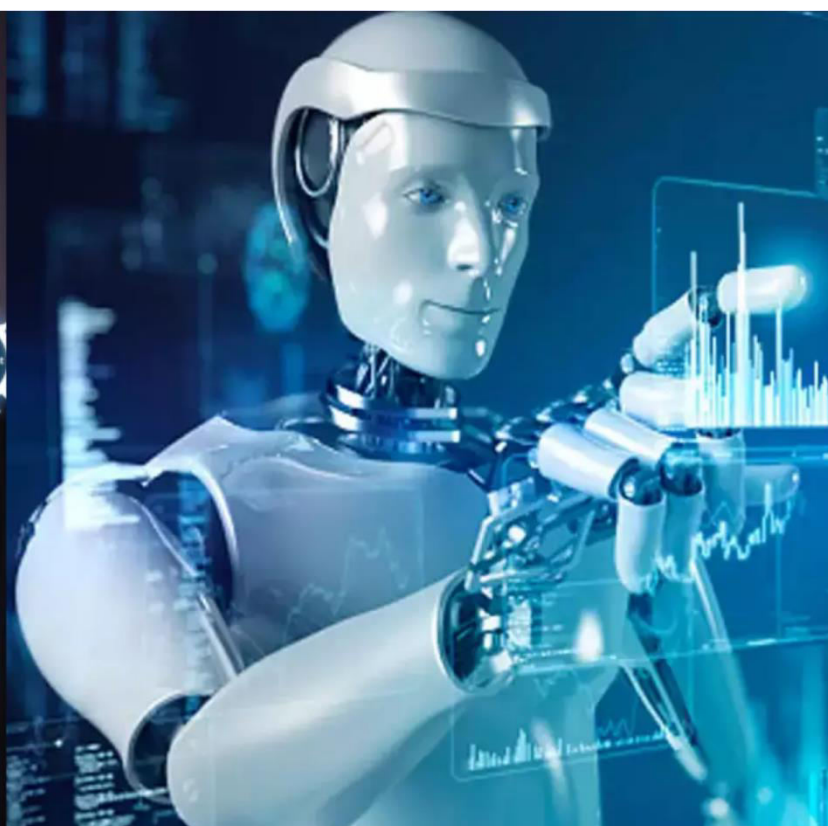




International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 14, Issue 7, July 2025

Seismic Performance and Design of Industrial Pipe Rack Structures”: A Comprehensive Review

Ganesh D. Khot¹, Girish V. Joshi²

M. Tech Student, Department of Civil Engineering, G H Raison College of Engineering and Management, Wagholi,
Pune, India¹

Assistant Professor, Department of Civil Engineering, G H Raison College of Engineering and Management, Wagholi,
Pune, India²

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

I. 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.

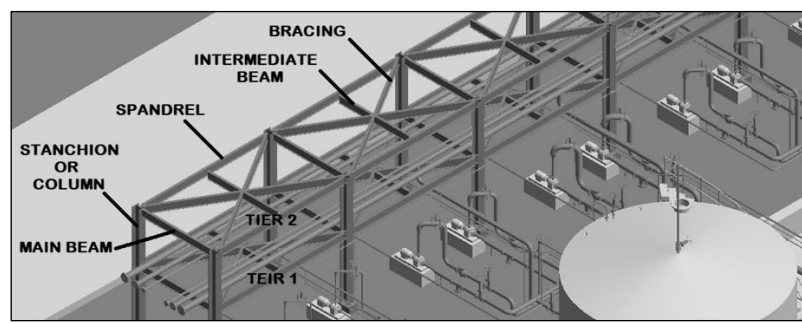


Figure 1 Typical Pipe Rack System

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.

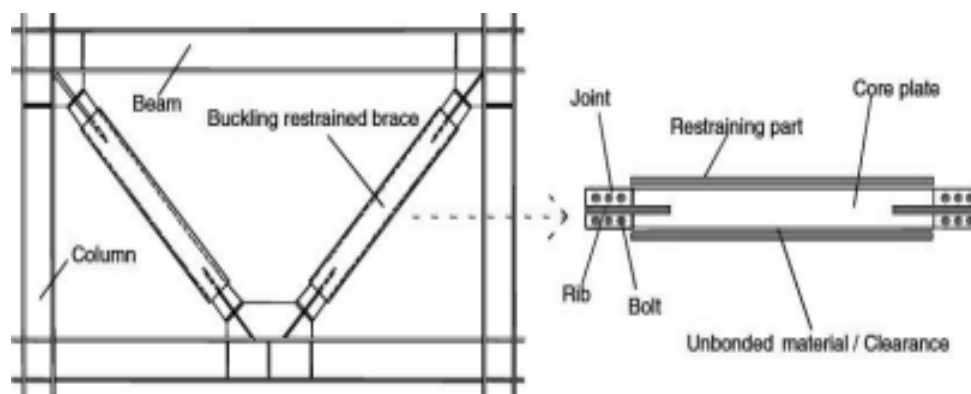


Figure 2 Buckling Restrained Brace

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.

