Seismic Risk Reduction in Industrial Pipe Rack Structures through Buckling-Restrained Bracing (BRB): A Comprehensive Review

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Abstract:
This review critically evaluates the seismic performance, design methodologies, and structural enhancement strategies for industrial pipe rack systems, with a particular focus on steel pipe racks subjected to dynamic loading. It synthesizes findings from analytical, experimental, and computational studies, emphasizing the unique challenges associated with non-building structures in industrial environments. Key areas of focus include the dynamic interaction between piping systems and their supporting frameworks, the effectiveness of advanced bracing mechanisms such as buckling-restrained braces (BRBs), and the impact of accidental torsional moments during seismic events. The analysis identifies significant gaps in existing design codes—particularly within Indian standards—related to the treatment of bracing performance, torsional irregularities, and the development of simplified performance-based design methodologies. The review highlights the need for integrated seismic assessment approaches that incorporate advanced dynamic analysis, resilient bracing systems, and region-specific design provisions. Bridging these gaps is crucial for preventing structural failures, mitigating environmental and economic risks, and enhancing the operational resilience of industrial infrastructure.

Keywords: *Industrial pipe racks, seismic performance, buckling-restrained braces (BRBs), dynamic seismic analysis, critical infrastructure resilience*

1. INTRODUCTION

Pipe networks are essential to the operation of refineries and industrial plants, serving as the primary means for transporting liquids and gases throughout a facility. A typical piping system consists of interconnected pipes, fittings, flanges, and key components such as pumps, heat exchangers, valves, and tanks. These systems are often referred to as the "veins" of industrial processes, reflecting their critical role in plant functionality. Notably, piping systems can represent a substantial portion of a facility's capital investment—sometimes up to one-third of the total cost. The challenge of routing pipes within limited spaces adds further complexity for engineers tasked with ensuring both efficient layout and reliable support.

Proper support is fundamental to the safe and efficient operation of piping systems. Pipe supports are designed to bear the weight of the pipes and their contents, maintain alignment, and transfer various loads—including those from weight, pressure, temperature changes, and occasional events—to the supporting structure. Pipe racks, sometimes called pipe bridges, are specialized frameworks—commonly made of steel, concrete, or a combination—that elevate and organize pipes, cable trays, and sometimes mechanical equipment. Their design must account for the dynamic interaction between the rack and the piping, particularly under seismic loading, which can induce separation and large forces at support points. Pipe racks are distinct from storage racks, as their primary function is to support active process and utility lines rather than store materials.

In industrial settings, pipe racks are classified as nonbuilding structures (NBS), similar to buildings in terms of their lateral force-resisting systems. They are typically constructed from either structural steel or reinforced concrete, with fire protection measures applied as needed. The racks support multiple levels of piping and cable trays, using various support types—anchors, guides, and springs—based on the required restraint. While structural engineers often model only the rack, and piping engineers focus solely on the piping, it is crucial to consider the combined behaviour of both systems, especially during seismic events. The choice between steel and concrete racks depends on factors such as cost, construction schedule, and material availability. Steel racks, fabricated off-site and assembled quickly, require periodic maintenance, while concrete racks, including precast options, offer durability but may involve longer installation times.

Seismic activity poses a significant risk to pipe rack structures, potentially causing extensive damage due to the unpredictable nature of earthquake forces. Understanding and improving their seismic performance is essential to minimize damage and maintain plant safety. One effective strategy is the installation of damping systems, such as buckling restrained braces (BRBs), which enhance lateral stability and energy dissipation. BRBs are designed to yield in both tension and compression, reducing structural deformations and absorbing seismic energy through controlled inelastic behaviour.

