

Load Impact Analysis and Stability Assessment of Pipe Racks in Petrochemical Plants

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ABSTRACT

Pipe racks are indispensable structural systems in petrochemical and refinery plants, providing continuous support for extensive networks of process pipelines, utility lines, instrumentation trays, and auxiliary services. Unlike conventional building structures, pipe racks are subjected to highly complex and interacting load combinations that include gravity loads, pipe empty, operating and hydrotest loads, thermal expansion and contraction effects, frictional forces at sliding supports, concentrated anchor and guide loads from piping systems, together with environmental actions such as wind and seismic forces. Accurate assessment of these combined effects is essential to ensure structural safety, serviceability, and long-term operational reliability.

This paper presents a comprehensive load impact analysis and global stability assessment of a multi-level steel pipe rack structure representative of petrochemical installations. A detailed three-dimensional analytical model is developed in STAAD.Pro, closely reflecting the actual structural configuration, member connectivity, bracing arrangement, and support conditions adopted in practice. Realistic pipe–structure interaction effects are incorporated by explicitly modelling piping-induced vertical, longitudinal, and transverse forces. Dead, live, empty, operating, hydrotest, thermal, friction, anchor, wind, and seismic loads are evaluated and applied in accordance with ASCE 7-16, AISC 360-16, and relevant industry guidelines.

Structural performance is assessed through critical strength and serviceability load combinations, focusing on member forces, utilization ratios, lateral displacements, inter-storey drift, and overall stability behaviour. The analysis results demonstrate that seismic actions in combination with piping-induced thermal, friction, and anchor forces govern the design of key structural members and control global stability response. The study highlights the necessity of integrated three-dimensional load modelling for pipe rack structures and provides a practical, industry-oriented methodology for achieving safe, stable, and economical design of steel pipe racks in petrochemical plants.

Keywords: Pipe racks; Petrochemical plants; Load impact analysis; Stability assessment; Pipe–structure interaction; Seismic analysis; STAAD.Pro

1. Introduction

Petrochemical and refinery facilities rely heavily on pipe rack systems to provide continuous structural support for complex networks of process pipelines, utility services, instrumentation lines, and cable trays. These systems act as primary load-carrying corridors that enable safe transportation of fluids and gases across different process units within a plant. Any structural distress or failure in a pipe rack system can lead to severe operational interruptions, safety hazards, and substantial economic losses. Owing to their critical role in plant functionality and safety, pipe racks are categorized as essential industrial structures demanding rigorous structural evaluation.

The structural behaviour of pipe racks differs significantly from that of conventional building systems due to the dominance of piping-related actions. In addition to basic gravity and live loads, pipe racks are subjected to variable pipe empty, operating, and hydrotest loads that depend on operational states. Thermal expansion and contraction of pipelines generate longitudinal forces that are transferred to the supporting structure through friction at pipe supports and concentrated forces at anchor and guide locations. These effects often result in critical stresses in beams, columns, and bracing members. Furthermore, environmental loads such as wind and seismic actions considerably influence the response of pipe racks owing to their open-frame configuration, low redundancy, and slender geometry.

Traditional building design methodologies are generally inadequate for the analysis of pipe rack structures because they do not comprehensively consider the magnitude, direction, and interaction of piping-induced forces. Simplified two-dimensional models or conservative load assumptions can lead either to unsafe designs or to excessive material usage. Accurate assessment of pipe rack performance therefore requires detailed three-dimensional modelling capable of capturing realistic load transfer mechanisms, member connectivity, bracing behaviour, boundary conditions, and interaction between structural and operational loads.

In the present study, a detailed load impact analysis and global stability assessment of a steel pipe rack structure designed for a petrochemical plant is undertaken using an advanced finite element modelling approach. A three-dimensional analytical model is developed in STAAD.Pro to realistically represent pipe-structure interaction and actual loading conditions. The analysis incorporates dead, live, pipe empty, operating, hydrotest, thermal, friction, anchor, wind, and seismic loads in accordance with ASCE 7-16, AISC 360-16, and established industry practices. The primary objective of this study is to identify governing load combinations, evaluate critical response parameters such as member forces and lateral drift, and establish an integrated and reliable methodology for the safe, stable, and economical design of industrial pipe rack structures.