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.

II. 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.

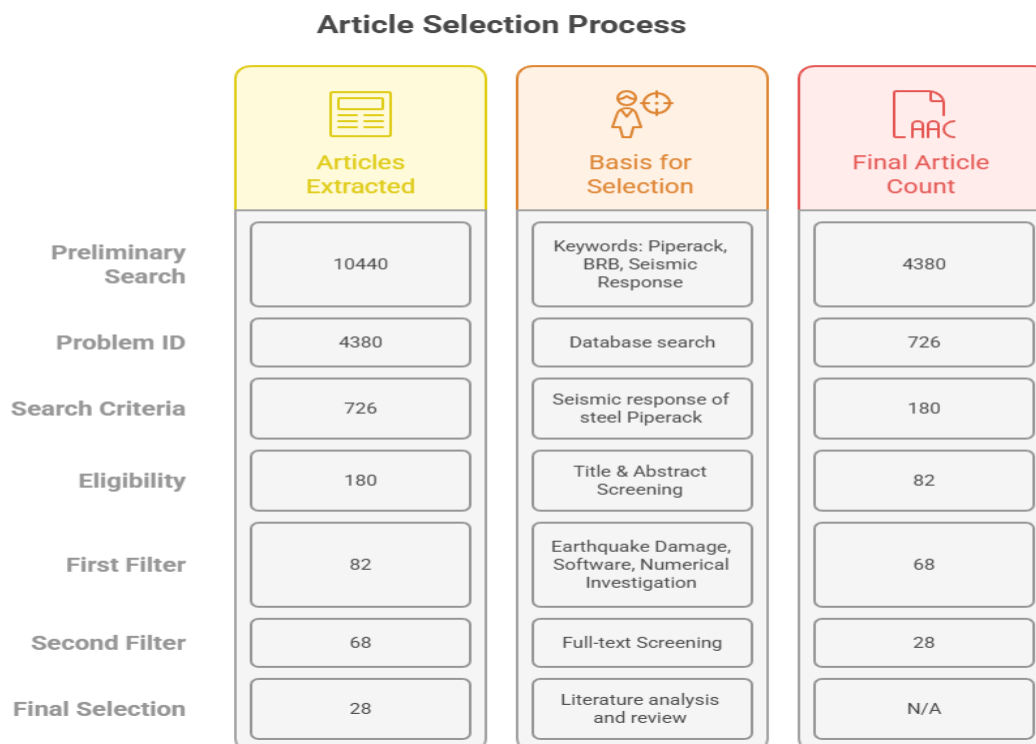


Figure 3 Methodology for Comprehensive Literature Review

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. A first filter further refined this group to 82 articles, and a second filter involving full-text screening led to the selection of 68 highly relevant studies. Ultimately, 28 articles were chosen for in-depth analysis and critical review, focusing on key themes such as dynamic analysis, bracing effectiveness, torsional irregularities, and code compliance. The final synthesis involved a detailed discussion of the findings, identification of research gaps, and formulation of future research directions to advance the seismic design and performance assessment of industrial pipe rack structures.

