Design of Structural Steel Pipe Racks

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ABSTRACT

Pipe racks are structures in petrochemical, chemical and power plants that are designed to support pipes, power cables and instrument cable trays. They may also be used to support mechanical equipment, vessels and valve access platforms. Pipe racks are non-building structures that have similarities to structural steel buildings. The design requirements found in the building codes are not clear on how they are to be applied to pipe racks. Several industry references exist to help the designer apply the intent of the code and follow expected engineering practices. This paper summarizes the building code and industry practice design criteria, design loads and other design consideration for pipe racks.

Keywords: non-building structures, pipe, racks, support, design

Pipe racks are structures in petrochemical, chemical and power plants that support pipes, power cables and instrument cable trays. Occasionally, pipe racks may also support mechanical equipment, vessels and valve access platforms. Pipe racks are also referred to as pipe supports or pipeways. Main pipe racks transfer material between equipment and storage or utility areas. Storage racks found in warehouse stores are not pipe racks, even if they store lengths of piping.

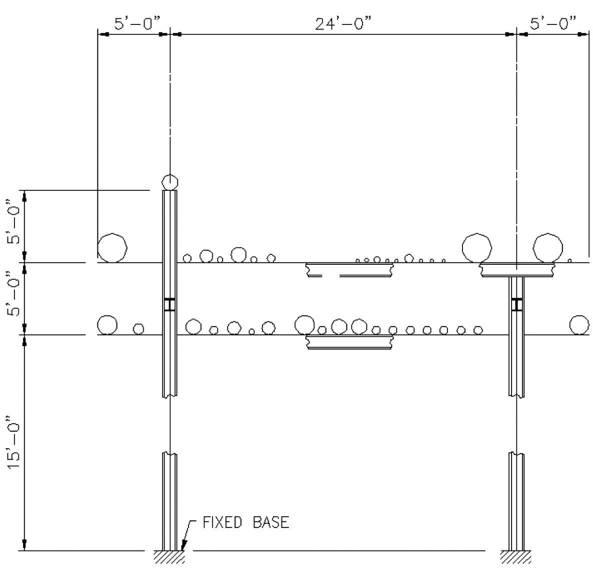

Fig 1. Typical transverse frame (bent).

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To allow maintenance access under the pipe rack, transverse frames (bents) are typically moment-resisting frames that support gravity loads and resist lateral loads transverse to the pipe rack. See Figure 1 for a typical pipe bent. Although the bent is shown with fixed base columns, it can also be constructed with pinned base columns if the supported piping can tolerate the lateral displacement.

The transverse frames are typically connected with longitudinal struts. If diagonal bracing is added in the vertical plane, then the struts and bracing act together as concentrically braced frames to resist lateral loads longitudinal to the pipe rack. See Figure 2 for an isometric view of a typical pipe rack.

If the transverse frames are not connected with longitudinal struts, the pipe rack is considered to be "unstrutted." The frame columns act as cantilevers to resist lateral loads longitudinal to the pipe rack.

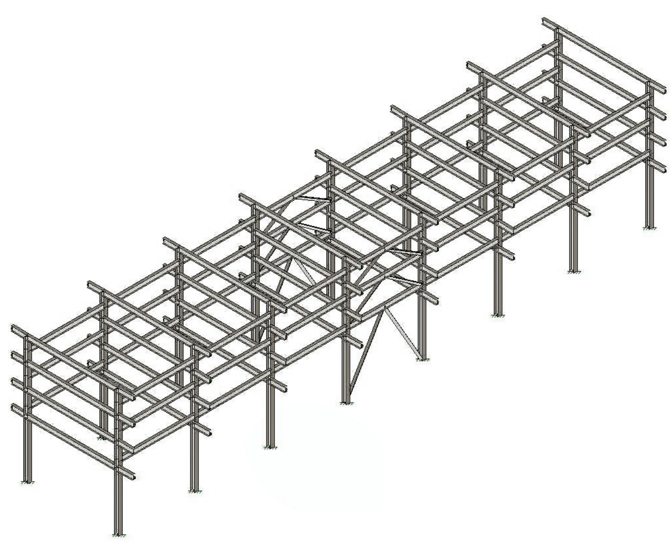


Fig. 2. Typical four-level pipe rack consisting of eight transverse frames connected by longitudinal struts.

DESIGN CRITERIA

In most of the United States, the governing building code is the International Building Code (IBC) (ICC, 2009). The scope of this code applies to buildings and other structures within the governing jurisdiction. The IBC prescribes structural design criteria in Chapters 16 through 23. These design criteria adopt by reference many industry standards and specifications that have been created in accordance with rigorous American National Standards Institute (ANSI) procedures.

By reference, many loads are prescribed in ASCE 7 (ASCE, 2006). Similarly, most structural steel material references are prescribed in AISC 360 (AISC, 2005b). Most structural steel seismic requirements are prescribed in AISC 341 (AISC, 2005a) and AISC 358 (AISC, 2006, 2009).

The IBC and its referenced industry standards and specifications primarily address buildings and other structures to a lesser extent. Design criteria for non-building structures are usually provided by industry guidelines. These guidelines interpret and supplement the building code and its referenced documents. In the case of pipe racks, additional design criteria are provided by Process Industry Practices, PIP STC01015 (PIP, 2007) and ASCE guidelines for petrochemical facilities (ASCE, 1997a, 1997b). In this article, the IBC requirements govern. The aforementioned industry standards and specifications apply because they are referenced by the IBC. The PIP practices and ASCE guidelines may be used for pipe racks because they supplement the IBC and the referenced industry standards and specifications. However, the PIP practices and ASCE guidelines are not code-referenced documents.

DESIGN LOADS

Dead Loads *(D)*

Dead loads are defined in the IBC as "the weight of materials of construction … including, but not limited to … structural items, and the weight of fixed service equipment, such as cranes, plumbing stacks and risers, electrical feeders …" Dead loads are prescribed in the IBC Section 1606, with no reference to ASCE 7 or any industry standard or specification.

The PIP *Structural Design Criteria* prescribes specific dead loads for pipe racks. Pipe racks and their foundations should be designed to support these loads applied on all available rack space, unless other criteria is provided by the client.

- Structure dead load (D_s): The weight of materials forming the structure and all permanently attached appurtenances. This includes the weight of fire protection material, but does not include the weight of piping, cable trays, process equipment and vessels.
- Operating dead load (D_o): The operating dead load is the weight of piping, piping insulation, cable tray, process equipment and vessels plus their contents (fluid load). The piping and cable tray loads may be based on actual loads or approximated by using uniform loads. The PIP *Structural Design Criteria* recommends a uniformly distributed load of 40 psf for pipe, which is equivalent to 8-in.-diameter schedule 40 pipes filled with water at 15-in. spacing. Other uniform loads may be used based on client requirements and engineering judgment. For cable tray levels, a uniform distributed load of 20 psf for a single level of cable trays and 40 psf for a double level of cable trays may be used unless actual loading is greater.
- Empty dead load (D_e): The empty weight of piping, piping insulation, cable tray, process equipment and vessels. When using approximate uniform loads, 60% of the operating dead load for piping levels is typically used. Engineering judgment should be used for cable tray levels.
- Test dead load (D_t): The empty weight of the pipes plus the weight of the test medium.

The use of large approximate uniform loads may be conservative for the sizing of members and connections. However, conservatively large uniform loads can become unconservative for uplift, overturning and period determination.

Live Loads (*L*)

Live loads are defined in the IBC as "Those loads produced by the use and occupancy of the … structure, and do not include construction or environmental loads such as wind load, snow load, rain load, earthquake load, flood load, or dead load." Live loads are prescribed in IBC Section 1607, with no reference to ASCE 7 or any industry standard or specification.

The minimum live loads applied to platforms and stairs that are part of the pipe rack structure shall meet the minimum loads per IBC Table 1607.1:

- Stairs: Per item 35, "stairs and exits—all others" shall be designed for a 100-psf uniform load or a 300-lb point load over an area of 4 in.^{2}, whichever produces the greater load effects.
- Platforms: Per item 39, "Walkways and elevated platforms" shall be designed for 60-psf uniform load.

The PIP *Structural Design Criteria* also prescribes specific live loads which may be applicable to platforms and stairs that are part of the pipe racks. These loads are higher than required by the IBC Building Code:

- Stairs: Design for separate 100-psf uniform load and 1,000-lb concentrated load.

- Platforms: Design for separate 75-psf uniform load and 1,000-lb concentrated load assumed to be uniformly distributed over an area 2½ ft by 2½ ft.

Either of the preceding design criteria is acceptable and may be reduced by the reduction in live loads provisions of IBC. Often, the live load design criteria are specified by the client and may be larger to accommodate additional loads for maintenance.

Thermal Loads (*T*)

Thermal loads are defined in the IBC as "Self-straining forces arising from contraction or expansion resulting from temperature change." Thermal loads may be caused by changes in ambient temperature or may be caused by the design (operating) temperature of the pipe.

The PIP *Structural Design Criteria* prescribes specific thermal loads for pipe racks:

- Thermal forces (T): The self-straining thermal forces caused by the restrained expansion of the pipe rack structural members.
- Pipe anchor and guide forces (A_f): Pipe anchors and guides restrain the pipe from moving in one or more directions and cause expansion movement to occur at desired locations in a piping system. Anchor and guide loads are determined from a stress analysis of an individual pipe. Beams, struts, columns, braced anchor frames and foundations must be designed to resist actual pipe anchor and guide loads.
- Pipe friction forces (F_f): These are friction forces on the pipe rack structural members caused by the sliding of pipes in response to thermal expansion due to the design (operating) temperature of the pipe. For friction loads on individual structural members, use the larger of 10% of the total piping weight or 40% of the weight of the largest pipe undergoing thermal movement: 10% of the total piping weight assumes that the thermal movements on the individual pipes do not occur simultaneously; 40% of the largest pipe weight assumes steel-on-steel friction.

Earthquake Loads (*E*)

Earthquake loads are prescribed in IBC Section 1613. This section references ASCE 7 for the determination of earthquake loads and motions. Seismic detailing of materials prescribed in ASCE 7 Chapter 14 is specifically excluded from this reference. Seismic detailing of structural steel materials are prescribed in IBC Chapter 22.

The PIP *Structural Design Criteria* prescribes that earthquake loads for pipe racks are determined in accordance with ASCE 7 and the following:

- Evaluate drift limits in accordance with ASCE 7, Chapter 12.
- Consider pipe racks to be non-building structures in accordance with ASCE 7, Chapter 15.
- Consider the recommendations of *Guidelines for Seismic Evaluation and Design of Petrochemical Facilities* (ASCE, 1997a).
- Use occupancy category III and an importance factor (I) of 1.25, unless specified otherwise by client criteria.
- Consider an operating earthquake load (E_o). This is the load considering the operating dead load (D_o) as part of the seismic effective weight.
- Consider an empty earthquake load (E_e). This is the load considering the empty dead load (D_e) as part of the seismic effective weight.