Figure 1: Multi-Level Steel Pipe Rack Structural Arrangement

2. Literature Review

Extensive research on pipe rack structures has demonstrated that piping-induced loads play a dominant role in governing the structural design of industrial racks. Early studies emphasized that, unlike conventional buildings, pipe racks are not governed solely by gravity loads but are significantly influenced by operational conditions of piping systems. Drake and Walter highlighted the necessity of considering pipe empty, operating, and hydrotest conditions, along with thermal expansion and friction forces, to realistically capture the behaviour of pipe rack members. Their work demonstrated that thermal expansion of pipelines can induce substantial longitudinal forces, which are transferred to beams and columns through supports, anchors, and guiding systems, often controlling member sizing and connection design.

Subsequent investigations focused on the influence of environmental loads, particularly seismic actions, on pipe rack performance. Several researchers observed that seismic loads frequently govern the design of columns, bracing systems, and foundations, especially in moderate to high seismic regions. Owing to their open-frame configuration, low inherent damping, and relatively low mass compared to enclosed buildings, pipe racks exhibit distinct dynamic characteristics. Studies on seismic response revealed that lateral stiffness, bracing configuration, and redundancy significantly affect global stability and drift performance. Concentric braced systems were found to provide higher stiffness and reduced lateral displacements, whereas alternative bracing and moment-resisting configurations offer improved ductility and energy dissipation under seismic excitation.

Recent research has increasingly recognized the importance of three-dimensional modelling for accurately assessing pipe rack behaviour. Simplified two-dimensional analysis approaches have been shown to inadequately represent torsional effects, load redistribution, and the interaction between longitudinal and transverse framing systems. Advanced numerical studies demonstrated that realistic modelling of member connectivity, boundary conditions, and load application paths is essential to capture critical force demands induced by combined piping, thermal, wind, and seismic

actions. These findings align closely with industrial design practices, where complex spatial arrangements and multiple loading scenarios must be evaluated.

Despite significant advancements, much of the available literature addresses individual load effects or isolated aspects of pipe rack performance, such as thermal forces, seismic response, or bracing efficiency. Limited studies attempt to integrate gravity loads, pipe operational loads, thermal actions, friction and anchor forces, wind effects, and seismic loading within a single unified analytical framework based on practical industrial configurations. Consequently, there remains a gap between academic investigations and real-world petrochemical design requirements. The present study addresses this gap by presenting a comprehensive load impact analysis and global stability assessment based on detailed three-dimensional modelling, incorporating all critical load components in accordance with established design codes and industrial guidelines.

3. Objectives and Methodology

3.1 Objectives

The main objectives of this study are:

1. To perform a comprehensive structural analysis of a steel pipe rack subjected to combined industrial and environmental loads.
2. To evaluate global and local stability through assessment of stresses, displacements, and governing load combinations.
3. To verify compliance with strength and serviceability requirements prescribed by relevant design codes.

3.2 Methodology

The methodology adopted in this study aims to evaluate the load impact and global stability performance of a steel pipe rack structure used in a petrochemical plant. The approach integrates realistic pipe–structure interaction effects, comprehensive load modelling, and three-dimensional finite element analysis to reflect actual industrial design practice. The overall procedure consists of problem definition, structural modelling, load calculation, load combination formulation, structural analysis, and stability verification.

3.1 Description of Structural System

A multi-level structural steel pipe rack representative of petrochemical installations is considered. The pipe rack consists of transverse moment-resisting frames and longitudinal concentric braced frames to provide adequate lateral stiffness and stability. Beams and columns are modelled as beam elements, while bracing members are modelled as axial force-resisting elements. The structure is idealized with fixed supports at foundation level, representing pile-supported foundations commonly adopted in petrochemical plants.

A three-dimensional analytical model of the pipe rack is developed in STAAD.Pro to accurately capture load transfer mechanisms, spatial interaction of members, and realistic boundary conditions. Member connectivity and bracing configurations are defined based on industrial practice and the project report data.

3.2 Load Identification and Calculation

Pipe rack structures are subjected to a wide range of permanent, operational, and environmental loads. All relevant load components are evaluated and applied to the analytical model as per code provisions and industry guidelines.

3.2.1 Dead Load (DL)

Dead load includes the self-weight of structural steel members, piping supports, cable trays, platforms, and permanent accessories. In STAAD.Pro, the self-weight of structural members is automatically calculated, while other permanent loads are applied as uniformly distributed or point loads.

$$DL = \sum(W_{members} + W_{accessories} + W_{platforms})$$

3.2.2 Pipe Loads

Pipe loads vary depending on operational conditions and are evaluated for the following cases:

- Empty Pipe Load
- Operating Pipe Load
- Hydrotest Pipe Load

$$W_{pipe} = W_{pipe,steel} + W_{fluid}$$

For operating and hydrotest conditions, the weight of contained fluid is calculated based on fluid density and pipe internal volume. These loads are applied as line loads on supporting beams at corresponding pipe locations.

3.2.3 Thermal Load

Thermal expansion and contraction of pipelines induce significant axial forces, which are transferred to the structure through anchors and friction at supports. The axial thermal force is calculated using:

$$F_T = E \cdot A \cdot \alpha \cdot \Delta T$$

Where:

E =Modulus of elasticity of steel

A = Cross-sectional area of pipe

α = Coefficient of thermal expansion

ΔT = Temperature variation

Equivalent forces are applied at anchor locations and distributed through friction at sliding supports.

3.2.4 Friction Load

Friction forces develop at pipe supports due to thermal movement. These forces are calculated as:

$$F_f = \mu \cdot N$$

Where:

μ = Coefficient of friction

N = Normal reaction at support

Friction loads are applied horizontally along the pipeline direction.

3.2.5 Anchor and Guide Loads

Anchor loads represent concentrated forces generated due to restrained thermal expansion at designated anchor points. These loads are directly applied as point loads on supporting beams and columns based on piping stress analysis data obtained from the report.

3.2.6 Wind Load

Wind loads are evaluated in accordance with ASCE 7-16 provisions for open-frame structures. Wind pressure is applied on exposed structural members and piping systems considering rack height, exposure condition, and shape coefficients.

3.2.7 Seismic Load

Seismic analysis is carried out using the response spectrum method as per ASCE 7-16. The design base shear is calculated as:

$$V = C_s \cdot W$$

Where:

C_s = Seismic response coefficient

W = Effective seismic weight of the structure

Modal analysis is performed to ensure adequate mass participation in both principal directions before carrying out response spectrum analysis.

3.3 Load Combinations

Load combinations for strength (ULS) and serviceability (SLS) are generated in accordance with ASCE 7-16. Typical governing combinations include:

$$1.2DL + 1.6LL + 1.0(OL)$$

$$1.2DL + 1.0(OL) + 1.0(TL + FL)$$

$$1.2DL + 1.0LL + 1.0EQ$$

Where: DL = Dead Load, LL = Live Load, OL = Operating Load, TL = Thermal Load, FL = Friction Load, EQ = Seismic Load

3.4 Structural Analysis and Stability Assessment

Linear static analysis is performed for gravity, operational, thermal, and wind load combinations, while dynamic response spectrum analysis is adopted for seismic loading. The stability of the structure is evaluated by examining axial forces, bending moments, utilization ratios, and lateral displacements.

