# Design Guide for Tilt-Up Concrete Panels

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# ACI 551.2R-15

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*This guide presents information that expands on the provisions of ACI 318 applied to the design of site-cast precast, or tilt-up, concrete panels, and provides a comprehensive procedure for the design of these important structural elements. In addition, this guide provides design recommendations for various support and load conditions not specifically covered in ACI 318, including design guidelines for in-plane shear.*

**Keywords:** panel; panel design; panel lifting; precast; reinforcement design; seismic design of tilt-up; slender wall analysis; tilt-up; tilt-up design, tilt-up detailing.

### CONTENTS





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## CHAPTER 1—INTRODUCTION

Tilt-up concrete buildings have been constructed in North America for over 100 years, but it was not until the late 1990s that ACI 318 specifically addressed the requirements for design of slender concrete walls. ACI 318-11, 14.8, provides a method of analysis and covers only the basic requirements for evaluating the effects of vertical and transverse out-of-plane loads. ACI 318-11, Chapter 10, may also be used to design slender walls, but the requirements are more general and should be applied with discretion.

This guide expands on the provisions of ACI 318-11, Section 14.8, and ASCE/SEI 7 and provides a comprehensive procedure for the design of these structural elements. This guide also provides design recommendations for various support and load conditions not specifically covered in ACI 318, and includes design guidelines for in-plane shear.

## CHAPTER 2—NOTATION AND DEFINITIONS

### 2.1—Notation

$A_g$ = gross area of concrete section, in.$^2$ (mm$^2$)
$A_s$ = area of tension reinforcement, in.$^2$ (mm$^2$)
$A_{se}$ = effective area of tension reinforcement, in.$^2$ (mm$^2$)
$A_v$ = area of shear reinforcement, in.$^2$ (mm$^2$)
$a$ = depth of equivalent rectangular stress block, in. (mm)
$b_d$ = design width, in. (mm)
$b_t$ = tributary width, in. (mm)
$b_w$ = width of the concrete section, in. (mm)
$c$ = distance from the extreme fiber to the neutral axis, in. (mm)
$D$ = dead load
$d$ = distance from the extreme concrete compression fiber to the centroid of tension reinforcement, or the effective depth of section, in. (mm)
$d_t$ = distance from the extreme compression fiber to centroid of extreme layer of longitudinal tension steel, in. (mm)
$E$ = loads due to seismic force
$E_c$ = concrete modulus of elasticity, psi (MPa)
$E_s$ = steel modulus of elasticity, psi (MPa)
$e_{cc}$ = eccentricity of applied load(s), in. (mm)
$F$ = loads due to weight or pressure of fluids
$F_p$ = factored load
$f_c'$ = specified compressive strength of concrete, psi (MPa)
$f_r$ = modulus of rupture, psi (MPa)
$f_y$ = reinforcement yield stress, psi (MPa)
$GC_p$ = external pressure coefficient
$GC_{pi}$ = internal pressure coefficient
$H$ = horizontal line load or soil pressure
$h$ = panel thickness, in. (mm)
$I_e$ = importance factor
$I_{cr}$ = cracked section moment of inertia, in.$^4$ (mm$^4$)
$I_e$ = effective moment of inertia, in.$^4$ (mm$^4$)