The ASCE *Guidelines for Seismic Evaluation and Design of Petrochemical Facilities* is based on the 1994 Uniform Building Code (UBC) (ICBO, 1994), and references to various seismic load parameters are based on obsolete allowable stress design equations not used in the IBC. Nevertheless, this document is a useful resource for consideration of earthquake effects.

Wind Loads (*W*)

Wind loads are prescribed in IBC Section 1609. This section references ASCE 7 as an acceptable alternative to the IBC requirements. Most design practitioners use the ASCE 7 wind load requirements.

The PIP *Structural Design Criteria* prescribes that wind loads for pipe racks are determined in accordance with ASCE 7 and the following:

- Wind drift with the full wind load should not exceed the pipe rack height divided by 100.
- Consider partial wind load (W_p). This is the wind load determined in accordance with ASCE 7 based on a wind speed of 68 mph. This wind load should be used in load combination with structure dead loads (D_s) and test dead loads (D_t).

The ASCE Wind Guideline (ASCE, 1997b) recommends that wind loads for pipe racks are determined in accordance with ASCE 7 and the following:

- Calculate wind on the pipe rack structure, neglecting any shielding. Use a force coefficient of C_f = 1.8 on structural members, or alternatively use C_f = 2.0 below the first level and C_f = 1.6 above the first level.
- Calculate transverse wind on each pipe level. The tributary height for each pipe level should be taken as the

pipe diameter (including insulation) plus 10% of the pipe rack transverse width. The tributary area is the tributary height times the tributary length of the pipes. Use a minimum force coefficient of $C_f = 0.7$ on pipes.

- Calculate transverse wind on each cable tray level. The tributary height for each pipe level should be taken as the largest tray height plus 10% of the pipe rack transverse width. The tributary area is the tributary height times the tributary length of the cable tray. Use a minimum force coefficient of $C_f = 2.0$ on cable trays.

Rain Loads (*R*)

Rain loads are prescribed in IBC Section 1611. The IBC requirements are intended for roofs that can accumulate rain water. Pipe rack structural members, piping and cable trays do not accumulate rain water. Unless the pipe rack supports equipment that can accumulate rain water, rain loads need not be considered.

Snow Loads (*S*)

Snow loads are prescribed in IBC Section 1608. This section references ASCE 7 for the determination of snow loads. The IBC provisions are intended for determining snow loads on roofs. Typically, pipe racks are much different than building roofs, and the flat areas of a pipe rack where snow can accumulate vary. Thus, engineering judgment must be used when applying snow loads.

The flat-roof snow load could be used for determining the snow load on a pipe rack. The area to apply the snow load depends on what is in the pipe rack and how close the items are to each other. For example, if the pipe rack contains cable trays with covers, the area could be based on the solidity in the plan view. If the pipe rack only contains pipe with large spacing, the area would be small because only small amounts of snow will accumulate on pipe.

By using this approach, combinations with snow load usually do not govern the design except in areas of heavy snow loading. In areas of heavy snow loading, the client may provide snow load requirements based on their experience.

Ice Loads (D_i)

Atmospheric ice loading is not a requirement of the IBC code. However, atmospheric ice load provisions are provided in ASCE 7, Chapter 10. It is recommended that ice loading be investigated to determine if it may influence the design of the pipe rack.

Load Combinations

Load combinations are defined in IBC Section 1605, with no reference to ASCE 7 or any industry standard or specification. The IBC strength load combinations that are listed below consider only the load types typically applicable to pipe racks (*D*, *L*, *T*, *W* and *E*). Loads usually not applicable to pipe racks are roof live (L_r), snow (*S*), rain (*R*), ice (D_i) and lateral earth pressure (*H*).

$$1.4(D + F) \qquad \text{[IBC Eq. 16-1]}$$

$$1.2(D + T) + 1.6L \qquad \text{[IBC Eq. 16-2]}$$

$$1.2D + (0.5L \text{ or } 0.8W) \qquad \text{[IBC Eq. 16-3]}$$

$$1.2D + 1.6W + 0.5L \qquad \text{[IBC Eq. 16-4]}$$

$$1.2D + 1.0E + 0.5L \qquad \text{[IBC Eq. 16-5]}$$

$$0.9D + 1.6W \qquad \text{[IBC Eq. 16-6]}$$

$$0.9D + 1.0E \qquad \text{[IBC Eq. 16-7]}$$

The PIP *Structural Design Criteria* prescribes specific strength load combinations for pipe racks. However, the PIP load combinations do not consider platforms as part of a pipe rack structure and do not include live loads. The following combinations have been modified by the authors to include live loads for pipe racks that may have platforms. These load combinations are judged to be consistent with the IBC load combinations and include loads not considered by the IBC.

$$1.4(D_s + D_o + F_f + T + A_f)$$

$$1.4(D_s + D_t)$$

$$1.2(D_s + D_o + F_f + T + A_f) + 1.6L$$

$$1.2(D_s + D_o + A_f) + (1.6W \text{ or } 1.0E_o) + 0.5L$$

$$1.2(D_s + D_t) + 1.6W_{partial}$$

$$0.9(D_s + D_e) + 1.6W$$

$$0.9(D_s + D_o) + 1.2A_f + 1.0E_o$$

$$0.9(D_s + D_e) + 1.0E_e$$

To evaluate effects of these load combinations, they must be further expanded to consider the possible directions that lateral loads may occur. For example, wind loads would be applied in all four horizontal directions. In addition, lateral loads must consider multiple gravity load conditions.

DESIGN CONSIDERATIONS

Layout

An elevated multi-level pipe rack may be required for plant layout, equipment or process reasons. Multiple levels are not mandatory; it is simply a question of space. As long as the required space beneath the pipe rack for accessibility and road crossings has been taken into account, the rack can remain single level. However, in most cases, multiple levels will be required. Within plant units, most process pipes are connected to related unit equipment. Placing these pipes in the lower levels results in shorter pipe runs, savings on piping costs and better process flow conditions.

There are two main purposes of the cantilevers outside the pipe-rack columns: (1) to support sloping nonpressure pipes and (2) to support lines connecting adjacent equipment on the same side of the pipe rack. In both cases, using cantilevers allows long straight runs of level pressure piping and electrical work without interruption.

Ambient thermal loads are typically neglected for pipe racks because they are often insignificant to other loads. However, there may be cases where they should be considered, such as project sites in locations with extreme temperature ranges. If thermal loads are considered for long pipe racks, structure expansion joints should be placed approximately 200 to 300 ft apart. These expansion joints could be provided by either omitting the struts at one bay or by using long-slotted holes in the strut-to-column connections in the bay. If expansion joints are provided, each pipe rack section between joints should have at least one bay of horizontal and vertical bracing near the center of the section.

Based on the authors' experience, adjustments to the layout can also be used to help prevent vibration of piping due to wind in long pipe racks. Harmonic pipe vibration is reduced if every seventh bent is spaced at approximately 80% of the typical bent spacing.

Seismic

ASCE 7 defines a *non-building structure similar to buildings* as a "Non-building Structure that is designed and constructed in a manner similar to buildings, that will respond to strong ground motion in a manner similar to buildings, and have basic lateral and vertical seismic force resisting systems similar to buildings." Examples of non-building structures similar to buildings include pipe racks.

As a non-building structure, consideration of seismic effects on pipe racks should be in accordance with ASCE 7 Chapter 15. ASCE 7 Chapter 15 refers to Chapter 12 and other chapters, as applicable.

Seismic System Selection

Select seismic-force-resisting-system (SFRS), design parameters (R, Ω_o, C_d), and height limitations from either ASCE 7 Table 12.2-1 or ASCE 7 Table 15.4-1. Use of ASCE 7 Table 15.4-1 permits selected types of non-building structures that have performed well in past earthquakes to be constructed with less restrictive height limitations in Seismic Design Categories (SDC) D, E and F than if ASCE 7 Table 12.2-1 was used. Note that ASCE 7 Table 15.4-1 includes options where seismic detailing per AISC 341 is not required for SDC D, E or F. For example, ordinary moment frames of steel can be designed with $R = 1$ without seismic detailing per AISC 341. The AISC 341 seismic detailing requirements can also be avoided in SDC B and C for structural steel systems if $R = 3$ or less, excluding cantilevered column systems.

The transverse bents are usually moment-resisting frame systems, and the choices are special steel moment frame (SMF), intermediate steel moment frame (IMF) and ordinary steel moment frame (OMF).

In the longitudinal direction, if braced frames are present, the choices are usually special steel concentrically braced frame (SCBF) and ordinary concentrically braced frame (OCBF), although there is nothing to preclude choosing steel eccentrically braced frames (EBF) or buckling-restrained braced frames (BRBF). If braced frames are not present, the choices in the longitudinal direction are one of the cantilevered column systems.

In both directions, the seismic system selected must be permitted for the SDC and for the pipe rack height. ASCE Table 15.4-1 footnotes (italics below) permit specific height limits for pipe racks detailed for specific seismic systems:

- With $R = 3.25$: *Steel ordinary braced frames are permitted in pipe racks up to 65 ft (20 m).*
- With $R = 3.5$: *Steel ordinary moment frames are permitted in pipe racks up to a height of 65 ft (20 m) where the moment joints of field connections are constructed of bolted end plates. Steel ordinary moment frames are permitted in pipe racks up to a height of 35 ft (11 m).*
- With $R = 4.5$: *Steel intermediate moment frames are permitted in pipe racks up to a height of 65 ft (20 m) where the moment joints of field connections are constructed of bolted end plates. Steel intermediate moment frames are permitted in pipe racks up to a height of 35 ft (11 m).*

Period Calculations

The fundamental period determined from ASCE 7 Chapter 12 equations is not relevant for non-building structures, including pipe racks, because it does not have the same mass and stiffness distributions assumed in the Chapter 12 empirical equations for building structures. It is acceptable to use any analysis method that accurately models the mass and stiffness of the structure, including finite element models and the Rayleigh method. The determination of the pipe rack period can be affected by the stiffness of the piping leaving the pipe rack. When this stiffness is not accounted for in the period calculation, it is recommended that the calculated period be reduced by 10%.

Analysis Procedure Selection

ASCE 7 Chapter 12 specifies when a dynamic analysis is required. The philosophy underlying this section is that dynamic analysis is always acceptable for design. Static procedures are allowed only under certain conditions of regularity, occupancy and height.

A dynamic analysis procedure is required for a pipe rack if it is assigned to SDC D, E, or F and it either:

- has $T \geq 3.5T_s$, or
- exhibits horizontal irregularity type 1a or 1b or vertical irregularity type 1a, 1b, 2, or 3 (see ASCE 7 Chapter 12).

A dynamic analysis procedure is always allowed for a pipe rack. The most common dynamic analysis procedure used for pipe racks is the Modal Response Spectrum Analysis (ASCE 7 Chapter 12). The Equivalent Lateral Force Procedure (ASCE 7 Chapter 12) is allowed for a pipe rack structure if a dynamic analysis procedure is not required. The Simplified Alternative Structural Design Criteria for Simple Bearing Wall or Building Frame Systems is not appropriate and should not be used for pipe racks.

Equivalent Lateral Force Method Analysis

The Equivalent Lateral Force (ELF) procedure is a static analysis procedure. The basis of the ELF procedure is to calculate the effective earthquake loads in terms of a base shear, which is dependent on the structure's mass (effective seismic weight), the imposed ground acceleration, the structure dynamic characteristics, the structure ductility, and the structure importance. The base shear is then applied to the structure as an equivalent lateral load vertically distributed to the various elevations using code prescribed equations that are applicable to building structures. Using this vertical distribution of forces, seismic design loads in individual members and connections can be determined.

ASCE 7 determines design earthquake forces on a strength basis, allowing direct comparison with the design strength of individual structural members.

Modal Response Spectra Analysis

It is acceptable to use Modal Response Spectrum Analysis (MRSA) procedure for the analysis of pipe racks. It may be required to use a dynamic analysis procedure, such as MRSA, if certain plan and/or vertical irregularities are identified. The basis of MRSA is that the pipe rack's mass (effective seismic weight) and stiffness are carefully modeled, allowing the dynamic analysis of multiple vibration modes, resulting in an accurate distribution of the base shear forces throughout the structure. The MRSA shall include sufficient number of modes in order to obtain a minimum of 90% mass participation. Two MRSA runs would be required. The first run would include the operating dead load (D_o) as the seismic effective weight to determine the operating earthquake load (E_o). The second run would include the empty dead load (D_e) as the seismic effective weight to determine the empty earthquake load (E_e).

The MRSA input ground motion parameters (S_{DS}, S_{D1}) are used to define the ASCE 7 elastic design response spectrum. To obtain "static force levels," the MRSA force results must be divided by the quantity (R/I). ASCE 7 does not allow you to scale down MRSA force levels to ELF force levels because the ELF procedure may result in an underprediction of response for structures with significant higher mode participation. On the other hand, when the MRSA base shear is less than 85% of the ELF base shear, the MRSA results must be scaled up to no less than 85% of the ELF values. This lower limit on the design base shear is imposed to account for higher mode effects and to ensure that the design forces are not underestimated through the use of a structural model that does not accurately represent the mass and stiffness characteristics of the pipe rack.

$$V_{\text{MRSA}} \geq 0.85V_{\text{ELF}} \tag{1}$$

Drift

To obtain amplified seismic displacements, the displacement results calculated from the elastic analysis must be multiplied by the quantity C_d/I to account for the expected inelastic deformations. The displacement results must be multiplied by C_d for checking pipe flexibility and structure separation. The displacement results must multiplied by the quantity C_d/I when meeting the drift limits of Table 12.12-1.

It is important that the drift of pipe racks is compared to other adjacent structures where piping and cable trays run. The piping and cable tray must be flexible enough to accommodate the movements of the pipe rack and other adjacent structure.

Seismic Detailing Requirements

The selection of a seismic-force-resisting system from ASCE 7 Table 12.2-1 invokes seismic detailing requirements prescribed in ASCE 7 Chapter 14. Because ASCE 7 Chapter 14 is specifically excluded by the IBC, seismic detailing requirements for structural steel systems shall be taken from IBC Chapter 22 and AISC 341. The selection of a seismic-force-resisting system from ASCE 7 Table 15.4-1 directly invokes seismic detailing requirements prescribed in AISC 341.

AISC 341 includes seismic detailing requirements for each structural steel system listed in the ASCE 7 tables. In general, there is a relationship between R values and seismic detailing requirements. Lower R values and higher earthquake design forces are accompanied by minimal seismic detailing requirements. Higher R values and lower earthquake design forces are accompanied by more restrictive seismic detailing requirements to provide greater ductility.

AISC 341 prescribes that beams in OMF systems do not require lateral bracing beyond those requirements prescribed in AISC 360. However, beams in IMF and SMF systems have progressively more restrictive requirements for lateral bracing of beams that can only be met by the addition of a horizontal bracing system at each pipe level. For this reason, it may be more economical to select an OMF system for the transverse bents.

AISC 341 prescribes that beam-to-column connections for IMF and SMF systems must be based on laboratory testing. OMF beam-to-column connections may be either calculated to match the expected plastic moment strength of the beam or based on laboratory testing. AISC 358 prescribes specific requirements for laboratory tested systems appropriate for use in seismic moment frame systems. One of the systems included in AISC 358 is the bolted end plate moment connection, commonly used in pipe rack construction. These connections are popular in industrial plants because they involve no field welding. See Figure 3 for the AISC 358 extended end plate connections.

Supplement No. 1 to AISC 358 adds another laboratory tested connection that does not involve field welding, the bolted flange plate moment connection (along with two additional connections). This type of connection is not used in pipe racks because it is not practical to support piping at the bolted top flange plates.

Redundancy in SDC A, B or C

In accordance with ASCE 7 for all structures, $\rho = 1.0$.

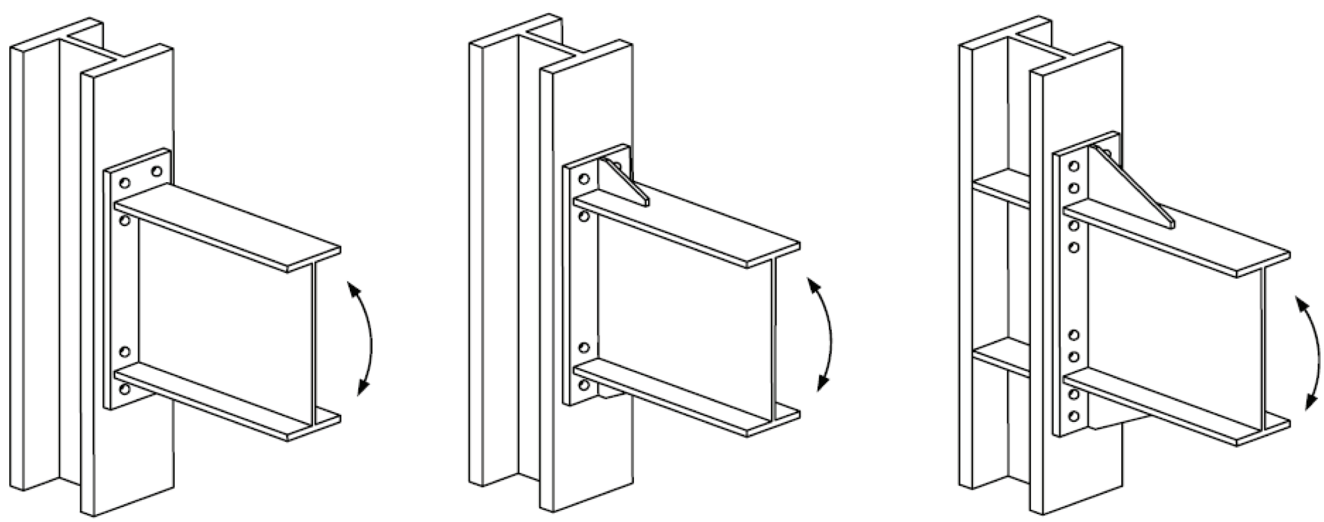
Redundancy in SDC D, E or F

The typical pipe rack has no horizontal bracing system that would serve as a diaphragm. If one individual bent fails, there is no load path for lateral force transfer to the adjacent frame. As a result, the pipe rack must be treated as a nonredundant structure.

- For a transverse bent to qualify for $\rho = 1.0$, it would need to have four or more columns and three or more bays at each level. This would ensure that the loss of moment resistance at both ends of a single beam would not result in more than a 33% loss of story strength. Otherwise, $\rho = 1.3$.
- For an individual longitudinal braced frame to qualify for $\rho = 1.0$, it would need to have two or more bays of chevron or X-bracing (or four individual braces) at each level on each frame line. This would ensure that the loss of an individual brace or connection would not result in more than a 33% loss of story strength nor cause an extreme torsional irregularity (type 1b). Otherwise, $\rho = 1.3$.

If the pipe rack is provided with a horizontal bracing system that would serve as a diaphragm and provide a load path for lateral transfer, the pipe rack can be treated as a redundant structure.

- For a pipe rack to qualify in the transverse direction for $\rho = 1.0$, it would need to have horizontal bracing between all transverse bents and a minimum of four transverse bents required. Otherwise, $\rho = 1.3$.
- For a pipe rack to qualify in the longitudinal direction for $\rho = 1.0$, there would need to be a minimum of four transverse bents, and each longitudinal frame line would need to have two or more individual braces at each level. Otherwise, $\rho = 1.3$.



(a) Four-bolt unstiffened, 4E

(b) Four-bolt unstiffened, 4ES

(c) Eight-bolt stiffened, 8ES

Fig. 3. Extended end plate connections as shown in AISC 358-05.

Wind

Most of the wind provisions in ASCE 7 pertain to the determination of wind forces on buildings. Section 6.5.13 pertains to open structures such as pipe racks. The shape factors provided previously in this article are based on ASCE 7 Figure 6-21.

Pressures and Forces

Usually, wind pressures are applied to all structural elements of a pipe rack with no shielding in the four horizontal directions. However, it is common practice to omit wind loads on horizontal bracing or other interior horizontal members when they are enclosed by beams and stringers in all four directions. This is a reasonable approach considering that wind loads are already applied on the beams or stringers surrounding the interior members, the bracing members are not perpendicular to the wind direction, and the piping and tray above the horizontal member further shield these members.

The determination of the wind force on piping and cable trays, which assumes shielding, has already been provided earlier in this article. These loads are typically applied as a point load at the midspan of the beam supporting the piping and cable trays.

Where pipe racks include platforms, the beams supporting the handrail would include the wind load based on the area of the handrail. The torsion due to the wind load on the handrail is usually negligible. The clips and bolts attaching the handrail posts to the supporting beam should be sized for the moment due to wind. The wind load may be larger than the point loads required per IBC 1607.7 or ASCE 7 Section 4.4 when light fixtures, cable trays or conduit are attached to the handrail posts.

The bolted end plate moment connection is commonly used for the beam-to-column connections in pipe rack construction. These connections are popular in industrial plants because they involve no field welding. Design of these connections for wind loads is prescribed in AISC *Steel Design Guide 4* (Murray and Sumner, 2003). These connections are very similar to those used in AISC 358 and share common laboratory test results and procedural steps. Figure 3 is also applicable for the AISC *Steel Design Guide 4* extended end plate connections.

Drift

Drift limitations for wind loads are typically limited to the lesser of either a drift limit ratio as a function of pipe rack height or the amount of displacement that the piping can tolerate. The acceptable drift limit ratio varies based on the specific industry or owner. A typical drift limit ratio is the pipe rack height divided by 100.

Piping flexibility and the resulting loads to adjacent structures or equipment must also be considered.

Coatings

The coatings used for pipe racks are typically specified by the client to match the rest of the facility and to meet demands of the environment. The following coating systems are typically used:

- *Hot dip galvanizing:* Hot dip galvanizing is the most commonly used coating because it usually provides the lowest life-cycle cost. The disadvantage is that field welding should be avoided to minimize repair of galvanizing and the safety issues with welding of galvanized materials. Connections and members must be detailed to mitigate the temperature effects of hot dip galvanizing.
- *Paint:* Paint can be shop or field applied. Painted structural steel usually has a higher life-cycle cost.
- *Hot dip galvanized and painted:* For extremely corrosive environments, such as locations with frequent salt spray, both hot dip galvanizing and compatible paint systems are used.

For the coating system to perform properly, all members and connections must use an orientation and be detailed to avoid the collection of water. Where water accumulation cannot be avoided, drain holes must be provided. Some member combinations such as back-to-back angles or tees should be avoided. These types of configurations cannot be repainted without disassembling.

Fire Protection

Fire protection can be provided by passive systems or active systems. There are many commercially available tested and listed passive systems. Systems are usually rated for two to four hours. Typical passive systems include normal weight concrete, lightweight concrete, spray-on cementitious coatings and intumenscent coatings. Coatings may be shop or field applied. Active systems, such as fire water spray systems, are less common. The type of system selected depends on client preference and economics. It also may be dictated by the industry specific standards provided by the National Fire Protection Association (NFPA).

The design of the pipe rack is required to take into account the following considerations when fire protection systems or coatings are used:

- Additional dead weight, which must be included in the dead load of the structure (D_s) and included in the seismic mass.
- Additional wind load due to the increased size of the member profile with fire proofing.
- Connection types and geometry, which may require offsets to accommodate members with shop applied fire protection.
- Structural steel coating selection to be compatible with

fire protection system. Fire protection material should not be considered as a coating that will prevent corrosion. Fire protection material may accelerate corrosion if improperly detailed or applied.

- The stiffness of fire protection materials cannot be used to resist loads.

Cold Spill Protection

For pipe racks supporting piping that contains low-temperature or cryogenic fluid, cold spill protection may be required. The requirements are usually dictated by the client or industry standards. Typically, full-weight concrete or cementitious spray-on coatings used for fire protection are used for cold spill protection. Currently, a few industry standards have requirements pertaining to cold spill protection, but they are subject to interpretation. There are few guidelines provided for the volume or duration of the cold spill and little information on the effectiveness of fire proofing materials used for cold spill protection. The locations and the type of cold spill protection are often specified by the client. The same design considerations used for fire protection must be used when cold spill protection is to be provided.

Support Beams

Beams that support pipe and cable trays have several considerations for their proper design. Support beams are typically the beams of the transverse bents and may also include the stringers running longitudinally.

Lateral Bracing of Support Beams

Piping and cable trays do not act as reliable lateral bracing for the compression flange of support beams. Piping is typically not attached to the support beam, and friction alone cannot provide reliable restraint against lateral torsional buckling (LTB). Piping thermal movements may also help cause LTB rather than prevent it. Cable trays should not be considered as lateral bracing because they do not sufficiently prevent movement in the longitudinal direction of the pipe rack.

Interface between Pipes and Support Beams

There are many configurations in which pipes may be supported and restrained. Vertical supports, intended to support gravity loads, may also have horizontal loads due to friction. The friction could be a result of thermal, operating, wind or seismic loads on the piping. Note that friction loads due to wind and seismic conditions must be considered for the design of the supporting member but are not considered as resisting the wind or seismic force for the pipe.

The support beam should be designed for some friction load even though the piping analysis may indicate no lateral load. Pipe supports acting as pipe guides or axial line stops should also have friction loads applied to the support beam in addition to the guide or axial line stop load.

When guides or other types of supports apply concentrated forces or moments to the top flange, the top flange must be checked for local bending effects. The reaction of a typical pipe shoe support is assumed to act over the beam web and would not cause local flange bending.

Pipe anchors and guides that resist forces are usually present in pipe racks. Bracing may be required if the pipe rack beams cannot provide the necessary strength and stiffness to accommodate the forces.

Pipe anchors that resist moments should be avoided in elevated pipe racks. It is usually difficult and expensive to provide the required torsional strength and stiffness to resist moments.

Interface between Cable Trays and Support Beams

Cable trays can be directly supported on the support beam steel, or Unistrut can be used between the beam and the cable tray.

Torsion on Support Beams

Horizontal loads from piping or cable tray loads are usually applied perpendicular to the top flange of the support beam. These loads do not pass through the shear center of the beam and a torsional loading is created. The resulting torsional loading should be evaluated in accordance with methods provided in AISC *Steel Design Guide 9* (Seaburg and Carter, 1997). The torsional stresses should be combined with other stresses as prescribed in AISC 360.

Stability Analysis and Design

Acceptable Methods

AISC 360 allows several methods for the stability analysis and design of frames:

- Second-Order Elastic Analysis
- Second-Order Analysis by Amplified First-Order Elastic Analysis
- Direct Analysis Method

If properly applied, all three methods are appropriate for use for pipe racks. The first two methods are acceptable for use provided that the ratio of second-order drift to first-order drift is less than or equal to 1.50. The Direct Analysis Method is always acceptable.

When using the first two methods, effective length factors (K) need to be calculated to determine the column strengths.

Unstrutted Pipe Racks

As previously discussed, pipeways may or may not include longitudinal struts connecting the columns of the transverse frames. Pipe racks without longitudinal struts are called unstrutted pipe racks. The transverse frame columns of unstrutted pipe racks will act as cantilevered columns in the longitudinal direction.

The "classical" differential equation solution for column buckling for cantilevered columns is based on the assumption that the axial column stress is constant for the entire length of the column. The effective length factor is determined to be 2.0, rounded up for design to 2.1 to account for less than full fixity at the base.

In the case of pipe racks, the axial load is usually applied to the cantilevered columns at multiple locations as reactions from the supported beams. The axial stress is minimum at the free end and maximum at the fixed end. As a result, using an effective length of K = 2.1 for unstrutted pipe rack columns can be conservative.

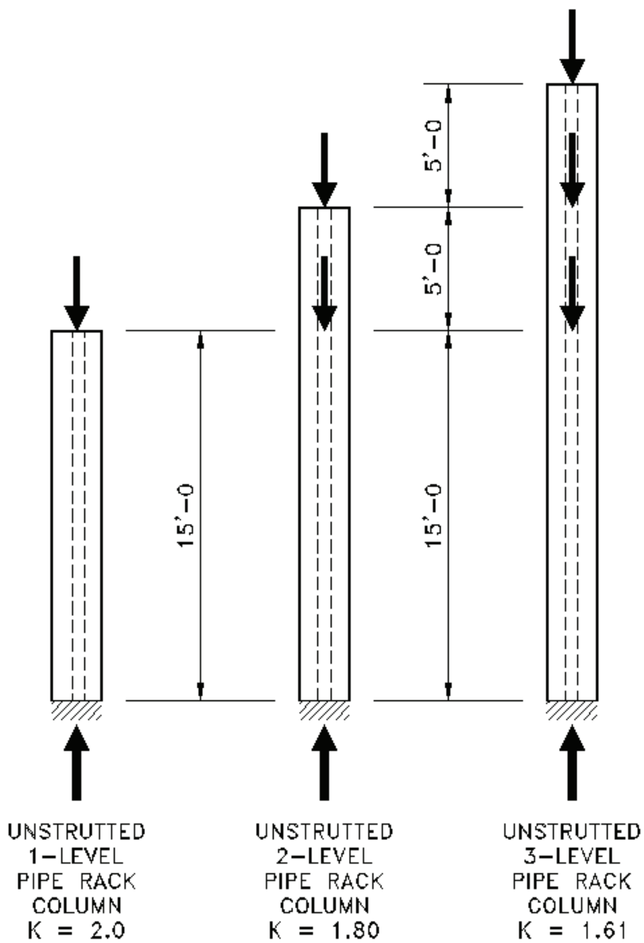


Fig. 4. Calculated effective length factors, K, for unstrutted pipe rack columns.

To quantify this conservatism, eigenvalue analyses were performed to determine effective length factors for unstrutted columns in typical pipe rack configurations with equal loads at each level (see Figure 4).

- For a single-level pipe rack loaded as shown in Figure 4, the effective length factor is determined to be 2.0. In accordance with AISC recommendations, use K = 2.1.
- For a two-level pipe rack loaded equally at each level as shown in Figure 4, the effective length factor is determined to be 1.80. Consistent with AISC recommendations, use K = 1.9.
- For a three-level pipe rack loaded equally at each level as shown in Figure 4, the effective length factor is determined to be 1.61. Consistent with AISC recommendations, use K = 1.7.

Commercial software can be used to perform the eigenvalue analysis necessary to determine effective length factors for other axial stress conditions. In the absence of commercial software, the recommended values may be used as guidance for arriving at an appropriate effective length factor.

The Direct Analysis Method does not involve the determination of effective length factors, and is recommended for use with unstrutted pipe racks.

Column Bases

Column base plates in the transverse (moment frame) direction may be designed as either fixed or pinned. Fixed column bases must be used for unstrutted pipe racks.

In general, the fixed base condition results in smaller structural steel sections and larger foundations with smaller calculated lateral frame deflections. Pinned base conditions result in heavier structural steel sections and smaller foundations with larger calculated lateral frame deflections.

The most common practice is to assume that the base of the column acts as a pinned connection. Even though the Occupational Safety and Health Administration (OSHA) requires a minimum of four anchor rods and the strength to resist a small moment, sufficient rotational stiffness is not provided to consider the base as a fixed connection. The combination of the flexibility of the base plate, the elastic deformation of the anchor rods, and the rotation of the foundation due to lateral loads usually allows enough rotation at the base for the base to act as a pinned connection when the larger wind and seismic loads are applied.

To minimize layout errors, the base plate is usually square with a square and concentric anchor rod hole pattern.

Foundations

The foundation type to be used will be dictated by site soil conditions. Foundation design parameters are normally stated in the project design specifications based on a site geotechnical investigation report. Typically, independent spread footings or pile caps are used at each column. Combined foundation or grade beams could be used for the columns of transverse frames and/or braced frames if the column spacing is not too large. Building codes may require that pile caps be connected with grade beams.

CONCLUSION

Pipe racks are not only non-building structures that have similarities to structural steel buildings but also have additional loads and design considerations. The requirements found in the building codes apply and dictate some of the design requirements. Some code requirements are not clear on how they are to be applied to pipe racks, because most are written for buildings. Several industry references exist to help the designer apply the intent of the code and follow expected engineering practices. Engineering practices vary and are, at times, influenced by client requirements and regional practices. Additional and updated design guides are needed so that consistent design methods are used throughout the industry.

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