
Design of Commercial/Industrial Guardrail Systems for Fall Protection

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by Brian M. McCaffrey, P.E.

1.0 Introduction

Falls are among the most common causes of serious work related injuries and deaths. Employers are required to provide and install fall protection systems to prevent employees from falling off of overhead platforms and elevated work stations or into holes in the floor. Falls can be prevented through the use of proper fall protection systems, such as guardrail systems, safety net systems, personal fall arrest systems, and positioning device systems. Fall protection systems are an expansive topic, and this course will focus solely on guardrail systems.

Whether in construction or general industry, a structural engineer may be called upon to design a new guardrail system or to evaluate the adequacy of an existing guardrail system in accordance with the Codes of the local jurisdiction. The design of a simple guardrail system has become more complicated as there is no single guardrail design that will work for all situations. There are different functional Code requirements depending upon the local jurisdiction and the design engineer must interpret the latest version of these regulations and Codes and apply them to specific applications.

This course provides a procedure for designing or evaluating guardrail systems in commercial/industrial applications. A number of published methods, tables and charts from industry manuals, manufacturer's engineering data, and Codes provide a good source of design information and criteria for guardrail systems. It is not the intent of this course to duplicate this information but rather to extract appropriate data from these documents as well as provide direction regarding the proper use or application of such data so that engineers and designers involved in preparing the calculations can make the appropriate decision and/or apply proper engineering judgment. Also, since Codes change periodically and requirements may vary by jurisdiction, the engineer should consult the latest Code versions when designing guardrail systems.

This course includes a design example for better understanding of the subject matter.

2.0 Glossary of Terms

Commonly used terms relative to guardrail systems in this course are defined below in accordance with American Society of Testing and Materials *Standard Terminology of Railing Systems and Rails for Buildings* (ASTM E 1481), and National Association of Architectural Metal Manufacturers, *Pipe Railing Systems Manual including Round Tube* (NAAMM AMP 521-01).

ANCHOR	Any device used to secure a railing system or its parts to adjoining construction or a supporting member.
FASCIA	The exposed facing of the outer edge of a platform or floor.
FASTENER	A mechanical device that holds or joins two or more components in definite positions with respect to each other and is often described as a bolt, nut, rivet, screw, washer, or special formed part.
GUARDRAIL SYSTEM	A railing system, providing protection for building users against accidental fall and injury, located at or near the outer edge of a stair, ramp, landing platform, deck, balcony, hatchway, manhole, floor opening, porch, or accessible roof; at the perimeter of an opening or accessible surface, such as the opening of a stair; or at a location at which an operating condition requires access limitation to a designated area.
INTERMEDIATE RAIL	One of two or more rails between the top rail and floor.
MID RAIL	A rail located between the top rail and bottom rail or between top rail and floor if there is no intermediate rail.
PIPE	Hollow round section of metal or other material, the size of which is usually designated by nominal size, in inches (millimeters), as influenced by inside diameter and wall thickness.
POST	A vertical supporting member.
RAIL	A horizontal, inclined, or vertical member of a railing system, such as top or intermediate member connecting posts at specified intervals.
TOE BOARD	A vertical plate at the bottom of a railing system.
TOP RAIL	The uppermost member of railing system.
TUBE / TUBING	Hollow section of metal with other material having a round, square, rectangular, or other cross-sectional form, its size being designated by outside dimension(s) and wall thickness, in inches (millimeters).

3.0 General Design

The availability of complete structural information enables architects and engineers to properly design guardrail systems. The systems can then be designed to conform to specific building code criteria.

In the structural design of any guardrail system, the following information is essential:

1. The design criteria, as prescribed by governing regulations or the designer's specifications.
2. Mechanical and physical properties of guardrail components.
3. Formulas for structural design.
4. Anchoring systems.

3.1 Design Criteria

Design criteria for railing systems are set by the governing code for the area in which the railing systems are to be used. These criteria include both loading and dimensional requirements. The designer should consult governing codes, local ordinances, project specifications, and regulatory authorities to determine requirements for compliance.

For guardrail systems, local codes generally follow the requirements established by the International Building Code (IBC) and/or the Occupational Safety and Health Administration (OSHA).

Guardrail requirements are outlined in IBC Section 1013 (Guards) and Section 1607.8 (Loads on Handrails, Guards, Grab Bars, Seats and Vehicle Barriers).

OSHA fall protection requirements for general industry and construction are addressed in 29 CFR 1910.23 and 29 CFR 1926 Subpart M, respectively, in the Code of Federal Regulations.

Governing codes shall be checked for their specific requirements, and government regulations, such as Americans with Disabilities Act (ADA), shall be checked as well. In certain instances, exterior guardrails shall also be designed for wind loads calculated in accordance with the local Building Code. This typically pertains to guardrail systems with picket, perforated, wire mesh, or glass infill panels, which are located between the posts and are supported by the top and bottom rails.

3.1.1 Loading Requirements

Uniform loading, specified by some building codes, represents the force exerted by tightly grouped persons leaning on or pressing against the railing system. Such loading requirements range from 20 to 50 pounds per foot applied to the top rail depending upon the area occupancy load.

Concentrated loading represents the force exerted by a single individual leaning upon or over the rail or a person or object impacting upon the rail. A 200 pound concentrated load applied in any direction at any point along the top rail has become a requirement of a number of codes and government regulatory agencies. Current thinking by some organizations is to apply the concentrated load in a perpendicular direction at any point along the top rail, horizontally and downward in a vertical plane, but not simultaneously. Perpendicular horizontal loading applies the maximum moment to the post, and the downward loading simulates what a person leaning over the rail might apply.

3.1.2 Guardrail Height and Spacing

Building codes typically specify minimum and maximum heights for handrails and minimum spacing for intermediate rails. The minimum guardrail system height requirement of the majority of codes is 42 inches plus or minus 3 inches.

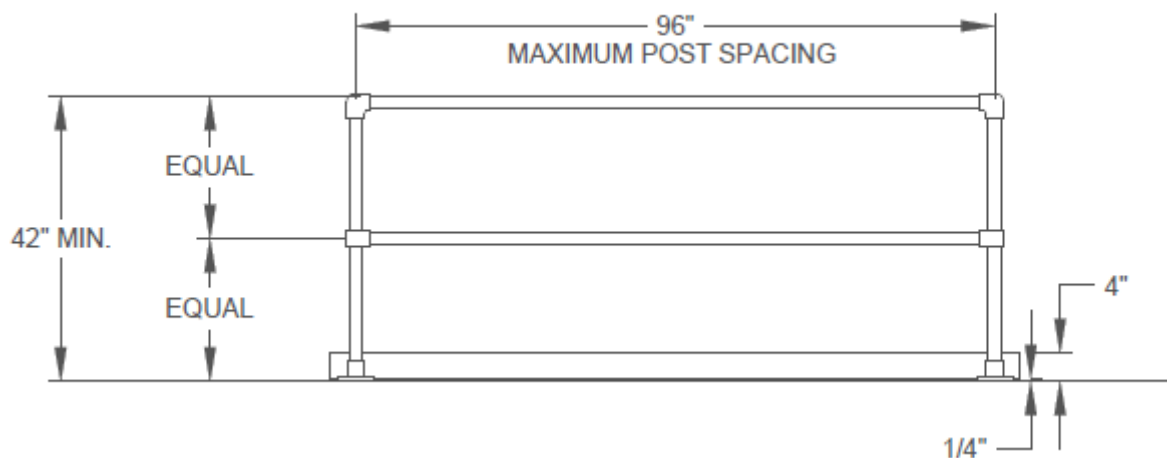
OSHA has a requirement that hand rails, posts, and top and intermediate rails shall be at least 1-1/2 inch nominal diameter, with posts spaced not more than 8 feet on centers.

For guardrail systems and stair-rail systems in areas accessible to the public, codes require spacing between rails, balusters or other infill, small enough to prevent the passage of a sphere of diameter varying between 4 inches and 6 inches. In areas of commercial and industrial occupancies, which are not accessible to the public, some codes permit this spacing to be increased to prevent passage of a 21 inch diameter sphere.

3.1.3 Code Illustrations

Illustrations of the OSHA and IBC code and loading requirements are provided in **Figures 1 and 2**, respectively. All codes shown in these illustrations are interpretations. The Engineer should consult local codes, since many municipalities use variations of these codes and the codes change continuously.

