in the ACI 307-98 standard was revised from fastest-mile to a 3-second gust speed to reflect the changes published in ASCE 7-02. Equation (4-1) was modified accordingly. In Eq. (4-1), 1.47 converts wind speed from mph to ft/s, and 0.65 converts the 3-second gust speed to a mean hourly speed. The revised power law coefficient 0.154 (as an approximation of 1/6.5) came from Table 6.2 of ASCE 7-02 for Exposure C and for flexible or dynamically sensitive structures; the increase in the exponent increases the calculated pressures over the chimney height for the same speed.

The 3-second gust speed is always higher than the previously specified fastest-mile speed. A fastest-mile wind speed may be converted to a 3-second gust speed for normal speeds of interest in chimney design using

$$3\text{-second gust } V = 1.0546 (\text{fastest mile } V + 11.94)$$

The relationship between a 3-second gust speed and any other averaging time can be found in texts such as Wind Effects on Structures (Simiu and Scanlon 1986).

The procedure was determined from simplified dynamic analyses that resulted in equivalent static load distributions. This approach requires that a wind speed averaged over a period approximately 20 minutes to 1 hour be used as a basis for design. Equation (4-1) permits the mean hourly speed at height z to be determined from the basic design speed that is the 3-second gust speed at 33 ft over open country. The conversion is based on the relationship recommended by Hollister (1969). The specified wind loads presume that the chimney is located in open country. In rougher terrains, the overall loads will be reduced, but for a tall chimney (with a height of approximately 650 ft), the reduction is not likely to exceed 20%.

In Eq. (4-1), V_r is the product of the square root of the importance factor I , and V , the basic wind speed as charted and defined in ASCE 7-02. I can be used to vary probability as well as to classify the importance of the structure. All chimneys should be designed to be part of an essential facility classified as a Category IV structure. The importance factor of 1.15 for Category IV buildings and structures corresponds to a mean recurrence interval of 100 years. Additional information can be found in ASCE 7-02.

The simplified provisions of this standard do not preclude the use of more detailed methods, and the results of a full dynamic analysis employing accepted approaches and recognizing the flow profile and turbulence levels at a specific site may be used in place of the standard provisions. The approximate methods have, however, been tested against more detailed analyses using probabilistic (Vickery 1969; Vickery and Basu 1985) and deterministic (Rumman 1985) approaches. These methods gave acceptable results.

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 $\bar{w}(z)$ and the fluctuating load $w'(z)$.

The mean load $\bar{w}(z)$ in lb/ft shall be computed from Eq. (4-2)

$$\bar{w}(z) = C_{dr}(z) \times \bar{V}(z) \times \bar{p}(z) \quad (4-2)$$