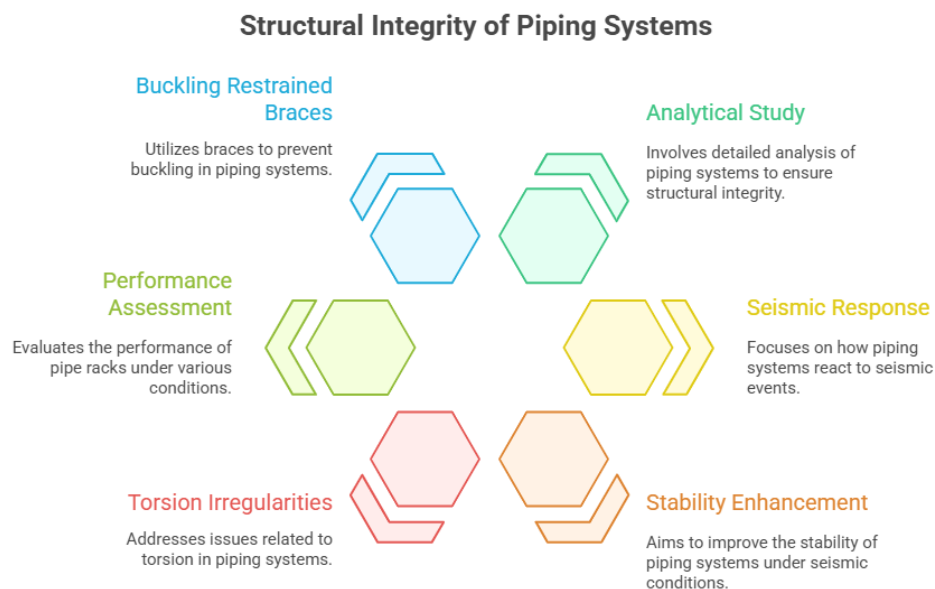


Figure 4 Major classification of literature review.

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.

2.1 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.

2.2 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.

2.3 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.

2.4 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.

2.5 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.

2.6 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.

III. 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.

IV. ACKNOWLEDGEMENT

While working on this paper through to its final form, I would like to express my sincere gratitude to all those who contributed to this research. It is a pleasure to convey my heartfelt thanks to each one of them. I am deeply indebted to my guide, **Asst. Prof. G. V. Joshi**, for his valuable guidance, encouragement, and continuous support throughout the research. I also extend my sincere thanks to the Head of the Department, **Dr. A. G. Dahake**, whose motivation and insightful suggestions have been instrumental in the completion of this study. words cannot fully express my

appreciation for the academic and moral support I received. I am especially grateful to all the professors and non-teaching staff of the department, whose cooperation proved to be a great advantage in successfully completing this work.

REFERENCES

1. Maghrabi, J., Landge, P. and Kotian, R., 2022, "Analysis and Design of Pipe Rack Structures: A Review". Smart Technologies for Energy, Environment and Sustainable Development, Vol 1, pp.167-176.
2. Karagiannakis, G., Di Sarno, L., Necci, A. and Krausmann, E., 2022, "Seismic Risk Assessment of Supporting Structures and Process Piping for Accident Prevention in Chemical Facilities". International Journal of Disaster Risk Reduction, Vol. 69, pp.102748.
3. Borkar, S.J. and Daule, S., 2021, "Dynamic Analysis of Pipe Rack System Subjected to Seismic Excitations". Open Access International Journal of Science & Engineering, Vol. 6, pp.71-79.
4. Chen, Z., Khan, K., Khan, A., Javed, K. and Liu, J., 2021, "Exploration of The Multidirectional Stability and Response of Prefabricated Volumetric Modular Steel Structures". Journal of Constructional Steel Research, Vol. 184, pp.106826.
5. Di Sarno, L. and Karagiannakis, G., 2021, Seismic Performance-Based Assessment of A RC Pipe Rack Accounting for Dynamic Interaction. Structures, Vol. 33, pp. 4604-4615.
6. Nagdeote, R.D., Suryawanshi, S.R. and Khadake, N., 2021, "A Review on Optimization in Design and Construction of Pipe Supports", International Research Journal of Engineering and Technology, Vol.8, pp.722-725.
7. Bedair, O., 2020, "Simplified Global Analysis of Steel Pipe-Racks Subject to Accidental Vapor Cloud Blast Explosions." Sustainable Structures and Materials, An International Journal, Vol. 3(2), pp.1-12.
8. Di Sarno, L. and Karagiannakis, G., 2020, "Seismic Fragility of Pipe Rack-Piping Systems Considering Soil-Structure Interaction". Bulletin of Earthquake Engineering, Vol.18(6), pp.2723-2757.
9. Di Sarno, L. and Karagiannakis, G., 2020, "Petrochemical Steel Pipe Rack: Critical Assessment of Existing Design Code Provisions and A Case Study". International Journal of Steel Structures, Vol. 20(1), pp.232-246.
10. Ghayoumian, G. and Emami, A.R., 2020, "A Multi-Direction Pushover Procedure for Seismic Response Assessment of Low-to-Medium-Rise Modern Reinforced Concrete Buildings with Special Dual System Having Torsional Irregularity". Structures, Vol. 28, pp. 1077-1107.
11. Katsimpini, P., Konstandakopoulou, F., Papagiannopoulos, G.A., Pnevmatikos, N. and Hatzigeorgiou, G.D., 2020, "The Effect of Long Duration Earthquakes on the Overall Seismic Behavior of Steel Structures Designed According to Eurocode 8 Provisions". Vibration 2020, 3(4), 464-477; <https://doi.org/10.3390/vibration3040029>
12. Palazzi, N.C., Favier, P., Rovero, L., Sandoval, C. and de la Llera, J.C., 2020, "Seismic Damage and Fragility Assessment of Ancient Masonry Churches Located in Central Chile. Bulletin of Earthquake Engineering, 18(7), pp.3433-3457.
13. Karagiannakis, G. and Di Sarno, L., 2019, "Investigation of the Seismic Risk of Industrial Pipe Rack-Piping Systems Accounting for Soil-Structure Interaction". Proceedings of the Pressure Vessels and Piping Conference, American Society of Mechanical Engineers. Vol. 58967, pp. V005T09A011.
14. Neelavathi, S., Shwetha, K.G. and Mahesh Kumar, C.L., 2019, "Torsional Behavior of Irregular RC Building under Static and Dynamic Loading". Materials Science Forum, Vol. 969, pp. 247-252.
15. Tan, J., Michael Ho, S.C., Zhang, P. and Jiang, J., 2019, "Experimental Study on Vibration Control of Suspended Piping System by Single-Sided Pounding Tuned Mass Damper". Applied Sciences, Vol.9(2), pp.285.
16. Rotta Loria, A.F., 2018, "Performance-Based Design of Energy Pile Foundations". DFI Journal-The Journal of the Deep Foundations Institute, Vol 12(2), pp.94-107.
17. Sakharkar, S.N., Khake, P. and Kolambakar, V., 2018, "Overview of Industrial Piping Structural Design". International Journal of Engineering Sciences & Research Technology. Vol. 7. pp.45-50.
18. Uzun, M., Unal, A., Kamanli, M. and Cogurcu, M.T., 2018, "Investigation of the Effect of Torsional Irregularity on Earthquake Behavior". Journal of Engineering Research and Applied Science, Vol. 7(1), pp.753-758.
19. Di Roseto, A.D.L., Palmeri, A. and Gibb, A.G., 2017, Performance-Based Seismic Design of a Modular Pipe-Rack. Procedia Engineering, Vol.199, pp.3564-3569.
20. Han, S.W., Kim, T.O., Kim, D.H. and Baek, S.J., 2017, "Seismic Collapse Performance of Special Moment Steel Frames with Torsional Irregularities". Engineering Structures, 141, pp.482-494.

