

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

Reported by ACI Committee 307

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This commentary discusses some of the background and consideration of Committee 307 in developing the provisions contained in "Design and Construction of Reinforced Concrete Chimneys (ACI 307-98)." The changes from the previous edition are noted. Two appendices provide the derivation of the equations for nominal strength and temperature stresses.

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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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 rather 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 decided to embark upon an effort to develop a rational design criteria for these structures. The group was organized into ACI Committee 505 (this committee was the predecessor of the present Committee 307) to develop such criteria in the early 1930s.

Committee 505 submitted to the Institute a "Proposed Standard Specification for the Design and Construction of Reinforced Concrete Chimneys," an outline of which was published in the *ACI JOURNAL*, *Proceedings* V. 30, Mar.-Apr. 1934. This specification was adopted as a tentative standard in February 1936. Although this tentative standard was never accepted by ACI as a regular 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 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.

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 as related to earthquake forces and the effects of wind.

In May 1959, the ACI Board of Direction again reactivated Committee 505 (Committee 307) to review the standard and to update portions of the specification in line 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 specification included criteria for working stress design. It was planned to add ultimate strength criteria in a future revision of this standard.

In preparing the earthquake design recommendations, 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 of the 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 relating 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 1969 and the specification was designated ACI 307-69. In that specification, the commentary and derivation of equations were published separately as a supplement to ACI 307-69.

In 1970, the specification 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.

The 1979, revision of the specification updated its requirements to agree with the then-accepted standard practice 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. [4600 mm]) and the requirement that horizontal sections through the chimney wall be designed for the radial wind pressure distribution around the chimney. Formulas were included to compute the stresses under these conditions. Many revisions of a less important nature were included to bring the specification up to date.

The editions of the specifications prior to 1979 included appendices 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. In view of these facts, the Committee agreed that the task of keeping the chimney liner recommendations current was not a responsibility of an ACI committee and could be misleading to designers using the chimney specification. It was the consensus of the Committee that the reference to chimney liner construction be dropped from future editions of the specification. Recognizing this, Committee 307 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 in 1975 a design guide entitled, "Design and Construction of Steel Chimney Liners." ASTM established two task forces for chimney liners, one for brick and the other 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. However, the Committee continued to consider strength design and encouraged experiments in this area.

Shortly after the 1979 edition was issued, the Committee decided to incorporate strength design provisions and update the wind and earthquake design requirements.

The 1988 edition of ACI 307 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 the 1995 standard 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 (91.4 m).

The subject of noncircular shapes was also introduced in 1995. However, due to the virtually infinite array of possible configurations, only broadly defined procedures were presented.

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

In summary, the following highlights the major changes that were incorporated into the 1995 standard:

- 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.

Synopsis of current revisions

Revisions to the ASCE 7-95 standard relating to wind and seismic forces required that several changes be made to the 1995 edition of ACI 307. The following highlights the changes incorporated into the current standard:

- Site-specific wind loads are calculated using a “3-sec gust” speed determined from Fig. 6-1 in ASCE 7-95 instead of the previously used “fastest-mile” speed.
- Site-specific earthquake forces are 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 has been reduced from 1.7 to 1.3.
- The vertical load factor for seismic forces has been reduced from 1.87 to 1.43.

- The load factor for across-wind forces has been reduced from 1.40 to 1.20.
- The vertical strength reduction factor ϕ has been reduced from 0.80 to 0.70.

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

The foregoing revisions are discussed in more detail in the following commentary.

Finally, the Committee believes that the ACI 307 standard is particularly unique in its inclusion of specific procedures to calculate wind and seismic forces on chimneys. Consequently, the Committee feels that the previous Commentary regarding these subjects should be retained wherever possible.

Similarly, the Committee believes that the Commentary regarding the assumptions and procedures for strength design and other recent revisions should also be retained for reference.

A chapter-by-chapter commentary follows.

CHAPTER 1—GENERAL

1.1—Scope

The scope of the 1995 standard was expanded to include precast chimney shells. Additional information may be found in PCI manuals.^{1,2} Warnes³ provides further guidelines on connection details for precast structures. Additional information is given in ACI 550R, “Design Recommendations for Precast Concrete Structures.”

1.4—Reference standards

The year of adoption or revision for the referenced standards has been updated.

CHAPTER 2—MATERIALS

No changes of note have been made in this section.

CHAPTER 3—CONSTRUCTION REQUIREMENTS

3.3—Strength tests

Requirements for testing precast concrete units were added in the 1995 standard.

3.4—Forms

Shear transfer within precast concrete shells must be considered in design especially if the structure has vertical as well as horizontal construction joints.

3.5—Reinforcing placement

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 comply with the minimum spacing requirements of ACI 318 when arranging reinforcement within the cores to permit proper bar splicing and concrete placement.

CHAPTER 4—SERVICE LOADS AND GENERAL DESIGN CRITERIA

4.1—General

The 1995 Committee re-evaluated the previous exemptions regarding two-face reinforcement and minimum wall

thickness for chimneys 300 ft (91.4 m) or less in height and less than 20 ft (6.1 m) 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 1995 Committee believed that two-face reinforcement should be required in all chimney columns, regardless of size, considering the aggressive environment surrounding chimneys.

4.1.3.1—A minimum wall thickness of 8 in. (200 mm) (7 in. [180 mm] if precast) is required to provide for proper concrete placement within and around two curtains of reinforcement.

4.1.3.2—The 1995 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 Chapter 10.10 of ACI 318.

If jamb buttresses are used, it is recommended that they be poured homogeneously with the section or adequately tied to ensure composite action.

4.1.7.2—Foundation design: The loading combinations in the 1995 version of this article have been deleted. The pseudo-bearing pressure/pile loads shall be computed by multiplying the unfactored dead and axial bending loads by their appropriate load factor from Sections 5.3.1 and 5.3.2.

4.2—Wind loads

4.2.1 General—The basic wind speed V in the current standard has been revised from “fastest-mile” to a “3-sec gust” speed to reflect the changes published in ASCE 7-95. Eq. (4-1) has been modified accordingly. In Eq. (4-1), 1.47 converts wind speed from mph to ft/sec and 0.65 converts 3-sec gust speed to a mean hourly speed. The revised power law coefficient 0.154 (as an approximation of $1/6.5$) comes from Table C6-6 in the Commentary to ASCE 7-95, 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-sec gust” speed is always higher than the previously specified “fastest-mile” speed. A “fastest-mile” wind speed may be converted to a “3-sec gust” speed for normal speeds of interest in chimney design using the following equation

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

The relationship between 3-sec gust speed and any other averaging time can be found in texts such as *Wind Effects on Structures*⁴ by Simiu and Scanlon.

The procedure was determined from simplified dynamic analyses that yield equivalent static load distributions. This approach requires that a wind speed averaged over a period on the order of 20 min to 1 hr be used as a basis for design.

Eq. (4-1) permits the mean hourly speed at height z to be determined from the basic design speed that is the “3-sec gust” speed at 33 ft (10 m) over open country. The conversion is based on the relationship recommended by Hollister.⁵ 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 (height on the order of 650 ft [198 m]) the reduction is not likely to exceed 20 percent.

V_R in Eq. (4-1) is the product of the square root of the importance factor I and V , the basic wind speed as charted and defined in ASCE 7-95. It should be noted that I can be used to vary probability, as well as to classify the importance of the structure. The Committee believes that 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 7-95.

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^{6,7} and deterministic⁸ approaches. These methods yielded acceptable results.

4.2.2 Along-wind loads—The recommended drag coefficients are consistent with slender chimneys [$h/d(h) > 20$] with a relative surface roughness on the order of 10^{-4} to 10^{-5} . Some reduction in the drag coefficient C_{dr} with decreasing $h/d(h)$ can be expected but unusually rough (e.g., ribbed) chimneys would have higher values of C_{dr} . The variations of C_{dr} with roughness and aspect ratio are discussed by Basu⁹ and Vickery and Basu.¹⁰

The total load per unit length is computed as the sum of the mean component $\bar{w}(z)$ and the fluctuating component $w'(z)$. The dynamic component was evaluated using a slightly modified form of the “gust factor” approaches described by Davenport,¹¹ Vickery,⁶ and Simiu.¹² The base moment is evaluated using the gust factor approach but the loads producing this moment are approximated by a triangular distribution rather than a distribution matching the mean. Eq. (4-6) is a simple empirical fit to values of G_w computed as before for a structural damping of 1.5 percent of critical. Except for referencing V as the 3-sec gust speed, no revisions have been made to the procedures for calculating along-wind loads.

The natural period of the chimney may include the effect of foundation springs.

4.2.3 Across-wind loads—No revisions have been made to the procedures for calculating across-wind forces. However, Eq. (4-8a) has been rewritten for simplification and several typographical errors were corrected.

The 1995 Committee had numerous user comments and discussions regarding the procedures included in the 1988 standard for across-wind forces. Virtually all of the com-

Table 4.2.3—Comparison of results: along- plus across-wind moments, 1988 versus 1995 procedures

Description of chimneys							
Chimney	Height, ft	TOD, ft	BOD, ft	Tapers	VI, mph	h/d at 5/6h	Frequency, hz
6	485	47.67	53.50	3	85.0	10.17	0.485
13	500	52.17	52.17	1	76.8	9.58	0.428
7	534	51.09	61.55	1	74.9	10.11	0.591
8	545	33.00	55.00	1	85.6	14.86	0.432
9	613	73.00	73.00	1	74.9	8.40	0.406
12	978	71.50	114.58	3	74.9	13.68	0.295
2	275	28.00	28.00	1	85.6	9.82	0.752
4	375	20.00	32.00	1	85.6	17.05	0.529
Calculated wind speeds							
Chimney	Per ACI 307-88		Per ACI 307-95				
	V_{cr} , mph	$\bar{V}(z_{cr})$, mph		$\bar{V}(z_{cr})$, mph	V , mph	V_{cr} , mph	k
6	78.9	93.9		93.3	88.3	77.8	1.135
13	76.2	84.0		83.5	83.5	76.3	1.094
7	106.4	84.8		84.3	84.3	105.2	0.802
8	54.0	96.0		95.5	55.2	48.6	1.135
9	101.1	86.4		85.9	85.9	104.9	0.820
12	72.0	92.3		91.7	66.0	66.0	1.000
2	71.8	87.2		86.7	86.7	71.5	1.214
4	39.7	91.1		90.6	45.3	34.6	1.310
Factored base wind moments in ft-tons							
Chimney	Per ACI 307-88, RMS combined along- and across-wind: $B_s = 0.015$; $LF = 1.40$		Per ACI 307-95, RMS combined along- and across-wind: $B_s = 0.010$; $LF = 1.40$		Per ACI 307-88 and ACI 307-95 along-wind only: $LF = 1.70$		
6	270,600		209,200		160,900		
13	283,500		224,100		148,000		
7	447,800		238,100		165,100		
8	117,500		79,400		161,200		
9	971,700		459,100		320,700		
12	1,475,800		977,400		865,300		
2	39,800		34,100		28,600		
4	16,500		11,600		43,800		

mentators felt that the 1988 procedures were unduly conservative, especially in the absence of any record of structural failure. As a result of these discussions, and with the availability of new data and full-scale observations, the procedures for calculating across-wind loads were extensively revised.

A general solution for the across-wind response of circular chimneys with any geometry was developed by Vickery.¹³ These procedures, based on Vickery's general solution, were simplified to some extent, which requires that their application be restricted to certain geometries. Similar models have provided the basis for vortex-induced forces incorporated by the National Building Code of Canada, and the ASME/ANSI STS-1-1992 Steel Stack Standard.

Circular chimneys outside the bounds of these procedures, or where a flare or strong taper (nozzle) exists for more than one diameter near the top, may be conservatively analyzed

using the procedures of Section 4.2.3.3 of ACI 307-88 or by the general approach put forth by Vickery.¹³

It should be noted, however, that the procedures for determining shedding forces are not materially affected by the configuration of the lower third of the shell, which may range from plumb to any degree of taper.

However, it should also be noted that noncircular shapes may be more sensitive to across-wind forces and may require analyses beyond the scope of this standard.

Eq. (4-16) establishes a basis for increasing structural damping from a minimum of 1.0 percent to a maximum of 4.0 percent when the wind speed $\bar{V}$ exceeds $\bar{V}(z_{cr})$. Structural damping of 1 percent of critical is consistent with measured values and moderate stress levels with little cracking. Damping of 4.0 percent, which would be permitted when $\bar{V} = 1.30 \bar{V}(z_{cr})$, is more consistent with damping values permitted in seismic design.