$K_b$ = bending stiffness, in.-lb/in. (N·mm/mm)
$K_d$ = wind directionality factor
$K_z$ = velocity pressure coefficient at height $z$
$K_{zt}$ = topographic factor
$L$ = live load
$L_r$ = roof live load
$\ell$ = vertical span of member between support
$\ell_c$ = cantilever height
$\ell_{floor}$ = distance from floor diaphragm to the bottom of panel, in. (mm)
$\ell_{main}$ = distance from main floor to bottom of panel, in. (mm)
$\ell_{panel}$ = distance from panel center of gravity to the bottom of panel, in. (mm)
$\ell_{roof}$ = distance from roof diaphragm to the bottom of panel, in. (mm)
$\ell_w$ = width of concrete section, in. (mm)
$M_a$ = maximum moment at midheight of wall due to service lateral and eccentric vertical loads, including $P$-$\Delta$ effects, in.-lb (N·mm)
$M_{cr}$ = moment causing flexural cracking of the concrete section, in.-lb (N·mm)
$M_{max}$ = maximum moment occurring over the span of the panel due to uniform lateral loads, in.-lb (N·mm)
$M_n$ = nominal moment strength at the midheight cross section due to service lateral and eccentric vertical loads only, in.-lb (N·mm)
$M_u$ = maximum factored combined bending moment, in.-lb (N·mm)
$M_{ua}$ = maximum factored moment at midheight of wall due to lateral and eccentric vertical loads, not including $P$-$\Delta$ effects, in.-lb (N·mm)
$n$ = modular ratio
$P$ = applied axial load at top of panel
$P$-$\Delta$ = secondary moment caused by axial load $P$ acting on a deflected shape with displacement $\Delta$, in.-lb (N·mm)
$P_{cr}$ = critical buckling load
$P_u$ = factored axial load
$q_z$ = effective velocity pressure at mean roof height $z$, lb/ft$^2$ (N·m$^2$)
$R$ = rain load in 4.4
$R$ = vertical reaction at footing in 8.1
$R$ = seismic response modification coefficient in 8.4
$S$ = snow load
$S_{DS}$ = short-period design spectral response acceleration
$S_{MS}$ = maximum considered spectral response acceleration
$S_S$ = mapped short-period spectral acceleration
$s$ = spacing of transverse shear reinforcement, in. (mm)
$T$ = cumulative effects of temperature, creep, shrinkage, settlement
$V_c$ = nominal shear strength of normalweight concrete, lb (N)
$V_{floor}$ = floor diaphragm shear force
$V_n$ = total shear strength of the concrete section, lb (N)
$V_{panel}$ = panel shear force (seismic only
$V_{R\ main}$ = resisting shear force at main floor
$V_{roof}$ = roof diaphragm shear force
$V_s$ = nominal shear strength of the reinforcement, lb (N)
$W$ = wind load
$W_a$ = wind load based on serviceability wind speed
$W_c$ = panel self-weight
$W_{floor}$ = weight of tributary floor structure
$W_{panel}$ = weight of panel
$W_{roof}$ = weight of tributary roof structure
$w$ = uniform lateral load
$w_c$ = factored self-weight of concrete wall panel above the base
$w_u$ = factored uniform lateral load on element
$z$ = mean roof height
$\delta_b$ = moment magnification factor
$\gamma_c$ = unit weight of concrete, lb/ft$^3$ (kg/m$^3$)
$\rho_l$ = ratio of area of distributed longitudinal reinforcement to gross concrete area perpendicular to that reinforcement
$\rho_t$ = ratio of area of distributed transverse reinforcement to gross concrete area perpendicular to that reinforcement
$\phi$ = strength reduction factor
$\Delta_i$ = initial deflection at midheight, in. (mm)
$\Delta_{max}$ = maximum total deflection at midheight, in. (mm)
$\Delta_n$ = maximum potential deflection at midheight, in. (mm)
$\Delta_s$ = maximum out-of-plane deflection due to service loads, including $P$-$\Delta$ effects, in. (mm)

## 2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource "ACI Concrete Terminology" at http://www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that resource.

**compressive strength**—measured maximum resistance of a concrete specimen to axial compressive loading; expressed as force per unit cross-sectional area.

**compressive stress**—stress directed toward the part on which it acts.

**connection**—a region that joins two or more members.

**modulus of elasticity**—ratio of normal stress to corresponding strain for tensile or compressive stress below the proportional limit of the material; also called elastic modulus, Young's modulus, and Young's modulus of elasticity; denoted by the symbol $E$.

**moment frame**—frame in which members and joints resist forces through flexure, shear, and axial force.

**net tensile strain**—tensile strain at nominal strength exclusive of strains due to effective prestress, creep, shrinkage, and temperature.

**seismic-force-resisting system**—portion of the structure designed to resist earthquake design forces required by the legally adopted general building code using the applicable provisions and load combinations.

**tensile stress**—stress directed away from the part on which it acts.

**tension-controlled section**—cross section in which the net tensile strain in the extreme tension fiber at nominal strength is greater than or equal to 0.005.

**slender wall**—wall, structural or otherwise, whose thickness-to-height ratio make it susceptible to secondary moments from eccentric axial loads and self-weight in addition to primary moments from out-of-plane (lateral) forces.