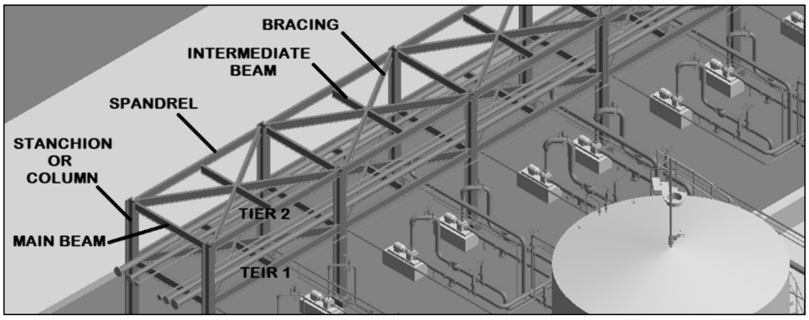

Figure 1 Typical Pipe Rack System

A buckling restrained brace (BRB) is a specialized structural element that improves a building or structure’s ability to withstand repeated lateral loads, such as those from earthquakes. The BRB consists of a slender steel core, which carries the axial load, surrounded by a concrete casing that prevents buckling, and a bond-preventing layer that allows the core to deform independently. Unlike conventional braces, which may lose strength and stiffness due to buckling under compression, BRBs maintain stable, ductile behaviour, allowing them to dissipate energy effectively during seismic events. This technology, first developed in Japan and now widely adopted and regulated internationally, has proven to be a reliable solution for enhancing the seismic resilience of both new and existing structures.

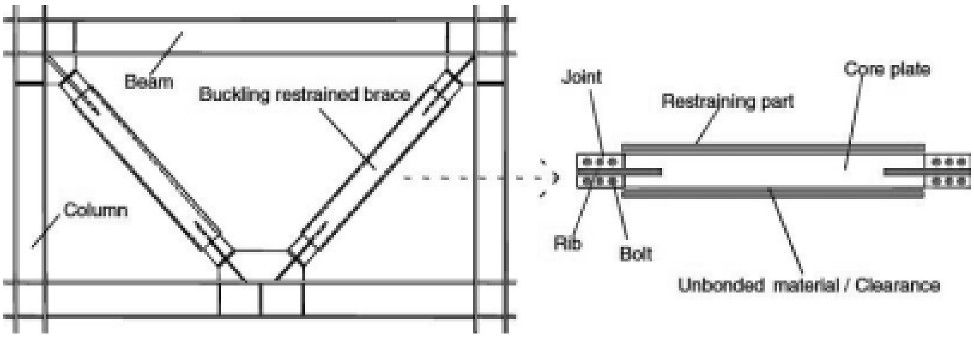

Figure 2 Buckling Restrained Brace (BRB)

A BRB is generally composed of a yielding steel core, a bond-delaminating interface, and an external confining element (typically, a concrete-filled steel tube). In strong earthquakes, the steel core is designed to behave inelastic in the mid-span portion, with the elastic ends straining to focus plastic deformations where they can be most managed. The bond-preventing layer ensures the core and casing act independently, and the external casing provides the necessary stiffness to prevent buckling. This configuration ensures that BRBs deliver predictable, robust performance, making them an effective choice for seismic protection in pipe rack structures.

2. PROBLEM STATEMENT

High Seismic Risk: Pipe rack systems are highly vulnerable to earthquakes, particularly in petrochemical and industrial facilities.

Oversimplified Design Practices: Current Indian design methods often overlook complex behaviours such as pipe–structure interaction and soil–structure interaction.

Inadequate Code Guidance: Existing seismic codes lack specific provisions for the unique geometry and functional requirements of pipe racks.

Neglected Torsional and Bracing Effects: Accidental torsional moments and ineffective bracing configurations are often ignored, leading to higher failure risk.

Lack of Optimized Bracing Design: There is limited research on practical and efficient bracing systems specifically for industrial pipe racks.

3. LITERATURE REVIEW

A comprehensive literature review methodology was employed to systematically identify, screen, and analyze research relevant to the seismic response of steel pipe rack systems, particularly those incorporating buckling restrained braces (BRBs) as stated in figure 1. The process began with a broad preliminary search using keywords such as "pipe rack," "BRB," and "seismic response," yielding a total of 10,440 articles from major academic databases including Springer, Elsevier, Google Scholar, ASCE Library, ScienceDirect, MDPI, and Hindawi, focusing on publications up to 2025. Problem identification was refined by filtering these results to studies specifically addressing the seismic behavior of steel pipe racks, reducing the pool to 4,380 articles. Applying strict search criteria, only articles directly related to the seismic response of steel pipe racks were retained, narrowing the selection to 726 articles. Subsequent eligibility screening was conducted based on titles and abstracts, resulting in 180 articles that addressed earthquake-related damage, software-based analysis, numerical and experimental investigations, and code provisions.

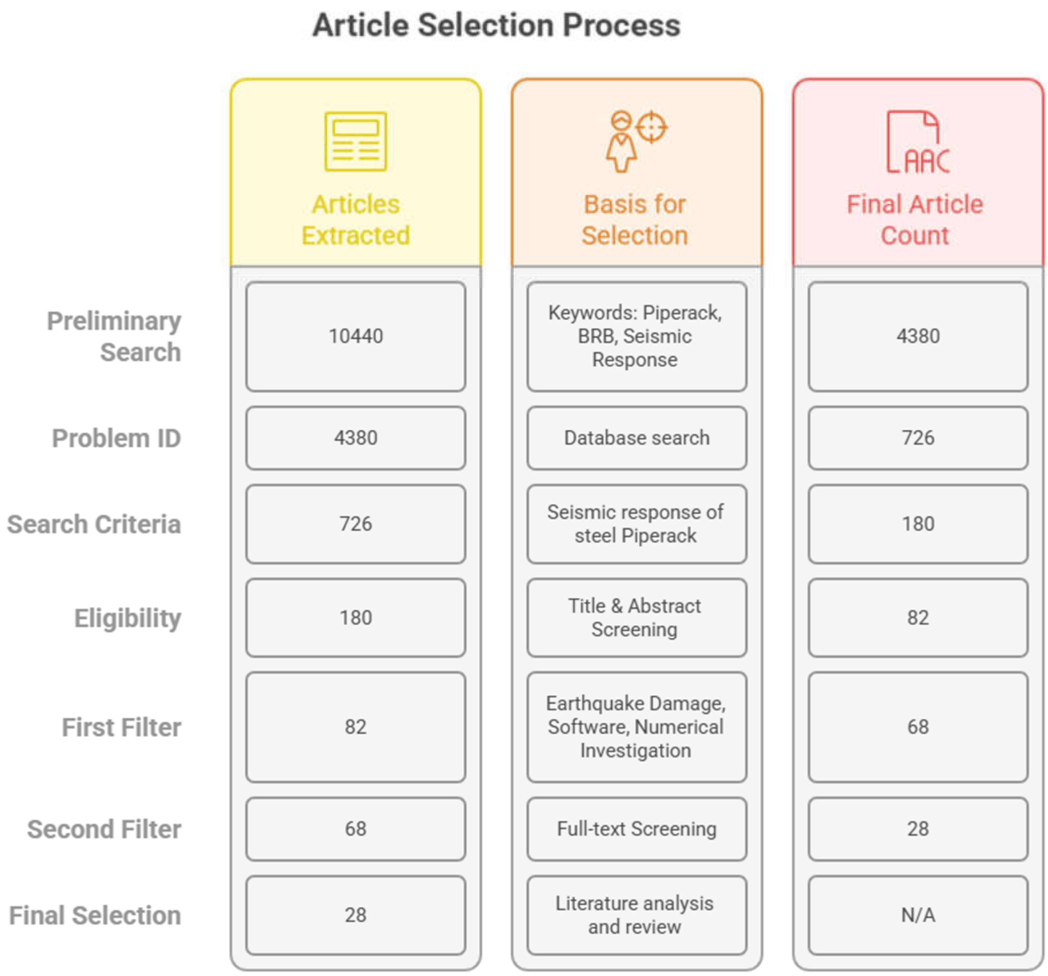

Figure 3 Methodology for Comprehensive Literature Review

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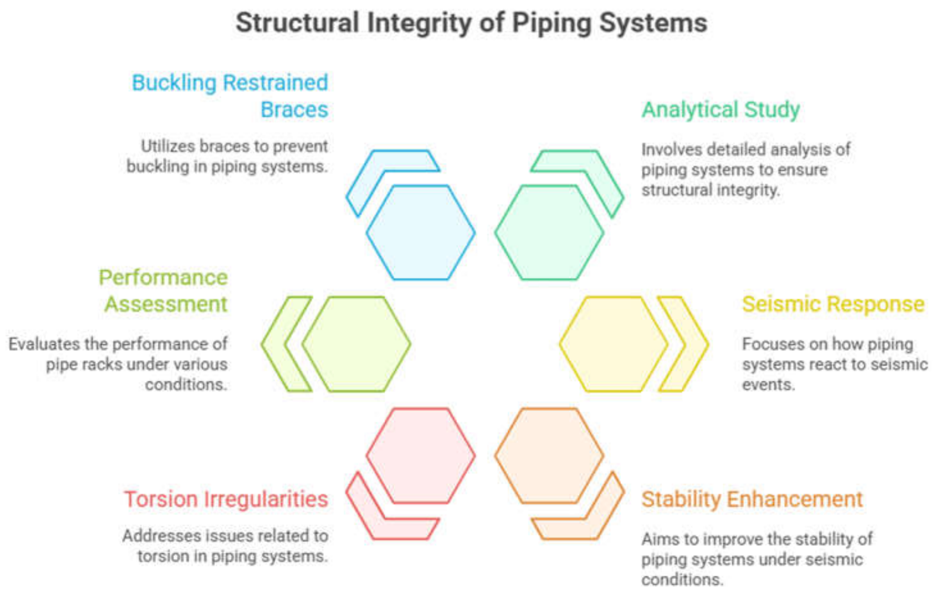

Figure 4 Major classification of literature review.

To provide a thorough and systematic understanding of the research landscape, this literature review is organized into six major categories, each addressing a critical aspect of industrial pipe rack systems. The first section, Analytical Study of Piping Systems, examines foundational research on the design, material selection, and stress analysis of piping networks, highlighting the importance of accurate modeling and computational methods in predicting system behavior under various loading conditions. The second section, Seismic Response of Piping Systems, focuses on studies evaluating how piping systems and their supporting racks respond to earthquake-induced forces, emphasizing the need for dynamic analysis and the identification of key vulnerabilities. The third section, Stability Enhancement on Exposure to Seismic Excitations, reviews advancements in structural control strategies, such as the application of damping devices and optimized support configurations, aimed at improving the resilience of pipe racks during seismic events. The fourth section, Torsion Irregularities and Accidental Torsion, explores the challenges posed by asymmetric mass and stiffness distributions, with particular attention to the development and mitigation of accidental torsional moments that can precipitate unexpected failures. The fifth section, Performance Assessment of Pipe Racks, synthesizes research on the evaluation of pipe rack safety and functionality, including the use of numerical simulations, experimental investigations, and code compliance checks to benchmark structural performance. Finally, the sixth section, Buckling Restrained Braces, delves into the latest developments in bracing technology, especially the use of BRBs, and assesses their effectiveness in enhancing seismic resistance and energy dissipation capacity. Together, these categories provide a comprehensive framework for critically appraising the state-of-the-art in seismic design and performance assessment of industrial pipe rack structures.

3.1. Analytical Study of Piping Systems

Sakharkar et al. [17] provided an overview of the design and analysis of piping systems, emphasizing the process design and steam distribution networks specifically within chemical industry plants. The study investigated various design procedures and performed stress and strain analyses induced by mechanical loads. Such analyses aid in understanding fatigue strength and service life of materials under different loading conditions. The selection of appropriate materials and loading scenarios was highlighted as critical to the evolution of piping system design.

Gupta et al. [62] conducted a comparative analysis of piping systems used in process plants using software tools such as CAD, CAEPIPE, and CAESAR II. They elaborated on piping flexibility, flexibility characteristics and factors, as well as stress intensification factors based on relevant codes. CAEPIPE's CAD features facilitated finite element analysis (FEA) to compute code-compliant stresses, compliance stresses, element forces, moments, and deflections at pipeline nodes. The comparison of stress concentration factors showed strong agreement with FEA results from CAEPIPE. The authors determined that if the ratio of maximum applied stress to maximum allowable stress is less than one, the piping system is safe by design. They concluded that using CAEPIPE software provided a more disciplined and efficient design process with higher accuracy.

Kadagaonkar and Yadav [26] studied the sustainability and safety of a proposed steam piping system used in dryers for paper machinery using finite element analysis. Their research considered both 2-D and 3-D piping system designs compliant with industry standards, analyzing various loading scenarios under typical service conditions. They demonstrated that primary and secondary stresses remained within allowable code limits. Furthermore, pipe weight contributed to minimizing vibrations and shock movements, enhancing pipeline flexibility. Pipe support elements were designed to mitigate stresses, prevent joint leakage, and control excessive thrusts and movements in connected equipment. Their work underscored the importance of material strength and its interaction with substances and equipment in the pipeline system.

Pradeep et al. [30] carried out a comprehensive stress analysis of process pipeline systems. Their study aimed to highlight flexibility characteristics, external forces, displacements, and stress intensification factors compliant with standard codes under various loading conditions including hydrostatic, sustained, operating, and experimental loads. Experimental analysis employing CAESAR II demonstrated good accuracy, validating stress intensification factor (SIF) computations.

More and Kulkarni [40] investigated the development of steam piping systems alongside stress analysis, optimizing both weight and thermal performance. Their study detailed piping design processes and conducted stress analyses based on specific flow diagrams. Pipe wall thicknesses were determined considering safety constraints related to internal pressures.

Senthilkumar et al. [37] analyzed piping layouts subjected to static loads in the petrochemical sector. Their research focused on critical pipeline segments connecting main distillation units and air fin coolers. They interconnected the design of piping layouts, pipe supports, and stress analyses. Notably, their findings included an examination of functional pipe failures causing shutdowns, accidents, extensive damage, and human injury due to fluid leaks in refineries. They observed that steel pipe racks exhibited lower base shear compared to combined (steel and concrete) pipe racks due to lower seismic weight, resulting in better seismic response. They recommended combined pipe racks for enhanced fire protection.

Bisht and Jahan [39] examined stress analysis methods essential for piping network design, focusing on critical parameters influencing the safety of piping components and connected equipment. The primary objective was to prevent premature piping failures. Their research offered significant insights into principles of material selection, adherence to standard code criteria, and the use of stress analysis software tools. They aimed to optimize support spacing to maintain stress and deflection values within safe limits, thereby reducing the number of supports and lowering overall construction costs

3.2. Seismic Response of Piping Systems

Research indicates piping systems are highly susceptible to earthquakes, with damage potentially leading to severe industrial accidents. Conducting seismic analyses can significantly reduce vulnerabilities. Paolacci et al. [53] reviewed challenges associated with the seismic analysis and design of refinery piping systems. Using practical examples, they highlighted that recent earthquakes demonstrated vulnerabilities ranging from minor joint failures to substantial structural support issues. European (EN13480:3) and American (ASME B31.3) standards were discussed, emphasizing the distinct mechanical and geometric properties of pipe rack structures.

Di Sarno and Karagiannakis [9] conducted a detailed case study on a liquefied natural gas terminal’s concrete pipe rack system, underscoring the critical yet often-neglected interactions between dynamic pipelines and structural supports. Their study revealed how monitoring intensity dispersion can significantly influence soil deformability, aligning with both structural and non-structural engineering criteria.

Within the petroleum industry, extensive piping networks transport raw and processed materials, connecting various plant components such as tanks, columns, and furnaces. Recognizing the seismic vulnerability of these structures, Paolacci, Reza, and Bursi [53] examined existing seismic analysis methodologies stipulated by EN13480:3 and ASME B31.3. Their findings emphasized limitations in current design standards, particularly regarding dynamic interactions between pipes and supports, accurate response factor definitions, and differences between strain and stress conditions.

Katsimpini et al. [11] sought to enhance seismic guidelines in Eurocode 8, calculating key seismic response parameters such as interstory drifts, overturning moments, base shears, and foundation settlements. Their analyses concluded that seismic performance was acceptable for low- to mid-rise steel structures, whereas taller buildings required improved seismic design measures, especially when incorporating soil-structure interaction (SSI) effects.

Bursi et al. [33] experimentally evaluated the seismic behavior of full-scale petrochemical piping systems. Employing hybrid simulation techniques (pseudo-dynamic and real-time testing with dynamic sub structuring), they demonstrated that standard piping components (e.g., elbows, bolted flange joints, tee joints) performed reliably, remaining within allowable stress limits and preventing leakage, even under near-collapse limit state conditions.

3.3. Stability Enhancement on Exposure to Seismic Excitations

Piping systems must withstand diverse loads, including dead weight, internal pressure, thermal fluctuations, accidental impacts, and seismic forces. Researchers have explored various vibration mitigation devices such as snubbers, hangers, support systems, and isolators. Kunieda et al. [101] proposed three damping enhancement devices: direct dampers, vibration absorbers, and connecting dampers. Olson and Tang [100] recommended snubbers and seismic stops to minimize piping vibrations in nuclear facilities; however, their frequent inspections and high installation costs present challenges.

Erduran and Ryan [50] formulated a seismic response analysis methodology, validating simulations against experimental results. Park et al. [86] conducted shake-table tests and simulations for main steam and feedwater lines, comparing traditional snubbers against energy-absorbing supports. Parulekar et al. [64] analytically and experimentally investigated elastoplastic dampers (EPDs) to reduce nuclear piping vibrations.

Abe et al. [73] performed seismic validation tests on Lead Extrusion Dampers (LED), developing characteristic evaluation formulas. Fujita et al. [92] introduced a nonlinear seismic response analysis technique for piping systems integrating Finite Element Method (FEM) and Differential Algebraic Equations (DAE). Bakre et al. [65] evaluated sliding friction dampers and optimized X-plate dampers for seismic performance in industrial piping.

Stockbridge dampers (SBD), developed initially in 1925, have been recommended for mitigating piping vibrations during seismic events. Chang et al. [23] conducted theoretical assessments validating experimental predictions. Vecchiarelli et al. [79] numerically simulated aeolian vibrations in conductor spans using Stockbridge dampers, while Barry et al. [43] developed finite element models to explore damper effectiveness. Urushadze et al. [49] experimentally and numerically studied wind-induced vibrations on bridge hangers, recommending Stockbridge dampers. Barbieri and Barbieri [67] analyzed linear and nonlinear dynamics of asymmetric Stockbridge dampers.

Structural control systems, especially passive and active damping solutions, have increasingly attracted research attention. Soong and Spencer [78] comprehensively reviewed passive systems (improving damping, stiffness, and strength) and active/hybrid systems involving sensors, real-time data analysis, and controlled devices.

Takahashi and Maekawa [48] introduced a single-sided pounding tuned mass damper (PTMD) for vibration control in suspended piping systems, highlighting its cost-effective construction and rapid energy dissipation. PTMD technology effectively reduces both free and forced vibrations, significantly enhancing structural resilience and safety under seismic conditions
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3.4. Torsion Irregularities and Accidental Torsion

During earthquakes, structures experience lateral displacements influenced by structural system type, building mass distribution, and material properties. Structural irregularities, notably torsional irregularities, adversely affect seismic performance, potentially causing uneven inter-story drifts, excessive rotation, and structural failures.

Torsional effects are classified into inherent torsion (resulting from structural characteristics) and accidental torsion (arising from unforeseen mass/stiffness variations and rotational seismic excitation). Current seismic design methodologies typically address accidental torsion by applying static torque computed as shear-story force multiplied by accidental eccentricity. However, De la Llera and Chopra [88] proposed a more precise method that involves amplifying inherent torsional effects, emphasizing accurate estimations of elastic torsional responses.

Elastic analysis generally assesses accidental torsion effects, considering mass/stiffness distribution variations and rotational seismic inputs. While methods by De la Llera and Chopra [89] incorporate torsional stiffness and plan aspect ratios, they omit eccentricity and period variations. Khan et al. [4] emphasized evaluating two-way eccentricities and period differences along orthogonal axes, typically represented through single-story models.

Gokdemir et al. [44] examined torsional irregularity effects, highlighting the critical importance of lateral stiffness distribution and appropriate separation distances to minimize structural vulnerabilities. Han et al. [21] studied multi-story models using nonlinear response history analysis, proposing a method to uniformly assess collapse risk regardless of torsional irregularity degree.

Uzun et al. [18] further investigated torsional irregularities, noting their inclusion as critical irregularities within global seismic regulations. Symmetrical structures typically experience torsion only from accidental eccentricity, whereas asymmetrical structures exhibit more pronounced torsional behavior due to mass-stiffness misalignment. Adarsh and Rajeeva [12] evaluated structural performance based on IS 1893:2002, underscoring the need for regular geometric layouts to minimize torsional impacts.

Erduran and Ryan [50] demonstrated through response spectrum analyses that significantly irregular structures are more severely impacted by torsion, accelerating plastic hinge formation and increasing structural vulnerability.

3.5. Performance Assessment of Pipe Racks

Piping supports are essential for the reliable operation of industrial piping systems. They bear the weight of the pipes and their contents and must be carefully spaced to ensure structural stability. A pipe rack, typically constructed from concrete or steel, supports numerous piping lines transporting liquids or gases, electrical cable trays, instrumentation lines, telecom cables, and auxiliary equipment such as air coolers and pressure relief valves. These racks facilitate efficient and organized transportation of fluids or gases of varying diameters across different equipment units or sections within an industrial plant, thus making them indispensable in the chemical, petrochemical, oil, and gas industries. Additionally, pipe racks help streamline the routing of electrical and instrumentation cable trays, ensuring orderly connectivity between various plant units (Sakharkar et al. [17]; Singh and Ishtiyaque [31]

Previous earthquake events have demonstrated that pipelines are highly susceptible to seismic damage. According to Kidam and Hurme [45], pipelines are approximately 44% more likely to sustain damage than other components such as storage tanks or reactors, based on the analysis of 364 industrial accidents. Despite these risks, the dynamic interaction between supporting structures (pipe racks) and piping systems has received limited research attention, with many existing studies analyzing structural components independently rather than examining their dynamic interactions comprehensively. For example, Salimi Firoozabad et al. [34] evaluated seismic excitation methods for nuclear piping but did not address the coupling effects between pipes and supporting structures. Azizpour and Hosseini [58] provided one of the few thorough investigations of dynamic interactions, highlighting that pipe end conditions and U-bolt ring stiffness significantly influence seismic responses.

The seismic fragility of reinforced concrete (RC) pipe racks and associated piping systems has been assessed to better understand their vulnerabilities. Di Sarno and Karagiannakis [10,11] conducted fragility analyses of typical RC pipe racks, observing that shear failure, rather than flexural failure, commonly governed the collapse limit state (LS). They underscored that shear failures, which capacity design aims to avoid, were predominantly influenced by modeling parameters such as stirrup spacing. Although probabilistic approaches have been partly explored for standard building structures and bridges (Karapetrou et al. [35]; Kwon and Elnashai [63]; Mitropoulou et al. [29]), there remains a significant knowledge gap concerning probabilistic methods specifically tailored for pipe racks and their dynamic coupling with piping systems considering soil-structure interactions.

Pipe racks exhibit distinct mechanical and geometric characteristics compared to conventional buildings, with seismic responses heavily influenced by pipeline layouts. Significant design considerations, such as the dynamic interaction between pipes and support structures and uncertainties related to soil behavior or seismic input, are frequently overlooked or inadequately quantified in existing design practices. Consequently, industry guidelines need clearer specifications for pipe racks (Di Sarno and Karagiannakis [9]).

Pipe racks in oil and gas facilities require meticulous planning and engineering due to the substantial loads they must withstand, including both dead loads and live loads from piping and auxiliary systems. Structural elements of pipe racks must comply with various national and international standards (e.g., Indian, American, British codes), depending on project requirements and geographical conditions, ensuring strength, stability, and serviceability criteria, including controlled vertical and horizontal deflections (Borkar and Daule [3]; Singh and Ishtiyaque [31]).

Drake and Walter [55] discussed challenges in structural steel pipe rack design, highlighting the limited guidance provided by existing building codes. They emphasized the necessity of updated and comprehensive design provisions and offered recommendations on load considerations and structural analysis approaches to standardize industry practices.

Di Sarno and Karagiannakis [9,11] conducted linear and nonlinear analyses of pipe racks using Italian, European, and American standards, noting inconsistencies across these codes. They pointed out limitations in commonly applied nonlinear static (pushover) methods, suggesting the need for refined behavior factors and improved engineering demand parameters, such as inter-story drift ratios, particularly regarding their impacts on nonstructural components.

Karimi et al. [51] investigated the seismic performance of pipe rack supporting structures in petrochemical complexes, recognizing their crucial role in operational safety. Their analysis utilized both qualitative approaches (visual inspections and walkdowns) and quantitative methods (equivalent static and linear dynamic analyses, including torsion and P-Δ effects) per ASCE standards.

Karagiannakis and Di Sarno [13] assessed seismic risks for industrial pipe rack systems, analyzing European and American standards, and performed reliability evaluations for decoupled and coupled pipe rack–piping systems under varying ground motions and soil conditions. Their findings revealed potential overestimations of pipe rack strength by traditional nonlinear static analyses and indicated that standard drift limits might be unsuitable, particularly when accounting for soil-structure interaction effects.

Karagiannakis et al. [2] further investigated seismic risk and accident scenarios for refinery process units using contemporary seismic hazard maps. Their results identified steel support structures as more vulnerable than the piping itself, providing customized fragility curves and risk assessments relevant to modern refinery practices.

Bedair [7] addressed the design of steel pipe racks subjected to blast loading, a significant concern for petrochemical plants. He proposed practical guidelines enabling engineers to assess dynamic responses of pipe racks efficiently, circumventing computationally intensive numerical simulations.

Di Sarno and Karagiannakis [9] also critiqued current engineering practices for pipe racks, noting that conservative seismic codes often keep pipes within the elastic range, potentially resulting in inconsistent risk management. They argued that static analyses inadequately capture complex pipe behaviors, recommending performance-based assessments utilizing spectral acceleration as a more effective intensity measure.

Finally, Nagdeote et al. [6] reviewed various optimization approaches for pipe rack and support structures, emphasizing that steel pipe supports play a vital role in the safe transportation of fluids within industrial facilities. They highlighted the complexities inherent in achieving optimal designs, noting the importance of adhering to international standards to ensure safety, efficiency, and timely project completion.

3.6. Bucking Restrained Braces

Careful consideration must be given to the design, construction, and installation of pipe racks in seismically active regions. While steel moment-resisting frames—often integrated with vertical bracing at selected bays—are commonly employed in pipe rack structures, they remain vulnerable to significant lateral displacements under intense seismic loading. This vulnerability presents substantial challenges for structural engineers, particularly in selecting the most effective bracing types and their optimal locations to provide adequate lateral resistance along the routing of multiple pipelines (Pathak and Saikia [41]).

In addition to ensuring the structural safety of pipe racks, it is essential to address the performance of nonstructural components and account for second-order effects such as P-Δ (P-delta) moments, which can compromise global stability during seismic events. These considerations are particularly critical in industrial facilities where pipe racks must maintain operational functionality post-earthquake and avoid damage to the extensive network of pipes and equipment they support.

As part of the most extensive full-scale pushover testing program on racking systems conducted in Europe, Kanyilmaz et al. [27] carried out an in-depth experimental study on pallet racks constructed from thin-walled cold-formed steel profiles—commonly used in logistics and industrial storage applications. Their research revealed that conventional rack connections often lack the necessary stiffness and flexural strength to resist seismic forces effectively. The study emphasized the importance of incorporating spine (longitudinal) bracing in the down-aisle direction to enhance the global seismic performance of racking systems. While the context was pallet racking, the findings are highly relevant to pipe rack design, particularly with respect to lateral stability and bracing configuration strategies.

4. CONCLUSION

The seismic safety of industrial pipe rack systems is of paramount importance due to the potential for catastrophic consequences, including the release of hazardous fluids, environmental harm, and significant financial losses. Unlike traditional buildings, the failure of pipe racks during seismic events can lead to widespread disruption and societal risk, underscoring the need for rigorous assessment of the dynamic interaction between piping systems and their supporting structures. Despite ongoing advancements, current Indian design practices and seismic guidelines for pipe racks remain limited in several key areas. There is a notable lack of focus on the effectiveness of steel bracing systems, the structural response to accidental torsional moments, and the development of simplified, practical design procedures tailored to local conditions. The emergence of unexpected torsional moments has been identified as a principal factor in the unforeseen collapse of pipe rack structures, yet this phenomenon remains insufficiently addressed in both research and practice. While some researchers have advanced the understanding of dynamic analysis for piping systems and pipe racks, the specific issue of accidental torsional moment development under seismic excitation requires further investigation. The literature consistently highlights the need for comprehensive research into these critical aspects, as well as the adaptation of international codal provisions to better suit local market realities and hazards. In summary, enhancing the seismic resilience of pipe rack systems demands a more integrated approach—one that incorporates advanced analysis of dynamic and torsional effects, practical bracing solutions, and the development of robust, region-specific design guidelines. Addressing these gaps will be essential for minimizing the risk of severe damage and ensuring the continued safety and reliability of industrial infrastructure.

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