

Structural Design of Steel Pipe Support Structures

By Kasi V. Bendapudi, P.E., S.E.

Structural steel pipe supports are extensively utilized in industrial and manufacturing facilities. Lack of uniform industry standards for this topic leads to each organization adopting its own engineering standards, at times, without a clear understanding of the underlying theoretical concepts and the cost implications. This is the first of a two-part series of articles on the behavior and design of steel support structures for pipes. This article (Part 1) discusses the effects of ambient temperature changes, expansion joint requirements, and an introduction to design loads. Part 2 concludes with the continuation of design loads, structure stability concepts and detailing for stability requirements.



Side view of 4 tier process pipe rack with longitudinal bracing. Courtesy of Midrex Corporation, Inc., Charlotte, NC.

It is common to overemphasize the structural design of pipe support structures, rather than focus on detailing for stability or economics and practical aspects of the steel structure and the foundations. This is sometimes referred to as “over-designing” and “under-detailing”. Sometimes the hanger-type pipe supports or the trapezes supported by another structure, such as the main building frame, are referred to as “pipe support structures.” For the purposes of this discussion, the terms “pipe racks,” “pipe supports,” and “pipe support structures” are interchangeable. Essential elements for limit states of pipe support systems are often ignored, since these systems are comprised of secondary elements and rarely impact the structural integrity of any industrial facility.

Structural failures of pipe supports are neither documented nor disseminated to the structural community. The structural design of pipe racks varies widely depending upon the plant operations and the associated plant standards. However, pipe rack failures could cause serviceability problems for plant operations. Failures of pipe support systems could potentially impact the health, welfare, and safety of

plant personnel due to pipe breakage or leaks. The following discussion includes a review of the considerations involved in the design, detailing, and structural stability of pipe racks. Optimal solutions are still governed by the judgment of the design engineer.

Overview of piping design

In general, pipes are designed to move freely on their supports in the longitudinal direction (along the axis of the pipe), except at the anchor points. Pipe anchorages are required to account for expansion and contraction of pipes due to variations in the ambient temperatures. The expansion/contraction of pipes resulting from changes in temperature and pressure of the contents is taken into consideration by the piping engineers during piping design. Anchor points will be required to maintain the pipes in a state of equilibrium. Expansion loops are also used to limit pipe stresses and the associated failures in the piping

systems. The movements of the pipes occur due to expansion, contraction, and transient loads. System shutdowns and restarts could also cause movements in the pipes. Transverse guides limit the lateral displacements of the pipes.

Temperature effects

Ambient temperature differentials induce forces in both pipes and pipe supports. These forces are generally induced over a period of time if they are due to variations in the ambient temperature. However, the forces occur more rapidly if the thermal variations are affected by the contents in the pipes. Particularly during the time of plant startups and shutdowns, these forces can occur rapidly. A pipe rack or a pipe support is not typically subjected to noticeable punishment under seasonal temperature differentials, because it responds like an “accordion”. Thermal variations due to the contents of the pipe result in anchor forces that are more severe

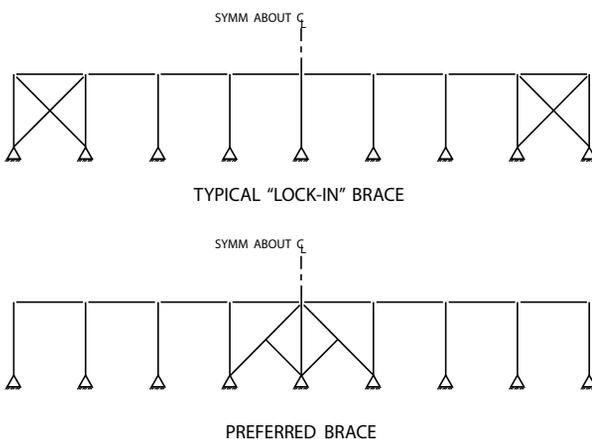


Figure 1: Vertical bracing arrangements.

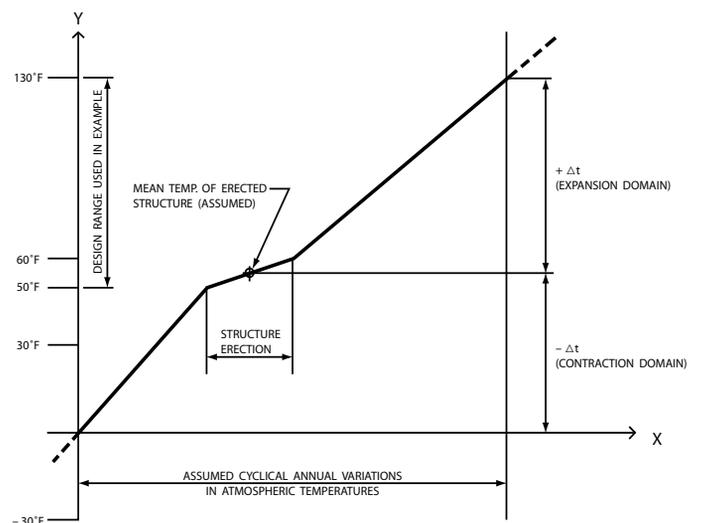


Figure 2: Thermal variations of structure.

and should be considered in the design of the supporting structure.

The effects of temperature change (expansion or contraction) occur with respect to the center of thermal stiffness of the structure. As a matter of good practice, "lock-in" bracing (*Figure 1*) should be avoided. Such vertical bracing provided at the ends of the pipe rack structure, in any given straight segment of the structure, tends to restrain the thermal forces. On the other hand, if the vertical bracing is provided at the center or close to the center of the pipe rack structure, the "accordion" effect can be achieved in the structural system. Expansion joints are not necessary for pipe rack structures less than approximately 400 to 500 feet (125m to 155m) in length, if lock-in bracing is avoided. Failures of pipe rack structures due to lack of expansion joints are rare, and no recorded evidence is readily available.

The coefficient of linear expansion (ϵ) is the change in the length, per unit length, for a change of one degree of temperature. The thirteenth edition of the AISC *Steel Construction Manual* recommends a value of 0.0000065 for each degree Fahrenheit (F) as a reasonable approximation of the coefficient of thermal expansion for temperatures less than 100 degrees F.

The change in length

$$\Delta l = \epsilon t l \quad \text{Equation 1}$$

Where l is the original length of the member and t is the change in temperature.

The force imparted (P) due to restraint of free thermal expansion (Δl)

$$P = AE (\Delta l) / l \quad \text{Equation 2}$$

Substituting $\epsilon t l$ for Δl in *Equation 2* the change in stress σ (psi) is expressed as

$$\sigma = E \epsilon t \quad \text{Equation 3}$$

$$P = A \sigma = A E \epsilon t, \quad \text{Equation 4}$$

where A is the cross-sectional area of the member.

The metrics for establishing ambient temperature differential are to some extent subjective and should be based on recorded historical data of the atmospheric temperature conditions, preferably site-specific. The variations in the seasonal temperature with respect to the in-place condition of the structure need not be more than 80° F at most locations of the structural systems (*Figure 2*). A similar temperature gradient diagram should be established for each project location.

Variation of 80° F in temperature would cause an elongation (*Equation 1*) of approximately 1/8-inch in a 20-foot-long structural member and, if fully restrained, would cause a stress of 15.1 ksi (*Equation 3*). For a pipe rack longitudinal beam (W12x26), the internal force induced to restrain the elongation

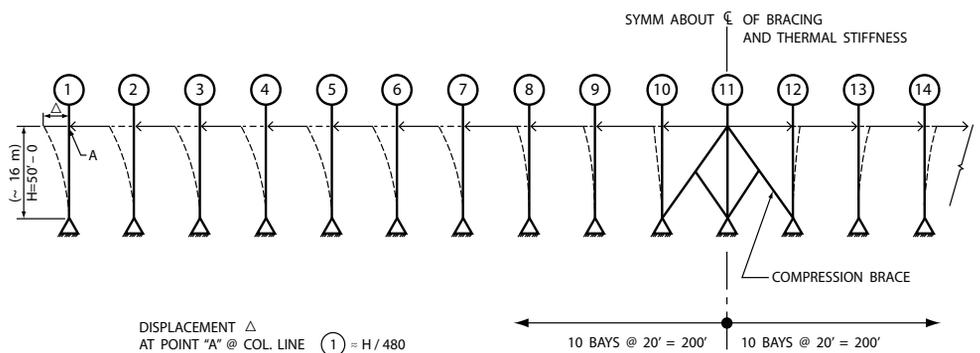


Figure 3: Partial elevation of pipe rack with no expansion joints.

would be 116 kips (*Equation 4*). Design considerations should be segregated between the design of the piping for its own movements and the design of pipe rack steel for the effects of variations in the ambient conditions. The movements of pipes during the operating conditions, or at the time of startups and shutdowns, could either happen in the expansion domain or the contraction domain (*Figure 2*). Any attempt to establish a design basis for the pipe rack steel to combine both of these effects occurring concurrently is very cumbersome and impractical.

Any attempt to restrain such forces at each frame of the pipe rack would also be impractical and uneconomical. Therefore, lock-in bracing as shown in *Figure 1* should be avoided. For example, in a 440-foot-long stretch of pipe rack with frames spaced 20 feet apart, the middle two frames should be braced in accordance with the preferred method as shown in *Figure 1*. In this arrangement, the extreme column would be displaced approximately 1.25 inches (0.125 x 10 bays) at the top in the longitudinal direction. Column slope caused by this

expansion is $H/480$ for a column height of 50 feet. Typically, longitudinal drift will not cause serviceability problems. There are no codes or industry standards that prescribe limits on longitudinal drift. For long stretches of pipe racks, the pipe stress engineer should be consulted for any special requirements for longitudinal drift control. As a matter of interest, Process Industry Practice (PIP) *Structural Design Criteria* 2007 (STC 01015) limits transverse drift of the pipe rack bents to $H/100$, which is very lenient. Therefore, the column displacement at the top is not significant, and the structure should be allowed to expand and contract due to the variations of the ambient temperatures. The total column displacements would be reduced along the longitudinal direction (see Δ in *Figure 3*) if the column bases are fixed in the longitudinal direction; however, this is neither a common practice nor necessary. No expansion joints in the pipe racks are necessary for rack lengths less than 500 feet (approximately 155m). Under such provisions (*Figure 3*), the structure is considered stable and serviceable.

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Design loads

Pipe racks should be designed for all gravity and natural hazards such as wind and seismic loads, internal forces induced by restraint of free thermal expansion, and the pipe anchor and guide support loads. Gravity loads are the largest of the operating loads during normal plant operations or under the hydro-test condition. The primary anchor forces consist of longitudinal and transverse forces. Calculated and identifiable load paths for strength and stability should be provided. The longitudinal anchor forces are typically resisted by the vertical bracing of the pipe rack (Figure 3, page 7). If adequate stiffness for the bracing is provided, it will function as a “lean-on” brace. Pipe anchor supports should be stabilized in both orthogonal planes. Bracing in the longitudinal direction for long stretches (greater than 500 feet) are typically located at or near the center of thermal stiffness. The transverse bracing, or bracing perpendicular to the length of the pipe rack, does not provide restraint to the longitudinal thermal movements of the pipe rack.

Designing pipe supports for seismic conditions consists of two parts: 1) design of connections (anchorage or fastening) of the pipes to the supporting structure for the seismic loads; and, 2) design of the pipe support structure for the seismic forces. These two cases are independently investigated and should not be combined. The controlling combinations for loads are specified in the governing codes and standards. The base shears at the pipe support structure must be transferred to the foundations by means of appropriate anchorage. The guidance given by the building codes is minimal in this regard, since pipe racks are not considered to be buildings and must be treated as “Other Structures.”

Design of the pipe support structure, including the lateral-load-resisting elements, should typically be on the basis of the “equivalent lateral force procedure.” ASCE 7 and the International Building Code (IBC) also permit the “modal analysis procedure” and “linear response history analysis” for non-building structures. Dynamic analysis may not be necessary unless the contents of the pipes are hazardous to the environment and there is a concern for public safety. Pipe support structures should maintain symmetry and uniformity. Irregularities should be eliminated as much as possible.

Proper fastening of the pipes to the supporting structure is essential in the seismic design of pipe racks. The design of connections between the pipes and the supporting structure should be based on the seismic base shear attributable to the dead weight of the pipes and their contents. Such seismic force should be applied at the centroid of the pipe, and the

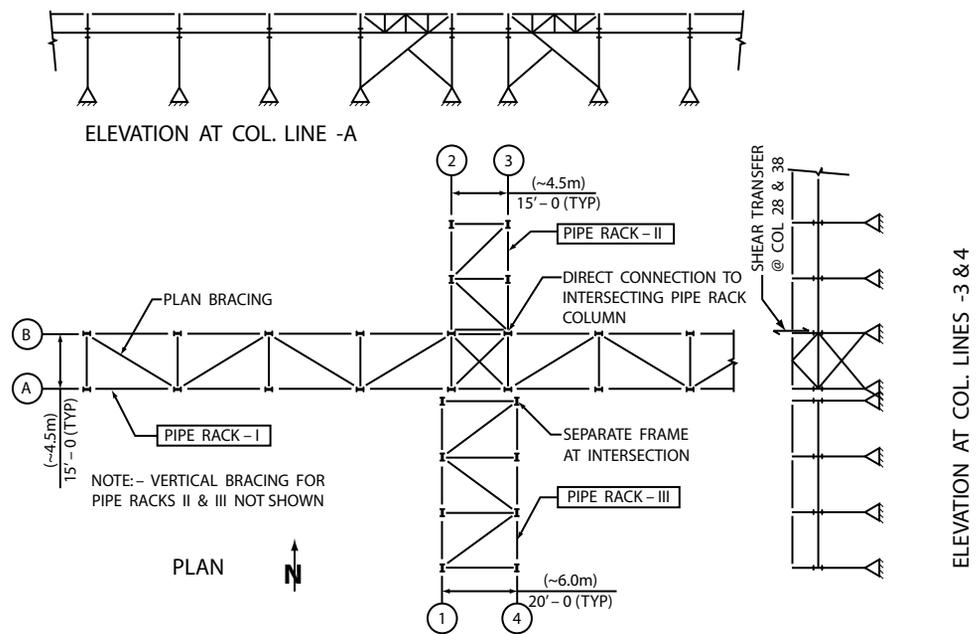


Figure 4: Intersecting pipe racks.

associated eccentricity should be considered in the design of the fastening system between the pipe and the supporting structure. All pipe support structures should be provided with adequate bracing required for frame stability as discussed in this article. Horizontal bracing (plan bracing) underneath the pipes may be required to transmit the horizontal seismic loads applied at the centroids of the pipes (Figure 4). The plan bracing would function as a collector element (diaphragm) in order to transmit the seismic loads to the vertical bracing. The transverse force component of anchor loads should be assumed to be shared by the adjoining two frames on either side of the anchor point. This load-sharing concept assumes decay of this force beyond these five frames. This is only possible when the plan bracing is provided. Therefore, it is imperative that the anchor points be located with at least two frames before the end of the pipe support segment.

Summary

Part 1 of this two-part series discussed temperature effects on pipe racks, including the forces imparted, recommended bracing arrangements, drift control requirements, and an introduction to design loads. The upcoming Part 2 will discuss the interaction between the pipe support structure and the pipes, stability requirements, and detailing for the stability of pipe racks. ■

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