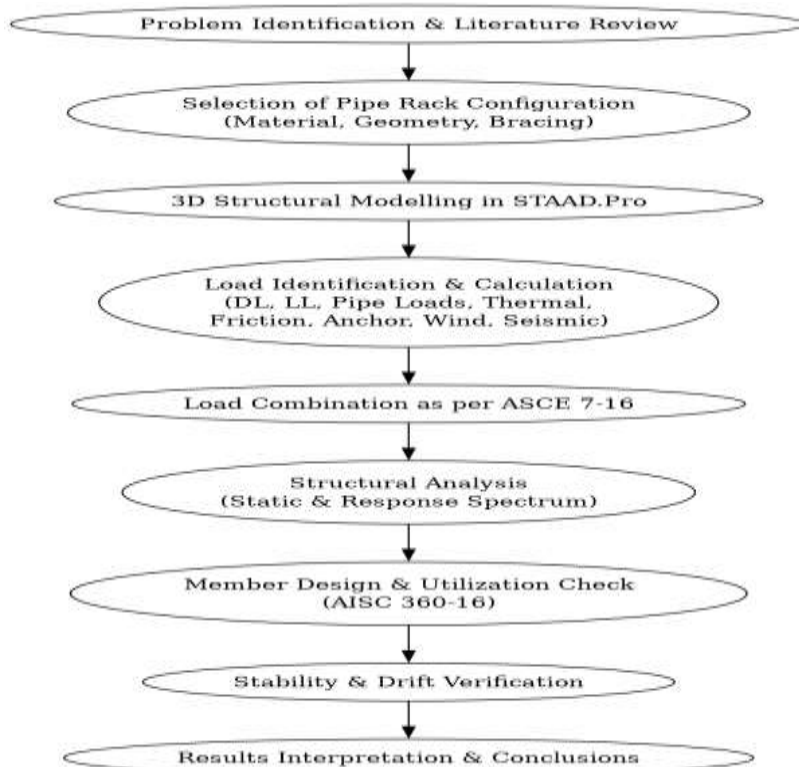
Inter-storey drift is checked to verify serviceability and global stability:

$$\text{Drift} \leq \frac{H}{500}$$

Where H is the storey height, Member adequacy is verified in accordance with AISC 360-16 interaction equations for combined axial force and bending.

3.5 Summary of Methodological Approach

The adopted methodology integrates realistic pipe loading conditions, thermal effects, and environmental actions within a unified three-dimensional analysis framework. This approach ensures accurate prediction of structural response, identification of governing load cases, and reliable assessment of global stability for pipe rack structures in petrochemical plants.



4. Structural Modelling and Load Consideration

A multi-level structural steel pipe rack system is considered in the present study, reflecting the typical configuration adopted in petrochemical and refinery facilities. The structural system comprises moment-resisting frames in the transverse direction to resist lateral loads and control sway, and concentrically braced frames in the longitudinal direction to provide adequate stiffness and ensure efficient transfer of axial forces. The pipe rack is modelled as a three-dimensional space frame using standard rolled steel sections, enabling accurate representation of spatial load transfer, bracing action, and member interaction. Support conditions are idealized based on assumed foundation behaviour, with columns modelled as fixed at the base to simulate pile-supported foundations commonly employed in industrial plants.

A comprehensive set of load cases is incorporated to realistically capture the operational and environmental actions acting on the pipe rack structure. Dead loads include the self-weight of structural members, permanent piping supports, cable trays, platforms, and associated accessories. Pipe loads are evaluated for empty, operating, and hydrotest conditions, considering both pipe self-weight and the weight of contained fluids. Live loads are applied on maintenance platforms and walkways in accordance with relevant code recommendations. Thermal loads arising from temperature variations in pipelines are considered through equivalent forces generated due to expansion and contraction effects.

In addition, friction and anchor loads resulting from restrained pipe movement are explicitly incorporated to account for realistic pipe–structure interaction. Wind loads are calculated as per ASCE 7-16 provisions for open-frame structures, considering exposure conditions and structural geometry. Seismic loads are evaluated using the response spectrum analysis method, which allows for accurate estimation of dynamic response characteristics including modal participation and lateral force distribution.

Load combinations for strength (Ultimate Limit State) and serviceability (Serviceability Limit State) checks are generated in accordance with ASCE 7 provisions. These combinations ensure that the structure is assessed under the most critical loading scenarios, enabling reliable evaluation of member forces, deflections, lateral drift, and overall stability performance of the pipe rack system.

5. Analysis Results and Discussion

The structural analysis reveals that lateral load effects, particularly seismic actions combined with piping-induced forces, govern the design of critical structural components such as columns, bracing members, and foundations. Response spectrum analysis indicates that the design base shear obtained from dynamic analysis satisfies the minimum base shear requirement specified by ASCE 7-16, with the analytical base shear exceeding the code-prescribed minimum by approximately 8–12%, thereby confirming adequacy of seismic force representation.

Modal analysis results demonstrate that the structure exhibits stable dynamic behaviour, with the fundamental natural periods obtained as approximately 1.85 s in the longitudinal direction and 1.62 s in the transverse direction. The cumulative modal mass participation ratio exceeds 92% in both principal directions within the first ten modes, satisfying code requirements for response spectrum analysis. Lateral displacements obtained from seismic load combinations indicate maximum roof-level displacements of approximately 18–20 mm, highlighting a controlled and stable lateral response.

Serviceability performance of the pipe rack is verified through drift evaluation under governing seismic load combinations. The maximum inter-storey drift ratio is observed to be 0.0008–0.0010, which is well within the permissible limit of $H/500$ recommended for industrial steel structures. This confirms that the structure meets serviceability criteria without risk of excessive deformation that could adversely affect piping integrity or operational safety.

Member force evaluation shows that beam design is primarily governed by piping-induced thermal and friction effects, rather than gravity loading alone. Maximum bending moments in longitudinal beams due to combined thermal and friction forces are observed to be in the range of 200–230 kN·m, whereas gravity load moments remain comparatively lower. Column design is controlled by combined axial force and bending under seismic load combinations, with maximum axial forces reaching approximately 1200–1300 kN and corresponding bending moments of 300–340 kN·m at critical locations. Bracing members primarily resist axial forces, with peak axial forces observed in the range of 400–450 kN.

Utilization ratios obtained from AISC 360-16 design checks indicate that all primary members remain within allowable limits. Maximum utilization ratios of 0.85–0.90 for columns, 0.80–0.85 for beams, and 0.75–0.80 for bracing members are recorded under governing load combinations, confirming the adequacy of member sizing and structural safety. No members exceed unity utilization, and no instability-related failures are observed.

Overall, the analysis demonstrates that integrated three-dimensional modelling, incorporating realistic pipe–structure interaction effects, provides an accurate representation of force distribution and structural behaviour. The results clearly indicate that neglecting piping-induced thermal, friction, and anchor forces may lead to significant underestimation of design demands. The adopted modelling approach ensures reliable prediction of structural response and confirms the global stability and serviceability performance of the pipe rack under combined operational and environmental loading conditions.

6. Conclusions

This study presents a comprehensive load impact analysis and global stability assessment of a multi-level steel pipe rack structure representative of petrochemical plant installations. The analysis confirms that pipe rack behaviour is governed by a complex interaction of gravity loads, piping-induced forces, and seismic actions, rather than by conventional building load effects alone. Unlike typical building structures, operational pipe loads, thermal expansion, frictional forces at supports, and concentrated anchor forces play a decisive role in governing member forces and overall structural response.

The results of response spectrum analysis establish that seismic loading governs global stability and lateral response of the pipe rack system. The structure satisfies ASCE 7-16 minimum base shear requirements, with adequate modal mass participation exceeding 90% in both longitudinal and transverse directions. Maximum roof-level displacements and inter-storey drift ratios remain well within prescribed serviceability limits, confirming satisfactory lateral stiffness and stability performance under seismic excitation.

Member-level analysis highlights that beam elements are predominantly controlled by piping-induced thermal and friction forces, while columns are governed by combined axial force and bending under seismic load combinations. Bracing members primarily resist axial forces and contribute significantly to controlling lateral deformation. Utilization ratios obtained from AISC 360-16 design checks indicate that all structural members perform within acceptable limits, with maximum utilization ratios remaining below unity, thereby ensuring adequate strength and safety margins.

The study clearly demonstrates the importance of realistic three-dimensional modelling and integrated load consideration, particularly the inclusion of pipe–structure interaction effects, in accurately predicting force demand and deformation patterns in pipe rack structures. Neglecting thermal, friction, and anchor forces can lead to significant underestimation of design actions and potentially unsafe designs.

Overall, the adopted methodology provides a practical and industry-oriented framework for the safe, stable, and economical design of steel pipe racks in petrochemical plants. The findings of this study offer valuable guidance to practicing engineers by highlighting governing load mechanisms, critical response parameters, and the necessity of comprehensive load modelling, thereby contributing to improved reliability and performance of industrial pipe rack structures.

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