

STRUCTURAL PERFORMANCE

performance issues relative to extreme events

Seismic Design of Structural Steel Pipe Racks

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Structural steel pipe racks typically support pipes, power cables and instrument cable trays in petrochemical, chemical and power plants. Occasionally, pipe racks may also support mechanical equipment, vessels and valve access platforms. Main pipe racks generally transfer material between equipment and storage or utility areas. Storage racks found in warehouses are not pipe racks, even if they store lengths of piping.

To allow maintenance access under the pipe rack, transverse bents are typically moment-resisting frames (Figure 1). Although the bent is shown with fixed-base columns, it can also be constructed with pinned bases if the supported piping can tolerate the resulting lateral displacement.

The transverse bents are typically connected with longitudinal struts. If bracing is added in the vertical plane, then the struts and bracing act together to resist lateral loads longitudinal to the pipe rack (Figure 2).

If the transverse frames are not connected with longitudinal struts, the pipe rack is considered “unstrutted.” The frame columns must act as cantilevers to

resist lateral loads longitudinal to the pipe rack.

Design Criteria

In most of the United States, the governing code is the *International Building Code* (IBC), which applies to buildings and other structures. IBC prescribes structural design criteria in Chapters 16 through 23, and adopts by reference many industry standards and specifications that have been created in accordance with rigorous *American National Standards Institute* (ANSI) procedures.

For the most part, design loads are prescribed in ASCE 7, structural steel material references are prescribed in AISC 360, and structural steel seismic requirements are prescribed in AISC 341 and AISC 358. The edition of each standard that is used should be based on the edition of the governing building code or as otherwise approved by the authority having jurisdiction.

Design criteria for nonbuilding structures are usually provided by industry guidelines that 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, and the ASCE *Guidelines for Seismic Evaluation and Design of Petrochemical Facilities*. In this article, the IBC requirements govern; the PIP practices and ASCE guidelines may be used for pipe racks, as they supplement the IBC and the referenced industry standards and specifications, but they are not code-referenced documents themselves.

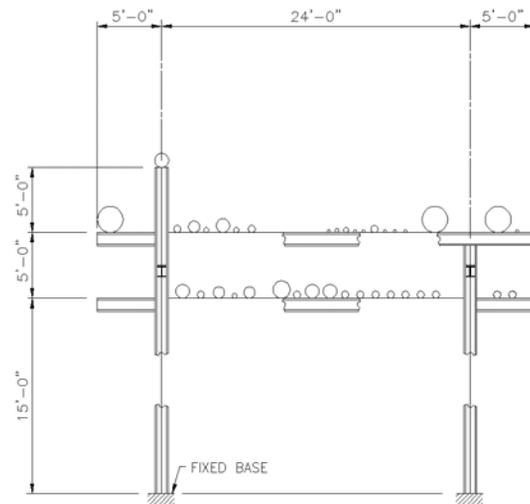


Figure 1: Typical transverse bent.

Earthquake Loads

Earthquake loads are prescribed in IBC section 1613, which references ASCE 7. Seismic detailing of materials as prescribed in ASCE 7 Chapter 14 is specifically excluded; instead, seismic detailing of structural steel materials is prescribed in IBC Chapter 22.

PIP STC01015 recommends that earthquake loads for pipe racks be determined in accordance with ASCE 7 and the following:

- Evaluate drift limits in accordance with ASCE 7 Chapter 12.
- Consider pipe racks to be nonbuilding structures in accordance with ASCE 7 Chapter 15.
- Consider the recommendations of the ASCE guidelines.
- 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) that includes the operating dead load (D_o) as part of the seismic effective weight.
- Consider an empty earthquake load (E_e) that includes only the empty dead load (D_e) as part of the seismic effective weight.

Seismic Design Considerations

ASCE 7 Chapter 11 defines a nonbuilding structure similar to a building as: “A nonbuilding structure that is designed and constructed in a manner similar to buildings, will respond to strong ground motion in a fashion similar to buildings, and has a basic lateral and vertical seismic force-resisting system conforming to one of the types indicated.” Examples include pipe racks.

As a nonbuilding structure, consideration of seismic effects on pipe racks should be in accordance with ASCE 7 Chapter 15, which refers to other chapters as applicable.

Seismic System Selection

Either ASCE 7 Table 12.2-1 or ASCE 7 Table 15.4-1 can be used to choose a seismic force-resisting system, which will provide the prescribed seismic detailing requirements, design parameters (R , Ω_o , C_d), and height limitations. Table 15.4-1 permits select types of nonbuilding 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 those specified in Table 12.2-1. Note that Table 15.4-1 includes options where seismic detailing per AISC 341 is not required for SDC D, E, or F. For example, steel ordinary moment frames can be designed with $R = 1$ without seismic detailing. Seismic detailing requirements can also be avoided in SDC B and C for any structural steel system if $R = 3$ or less, excluding cantilevered column systems.

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

In the longitudinal direction, when bracing is present, the choices are usually special concentrically braced frame or ordinary concentrically braced frame. Less common choices are eccentrically braced frame or buckling-restrained braced frame. If bracing is not present, the choices in the longitudinal direction are the cantilevered column systems.

In both directions, the seismic system selected must be permitted for both the SDC and the pipe rack height. ASCE 7 Table 15.4-1 footnotes permit specific height limits for pipe racks detailed with specific seismic systems:

- With $R = 3.25$, "Steel ordinary braced frames are permitted in pipe racks up to 65 feet (20 m)."
- With $R = 3.5$, "Steel ordinary moment frames are permitted in pipe racks up to a height of 65 feet (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 feet (11 m)."
- With $R = 4.5$, "Steel intermediate moment frames are permitted in pipe racks up to a height of 65 feet (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 feet (11 m)."

Period Calculations

The fundamental period determined from ASCE 7 Chapter 12 equations is not applicable for nonbuilding structures, including pipe racks, because they do not have the same mass and stiffness distributions assumed for buildings. It is acceptable to use any analysis approach that accurately includes 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

Static or dynamic analysis methods can be used. Static procedures are allowed only under certain conditions of regularity, occupancy, and height. 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. A dynamic analysis procedure is required for a pipe rack if it is assigned to SDC D, E, or F and it either:

- has $T \geq 3.5T_s$;
- exhibits horizontal irregularity type 1a or 1b; or
- exhibits vertical irregularity type 1a, 1b, 2, or 3.

The most common dynamic procedure used for pipe racks is modal response spectrum analysis. The equivalent lateral force (ELF) procedure 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 are not appropriate and should not be used for pipe racks.

Equivalent Lateral Force Procedure

The ELF procedure involves calculating the effective earthquake loads in terms of a static base shear that is dependent on the imposed ground acceleration and the structure's mass (effective seismic weight), dynamic characteristics, ductility and 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.

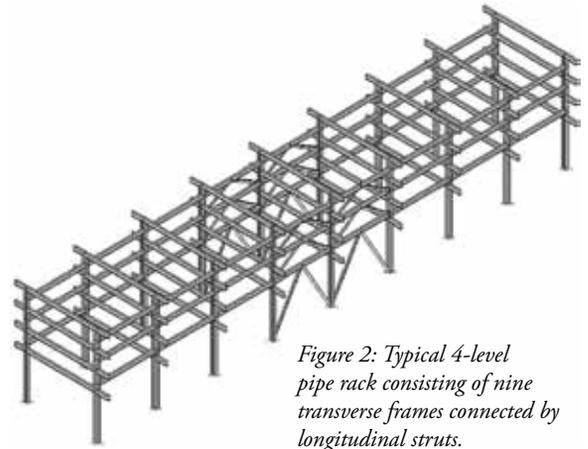


Figure 2: Typical 4-level pipe rack consisting of nine transverse frames connected by longitudinal struts.

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

Modal Response Spectrum Analysis

MRSA is acceptable for the analysis of pipe racks, and may be required 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 that result in an accurate distribution of the base shear forces throughout the structure. The MRSA must include a sufficient number of modes in order to achieve a minimum of 90% mass participation.

Two MRSA runs are typically required for pipe racks. The first run includes the operating dead load (D_o) as the seismic effective weight to determine the operating earthquake load (E_o). The second run includes 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 an engineer 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.

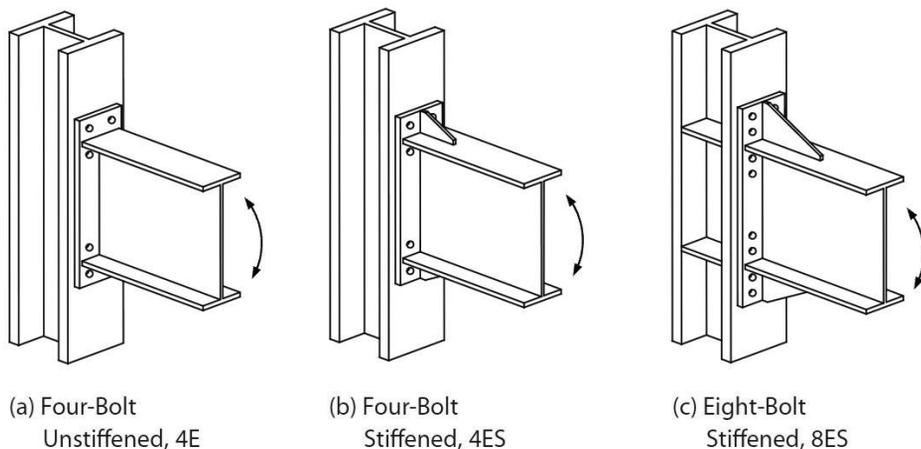


Figure 3: AISC 358 extended end plate connections.

Drift

To obtain amplified seismic displacements, the displacement results calculated from the elastic analysis must be multiplied by the quantity (C_d/I_c) to account for the expected inelastic deformations when checking against the drift limits of ASCE 7 Table 12.12-1. The displacement results must be multiplied by C_d for checking pipe flexibility and structure separation.

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

Seismic Detailing Requirements

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

AISC 341 includes such requirements for each structural steel system listed in the two 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 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 frames. One of the systems included in AISC 358 is the bolted end-plate moment connection, commonly used in pipe rack construction (Figure 3). These connections are popular in industrial plants because they involve no field welding.

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 serves 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 non-redundant structure.

- For a transverse bent to qualify for $\rho = 1.0$, it must have four or more columns and three or more bays at each level. This ensures that the loss of moment resistance at both ends of a single beam does 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 must have two or more bays of chevron or X bracing (or four individual braces) at each level on each frame line. This ensures that the loss of an individual brace or connection does 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 serves as a diaphragm and provides a load path for lateral transfer, it can be treated as a redundant structure.

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

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