Figure 1 – OSHA Requirements



Selected Code Requirements:

OSHA - General Industry

29 CFR 1910.23(e)(1) – A standard railing shall consist of a top rail, intermediate rail, and posts, and shall have a vertical height of 42 inches nominal from upper surface of top rail to floor, platform, runway, or ramp level. The intermediate railing shall be approximately halfway between the top rail and the floor, platform, runway, or ramp.

29 CFR 1910.23(e)(3)(ii) – For pipe railings, posts, and top and intermediate railings shall be at least 1-1/2 inches nominal diameter with posts spaced not more than 8 feet on centers.

29 CFR 1910.23(e)(3)(iv) – The anchoring of posts and framing of members for railings of all types shall be of such construction that the completed structure shall be capable of withstanding a load of at least 200 pounds applied in any direction at any point on the top rail.

29 CFR 1910.23(e)(4) – A standard toeboard shall be 4 inches nominal in vertical height from its top edge to the level of the floor, platform, runway, or ramp. It shall be securely fastened in place and with not more than 1/4-inch clearance above the floor level.

OSHA - Construction

29 CFR 1926.502(b)(1) – Top edge height of top rails shall be 42 inches plus or minus 3 inches above the walking/working level.

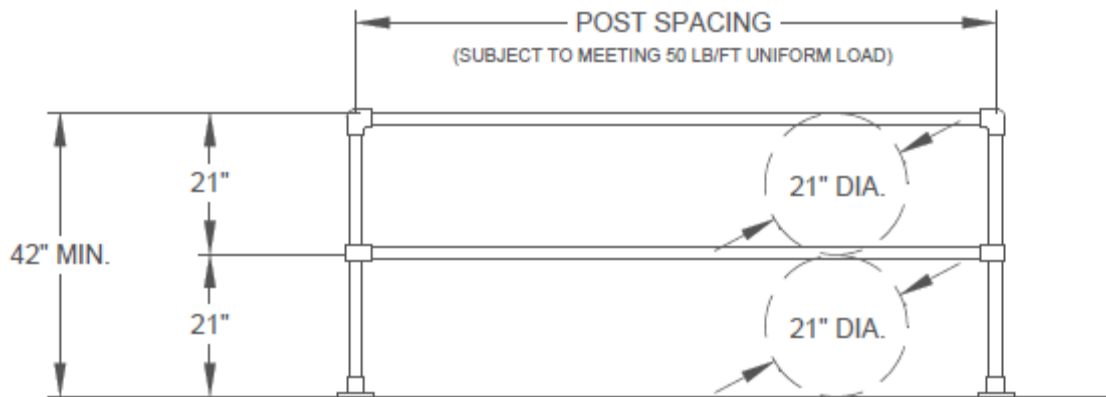
29 CFR 1926.502(b)(2)(i) – Midrails shall be installed at a height midway between the top edge of the guardrail system and the walking/working level.

29 CFR 1926.502(b)(3) – Guardrail systems shall be capable of withstanding, without failure, a force of at least 200 pounds applied within 2 inches of the top edge, in any outward or downward direction, at any point along the top edge.

29 CFR 1926.502(j)(3) – Toeboards shall be a minimum of 3-1/2 inches in vertical height from their top edge to the level of the walking/working surface. They shall have not more than 1/4 inch clearance above the walking/working surface. They shall be solid or have openings not over 1 inch in greatest dimension.

29 CFR Part 1926 Subpart M Appendix B – For pipe railings: posts, top rails, and intermediate railings shall be at least one and one-half inches nominal diameter (schedule 40 pipe) with posts spaced not more than 8 feet apart on centers.

**Figure 2 – IBC (2012) Requirements
(for areas not open to the public)**



International Building Code

IBC Section 1013.3 – Required guards shall be not less than 42 inches high, measured vertically above the adjacent walking surfaces.

IBC Section 1013.4 Exception 3 – At elevated walking surfaces for access to and use of electrical, mechanical or plumbing systems or equipment, guards shall not have openings which allow passage of a sphere 21 inches in diameter.

IBC Section 1607.8.1 – Handrails and guards shall be designed to resist a linear load of 50 pounds per linear foot in accordance with Section 4.5.1 of ASCE 7.

IBC Section 1607.8.1.1 – Handrails and guards shall also be designed to resist a concentrated load of 200 pounds in accordance with Section 4.5.1 of ASCE 7.

IBC Section 1607.8.1.2 – Intermediate rails shall be designed to resist a concentrated load of 50 pounds in accordance with Section 4.5.1 of ASCE 7.

Note: ASCE 7 states that guardrail systems shall be designed to resist a single concentrated load of 200 pounds applied in any direction at any point on the top rail and to transfer this load through the supports to the structure. Further, all guardrail systems shall be designed to resist a uniform load of 50 pounds per foot applied in any direction along the top rail. This uniform load need not be assumed to act concurrently with the 200 pound concentrated load.

3.2 Materials and Properties

3.2.1 Mechanical Properties of Guardrail Elements

For guardrail system and components to meet the OSHA and/or IBC loading requirements, the top-rails, mid-rails, and posts are typically constructed of 1-1/2 inch carbon steel, stainless steel, or aluminum pipe or tubing, though other materials such as bronze, copper alloys, fiberglass, and wood can also be used.

The materials most frequently used by manufacturers in construction of guardrail systems and components for commercial and industrial applications are:

Carbon Steel Pipe – ASTM A53 Type F Grade B or Type E Grade B
Carbon Steel Structural Tubing – ASTM A500 Grade B
Aluminum 6061-T6 Pipe and Tube – ASTM 429
Aluminum 6063-T6 Pipe and Tube – ASTM 429
Stainless Steel Pipe – ASTM A312
Stainless Steel Tubing – ASTM A554

Mechanical properties of carbon steel, aluminum alloys, and stainless steel are provided in NAAMM AMP 521-01 and are listed in Table 1 below.

TABLE 1 TENSILE, YIELD AND DESIGN STRESSES—PIPE AND ROUND TUBING

<u>Metal and Grade or Alloy</u>	<u>Minimum Tensile Strength, F_t ksi (MPa)</u>	<u>Minimum Yield Strength, F_y ksi (MPa)</u>	<u>Design Stress in Bending, F_b ksi (MPa)</u>
Carbon Steel Pipe [ASTM A 53]			
Type F	48 (330)	30 (205)	21.6 (150)
Type E and S, Grade A	48 (330)	30 (205)	21.6 (150)
Grade B	60 (415)	35 (240)	25.0 (170)
Carbon Steel Structural Tubing [ASTM A 500]			
Grade B	58 (400)	42 (290)	30.0 (205)
Grade C	62 (427)	46 (317)	33.0 (230)
[ASTM A 501]	58 (400)	36 (250)	26.0 (175)
[ASTM A 513] Type 5	60 (414)	50 (345)	30.0 (205)
Aluminum Pipe and Tube			
6063-T5, 6063-T52 [ASTM B 221]	22 (150)	16 (110)	11.5 (80)*
6063-T6 (Extruded) [ASTM B 221, B 429]	30 (205)	25 (170)	18.0 (125) *
(Drawn) [ASTM B 210, B 483]	33 (230)	28 (195)	20.0 (135)*
6063-T832 [ASTM B 210, B 483]	40 (275)	35 (240)	24.0 (165)*
6061 -T6 (Extruded) [ASTM B 221, B 429]	38 (260)	35 (240)	24.0 (165)**
(Drawn) [ASTM B 210, B 483]	42 (290)	35 (240)	24.0 (165)**
Stainless Steel Pipe [ASTM A 312]			
S30400, S31600 - Annealed	75 (515)	30 (205)	18.0 (125)
Stainless Steel Tubing [ASTM A 554]			
S30400, S31600, Annealed	75 (515)	30 (205)	18.0 (125)
S30400, S31600, Ornamental As-welded	75 (515)	50 (345)	30.0 (205)

*reduce to 8 (55) within 1 in. (25 mm) of weld

**reduce to 14 (95) within 1 in. (25 mm) of weld

3.2.2 Physical Properties of Guardrail Elements

Physical properties of sections of sections of guardrail elements are provided in NAAMM AMP 521-01 and are listed in Tables 2 and 3.

TABLE 2 PIPE DIMENSIONS AND PROPERTIES

Nominal Size	Schedule No.	Outside Diam.	Diameter Inside in.	Thickness Wall in.	Area in ²	Section Modulus, S in. ³	Moment of Inertia, I in. ⁴
1 in.	40	1.315 in.	1.049	0.133	0.494	0.133	0.087
	80		0.957	0.179	0.639	0.161	0.106
1-1/4 in.	5	1.660 in.	1.530	0.065	0.326	0.125	0.104
	10		1.442	0.109	0.531	0.193	0.161
	40		1.380	0.140	0.668	0.235	0.195
	80		1.278	0.191	0.882	0.291	0.242
1-1/2 in.	5	1.900 in.	1.770	0.065	.0375	0.166	0.158
	10		1.682	0.109	0.613	0.260	0.247
	40		1.610	0.145	0.799	0.326	0.310
	80		1.500	0.200	1.068	0.412	0.391
2 in.	5	2.375 in.	2.245	0.065	0.472	0.265	0.315
	10		2.157	0.109	0.776	0.420	0.499
	40		2.067	0.154	1.074	0.561	0.666
	80		1.939	0.218	1.477	0.731	0.868

In steel pipe, Schedule 40 is known as "Standard Weight" and Schedule 80 as "Extra Strong." Standard weight is measured by I.R.S. (Iron Pipe Size), a designation of the nominal size. Unless otherwise specified, Schedule 40 is normally supplied in steel, aluminum or copper pipe and Schedule 5 in stainless steel tubing.

TABLE 3 TUBE DIMENSIONS AND PROPERTIES

Nominal Size	Wall Thickness in.	Inside Diam. in.	Area in ²	Section Modulus, S in. ³	Moment of Inertia, I in. ⁴
1 in.	0.0625	0.875	0.184	0.041	0.020
	0.125	0.75	0.344	0.067	0.034
1-1/4 in.	0.0625	1.125	0.233	0.066	0.041
	0.125	1	0.442	0.113	0.071
1-1/2 in.	0.0625	1.375	0.282	0.097	0.073
	0.125	1.25	0.540	0.172	0.129
	0.1875	1.125	0.773	0.227	0.170
	0.25	1	0.982	0.266	0.199
2 in.	0.0625	1.875	0.380	0.179	0.179
	0.125	1.75	0.736	0.325	0.325
	0.1875	1.625	1.068	0.443	0.443
	0.25	1.5	1.374	0.537	0.537

3.2.3 Selecting Metal Alloys for Guardrail Systems

Guardrails will typically be designed with four key considerations: strength, corrosion resistance, joint connection (welded or non-welded), and cost. The following is a general discussion of these key considerations for the metal alloys typically used in guardrail systems.

Carbon Steel

Carbon steel has very high mechanical strength properties, allowing for typically wider spans than some aluminum guardrail systems, depending upon the alloy.

Carbon steel has a low resistance to corrosion; therefore, carbon steel railing systems are either finished by painting in the field or galvanized. When a galvanized guardrail system is required, the choices are either hot-dip galvanizing after fabrication or the use of galvanized pipe with zinc-rich paint being applied over welds and abrasions.

Connections in carbon steel railing systems are made by welding unless designated otherwise. A significant percentage of the cost in fabricating a railing system involves the grinding and sanding necessary to dress each joint. Additionally, when specifying welded connections for carbon steel, the engineer should require that zinc-rich paint be applied over welds since the welding process removes galvanization at the weld location. If left unprotected, the weld site could corrode and fail.

Structural carbon steel pipe typically costs less than aluminum pipe or tube, while structural carbon steel tube is typically more expensive.

Aluminum

When lightweight and/or corrosion resistance are key requirements, along with strength, typically it is time to look at aluminum alloys.

Aluminum has very good mechanical properties, though it is often necessary to install a structural insert at the base of the post to sustain the code-required loading.

Aluminum has excellent corrosion resistance properties, allowing it to be the preferred metal in most environments. However, a key concern with aluminum is when aluminum posts are embedded in concrete while in a corrosive (i.e., salt air) environment, such as a balcony overlooking an ocean. When the concrete is exposed to multiple wet cycles, it will transport alkalinity in the concrete to the surface of the aluminum leading to corrosion. Secondly, steel reinforced concrete used as the structural component of the balcony would produce a galvanic cell between the steel and the aluminum post leading to an accelerated rate of corrosion. As the aluminum oxide and iron oxide are generated, they expand which causes spalling of the concrete. In general, embedding aluminum in concrete for exterior applications should be avoided due to the increased risk of corrosion and the accompanying concrete cracking issues caused by the increased volume of the metal as it corrodes. Methods to connect posts to concrete, as advised by some local building codes, include using a metal plate or base flange to connect the post to existing concrete construction; or providing a sleeve for the post in new concrete construction and embedding the post in the concrete slab with epoxy grouting.

As a best practice, when aluminum is exposed to concrete and/or dissimilar metals in corrosive environments, the aluminum contact surfaces that are exposed to concrete and/or dissimilar metals

should be coated with heavy bodied bituminous paint, water-white methacrylate lacquer, zinc chromate, or other coating to prevent an aluminum-concrete reaction or an electrolytic action between aluminum and dissimilar metals.

Connections in aluminum railings are made either by welding or non-welded mechanical fittings. While welded connections may be more aesthetically pleasing than mechanical fittings, an important consideration in welded aluminum railings is the effect of welding heat on the structural properties of aluminum. A review of the mechanical properties of aluminum alloys and elements in Table 1 indicates that the allowable bending stress is significantly reduced within one inch of the weld. Since maximum bending moment generally occurs at points of support, the reduced design stress will often control design. As a result, non-welded mechanical fittings are often preferred over welded fittings in aluminum railing systems.

Aluminum alloy pipe and tubing typically cost less than stainless steel pipe & tubing and structural carbon steel pipe.

Stainless Steel

Stainless steels contain at least 12% chromium and form a thin, invisible protective, corrosion-resistant, passive film on their surface. This film forms spontaneously when the chromium reacts with oxygen in air and water. If the film is damaged or removed during fabrication or polishing, it self-repairs immediately so long as the surface is clean. If stainless steel corrodes, typically highly localized metal loss or pitting occurs – rarely general or uniform corrosion of the entire surface.

While problems with stainless products are infrequent, the name stainless can be somewhat misleading. It is not actually, stainless, but stain resistant – it is a corrosion resistant alloy, not rustproof. Stainless steel may show some forms of corrosion and/or deterioration, dependent upon the degree of contaminants in its particular environment. Under certain conditions, it can rust unless a program of preventive maintenance is followed.

The environment in and around swimming pools and salt water contain salts which actively attack stainless steel. Heat and humidity increase the corrosive activity of chlorine and bromine salts. In addition, the corrosive action caused by salts that occurs from ice melting agents such as calcium chloride and sodium chloride can create the formation of rust. Other chemical reactions that can cause deterioration include carbon pick up from bending or fabricating tools, finishing equipment or steel covered work benches. It is also typical for contractors or masons to use muriatic acid solution on masonry – even the fumes from this liquid can attack stainless steel.

Stainless steel is also the most expensive as compared to carbon steel and aluminum alloys.

3.3 Load, Stress, and Deflection Relationships

The calculations used for load, stress, and deflection relationships in guardrail systems are applicable to free standing straight runs of guardrail with uniform post spacing. The loads applied are defined by the Codes as either a concentrated load applied to the top rail at any point in any direction (OSHA), or as a uniformly distributed load per linear foot of rail applied at any direction along the top rail (IBC). These two types of loads are not specified to act concurrently. Both loading conditions must be considered when designing guardrail systems.

The design of guardrail systems will be illustrated using separate formulas to calculate the stresses in the posts, rails, and anchor points.

In general, the structural design of guardrail systems includes these steps:

1. With the rail height given and post spacing either given or arbitrarily assumed, post size shall be determined in accordance with the specified loading.
2. Assuming the rail member to be the same size as the post, this size shall be adequate to carry its own loading over the given (or assumed) span;
3. If the rail size is inadequate, either its maximum permissible span shall be computed and the post spacing shall be reduced accordingly or the size of the rail (and posts) shall be increased.

3.3.1 Post Design

Loads that are applied horizontally at the top rail of a guardrail system will produce the maximum bending moment on the posts. The post acts as a vertical cantilevered member in resisting the horizontal load applied to the rails or posts. The height of the post used in the calculations is measured from the centerline of the top rail to the top of the base attachment.

3.3.1.1 Post Design - Concentrated Loading

Concentrated loading is assumed to be applied at any point along the rail. In a railing system where posts are mounted securely into the floor or stair slab, the load applied to the rail at a post is distributed to other posts on either side of the post under stress, reducing the load applied to that post. This reduction is dependent on the stiffness of the rail relative to the stiffness of the post and a load proportion factor (Pf).

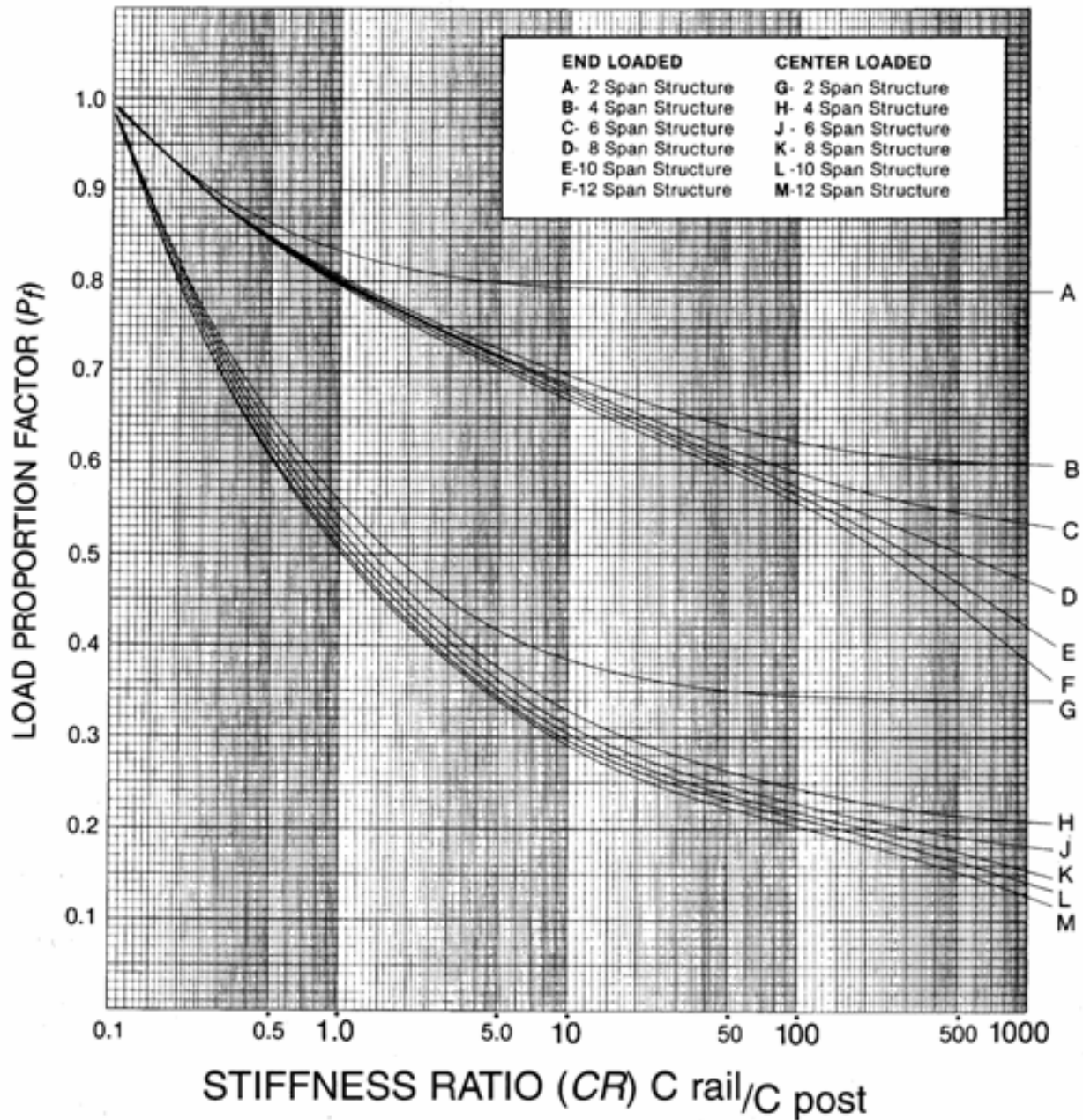
The equation for the stiffness ratio for distributing load is stated as:

$$CR = \frac{C_{\text{rail}}}{C_{\text{post}}} = \frac{[(E)(I) / L]}{[(E)(I) / h]} \quad (\text{Eq. 1})$$

where: CR = stiffness ratio
C_{rail} = stiffness of rail
C_{post} = stiffness of post
E = modulus of elasticity (psi x 10⁶)
I = moment of inertia (in⁴)
L = post spacing (inches)
h = post height (inches)

The stiffness ratio (CR) is then plotted on the Load Proportion Factor and Stiffness Ratio chart (**Figure 3**) to obtain the Load Proportion Factor (Pf). When the Load Proportion Factor has been determined, it is multiplied by the total load to determine the total load one post must sustain.

Figure 3 – Load Proportion Factor and Stiffness Ratio Chart



Credit: NAAMM AMP 521-01

The formula to calculate the required section modulus in a post for a concentrated load condition is:

$$S = \frac{(P)(P_f)(h)}{f_{db}} \quad (\text{Eq. 2})$$

where: S = section modulus (in³)
P = concentrated load applied to the top rail (lb.)
P_f = load proportion factor
h = post height (inches)
f_{db} = allowable design bending stress of post (psi)

Note: Equation 2 is derived from the standard moment (M = F x h = P x P_f x h) and bending stress formulas (f_b = M / S).

3.3.1.2 Post Design - Uniform Loading

Uniform loading shall be applied over the full length of the rail. There is no load distribution factor for the uniform loading condition. The size of all posts shall be determined by the loading on an intermediate post; e.g., the load per foot multiplied by the post spacing, or span, in feet, if the spans are of uniform length. End posts carry only half as much uniform rail load but the same concentrated load as the intermediate posts and shall be made of the same pipe size.

The required section modulus of the post under a uniform loading condition can be determined if the type of pipe material has already been chosen as follows:

$$S = \frac{(w/12)(L)(h)}{f_{db}} \quad (\text{Eq. 3})$$

where: S = section modulus (in³)
w = load per linear foot (lb/ft)
L = post spacing (inches)
h = post height (inches)
f_{db} = allowable design bending stress of post (psi)

Note: Equation 3 is derived from the standard moment (M = P x h = [(w/12) x L] x h) and bending stress formulas (f_b = M / S).

3.3.1.2 Post Design – Reinforcing Post

Since the greatest stresses on the posts are at the base, it may be more economical to reinforce the posts at the base to increase the section modulus, rather than use material with a thicker wall thickness or decrease the post spacing.

For example, from **Table 2**, a 1-inch diameter schedule 40 pipe (1.315 in. OD, 1.049 in. ID) will fit within a 1-1/2 inch diameter schedule 40 pipe (1.90 in. OD, 1.610 in. ID). The section modulus of the schedule 40 post and the schedule 40 reinforcing pipe would be:

$$S = \frac{\pi(D^4 - d^4)}{32D} \quad (\text{Eq. 4})$$

where: S = section modulus (in³)
D = outside diameter (OD) of post (in.)
d = inside diameter (ID) of reinforcing pipe (in.)

The required height of the reinforcing insert is given by:

$$h_1 = h - \frac{(f_{db})(S)}{(w/12)(L)} \quad (\text{Eq. 5})$$

where: h₁ = height of reinforcing insert (inches)
h = post height (inches)
f_{db} = allowable design bending stress of post (psi)
S = section modulus of post (in³)
w = load per linear foot (lb/ft)
L = post spacing (inches)

3.3.2 Rail Design

After the posts have been designed, it will be necessary to verify that the rail will support the loads specified by the applicable codes. These loads will be the same as specified for the post design (concentrated or uniform).

