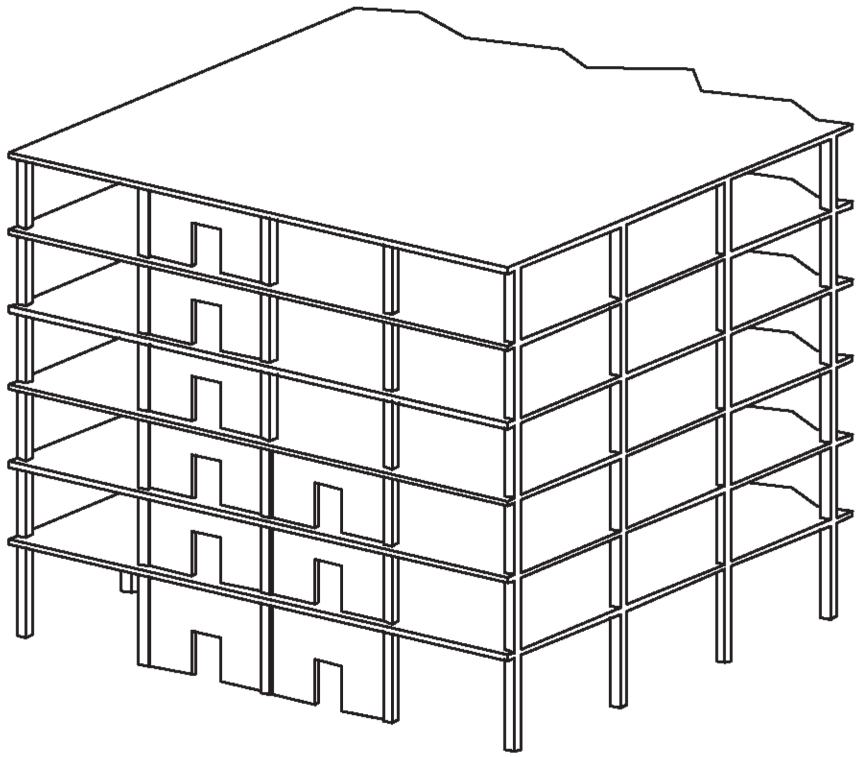
Design Example 2
Reinforced Concrete Wall with Coupling Beams



OVERVIEW

The structure in this design example is a six-story office building with reinforced concrete walls as its seismic-force-resisting system. The example focuses on the design and detailing of one of the reinforced concrete walls. This is a coupled wall running in the transverse building direction. The example assumes that design lateral forces have already been determined for the building and that the seismic moments, shears, and axial forces on each of the wall components are given from computer analysis.

The purpose of this design example is to illustrate the design of coupling beams and other aspects of reinforced concrete wall design.

OUTLINE

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9. Detailing of Coupling Beams

1. Building Geometry and Loads — ASCE 7

1.1 GIVEN INFORMATION

This design example follows the general building code requirements of the 2015 *International Building Code* (2015 IBC) and ASCE/SEI 7. For structural concrete design, the 2015 IBC references the *American Concrete Institute Building Code* (ACI 318), as indicated in Section 1901.2. This example follows the requirements of ACI 318-14. Discussions of the SEAOC Blue Book recommendations refer to the document *Recommended Lateral Force Recommendations and Commentary* (SEAOC, 1999) as well as the Blue Book online articles on specific topics (SEAOC, 2009) as applicable.

The wall to be designed is one of several reinforced concrete walls in the building. 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 (2009, Article 09.01.010) expresses the opinion that the R value for concrete bearing wall systems ($R = 5$) and that for walls in building frame systems ($R = 6$) should be the same, which may be justified based on detailing provisions. 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 22–11):

- $S_1 = 0.65$
- $S_S = 1.60$
- Site Class D

- $S_{DS} = 1.07$
- Risk Category II
- Seismic Design Category D
- Redundancy factor, $\rho = 1.0$
- Seismic Importance factor, $I = 1.0$
- Concrete strength, $f_c' = 4000$ psi
- Steel yield strength, $f_y = 60$ ksi

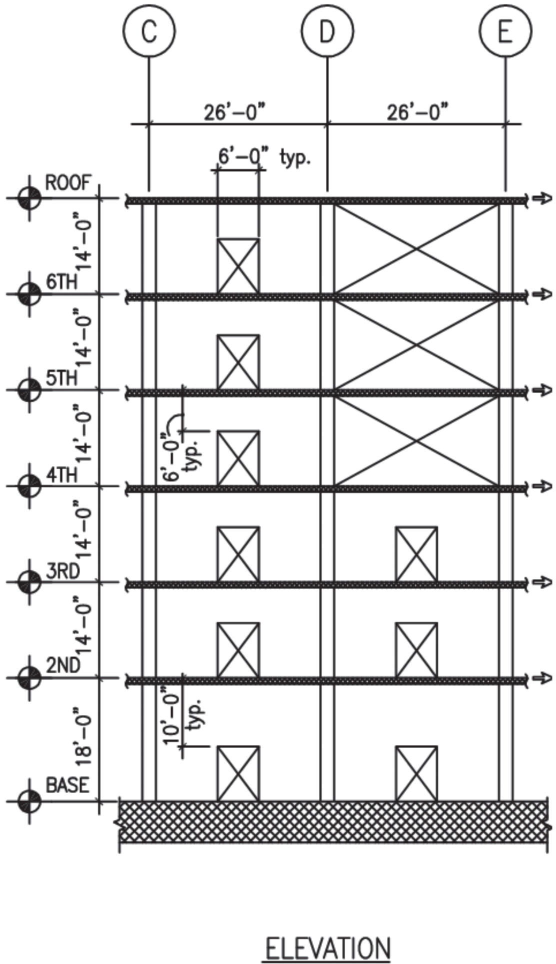
1.2 DESIGN LOADS AND LATERAL FORCES

The wall elevation, a plan section, and the design forces are shown in Figure 2–1. A linear static analysis of the wall for lateral forces, using a computer analysis program, gives the results shown in Figure 2–2, which shows the moments and shear for each coupling beam (i.e., wall spandrel), and the moments, shear, and axial forces for each vertical wall segment (i.e., wall pier).

Lateral story displacements corresponding to effective section properties are also shown on the figure. In the analysis model, the member stiffness used is 30 percent of the gross member stiffness for the walls and 10 percent of the gross member stiffness for the coupling beams. The recommendations for member stiffness assumptions are based on Section 5.3 of Paulay and Priestley (1992). ASCE/SEI 41-13 recommends an effective stiffness of 50 percent of the gross member stiffness for walls, though tests and moment curvature analysis predict lower stiffness depending on axial load, section geometry, reinforcement ratio, and loading history (Adebar et al 2007, Schotanus and Maffei 2007).

In this design example, the displacement output is used in Part 8.2 for determining the need for special boundary elements. In an actual building design, the displacements would also need to be considered for (a) design of elements not part of the lateral-force-resisting system, (b) building separations, and (c) P–Δ analysis.

Gravity loads are not included in the computer model. Gravity effects are added separately by hand calculations.



LATERAL FORCES F_{xi}	GRAVITY LOADS EACH COLUMN	
	P_D	P_L
337k	148	11
319k	309	28
259k	471	48
198k	634	69
138k	796	90
78k	962	110

P_D = EXCLUDES WALL WEIGHT

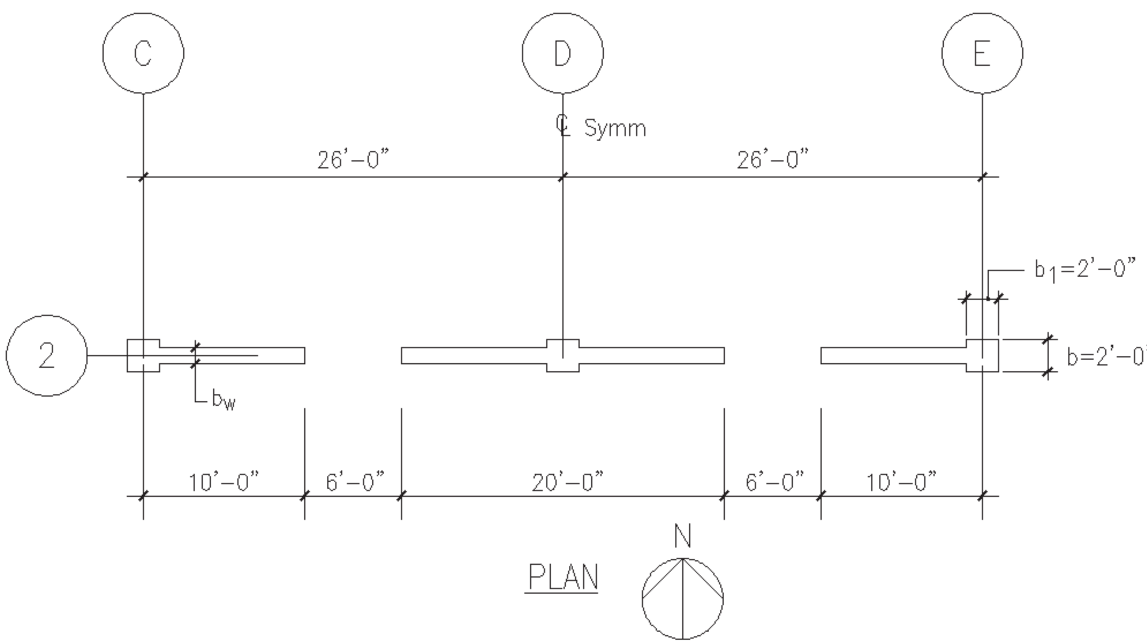


Figure 2–1. Wall elevation, plan section, and design forces

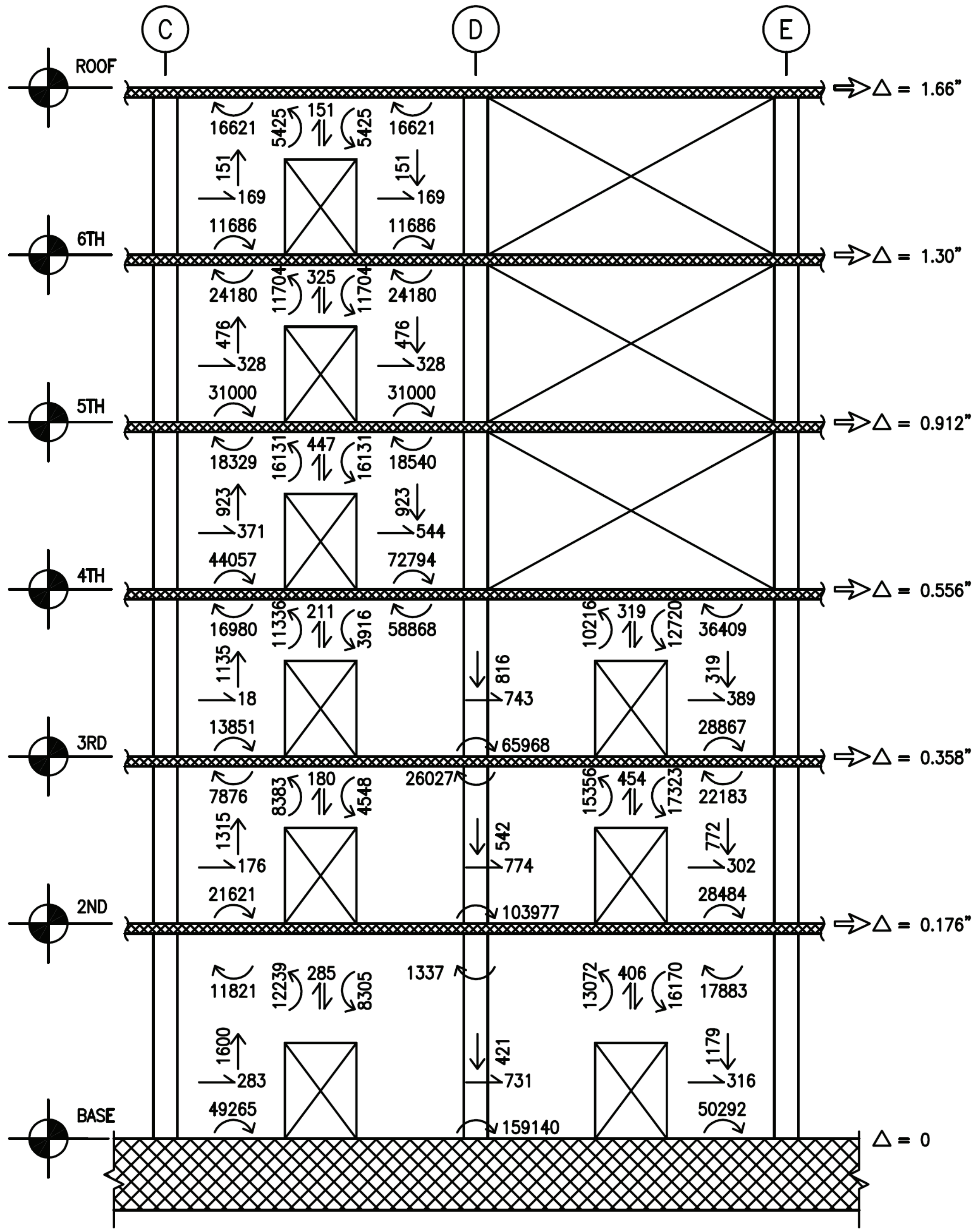


Figure 2–2. Results of ETABS computer analysis (kips, inches)

2. Load Combinations for Design — ASCE 7

Load combinations for reinforced concrete are discussed in detail in Part 2 of Design Example 1. As in that example, the governing load combinations become

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

Because there is no snow load, $S = 0$. As indicated in Section 12.4.2.3, the load factor on L in the above combination is permitted to equal 0.5 since the given structure is an office building with $L_o = 50$ psf per ASCE 7 Table 4.1.

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

$$1.41D + Q_E + 0.5L$$
$$0.686D + Q_E$$

The forces shown in Figure 2–2 correspond to Q_E.

3. Preliminary Sizing of Wall

For walls with diagonally reinforced coupling beams, the required wall thickness is often dictated by the layering of the reinforcement in the coupling beam, described in Part 9 of this example. For the subject wall, a wall thickness, b_w, of 16 inches will be tried.

Although not required by code, the SEAOC Blue Book (2009, Article 09.01.010) recommends rotation limits of 0.03 to 0.05 radians for confined coupling beams unless higher values can be justified by testing specimens that have aspect ratios and reinforcement similar to those to be used in the design. Rotation limits can affect the proportioning of walls so that coupling beams are not too short relative to wall piers. This design example assumes that the building walls and coupling beams have been proportioned to satisfy this requirement. This can be checked using the displacements δ_u from Table 2–12 and calculating the corresponding coupling beam rotation θ_{cb} as described in Part 6 of this example.

4. Coupling Beam Strength and Diagonal Reinforcement — ACI 318

4.1 REQUIREMENT FOR DIAGONAL REINFORCEMENT

Code requirements for the diagonal reinforcement of coupling beams (ACI 318 Section 18.10.7.4) are based on the clear length-to-overall-depth ratio for the coupling beam, l_n/h, and on the level of shear stress in the coupling beam.

For the wall in this design example, $l_n/h = 72 \text{ in} / 72 \text{ in} = 1.00$ for the typical coupling beam, and $l_n/h = 72 \text{ in} / 120 \text{ in} = 0.60$ for the coupling beams at the second floor.

As shown in Table 2–1 (5th column), for four of the nine coupling beams the shear exceeds $\left(4\lambda\sqrt{f'_c}\right)A_{cw}$, where $A_{cw} = b_w h$ and $\lambda = 1.0$ for normal weight concrete. For these coupling beams, diagonal reinforcement is required.

For the five coupling beams that have lower shear stress, diagonal reinforcement is not required by ACI 318. Designing these five coupling beams without diagonal reinforcement, using horizontal reinforcement to resist flexure and vertical stirrups to resist shear, might lead to cost savings in the labor to place the reinforcing steel.

In this design example, however, diagonal reinforcement is used in all of the coupling beams of the wall because (a) it can simplify design and construction to have all coupling beams detailed similarly, (b) research results show that diagonal reinforcement improves coupling beam performance, even at lower shear stress levels, as discussed in of the SEAOC Blue Book (1999, Section C407.7), and (c) uniform and consistent yielding up the height of the structure results in better overall performance.

Table 2–1. Coupling beam forces and diagonal reinforcement

Grid Line	Level	V_u (kips)	h (in)	$V_u/b_w h\sqrt{f'_c}$ (1)	Diagonal Bars	A_{vd} (in^2)	α (degrees)	ϕV_n (kips)	$\phi V_n/V_u$
C-D	Roof	151	72	2.1	4 #8	3.16	37.9	175	1.16
C-D	6th	325	72	4.5	4 #11	6.24	37.9	345	1.06
C-D	5th	447	72	6.1	6 #11	9.36	36.0	495	1.11
C-D	4th	211	72	2.9	4 #9	4.00	37.9	221	1.05
C-D	3rd	180	72	2.5	4 #9	4.00	37.9	221	1.23
C-D	2nd	285	120	2.3	4 #9	4.00	53.1	288	1.01
D-E	4th	319	72	4.4	6 #9	6.00	36.0	317	0.99
D-E	3rd	454	72	6.2	6 #11	9.36	36.0	495	1.09
D-E	2nd	406	120	3.3	4 #11	6.24	53.1	449	1.11

Note:

1. Diagonal bars are required per ACI 318 Section 21.9.7.2 when this ratio exceeds 4 and $l_n/h < 2$.

4.2 DESIGN OF DIAGONAL REINFORCEMENT

Diagonal reinforcement is provided in the coupling beams according to Equation 18.10.7.4 of ACI 318 Section 21.9.7.4

$$\phi V_n = \phi 2 A_{vd} f_y \sin\alpha \le 10\sqrt{f'_c} A_{cw}. \qquad \text{Eq 18.10.7.4}$$

Each group of diagonal bars must consist of at least four bars per ACI 318 Section 18.10.7.4(b). The calculation of the required diagonal reinforcement is shown in Table 2–1. For coupling beams with higher shear stresses, six bars are needed in each group, as shown in Table 2–1.

The angle, α, of the diagonal bars is calculated based on the geometry of the reinforcement layout, as shown in Figure 2–3. The value of α depends somewhat on the overall dimension of the diagonal bar group and on the clearance between the diagonal bar group and the corner of the wall opening. This affects the dimension, x, shown in Figure 2–3 and results in a slightly different value of α for a group of six bars compared to that for a group of four bars, as shown in Table 2–1.