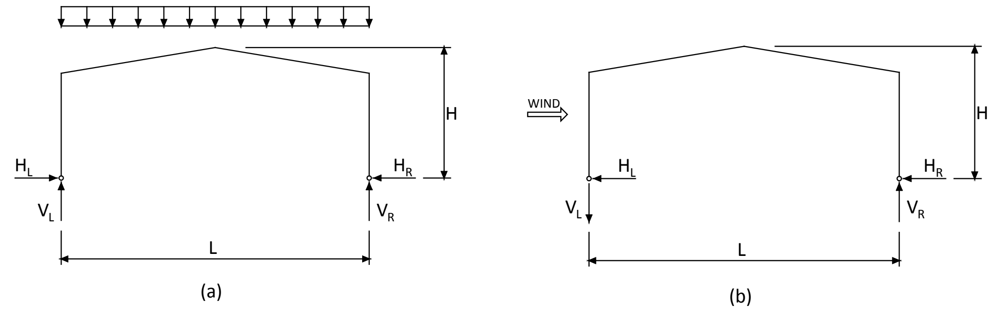

Figure 1: The direction of horizontal column reactions in a single-span rigid frame: (a) from gravity loads; (b) from wind or seismic loads.

Foundations for Metal Building Systems

Finding a Practical Solution for Your Project

By Alexander Newman, P.E., F. ASCE

Metal building systems (MBS), also known as pre-engineered metal buildings, are proprietary structures designed and manufactured by their suppliers. Metal buildings are extremely popular and they account for a substantial percentage of low-rise nonresidential buildings in the United States. The design of foundations for these structures often involves special challenges. The design procedures are often not well understood, because they are not specified in the building codes and technical design guides. Until the recent publication of *Foundation and Anchor Design Guide for Metal Building Systems* (McGraw-Hill, 2013), there have been no authoritative books on the subject. As a result, the foundation designs produced by different engineers for the same metal building structure could range from those that cost a trivial amount to those that are quite expensive to construct. This article discusses the reasons for such disparity and misunderstanding and examines the available design options.

The Main Challenges

Several challenges make foundations for metal building systems different from those used in conventional buildings:

- Single-story MBS are extremely lightweight. The total weight of the structure could be between 2 and 5 pounds per square foot (psf), which means that a strong wind results in a net uplift loading on the foundations.
- The most popular types of the primary frames used in MBS – gable rigid frames – exert significant horizontal column reactions on the foundations. Such reactions could be present in some conventional building foundations as well, but rarely at every column, and in combination with uplift.
- Because MBS are proprietary structures, the manufacturers often report slightly different column reactions for the buildings with identical loading and configuration. In the construction projects that use public funding and require competitive bidding, the MBS manufacturers cannot be selected prior to the foundations being designed. Accordingly, the column reactions must be estimated by the foundation designers, running the risk that the final reactions will exceed those used in the design.
- Unfortunately, in many situations the owner of the building decides to procure the metal building superstructure first and design the foundations later, as an afterthought. Without a structural engineer involved in establishing the design parameters for the MBS, some manufacturers might choose to provide the cheapest design possible. One such example is a building with fixed-base frame columns, which might result in minor cost savings for the manufacturer but in major cost increases for the foundation vis-à-vis pin-base columns.
- The lack of clear design procedures naturally results in uneven design solutions. Some foundation designs for metal buildings have been overly complicated, and some have been barely adequate for the imposed loads (or not adequate at all).

Uplift and Horizontal Column Reactions

In single-story MBS, the dead load is generally insufficient to counteract the effects of wind-generated uplift. In addition, building codes require that no more than 60% of "the dead load likely to be in place" be used in combination with wind uplift (the International Building Code (IBC) "basic" load combination for the allowable stress design method). Thus the weight of the "ballast" must be substantial. For a typical shallow foundation, such as an isolated column footing, the "ballast" consists of the footing, column pedestal (if any), and the soil on the ledges of the footing. Some engineers also include a contribution of the soil frictional resistance.

Alexander Newman, P.E., F. ASCE, is a forensic and structural consultant in the Boston area. He is the author, most recently, of the Foundation and Anchor Design Guide for Metal Building Systems (McGraw-Hill, 2013). He can be reached at ***Alexander-Newman@Outlook.com****.*

Quite often, the minimum size of column foundations is dictated by the minimum amount of "ballast," not by the soil-bearing capacity for downward loads. This often comes as a shock to the foundation designers unfamiliar with MBS specifics. The design example in the sidebar illustrates the process of sizing an isolated column footing for uplift.

Gable rigid frames exert horizontal column reactions on the foundations. This occurs under gravity loading, when the reactions are numerically the same but act in opposing directions (*Figure 1a*), as well as under wind or seismic loading, when the reactions usually act in the same direction (*Figure 1b*).

Some Available Foundation Systems

The vertical and horizontal column reactions can be resisted by a variety of foundation systems, such as those listed below and illustrated in *Figure 2 (page 14)*. Properly designed, each system can resist the required level of horizontal and vertical frame reactions. However, experience shows that some systems could be more or less applicable in various circumstances. Each system has advantages and disadvantages, as summarized in *Table 1*.

Table 1: Comparative cost, reliability and degree of versatility of selected foundation systems for metal building systems.

Foundation System	Cost	Reliability	Versatility
Tie Rod	Low to high	Low to high	Low to medium
Hairpins and Slab Ties	Low	Low	Low
Moment-Resisting Foundation	High	High	High
Slab with Haunch	Medium	Low to high	Low to medium
Trench Footing	Medium to high	High	High
Mat	High	High	Low
Deep Foundations	High	High	High

The table compares cost, reliability and degree of versatility of the selected foundation systems used in pre-engineered buildings. Here, reliability refers to the probability of the foundation system performing as intended for the desired period of time under various field conditions. The most reliable systems can tolerate inevitable irregularities in construction, loading and maintenance. The overall reliability of a foundation system depends on three factors that define the system's ability to function in adverse circumstances:

- *Simplicity of installation*. The foundations that are difficult to install or require a perfect installation tend to be less reliable, because some placement errors are common and perfection in foundation construction is rare.
- *Redundancy*. Redundant systems have more than one load path for transferring the column reactions to the soil. If one load path is blocked, another path takes over.
- *Survivability*. Can the system maintain its load-carrying capacity after some of the adjoining building elements have become damaged? For example, what happens if the slab on grade is cut or partly removed?

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Versatility, as noted in *Table 1*, is possessed by the systems that can be used with various floor and soil conditions (e.g., floor trenches and pits).

Some foundation systems commonly used in MBS are:

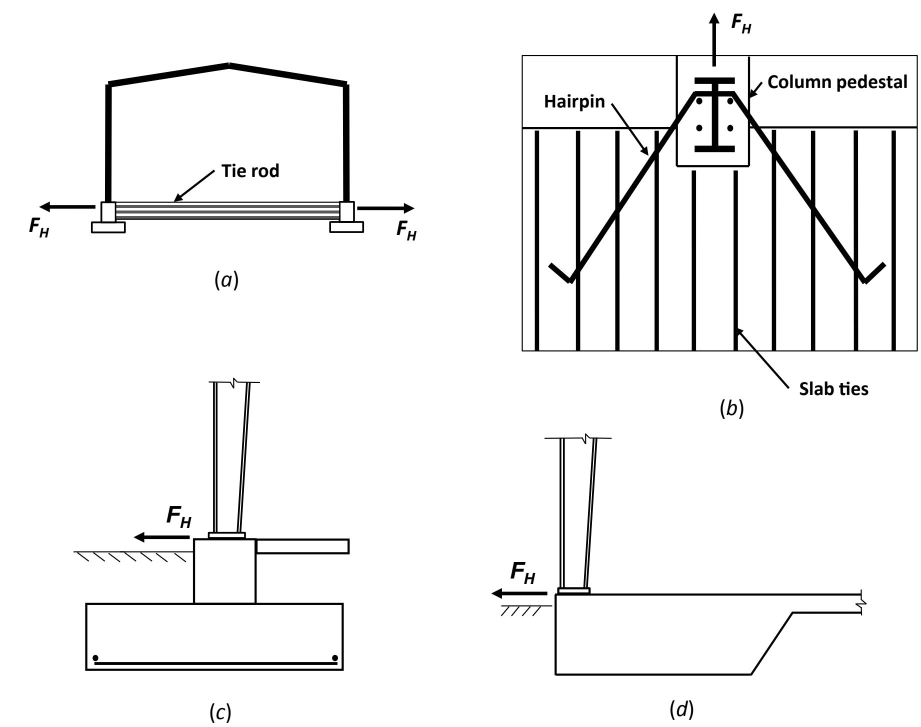
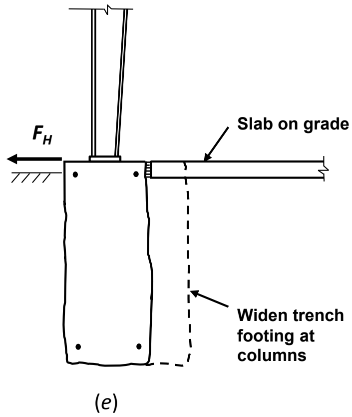


Figure 2: Common Foundations Used in Metal Building Systems: a) Tie rod; b) Hairpins with slab ties; c) Moment-resisting foundation; d) Slab with haunch.

- *Tie rods* (*Figure 2a*). In this intuitively appealing solution, the foundations at the opposite building columns are tied together, "extinguishing" both horizontal column reactions. Tie rod construction ranges from the cheapest and least reliable, such as a couple of reinforcing bars placed in a thickened slab, to the relatively expensive and much more reliable, such as concrete grade beams. The survivability of the former is low, because there is a distinct possibility that the slab on grade will be cut or partly removed at some point, while the grade beams placed below the slab will likely survive such a scenario. There are also the issues of elastic elongation of the tie rod under load and whether the tie rod is considered a "tension- tie member" under the provisions of the American Concrete Institute standard ACI 318. The versatility of this system is at the lower end of the spectrum, since tie rods cannot be used in buildings with deep trenches, depressions, and pits.
- *Hairpins with slab ties* (*Figure 2b*). The general idea behind this design is the same as in the tie-rod system, but the tension force is resisted by distributed steel reinforcement in the floor slab (slab ties) rather than by discrete tie rods. This is the least expensive method of resisting horizontal column reactions and, for this reason, hairpins have been widely used in the past. But the system suffers from multiple disadvantages. Among them is a total reliance on the floor slab, which makes the system vulnerable to the slab being cut or partly removed. Other issues include construction joints in slabs on grade, where the slab reinforcement generally stops, and even the fundamental issue of treating slabs on grade as structural elements. Slabs on ground are excluded from the scope of ACI 318, except when they transmit lateral forces from other portions of the structure to the soil. If the designer intends to have the slab on grade comply with ACI 318, the slab must be designed and constructed with greater care than the prevalent practices. At the very least, it should be reinforced more substantially than with a layer of light welded-wire fabric, to provide for a minimum percentage of "shrinkage" reinforcement.
- *Moment-resisting foundations* (*Figure 2c*). These foundations work similarly to cantilevered retaining walls: the weight of the foundation, and any soil on top of it, resists overturning and sliding caused by external horizontal forces. Because it does not depend on a contribution of the slab on grade, the moment-resisting foundation represents one the most reliable systems available. It also is one of the most versatile, since deep trenches, depressions, and pits in the floor – or no floor at all – do not affect its function. The system can even be used in hillside installations, where one end of the building is lower than the other. However, the design procedures for moment-resisting foundations are relatively lengthy and the construction costs could be high.
- *Slab with haunch* (*Figure 2d*). This system has been widely used in residential construction, and some have tried to use it for supporting large pre-engineered buildings as well. The slab with haunch, also known as a downturned slab, works similarly to the moment-resisting foundation, and a rigorous design would result in the "haunch" of the size similar to the footing of the moment-resisting foundation. Needless to say, this is not the size the proponents of this system hope for. The reliability and versatility of the slab with haunch depends on whether the design relies on the contribution of the slab on grade. If it does, both reliability and versatility would be at the low end of the spectrum, similar to the hairpin system.
- *Trench footing* (*Figure 2e*). In this design, a deep trench is excavated and filled with concrete. The resulting foundation could be made heavy enough to resist uplift and deep enough to develop passive pressure of the soil. Since the design does not depend on the contribution of the slab on grade, both reliability and versatility of this system are high. Obviously, the trench footings (also known as mass foundations or



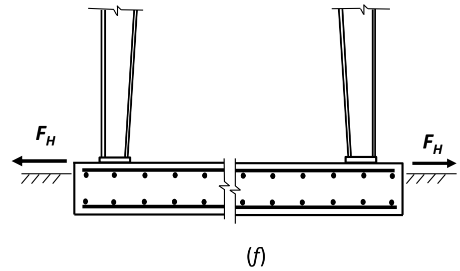
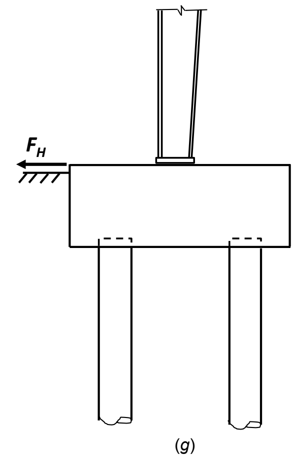


Figure 2 (continued): Common Foundations Used in Metal Building Systems: e) Trench footing; f) Mat; g) Deep foundations.



formless footings) can only be used in the soils that allow for the excavated trench to be stable during construction. This typically requires clayey soils.