3.3.2.1 Rail Design – Concentrated Loading

A concentrated load applied to the top rail at any point, in any direction, creates the maximum bending moment in the rail when applied at mid-span of the rail between posts. The distribution of loads over multiple spans decreases the maximum bending moment in rails. A bending moment constant (k) is used in the formulas depending on the number of spans in the length of rail. The formula to calculate the bending stress in the rail for concentrated loading at mid-span is as follows:

$$f_b = \frac{(P)(L)}{(S)(k)} \quad (\text{Eq. 6})$$

where: f_b = bending stress (psi)
P = concentrated load applied to the top rail (lb.)
L = post spacing (inches)
S = section modulus (in³)
k = bending moment constant (non-dimensional)
= 4 (for single span rail)
= 5 (for two or more spans)

Note: Equation 6 is derived from the standard moment (M = (P x L) / k) and bending stress formulas (f_b = M / S).
Values of k are defined based upon the maximum bending moment developed under various numbers of spans.

3.3.2.2 Rail Design – Uniform Loading

Additionally, the IBC requires that guardrails be designed to resist a load of 50 pounds per linear foot applied in any direction at the top and to transfer this load through the supports to the structure. Therefore, the engineer must perform calculations to determine if the loading conditions exceed the allowable design working stress of the material.

With a uniform load, the rail load is proportional to the rail span, which has been established by the post design calculation. As in the concentrated load formulas, a bending moment constant (k) is used to allow for the distribution of loads over multiple spans. The formula to calculate the bending stress in the rail for uniform loading is as follows:

$$f_b = \frac{(w/12)L^2}{(S)(k)} \quad \text{(Eq. 7)}$$

where: f_b = bending stress (psi)
w = load per linear foot (lb/ft)
L = post spacing (inches)
S = section modulus (in³)
k = bending moment constant (non-dimensional)
= 8 (for one or two spans)
= 9.5 (for three or more spans)

Notes: Equation 7 is derived from the standard moment ($M = [(w/12) \times L^2] / k$) and bending stress formulas ($f_b = M / S$).
Values of k are defined based upon the maximum bending moment developed under various numbers of spans.

3.3.3 Deflection Considerations

Excessive deflection of a railing under load, even though it meets strength requirements, will give the user a feeling of insecurity and may cause tripping or stumbling.

Deflection of posts under load is computed as follows:

For posts under concentrated load

$$\Delta = \frac{(P)h^3}{3(E)(I)} \quad \text{(Eq. 8)}$$

where: Δ = deflection (inches)
P = concentrated load (pounds)
h = post height (inches)
E = modulus of elasticity (psi)
= 29,500,000 (for steel)
= 10,000,000 (for aluminum)
I = moment of inertia (in⁴)

For posts under uniform load

$$\Delta = \frac{(w/12)(L)(h^3)}{3(E)(I)} \quad \text{(Eq. 9)}$$

where: Δ = deflection (inches)
w = load per linear foot (lb/ft)
L = post spacing (inches)
h = post height (inches)
E = modulus of elasticity (psi)
= 29,500,000 (for steel)
= 10,000,000 (for aluminum)
I = moment of inertia (in⁴)

Deflection of horizontal rails under load is computed as follows:

For rails under concentrated load

$$\Delta = \frac{(P)L^3}{(K)(E)(I)} \quad \text{(Eq. 10)}$$

where: Δ = deflection (inches)
P = concentrated load applied to the top rail (lb.)
L = post spacing (inches)
E = modulus of elasticity (psi)
= 29,500,000 (for steel)
= 10,000,000 (for aluminum)
I = moment of inertia (in⁴)
K = bending moment constant (non-dimensional)
= 48 (for one span)
= 66 (for two or more spans, load on end span)
= 87 (for three or more spans, load on intermediate span)

For rails under uniform load (one span)

$$\Delta = \frac{5(w/12)L^4}{384(E)(I)} \quad \text{(Eq. 11a)}$$

For rails under uniform load (two or more spans)

$$\Delta = \frac{(w/12)L^4}{145(E)(I)} \quad \textbf{(Eq. 11b)}$$

where: Δ = deflection (inches)
w = load per linear foot (lb/ft)
L = post spacing (inches)
E = modulus of elasticity (psi)
= 29,500,000 (for steel)
= 10,000,000 (for aluminum)
I = moment of inertia (in⁴)

There are few, if any, regulations or code requirements limiting deflection in a railing. However, the American Society of Testing and Materials (ASTM) has put forth the following criteria regarding Maximum Allowable Deflection ($\Delta_{\max}$) in ASTM E 985 “Standard Specification for Permanent Metal Railing Systems and Rails for Buildings”:

$$\text{For horizontal load at midspan} \quad \Delta_{\max} = \frac{h}{24} + \frac{L}{96} \quad \textbf{(Eq. 12a)}$$

$$\text{For horizontal load at top of post} \quad \Delta_{\max} = \frac{h}{12} \quad \textbf{(Eq. 12b)}$$

$$\text{For vertical load at midspan} \quad \Delta_{\max} = \frac{L}{96} \quad \textbf{(Eq. 12c)}$$

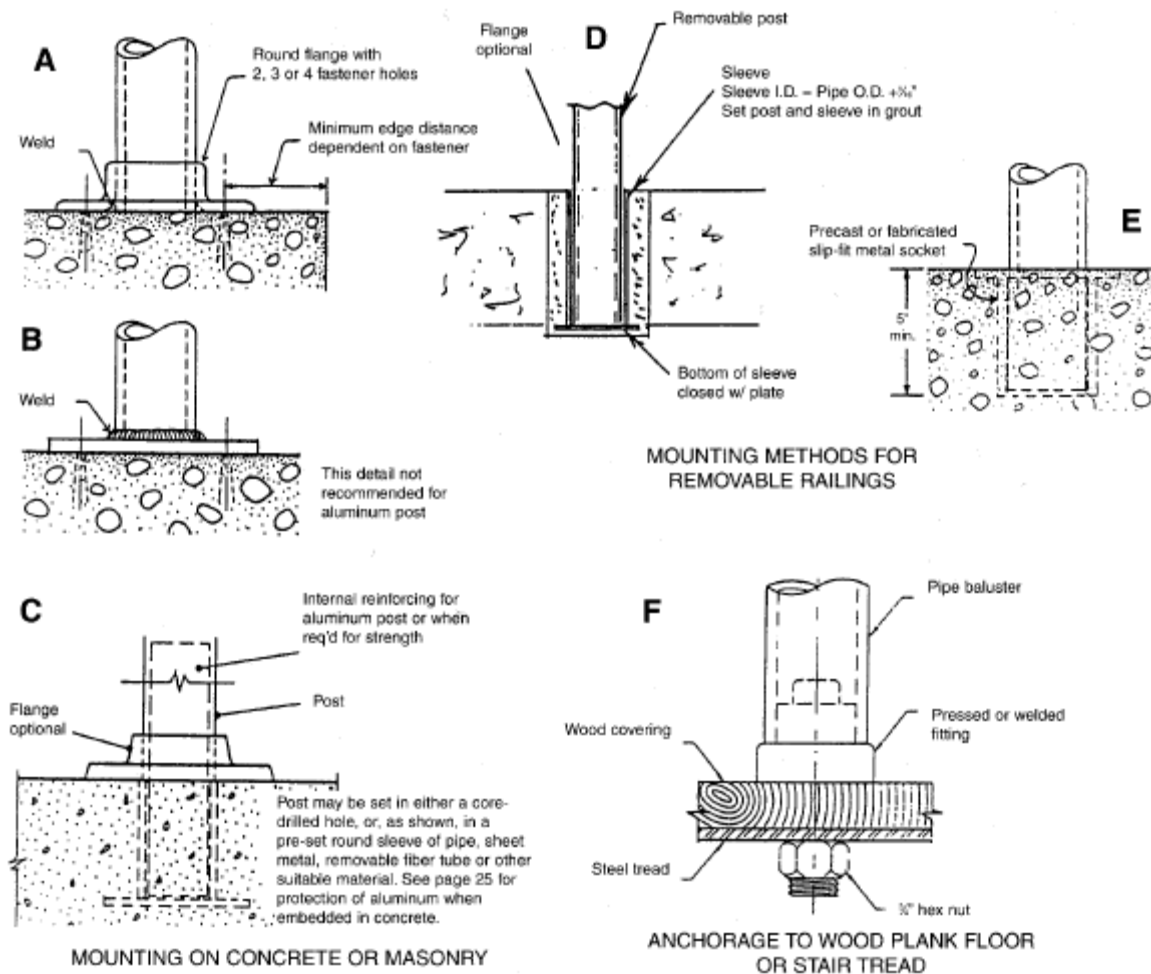
where: $\Delta_{\max}$ = maximum deflection (inches)
h = post height (inches)
L = post spacing (inches)

3.4 Anchorage

The point of greatest stress, and therefore the most critical point in any railing system, is at the base of the post, where it is attached to the supporting structure. Whether the supporting structure is metal, masonry or wood, attachment procedures are much the same; only the type of fastener will vary.

Typical methods of post anchoring on horizontal surfaces are shown in Figure 4 below.

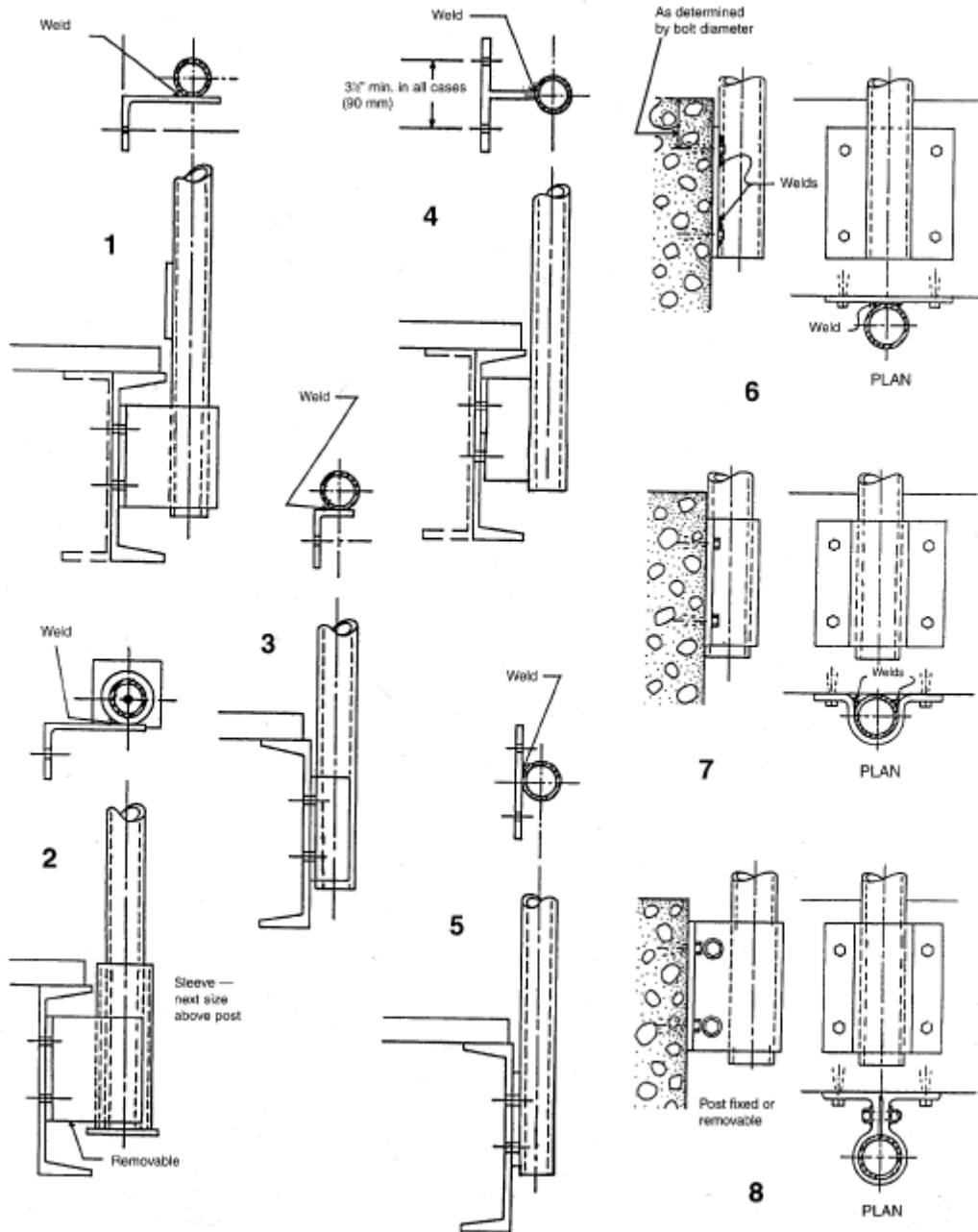
Figure 4 – Typical Methods of Post Anchoring on Horizontal Surfaces



Credit: NAAMM AMP 521-01

Additionally, typical methods of side-mount anchoring of posts are shown in Figure 5 below.

Figure 5 – Typical Methods of Side-Mount Anchoring of Posts



Credit: NAAMM AMP 521-01

Mounting on a fascia or stringer face has several advantages over mounting to a floor. The railing system does not reduce the width of the stair or platform. Available stock fittings or shop welding make installation easy without need for field welding. Fittings distribute the stress transmitted by the post, and, if required, include a reinforcing bar to strengthen the lower part of the post.

For welded connections, the required size of the weld should be determined using the appropriate Structural Welding Code:

- American Welding Society, AWS D1.1, Structural Welding Code – Steel
- American Welding Society, AWS D1.2, Structural Welding Code – Aluminum
- American Welding Society, AWS D1.6, Structural Welding Code – Stainless Steel

For bolted connections, the required fastener capacity is determined by computing the moment about a fastener or support and solving for required pullout strength using the following equation:

$$\text{For mounting to floor} \quad F = \frac{(P)(h)}{(d)} \quad \text{(Eq. 13a)}$$

$$\text{For mounting to fascia} \quad F = \frac{(P)(h + a + d)}{(d)} \quad \text{(Eq. 13b)}$$

where: F = force applied to fastener group in line (lb.)
P = concentrated force applied to top rail (lb.)
h = height at which force is applied (in.)
a = distance from floor to first set of anchors (in.)
d = distance from furthest anchor to point of rotation (in.)

Notes: Equations 13a and 13b are derived from applied moment and resisting moment equations.

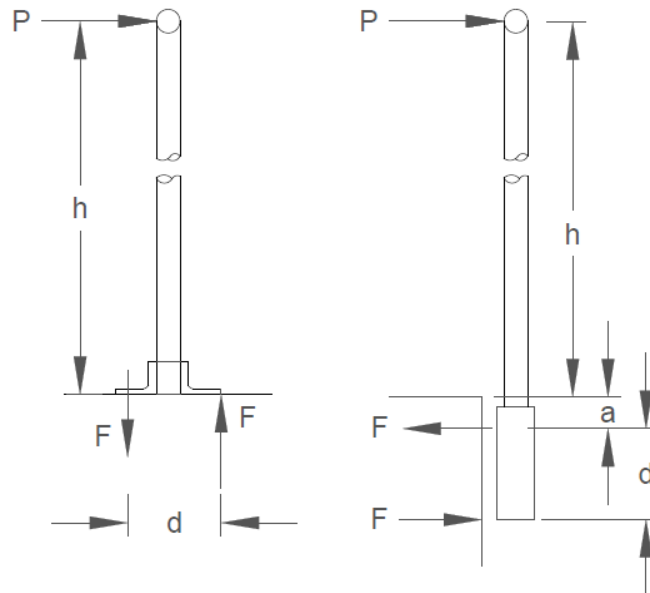
The force per bolt is then calculated by the following equation (applies to both mounting to floor and mounting to fascia):

$$F_a = \frac{SF(F)}{n} \quad \text{(Eq. 14)}$$

where: F_a = pullout force on a single anchor (lb.)
F = force applied to fastener group in line (lb.)
SF = safety factor (typically = 2)
n = number of anchors in line

The variables in Equations 13a, 13b, and 14 are illustrated in Figure 4 below.

Figure 6 – Post Anchoring



For bolted installations in concrete, minimum anchor embedment shall be determined from manufacturer's design data. Additionally, installation of anchors should follow pertinent Codes (e.g., ACI 318 Building Code) and manufacturer's instructions, especially with regard to distances to edges and effective embedment depth.

The strength of the mounting and support of a guardrail system is just as important as the strength of the guardrail system itself. In the few instances where guardrail systems have failed, weak anchorage has nearly always been the cause. The manufacturers of guardrail system components and fastening devices have made available the engineering information needed to provide proper anchorage; and qualified metal fabricators are ready to supply properly constructed railing systems. All of these are essential to good guardrail system design.

4.0 Final Considerations

Code requirements, material availability, and labor and material costs can affect efficiencies in design. As always, it is good to check with a local fabricator to get the best information on feasibility and costs.

5.0 Example Design Problem

A facility engineer has been tasked with designing a guardrail system to protect maintenance workers from the leading edges of an elevated communications generator platform, similar to the one in the photograph below. The platform is constructed of concrete and measures 30 feet by 30 feet.



Photo credit: WASKEY – www.waskey.com

Step 1 – Determine Applicable Codes and Requirements

Local building codes require that a guardrail system be designed to meet IBC guardrail requirements. Additionally, the company is required to install guardrail systems that comply with OSHA standards to protect employees as well as workers during construction. The loading, height, and spacing requirements that meet both OSHA and IBC are:

- 200-pound concentrated load acting on the top rail.
- 50-pound uniform load acting on the top rail.
- Post / rail height of 42 inches.
- Maximum post spacing of 96 inches.
- 1-1/2 inch nominal diameter for posts and rails.

Step 2 – Choose Material Type and Method of Construction for Guardrail Systems

For this particular exterior installation, the engineer selects 6061-T6 aluminum pipe over carbon steel due to its lower material cost and better corrosion-resistance properties which, in turn, reduces maintenance costs.

For ease of installation, the engineer selects a manufacturer of aluminum guardrail systems that incorporates slip-on fittings. Technical data on the components can then be obtained for use in the calculations.

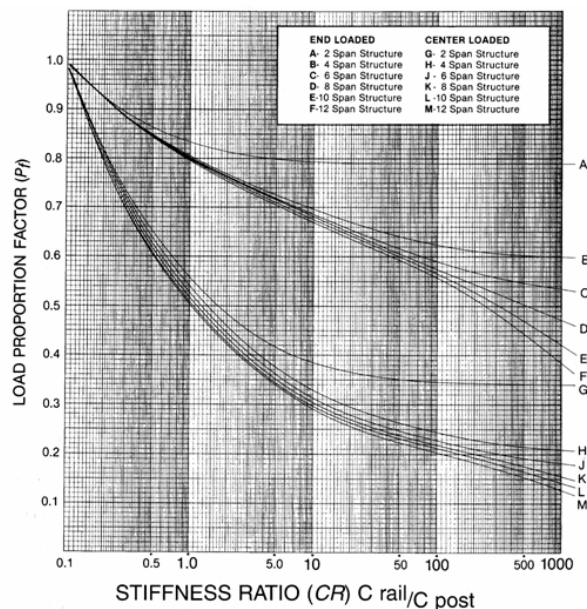
From the manufacturer's catalog, the engineer decides to support the posts using a surface-mount base flange.

Step 3 – Determine the Load Proportion Factors

With a required guardrail length of 30 feet per side, the engineer chooses five equal spans of 6 feet (72 inches), rather than three 8-foot spans and one 6-foot span, for aesthetic reasons. This also simplifies determining load proportion factors.

When posts and rails are of identical material and section, the stiffness ratio from Equation 1 can be simplified. Assuming the post spacing (L) of 72 inches and the post height (h) of 42 inches, the stiffness ratio can be calculated as:

$$CR = \frac{C_{\text{rail}}}{C_{\text{post}}} = \frac{[(E)(I)/L]}{[(E)(I)/h]} = \frac{(1/L)}{(1/h)} = \frac{(1/72'')}{(1/42'')} = 0.583$$



From the chart to the left and using $CR = 0.583$, the load proportion factors (P_f) for the posts and rails are estimated as follows:

End posts of 2-span rail – 0.85
End posts of 3 or more spans – 0.82

Intermediate posts of 2-span rail – 0.65
Intermediate posts of 3 or more spans – 0.60

Step 4 – Determine the Required Section Modulus for the Posts under a Concentrated Load

Using Equation 2, the following terms are known:

P = Concentrated load of 200 pounds

P_f = 0.82 for end posts, 0.60 for intermediate posts [5 spans]

Base Flange height: 3 inches

h = 38.05 inches [rail height from the centerline of the top rail to the top of the base flange]

f_{db} , allowable design bending stress = 24 ksi = 24,000 psi [6061 T-6 aluminum]

Pipe diameter: 1-1/2" nominal, 1.90 inches actual

From Equation 2, the required section modulus in the end post is:

$$S = \frac{(P)(P_f)(h)}{f_{db}} = \frac{(200)(0.82)(38.05)}{24,000} = 0.2600083 \text{ in}^3$$

and the required section modulus in the intermediate post is:

$$S = \frac{(P)(P_f)(h)}{f_{db}} = \frac{(200)(0.60)(38.05)}{24,000} = 0.190 \text{ in}^3$$

From Table 2 and using engineer's judgment, the engineer selects 1-1/2 inch diameter schedule 40 pipe with a section modulus of 0.326 in³.

Step 5 – Determine the Required Section Modulus for the Posts under a Uniform Load

Using Equation 3, the following terms are known:

w = uniform load of 50 pounds per foot applied horizontally

L = post spacing = 72 inches

Base Flange height: 3 inches

h = 38.05 inches [rail height from the centerline of the top rail to the top of the base flange]

f_b, allowable design bending stress = 24 ksi = 24,000 psi [6061-T6 aluminum]

Pipe diameter: 1-1/2" nominal, 1.90 inches actual

From Equation 3, the required section modulus is:

$$S = \frac{(w/12)(L)(h)}{f_{db}} = \frac{(50/12)(72)(38.05)}{24,000} = 0.476 \text{ in}^3$$

This **exceeds** the section modulus of any 1-1/2 inch pipe in Table 2. In order to meet an acceptable section modulus, the following options are available: the post spans could be shortened, the diameter of the posts could be increased to 2 inches, or the posts could be reinforced internally to increase the section modulus at the base of the post.

The most economical solution would be to reinforce the posts internally with pipe that would fit inside of a schedule 40 post. From Table 2, a 1-inch diameter schedule 40 pipe (1.315 in. OD, 1.049 in. ID) will fit within a 1-1/2 inch diameter schedule 40 pipe (1.90 in. OD, 1.610 in. ID).

Using Equation 4, the section modulus of the schedule 40 post and the schedule 40 reinforcing pipe would be, where *D* equals the OD of the post and *d* equals the ID of the reinforcing pipe:

$$S = \frac{\pi(D^4 - d^4)}{32D} = \frac{\pi(1.90^4 - 1.049^4)}{32(1.90)} = 0.611 \text{ in}^3$$

This is acceptable since the section modulus of the reinforced base exceeds the required section modulus of 0.476 in³.

To determine the length of the reinforcing pipe, Equation 5 is used. Using $S = 0.326 \text{ in}^3$ for the post, the required height, h_1 , of the reinforcing pipe is:

$$h_1 = h - \frac{(f_b)(S)}{(w/12)(L)} = 38.05 - \frac{(24,000)(0.326)}{(50/12)(72)} = 11.97 \cong 12 \text{ inches.}$$

Since h_1 is the height of the reinforcing pipe above the top of the 3-inch tall base flange, the total height of the reinforcing pipe is 15 inches.

In summary, the engineer would specify 1 1/2-inch diameter, schedule 40, 6061-T6 aluminum pipes for the posts along with 15-inch long by 1-inch diameter, schedule 40, 6061-T6 aluminum reinforcement pipes.

Step 6 – Check Bending Stress of Rails under a Concentrated Load

Assuming that posts and rails will be constructed from the same material, the applied bending stress on the rails will be checked versus the allowable bending stress for 6061-T6 aluminum pipe.

Using Equation 6, the following terms are known:

f_b = bending stress in the rail, psi

P = concentrated load of 200 pounds

L = post spacing = 72 inches

$S = 0.326 \text{ in}^3$ [1-1/2" schedule 40 pipe]

$k = 5$ [two or more spans]

f_{db} , allowable design bending stress = 24 ksi = 24,000 psi [6061-T6 aluminum]

From Equation 6, the applied bending stress in the rail is:

$$f_b = \frac{(P)(L)}{(S)(k)} = \frac{(200)(72)}{(0.326)(5)} = 8,834 \text{ psi}$$

The bending stress in the rail is less than the allowable design bending stress of 24,000 psi for 6061-T6 aluminum pipe, so the 72-inch spacing is acceptable with 1-1/2" schedule 40 pipe for the rail.

It should be noted that Equation 6 could also be solved to verify that the section modulus is acceptable by rearranging the equation.

Step 7 – Check Bending Stress of Rails under a Uniform Load

With a uniform load, the rail load is proportional to the rail span. As in the concentrated load formulas, a bending moment constant is used to allow for the distribution of loads over multiple spans.

Using Equation 7, the following terms are known:

f_b = bending stress in the rail, psi
 w = uniform load of 50 pounds per foot
 L = post spacing = 72 inches
 S = 0.326 in³ [1-1/2" schedule 40 pipe]
 k = 9.5 [three or more spans]
 f_{db} , allowable design bending stress = 24 ksi = 24,000 psi [6061-T6 aluminum]

From Equation 7, the applied bending stress in the rail is:

$$f_b = \frac{(w/12)L^2}{(S)(k)} = \frac{(50/12)(72)^2}{(0.326)(9.5)} = 6,974 \text{ psi}$$

The bending stress in the rail is less than the allowable design bending stress of 24,000 psi for 6061-T6 aluminum pipe, so the 72 inch spacing is acceptable with 1-1/2" schedule 40 pipe for the rail.

It should be noted that Equation 7 could also be solved to verify that the section modulus is acceptable by rearranging the equation.

Step 8 – Check Deflection of Posts under Concentrated and Uniform Loads

Using Equation 8 for posts under a concentrated load, the following terms are known:

Δ = deflection (inches)
 P = concentrated load of 200 pounds
 h = post height = 42 inches
 E = modulus of elasticity of post = 10,000,000 psi [aluminum]
 I = moment of inertia of post = 0.310 in⁴ [1-1/2" sch. 40 pipe]

From Equation 8, the deflection in the post is:

$$\Delta = \frac{(P)(h)^3}{3(E)(I)} = \frac{(200)(42)^3}{3(10E6)(0.310)} = 1.59 \text{ inches}$$

Using Equation 9 for posts under a uniform load, the following terms are known:

Δ = deflection (inches)
w = uniform load of 50 lbs/lf
h = post height = 42 inches
L = post spacing = 72 inches
E = modulus of elasticity of post = 10,000,000 psi [aluminum]
I = moment of inertia of post = 0.310 in⁴ [1-1/2" sch. 40 pipe]

From Equation 9, the deflection in the post is:

$$\Delta = \frac{(w/12)(L)(h^3)}{3(E)(I)} = \frac{(50/12)(72)(42)^3}{3(10E6)(0.310)} = 2.39 \text{ inches}$$

The greater deflection is calculated to be under a uniform load and will need to be checked versus the allowable deflections. Using Equation 12b, the maximum allowable deflection is:

$$\Delta_{\max} = \frac{h}{12} = \frac{42}{12} = 3.5 \text{ inches}$$

When the load is applied to the top of the post, the maximum allowable deflection is 3.5 inches. Since this is greater than the calculated deflections of the rail under concentrated or uniform loads, the deflection in the posts is acceptable.

Step 9 – Check Deflection of Rails under Concentrated and Uniform Loads

Using Equation 10 for rails under a concentrated load, the following terms are known:

Δ = deflection (inches)
P = concentrated load of 200 pounds
L = post spacing = 72 inches
K = bending moment constant = 87 [for three or more spans]
E = modulus of elasticity of post = 10,000,000 psi [aluminum]
I = moment of inertia of post = 0.310 in⁴ [1-1/2" sch. 40 pipe]

From Equation 10, the deflection in the rail is:

$$\Delta = \frac{(P)L^3}{(K)(E)(I)} = \frac{(200)(72)^3}{(87)(10E6)(0.310)} = 0.277 \text{ inches}$$

Using Equation 11b for rails with two or more spans under a uniform load, the following terms are known:

Δ = deflection (inches)

w = uniform load of 50 lbs/lf

L = post spacing = 72 inches

E = modulus of elasticity of post = 10,000,000 psi [aluminum]

I = moment of inertia of post = 0.310 in⁴ [1-1/2" sch. 40 pipe]

From Equation 11b, the deflection in the post is:

$$\Delta = \frac{(w/12)L^4}{145(E)(I)} = \frac{(50/12)(72)^4}{(145)(10E6)(0.310)} = 0.249 \text{ inches}$$

The greater deflection is calculated to be under a concentrated load and will need to be checked versus the allowable deflections. Using Equation 12a and 12c, the maximum allowable deflections are:

$$\Delta_{\max} = \frac{h}{24} + \frac{L}{96} = \frac{42}{24} + \frac{72}{96} = 2.5 \text{ inches}$$

$$\Delta_{\max} = \frac{L}{96} = \frac{72}{96} = 0.75 \text{ inches}$$

When the load is applied to the midspan of the rail, the maximum allowable deflection is 0.75 inches. Since this is greater than the calculated deflections of the rail under concentrated or uniform load, the deflection in the rails is acceptable.

Step 10 – Design Post Base Fasteners

In earlier steps, it was decided that the post bases would be mounted on the surface of the elevated concrete slab. The 5-inch square base flange has four 0.44-inch mounting holes, located at each corner of the base flange, and which are spaced 0.75 inches from the edges of the base flange.

For simplicity, as the force is applied to the top of the rail or post, the two fasteners furthest from the point of rotation will be subject to the greatest tensile force in order to resist the moment of the applied force. The fastener group is defined as the fasteners that are subject to tensile forces.

Using Equation 13a for mounting to a floor, the following terms are known:

F = force applied to fastener group in line (lb.)

P = concentrated load of 200 pounds applied to top rail

h = 41.05 inches [height from the centerline of the top rail to the floor]

d = 4.25 inches [5-inch wide base minus 0.75 inch from center of hole to edge]

From Equation 13a, the force applied to the fastener group is:

$$F = \frac{(P)(h)}{(d)} = \frac{(200)(41.05)}{4.25} = 1931.76 \text{ pounds (rounded up to 1932 pounds)}$$

The force per bolt is then calculated from Equation 14 where the following terms are known:

F_a = pullout force on a single anchor (lb.)

SF = safety factor = 2

F = force applied to fastener group in line (lb.)

n = number of anchors = 2

Due to the uneven quality of concrete, a safety factor (SF) of 2 shall be applied to the pullout requirement when selecting a bolt or anchor from a manufacturer's table of fastener pullout strengths.

From Equation 14, the required tensile strength or pullout of the fasteners is:

$$F_a = \frac{SF(F)}{n} = \frac{(2)(1932)}{2} = 1932 \text{ pounds}$$

The engineer would then select 3/8-inch diameter anchoring fasteners with an allowable tensile load greater than 1932 pounds. To select the appropriate fastener, the engineer would then consult with a fastener manufacturer's specifications with respect to the fastening base material strength and the embedment depth. For this application, since the post bases are to be fastened to concrete, the engineer would also evaluate the following criteria including but not limited to the following, and in accordance with ACI 318: steel strength of the anchor in tension & shear, concrete breakout strength in tension & shear, concrete pry-out strength of the anchor.

Design Summary

The guardrail system would then be specified to the following requirements to meet both IBC and OSHA guidelines:

- Post spacing of 72 inches;
- Post height of 42 inches;
- Mid-rail height of 21 inches;
- Posts and railings comprised of 1-1/2 inch diameter, schedule 40, 6061-T6 aluminum pipe;
- Reinforcing post inserts comprised of 15-inch long, 1-inch diameter, schedule 40, 6061-T6 aluminum pipe;
- Base flanges anchored to elevated concrete slab using four 3/8-inch anchors or fasteners having a tensile and pullout strength of at least 1932 pounds each; and,
- Toeboards shall be 4 inches nominal in vertical height from its top edge to the level of the floor and fastened in place and with not more than 1/4-inch clearance above the floor level.

6.0 References

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