**work**—entire construction or separately identified parts thereof that are required to be furnished under contract documents.

## CHAPTER 3—ANALYSIS CONCEPTS FOR SLENDER CONCRETE WALLS

### 3.1—Panel design model

Tilt-up concrete wall panels most often serve as load-bearing wall elements spanning vertically from the foundation or slab-on-ground to intermediate floor(s), roof, or both. Bending moments result from out-of-plane loads, eccentric axial loads, or both. Second-order bending effects resulting from axial load acting on a deflected panel shape will cause an increase in these moments, also known as the $P$-$\Delta$ effect. Ultimate strength failure of a slender wall panel is defined to occur when the maximum factored bending moment at or near midheight exceeds the nominal strength of the concrete section times a strength reduction factor.

The maximum bending moment can be separated into two components: 1) primary moment due to applied loads; and 2) secondary moment due to $P$-$\Delta$ effects.

Figure 3.1 illustrates the effects of these moments. Primary moments are obtained from applied loads, such as lateral wind or seismic pressures, and eccentric axial loads. In most cases, it is the moment at midheight that is of concern because this is normally where maximum $P$-$\Delta$ effects and eventual failure will occur. The following contribute to the primary moment in the panel:

(a) Eccentric axial loads
(b) Out-of-plane lateral loads (wind or seismic)
(c) Initial lateral deflections due to panel out-of-straightness

Small horizontal displacements of the top of the panel relative to the bottom have little effect on the bending moments and are typically ignored.

The deflection of a wall panel depends on its bending stiffness. For reinforced concrete, this bending stiffness can be difficult to evaluate because it is influenced by a number of parameters, including:

(a) Wall thickness
(b) Concrete compressive strength
(c) Concrete tensile strength
(d) Area of steel reinforcement
(e) Location of steel reinforcement in the wall section
(f) Applied axial load
(g) Bending curvature

The flexural properties of a concrete section vary in a nonlinear manner with increasing moment. Both strength and stiffness will vary with changes in axial compression and degree of bending curvature. As curvature increases, bending moment increases until concrete crushing or reinforcement yielding occurs. Bending stiffness of the panel remains relatively constant at small curvatures, but abruptly decreases as the concrete cracks in flexural tension. Following this, stiffness essentially does not deteriorate any further until reinforcement yields in tension. In most cases, however, the main concern is the failure condition due to factored loads, where the resisting moment and bending stiffness can be determined accurately by simple calculations.

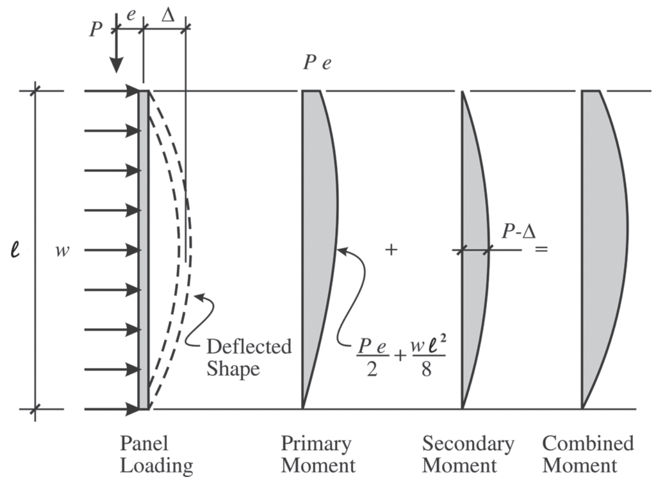


*Fig. 3.1—Panel design model—suction force acting with eccentric axial load.*

### 3.2—Bending stiffness evaluation

The relationship between the maximum bending moment in the wall panel and maximum lateral deflection can be expressed by the following ratio

$$K_b = \frac{M_{max}}{\Delta_{max}}$$

Simplify the procedure for calculating deflection and final bending moment by using a constant value for the bending stiffness $K_b$ that will provide reasonable, but conservative, results for the expected range of applied loading.

Where a simply supported slender wall element is subjected to uniform lateral load only (Fig. 3.2a), maximum moment $M_{max}$ will occur at midheight and the maximum deflection $\Delta_{max}$ is given by

$$\Delta_{max} = \frac{5w\ell^4}{384E_cI_e} = \frac{5M_{max}\ell^2}{48E_cI_e} = \frac{M_{max}\ell^2}{9.6E_cI_e}$$

in which

$$M_{max} = \frac{w\ell^2}{8}$$

When the same wall element is subjected to a constant moment $M$ along the height due to equal and opposite end moments (Fig. 3.2b), maximum deflection is

$$\Delta_{max} = \frac{M_{max}\ell^2}{8E_cI_e}$$

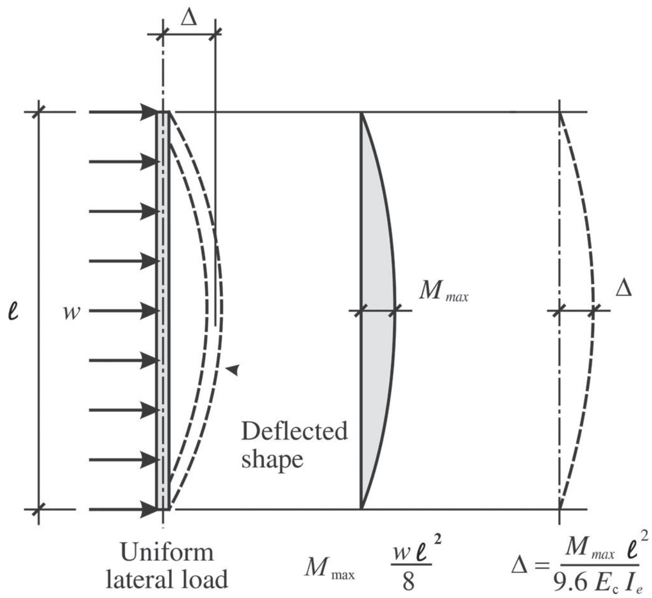


*Fig. 3.2a—Maximum deflection due to lateral load only.*

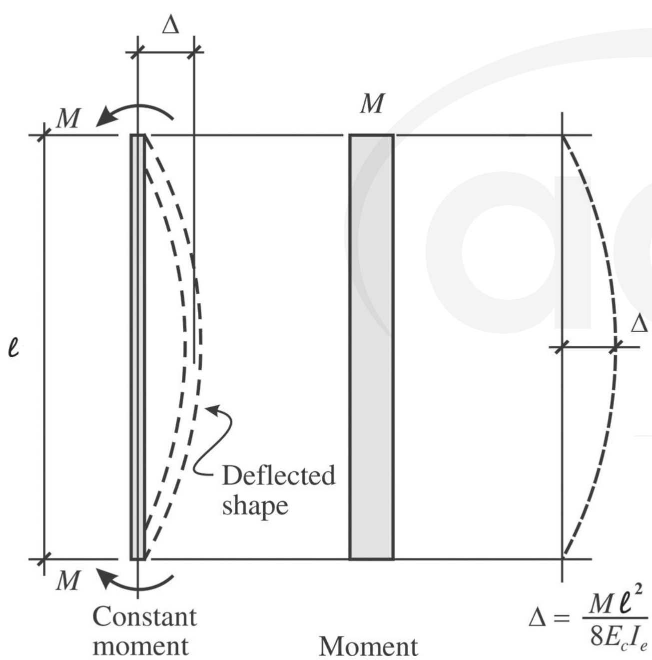


*Fig. 3.2b—Maximum deflection due to constant lateral moment.*

Where the wall element is subjected to axial load $P$, only as shown in Fig. 3.2c, plus a small initiating eccentricity, maximum deflection at midheight is given by

$$\Delta_{max} = \frac{M_{max}\ell^2}{\pi^2 E_c I_e} = \frac{M_{max}\ell^2}{9.87 E_c I_e}$$

in which

$$M_{max} = P\Delta_{max}$$

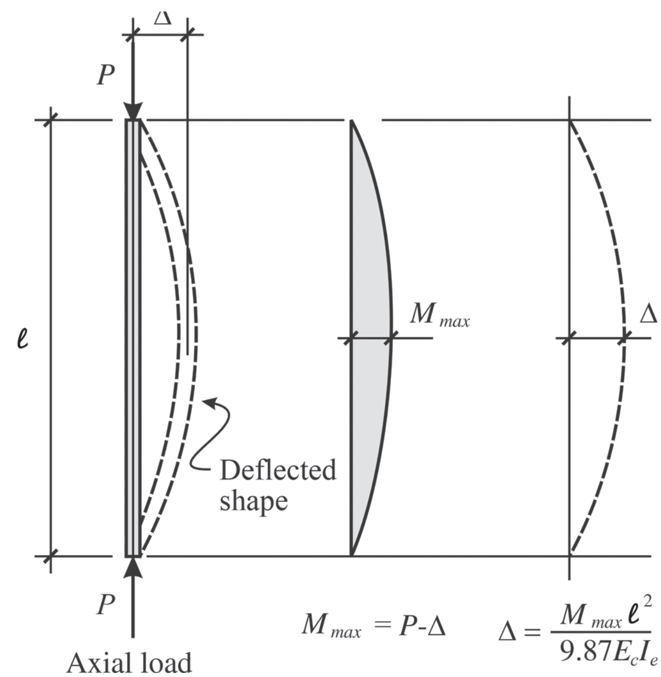


*Fig. 3.2c—Deflection due to axial load only.*

Maximum moment in a tilt-up panel is usually the result of a combination of these loading conditions. Lateral load effects are often large compared with end moments. Traditional methods for analyzing tilt-up panel walls have adopted the first of the aforementioned relations for deflection calculations

$$\Delta_{max} = \frac{5M_{max}\ell^2}{48E_c I_e} = \frac{M_{max}}{K_b}$$

Bending stiffness $K_b$ for a slender wall is therefore defined as

$$K_b = \frac{48E_c I_e}{5\ell^2} = \frac{9.6E_c I_e}{\ell^2}$$

This will slightly overestimate the deflection and maximum bending moment of a slender wall subjected to the combined effects of lateral and axial load for all axial loads that produce $P$-Δ moments larger than the moments produced by lateral loads.

$K_b$ is similar in value to the more familiar term for critical buckling load, $P_{cr}$

$$P_{cr} = \frac{\pi^2 E_c I_e}{\ell^2} = 9.87\frac{E_c I_e}{\ell^2}$$

Critical buckling capacity is a by-product of the $P$-Δ analysis and represents the maximum axial load that can be sustained by a pin-ended slender column or wall in the absence of any other applied loads. The factor $\pi^2 = 9.87$ defines a sinusoidal, single-curvature deflected shape due to the effects of a concentric axial load only. The applicable units for $P_{cr}$ are force (k or kip [N or Newton]) and for $K_b$, bending moment per unit deflection (ft-kip/ft or in.-kip/in. [N-m/m or N-mm/mm]).

Section stiffness $E_cI_e$ in the preceding equation varies with both axial and lateral loadings, degree of curvature of the panel, and properties of the concrete section. At ultimate load conditions, the concrete section exhibits cracks over most of the panel height. Full-scale testing in California in the early 1980s (SEAOSC 1982) and analytical studies by the SEAOSC Slender Wall Task Group (Lai et al. 2005) verified that a value of $E_cI_e$ equal to the cracked section stiffness $E_cI_{cr}$ correlates closely with the load-deflection characteristic of the test results. Ultimate load deflections using the preceding $\Delta_{max}$ equations will likely be overestimated. The cracked section moment of inertia, $I_{cr}$, can be taken as

$$I_{cr} = nA_{se}(d-c)^2 + \frac{bc^3}{3}$$

where

$c = a/\beta_1$

$$a = \frac{A_s f_y}{0.85 f_c' b}$$

$\beta_1 = 0.85$ for $f_c' \leq 4000$ psi (28 MPa)

$$= 0.85 - 0.05\left(\frac{f_c' - 4000}{1000}\right) \geq 0.65 \text{ for } f_c' > 4000 \text{ psi (in.-lb units)}$$

$$= 0.85 - 0.05\left(\frac{f_c' - 28}{7}\right) \geq 0.65 \text{ for } f_c' > 28 \text{ MPa (SI units)}$$

$n = E_s/E_c$

Rectangular stress block stiffness has been used because the panel is at the ultimate load state. The development of this relationship, and a comparison to $I_{cr}$ for a triangular concrete stress distribution, is provided in Appendix A.

Applied axial forces will counteract a portion of the flexural tension stresses in the concrete section, resulting in increased bending moment resistance. For small axial stresses less than $0.10f_c'$, this can be accounted for by a simple modification of the area of reinforcement as follows

$$A_{se} = A_s + \frac{P_u}{f_y}\left(\frac{h}{2d}\right)$$

$A_{se}$ can also be used to account for the increased bending stiffness when computing $P$-$\Delta$ deflections.

The assumption that concrete section stiffness is equal to $E_cI_{cr}$ and is constant over the entire height of the panel is considered valid for factored load conditions. The calculation for $I_{cr}$ is based on the value of $c$ for the rectangular concrete stress block that occurs at ultimate loads rather than $kd$ for the triangular stress distribution that occurs at service loads, because the purpose is to compute deflections at ultimate loads. ACI 318 adopted this approach in 1999, which had also been employed in this form by The Uniform Building Code (International Code Council 1997). These assumptions do not introduce significant variations to the final design of a slender tilt-up panel. Appendix A provides a derivation and comparison of the two methods.

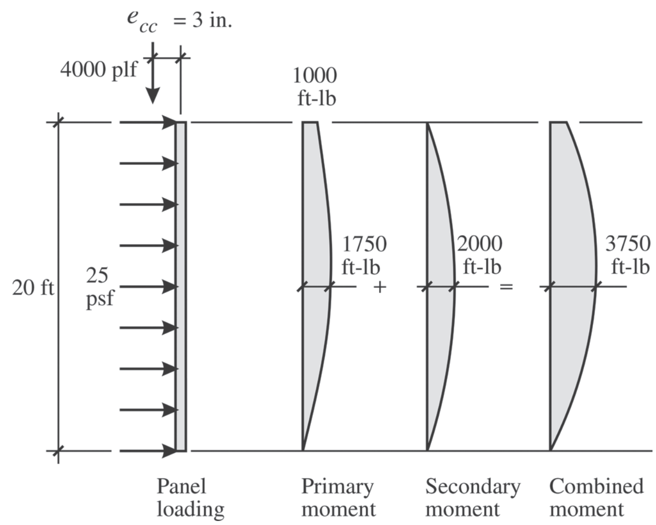


*Fig. 3.3—Slender wall example calculation—suction force acting with eccentric axial load. (Note: 1 in. = 24.5 mm; 1 ft = 0.3 m; 1 plf = 1.4 N/m; 1 ft-lb = 15 N-m; 1 lb/ft² = 0.048 kPa.)*

### 3.3—Iteration method for *P*-Δ effects

As noted in the previous section, the maximum moment $M_{max}$ in a slender wall element typically occurs at or near the midheight section. It is the sum of the applied moment $M_a$ and the $P$-$\Delta$ moment

$$M_{max} = M_a + P\Delta_{max}$$

The relation between maximum bending moment and deflection is

$$\Delta_{max} = \frac{5M_{max}\ell^2}{48E_cI_{cr}} = \frac{M_{max}}{K_b}$$

The solution to the previous two equations can be obtained by a simple iterative procedure. The following example illustrates the method, assuming a 12 in. (300 mm) wide panel strip depicted in Fig. 3.3.

The assumed parameters are:

$\ell$ = 20 ft (6.10 m)

$w$ = 25 lb/ft² (1.2 kPa)

$P$ = 4000 plf (5400 N/m) at top of panel

$e_{cc}$ = 3 in. (76 mm)

$E_cI_{cr} = 45 \times 10^6$ lb-in.² ($129 \times 10^6$ N-mm²)

$$K_b = \frac{48E_cI_{cr}}{5\ell^2} = \frac{48}{5}\frac{45\times10^6}{20^2\times12^2} = 7500 \text{ in.-lb/in. (33 kN-mm/mm)}$$

$$M_a = 25x\frac{20^2}{8} + 4000\times\frac{3}{2}\times\frac{1}{12} = 1250 + 500 = 1750 \text{ ft lb (25.5 kN-m)}$$

Start with: