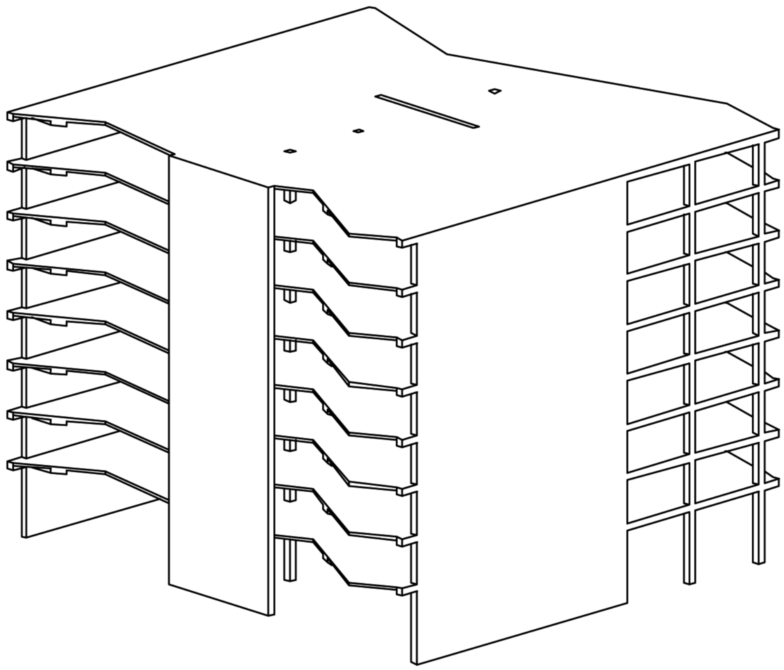
Design Example 1
Reinforced Concrete Wall



OVERVIEW

The structure in this design example is an eight-story office with load-bearing reinforced concrete walls as its seismic-force-resisting system. This design example focuses on the design and detailing of one of the 30-foot 6-inch-long walls running in the transverse building direction.

The purpose of this design example is twofold:

1. To demonstrate the design of a solid reinforced concrete wall for flexure and shear, including bar cut-offs and lap splices.

2. To demonstrate the design and detailing of wall boundary zones.

The design example assumes that design lateral forces have already been determined for the structure and that the forces have been distributed to the walls of the structure by a hand or computer analysis. This analysis has provided the lateral displacements corresponding to the design lateral forces.

OUTLINE

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2. Load Combinations for Design
3. Preliminary Sizing of Wall
4. Flexural Strength at Base of Wall
5. Flexural Strength and Lap Splices over Height of Wall
6. Shear Strength of Wall
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1. Building Geometry and Loads — ASCE 7

1.1 GIVEN INFORMATION

This design example follows the general building code requirements of the 2021 *International Building Code* (2021 IBC) and ASCE/SEI 7-16. For structural concrete design, the 2021 IBC references the *American Concrete Institute Building Code* (ACI 318), as indicated in Section 1901.2. This example follows the requirements of ACI 318-19. Discussions related to the *SEAOC Blue Book* recommendations refer to the document *Recommended Lateral Force Recommendations and Commentary* (SEAOC, 1999) as well as the *Blue Book Seismic Design Recommendations* articles on specific topics (SEAOC, 2019), as applicable.

Figure 1-1 shows the typical floor plan of the structure. The design and analysis of the structure is based on a response modification coefficient, R, of 5 (ASCE 7 Table 12.2-1) for a bearing wall system with special reinforced concrete shear walls. The deflection amplification factor, C_d, is 5. The *SEAOC Blue Book* (2019, Article 09.01.010) expresses the opinion that the R-value should be the same for concrete bearing-wall systems (R = 5) and walls in building frame systems (R = 6), which may be justified based on detailing provisions. The *SEAOC Blue Book* argues that placing gravity-load frame reinforcement in concrete walls to artificially create a building frame does not necessarily improve ductility, provided that the detailing for the concrete walls addresses the requirements for confinement and distribution of reinforcement. The authors of this design example agree with the *SEAOC Blue Book* on this topic. To be consistent with the current code requirements though, this design example uses R = 5.

Mapped spectral response acceleration values from ASCE 7 maps (Figures 22-1 through 22-8) are

$S_1 = 0.65$

$S_S = 1.60$

Site Class D

Risk Category II

Seismic Design Category D

Redundancy factor, ρ = 1.0

Seismic importance factor, I = 1.0

Concrete strength, f_c' = 5000 psi

Steel yield strength, f_y = 60 ksi

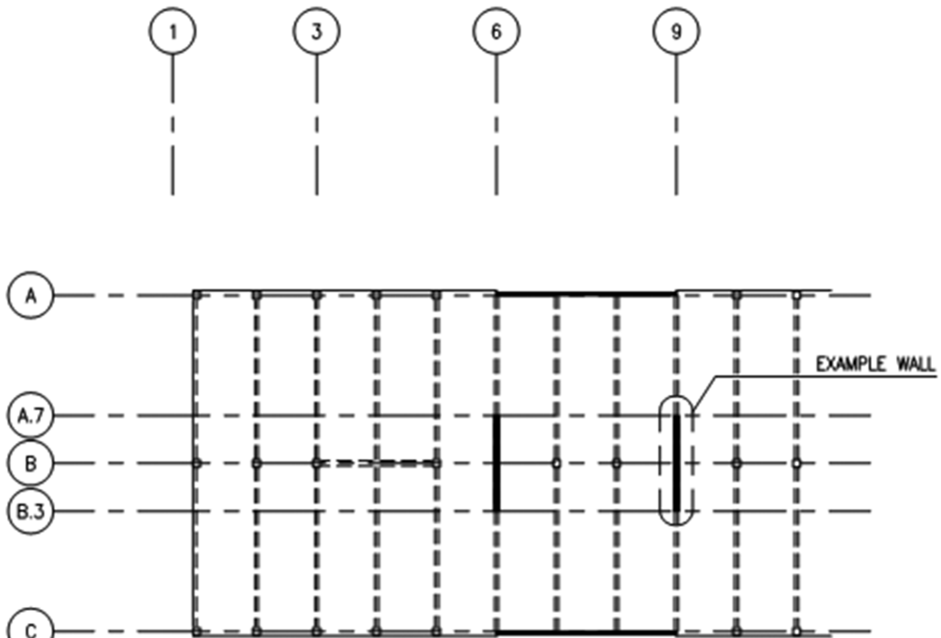

Figure 1-1. Floor plan

1.2 DESIGN LOADS AND LATERAL FORCES

Figure 1-2 shows the wall elevation and shear and moment diagrams. The wall carries axial forces P_D (resulting from dead load including self-weight of the wall) and P_L (resulting from live load), as shown in Table 1-1. Live loads have already been reduced according to IBC Section 1607.12. The shear, V_E, and moment, M_E, resulting from the design lateral earthquake forces are also shown in Table 1-1. The forces are from a linear static analysis.

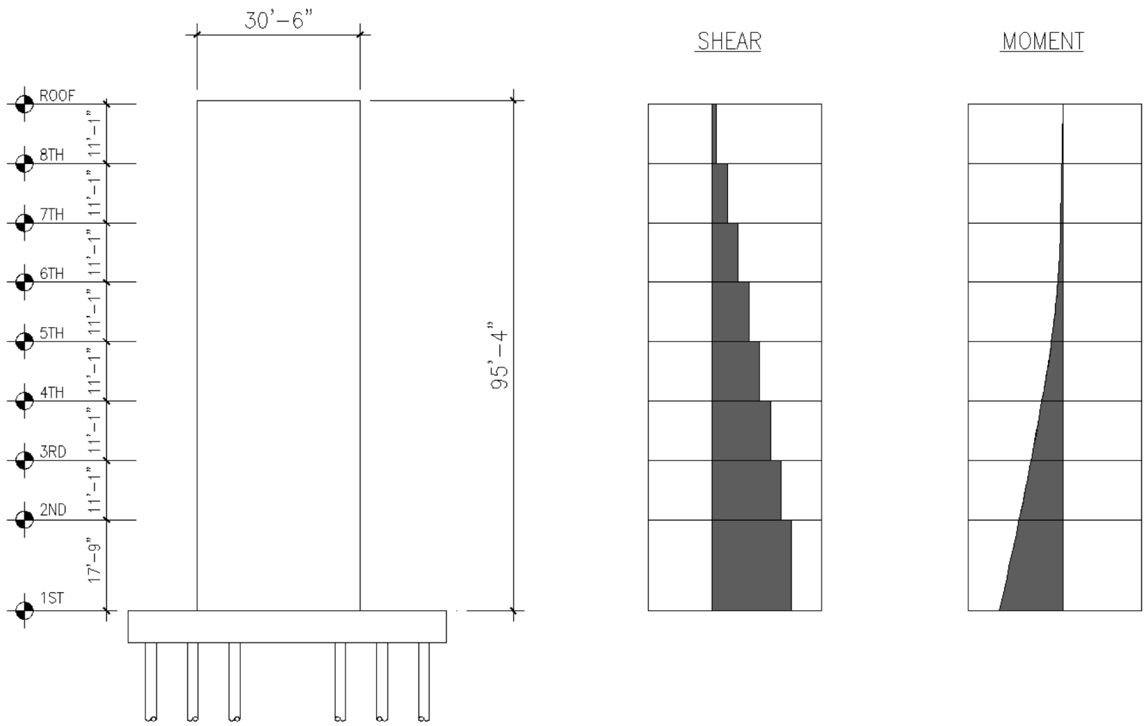

Figure 1-2. Wall elevation, shear, and moment diagram

Table 1-1. Design loads and lateral forces

Level	P_D (kips)	P_L (kips)	V_E (kips)	M_E (kip-ft)
Roof	193	37	84	0
8	388	72	244	928
7	573	108	414	3630
6	758	144	595	8210
5	945	181	785	14,800
4	1130	217	987	23,500
3	1310	253	1220	34,400
2	1540	290	1420	48,000
1				73,000

For this design example, it is assumed that the foundation system is rigid, and thus the wall is considered to have a fixed base. The fixed-base assumption is made here primarily to simplify the example. In an actual structure, the effect of foundation flexibility and its consequences on structural deformations should be considered.

The analysis uses effective section properties for the stiffness of concrete elements. Example 2 includes a discussion of effective section properties for use in analysis.

Using the fixed-base assumption and effective section properties, the horizontal displacement at the top of the wall corresponding to the design lateral forces is 1.24 inches. This displacement is needed for the detailing of boundary zones according to ACI 318 Section 18.10.6.1, which is illustrated in Part 8 of the design example.

2. Load Combinations for Design — ASCE 7

2.1 LOAD COMBINATIONS

Equations 6 and 7 of Section 2.3.6 are the seismic design load combinations to be used for concrete.

$$1.2D + 1.0E + L + 0.2S$$
$$0.9D + 1.0E$$

Load combinations for *nonseismic* loads for reinforced concrete are given in Section 2.3.1, Equations 1 through 5.

2.2 HORIZONTAL AND VERTICAL COMPONENTS OF EARTHQUAKE FORCE

The term E in the load combinations includes horizontal and vertical components according to Equations 12.4-1 and 12.4-2 of Section 12.4.2:

$$E = E_h + E_v \qquad \text{Eq 12.4-1}$$
$$E = E_h - E_v \qquad \text{Eq 12.4-2}$$

where E_h and E_v are defined according to Equations 12.4-3 and 12.4-4 of Section 12.4.2.1 and Section 12.4.2.2 as follows:

$$E_h = \rho Q_E \qquad \text{Eq 12.4-3}$$
$$E_v = 0.2S_{DS}D \qquad \text{Eq 12.4-4a}$$

Substituting this into the seismic-load combinations results in

$$(1.2 + 0.2S_{DS})D + \rho Q_E + L + 0.2S$$
$$(0.9 - 0.2S_{DS})D + \rho Q_E$$

Since there is no snow load, $S = 0$. Section 2.3.6 permits the load factor on L in the above combination to be reduced to 0.5 where the unreduced design live load is less than or equal to 100 psf, with the exception of garages or areas occupied as places of public assembly. Because this example building is an office building, the reduced factor on L is applicable.

Given Site Class D and $S_S = 1.60$, from Table 11.4-1, $F_a = 1.0$

$S_{MS} = F_a S_S = 1.60$ Eq 11.4-1

$S_{DS} = (2/3)S_{MS} = 1.07$ Eq 11.4-3

With $S_{DS} = 1.07$, $\rho = 1.0$, and a live load factor of 0.5, the governing load combinations for this design example become

$$1.41D + Q_E + 0.5L$$

$$0.686D + Q_E$$

2.3 ACTIONS AT BASE OF WALL

For the example wall, the dead and live loads cause axial forces only, and the earthquake forces produce shear and moment only. The second of the above combinations gives the lower bound axial force. Because the axial force is less than that which would cause the balanced strain condition, the second of the above load combinations will be the more critical for the flexural strength of the wall.

The governing axial force at the base of the wall is thus

$$P_u = 0.686P_D = 0.686(1540 \text{ kips}) = 1060 \text{ kips}$$

The governing moment and shear at the base of the wall is

$$M_u = M_E = 73{,}000 \text{ kip-ft}$$

$$V_u = V_E = 1420 \text{ kips}$$

3. Preliminary Sizing of Wall

3.1 SHEAR STRESS AND REINFORCEMENT RATIO RULES OF THUMB

The dimensions and required number of walls in a building can be selected by limiting the average shear stress in the walls, corresponding to factored lateral forces, to between $3\sqrt{f'_c}$ and $5\sqrt{f'_c}$. Walls with higher levels of shear stress are permitted by ACI 318, but shear stress within the range suggested leads to more easily constructible detailing for shear strength, sliding shear, and boundary confinement. For taller buildings with significant influence of higher modes, PEER *Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2017) recommends limiting shear stresses to the range of $2\sqrt{f'_c}$ to $3\sqrt{f'_c}$ for preliminary design.

For the example wall, the maximum factored shear force equals 1420 kips. Using a $3\sqrt{f'_c}$ criterion, for a wall length of 30 feet 6 inches, the wall thickness equals

$$\frac{1{,}420{,}000 \text{ lb}}{366 \text{ in}\left(3\sqrt{5000 \text{ psi}}\right)} = 18.3 \text{ in}$$

Assume $b = 20$ inches.

Detailed shear design for calculated demands is discussed in Section 6.

3.2 MINIMUM THICKNESS TO PREVENT WALL BUCKLING — SEAOC Blue Book

For structures with tall story heights, the designer should check that the wall thickness exceeds $l_u/16$ where l_u is the unsupported height or length of the wall, whichever is shorter. The *SEAOC Blue Book Commentary* (1999, C407.5.6, p. 198) recommends that "the wall boundary thickness limit of $l_u/16$ be applied at all potential plastic-hinge locations, regardless of whether boundary zone confinement is required." ACI 318 Section 18.10.6.4(b) has a less restrictive requirement in this regard, which requires that the flexural compression zone have width at least equal to $h_u/16$ (where h_u is equivalent to l_u for walls in compression) only in locations where special boundary elements are required. Section 18.10.6.4(c) also requires a minimum compression zone width of 12 inches for special boundary elements of wall piers designed to have a single critical section for flexure and axial loads.

For the example wall, the clear height at the first story is 17 feet.

Recommended thickness = $l_u/16 = 17(12)/16 = 12.8$ in < 20 in . . . OK

3.3 LAYOUT OF VERTICAL REINFORCEMENT — ACI 318

Based on brief calculations and the preliminary sizing considerations discussed here, the wall section and reinforcement layout shown in Figure 1-3 is proposed for the base of the wall.

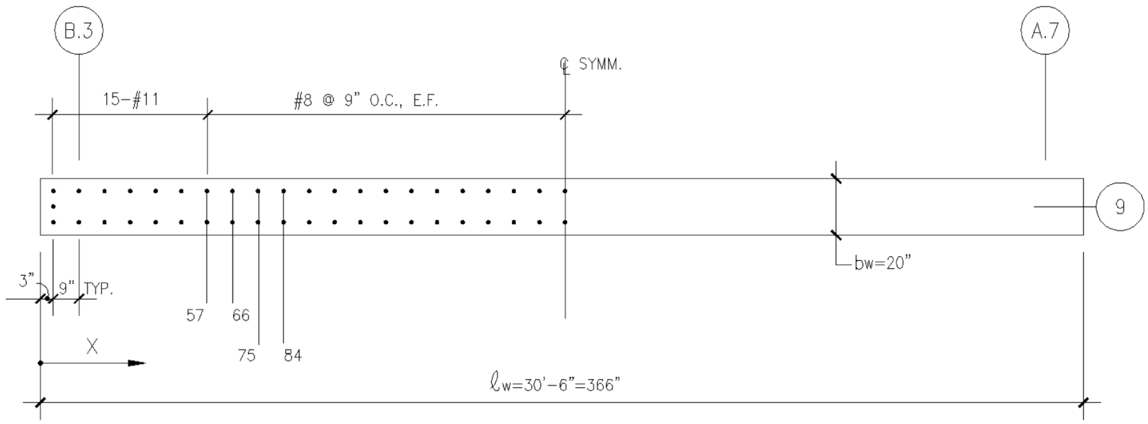

Figure 1-3. Layout of vertical reinforcement at wall base

The reinforcement layout addresses the following issues:

- Vertical bars are spaced longitudinally at 9 inches on center for ease of construction.
- The maximum permissible center-to-center spacing of vertical bars is 14 inches in boundary regions of walls where confinement is needed, according to ACI 318 Sections 18.7.5.2 and 18.10.6.4 (f). This means that at the ends of the 20-inch-thick wall, three bars are used as shown in Figure 1-3.
- The minimum requirements for longitudinal reinforcement at the end of wall segments per ACI 318, Section 18.10.2.4 are satisfied.

ACI 318 Section 18.10.2.1 specifies a minimum reinforcement ratio of 0.0025 for both vertical and horizontal reinforcement of structural walls. For the proposed layout, at the center portion of the wall's length

$$\rho_v = A_s/bs = 1.58 \text{ in}^2 / (9 \text{ in} \times 20 \text{ in}) = 0.0088 > 0.0025 \ \ldots \ \text{OK}$$

4. Flexural Strength at Base of Wall ACI 318

4.1 REINFORCEMENT CONSIDERED "EFFECTIVE"

As required by ACI 318 Section 18.10.5.1, all "developed longitudinal reinforcement within effective flange widths, boundary elements, and the wall web shall be considered effective." Thus, the vertical reinforcement in the web of the wall and axial force contributions to the flexural strength of wall sections may not be neglected.

The 1995 and earlier editions of ACI 318 and the 1991 and earlier editions of the UBC required wall boundaries to carry all moment and gravity forces. This practice results in higher flexural strengths in walls, which can lead to poor earthquake performance because it makes shear failure more likely to occur. By ACI 318 Section 18.10.5.1, this design practice is no longer permitted.

Wall flexural strength can be computed by hand calculations, spreadsheet calculations, or a computer program such as spColumn (American Structurepoint, 2018). All three calculation approaches are demonstrated in the following sections and are based on an assumed strain distribution and an iterative calculation procedure.

4.2 ASSUMED REINFORCEMENT STRAIN

For cyclic loading, all vertical reinforcement along the wall can be assumed to yield in either tension or compression. This assumption simplifies the hand calculation of moment capacity and is used in the hand calculations shown in Part 4.4.

Alternatively, the reinforcement strain can be assumed to be directly proportional to distance from the neutral axis, as discussed in ACI 318 Section 22.2.1.2. This assumption is used in the spreadsheet calculations demonstrated here and is also used by the spColumn computer program.

The assumption of all reinforcement yielding results in a slightly greater flexural strength compared to the strain assumption of Section 22.2.1.2, but the difference is not significant. The two possible assumed stress distributions are illustrated in Figure 1-4.

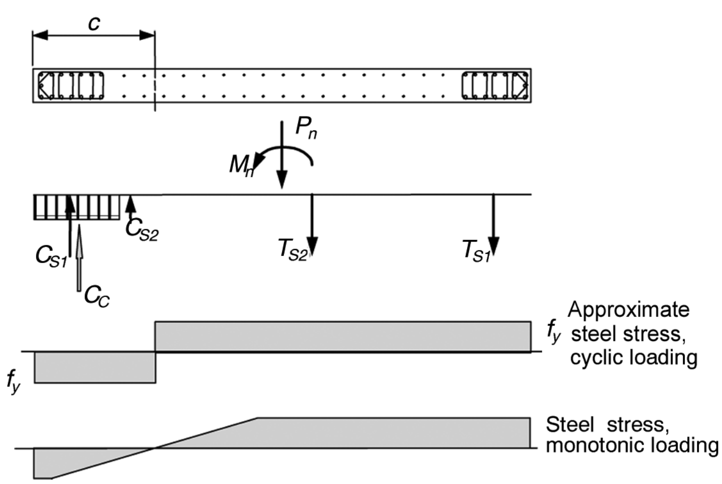

Figure 1-4. Steel stress and neutral axis depth