- *Mats* (*Figure 2f*). Using mats might be advantageous in metal building foundations bearing on poor soils. According to one rule of thumb, when isolated column footings cover more than 50% of the building's footprint, mats become economical. Mats are typically reinforced in two directions, both at the top and at the bottom. Heavyweight mats work well in resisting wind uplift, and their continuous reinforcement solves the problem of "extinguishing" the horizontal column reactions at the opposite ends of the frames. One challenge of using mats in metal buildings with multiple-span rigid frames is the placement of anchor bolts for interior columns. This often requires placing a separate "mud slab," which can be used to temporarily support anchor bolts. Mats possess high reliability – they are unlikely to be cut casually – but a low versatility, because they do not work with deep trenches, depressions, and pits. Their cost is relatively high.
- *Deep foundations* (*Figure 2g*). There are two main types of deep foundations: deep piers (also called caissons, or drilled shafts) and piles. Deep piers typically possess enough dead load to counteract moderate wind uplift. If additional "ballast" is needed, a contribution of the perimeter grade beams could be considered. The grade beams also engage the passive pressure-resistance of the soil and thus help resist horizontal column reactions. Piles can resist both uplift and horizontal forces in a variety of ways, including friction in cohesive soils and flexure. Because deep foundations generally do not depend on a contribution of the floor slabs, these foundations are both reliable and versatile. But they are also costly and are typically used in only poor soils, particularly those where weak strata are underlain by competent materials.

By understanding the advantages and disadvantages of various foundation systems used in pre-engineered buildings, designers should be able to select the foundation design that most closely matches the expected use, configuration and performance of the building as a whole.■

A Simplified Design Example for Sizing an Isolated Column Footing for Downward Forces and Uplift.

Given: Select the size of an isolated column footing to support an interior column of a single-story multiple-span rigid frame. The spacing of the interior columns within the frame is 60 feet; the frames are 25 feet on centers. The following loads act on the roof: 3 psf dead load, 30 psf design roof snow load, and 14 psf wind uplift. The depth of the footing must be at least 3 feet below the floor. The column is supported by a 20 inch by 20 inch concrete pedestal extending to the top of the floor. Use allowable soil bearing capacity of 4000 psf. Assume the average weight of the soil, slab on grade and foundation is 130 lbs/ft^3. The building is not located in the flood zone. Use IBC basic load combinations.

Solution. The tributary area of the column is 60 x 25 = 1500 (ft^2). The design loads on the column are:
Design dead load D = 4.5 kips Design snow load S = 45 kips
Design wind uplift load W = –21 kips
Total downward load D + S = 4.5 + 45 = 49.5 kips
Total uplift load on foundation (0.6D + W) = 0.6 x 4.5 – 21 = –18.3 kips
Weight of the soil, slab on grade and foundation is 0.130 kips/ft^3 x 3 ft. = 0.39 kips/ft^2 (ksf)
Net available soil pressure is 4.0 – 0.39 = 3.61 (ksf)
Required area of the footing for downward load is 49.5/3.61 = 13.71 (ft^2)
For <u>downward load only</u>, the sign of the footing is 3.7 feet by 3.7 feet at a minimum.

Check stability against wind uplift. Minimum required weight of the foundation, soil on its ledges and tributary slab on grade ($D_{min, found}$) can be is found from:

$0.6D_{min, found} + W = 0$

$D_{min, found} = 18.3/0.6 = 30.5$ (kips)

This corresponds to 30.5/0.130 = 234.62 (ft^3) of the average weight of "ballast"

With the depth of footing 3 feet below the floor, this requires the minimum square footing size of $(234.62/3)^{1/2} = 8.84$ (ft.)

To reduce the footing size, try lowering the bottom of the footing by 1 foot. Then the minimum required square footing is $(234.62/4)^{1/2} = 7.66$ (ft.).

To arrive at a nominal size, use 8.0 by 8.0-foot footing, with a depth of: $234.62/(8)^2$ = 3.67 (ft.).

<u>The final footing size is 8.0 ft. x 8.0 ft. x 3 ft. 8 in. deep, as controlled by uplift.</u>

The complete version of this design example, including concrete design for various loading conditions, can be found in the new book, <u>Foundation and Anchor Design Guide for Metal Building Systems</u> (McGraw-Hill, 2013).