21. Maekawa, A. and Takahashi, T., 2017, "Elasto-plastic response of piping systems with pipe support structures using three-dimensional strong excitation test," JSME Annual Meeting, Paper No. J1010101.
22. Chang, S., Sun, W., Cho, S. G. and Kim, D., 2016, "Vibration control of nuclear power plant piping system using Stockbridge damper under earthquakes," Science and Technology of Nuclear Installations, pp. 340–353.
23. Etedali, S. and Sohrabi, M. R., 2016, "A proposed approach to mitigate the torsional amplifications of asymmetric base-isolated buildings during earthquakes," KSCE Journal of Civil Engineering, Vol. 20, No. 2, pp. 768–776.
24. Ghuse, S. R. and Ghumde, M. K., 2016, "Study of torsional effect under seismic condition on building with irregularities," International Journal of Engineering Technology, Vol. 3, No. 12, pp. 768–774.
25. Kadagaonkar, M. T. R. and Yadav, M., 2016, "Design of steam piping system for dryers in paper machine and checking its sustainability through finite element analysis using CAESAR II," International Journal of Advance Research, Ideas and Innovations in Technology, Vol. 2, pp. 1–11.
26. Kanyilmaz, A., Brambilla, G., Chiarelli, G. P. and Castiglioni, C. A., 2016, "Assessment of the seismic behavior of braced steel storage racking systems by means of full-scale push-over tests," Thin-Walled Structures, Vol. 107, pp. 138–155.
27. Kumar, P., Jangid, R. S. and Reddy, G. R., 2016, "Comparative performance of passive devices for piping system under seismic excitation," Nuclear Engineering and Design, Vol. 298, pp. 121–134.
28. Mitropoulou, C. C., Kostopanagiotis, C., Kopanos, M., Ioakim, D. and Lagaros, N. D., 2016, "Influence of soil–structure interaction on fragility assessment of building structures," Structures, Vol. 6, pp. 85–98.
29. Pradeep, G. M., Kumar, K. A., Sharathi, I. J., Krishna, J. R. and Vishal, S., 2016, "Stress analysis of process piping using CAESAR II," Stainless Steel (Austenitic), Vol. 16, No. 10, p. 6.
30. Singh, N. J. and Ishtiyaque, M., 2016, "Optimized design and analysis of steel pipe racks for oil and gas industries as per international codes and standards," International Journal of Research in Engineering and Technology, Vol. 5, No. 10, pp. 16–28.
31. Bedair, O., 2015, "Rational design of pipe racks used for oil sands and petrochemical facilities," