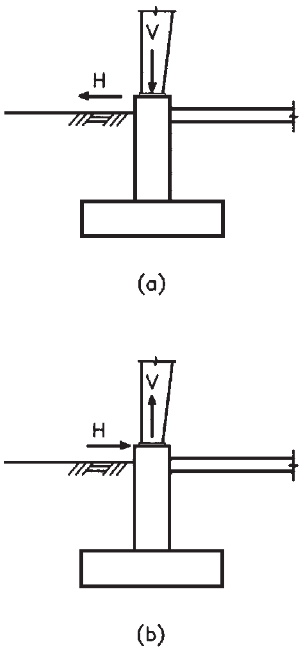

FIGURE 12.6 Loading combinations that typically control foundation design in rigid-frame buildings. The loads are combined as required by the governing building code: (*a*) dead + collateral + snow (or roof live load) + wind from right (also check this combination without wind; produces maximum outward reaction on the left foundation); (*b*) wind from left—dead (produces maximum uplift and inward load on the left foundation).

12.5.1 Tie Rods

A single-span rigid frame under uniform gravity loading will produce two equal horizontal reactions acting in the opposite directions (Fig. 12.1*a*). The most direct way of "extinguishing" both is to connect the opposing frame columns with a tie rod. Tie rods are suited best for large horizontal forces (upwards of 20 kip) and are not usually cost-effective for minor loads. The required cross-sectional area of a tie rod is determined by dividing the tension force by an allowable tensile stress in the rod.

Some designers take the maximum allowable tension stress for this purpose as 60 percent of the rod's yield strength, but this approach is fraught with danger. The elongation of a highly stressed rod under load can be substantial, as readily demonstrated by standard formulas. When a rod with the length L, area A, and modulus of elasticity E is subjected to force P, its length changes by the amount Δ_{rod}:

$$\Delta_{rod} = \frac{PL}{AE}$$

To get a sense of the numbers involved, assume $L = 120$ ft, $P = 36$ kip, and F_y of tie-rod reinforcing steel is 60 ksi. If the allowable stress in tension F_t is taken as $0.6F_y$, then

$$F_t = 0.6 \times 60 = 36 \text{ ksi}$$

and the required steel area A_{rq} is

$$A_{rq} = \frac{36}{36} = 1.00 \text{ sq in, or one \#9 bar}$$

The elongation of this bar under load would be

$$\Delta_{rod} = \frac{36 \times 120 \times 12}{1.00 \times 29{,}000} = 1.79 \text{ in}$$

If the columns spread out equally, each will be allowed to move

$$\frac{1.79}{2} = 0.895 \text{ in}$$

A tie rod that allows the frame columns to spread out almost 1 in under load can lead to frame damage, and for this reason, it is best to keep the tie-rod stresses low. Obviously, decreasing the allowable stresses by one-half reduces elongation under load by 50 percent. Alternatively, some designs allow tie rods to be post-tensioned after installation and curing of concrete, as explained below.

One of the oldest tie-rod designs uses a mild steel rod attached directly to the column base plate with a clevis and pin (Fig. 12.7*a*). Of course, the column base must be recessed below the floor for this approach to work. If the base is at the floor level or above, the tie rod can be hooked into the column pier (Fig. 12.7*b*). In this case, the most suitable tie-rod material is deformed reinforcing steel.

Naturally, steel bars hidden from view but exposed to moisture in the soil should be protected from corrosion. Tie rods should be galvanized or epoxy-coated and, as an extra measure of protection, encased in a plastic sheath filled with grout. Since building codes do not allow lap-spliced connections for tension-tie members, mechanical splices are required. Tie rods made of several reinforcing bars should have their splices staggered a minimum of 30 in.

One of two main disadvantages of both these designs is that the tie rods tend to sag under their own weight if they are simply placed in the soil. It is certainly possible to remove the slack by

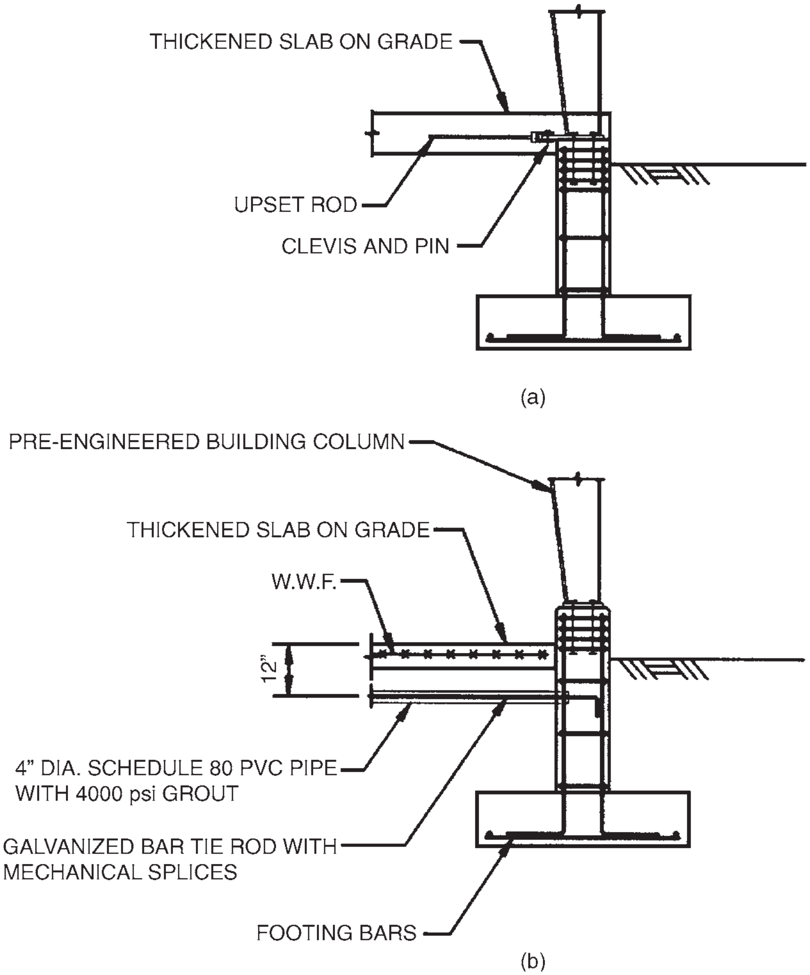

FIGURE 12.7 Foundations with tie rods: (*a*) tie rod connected to base plate; (*b*) tie rod embedded in column pier.

installing turnbuckles, but these may be difficult to encase in sheaths. Another, related disadvantage is the just-mentioned rod elongation under load. For the design of Fig. 12.7*a,* this elongation cannot be remedied by post-tensioning, as explained below, and for the design of Fig. 12.7*b* post-tensioning may be difficult to achieve.

Tensioning the rods of Fig. 12.7*a* does not make them elongate any less under future loading. Indeed, it can overstress the rods and their connections. Why? For post-tensioning to work, the rods must be anchored to concrete after stretching, and any future tensile stresses applied *to concrete* rather than directly to the rods. Anchoring the tensioned rods induces compression in the concrete, and any future tension forces acting on concrete will have to counteract these compressive stresses first. By contrast, when the tie rod is attached to the base plate, the outward column reactions are applied directly to the rod, and this stretching is added to any tensile stresses introduced during rod tensioning.

The foregoing suggests that in order for post-tensioning to work, the tie rods must be encased in column-like concrete grade beams designed to resist the corresponding compressive forces. One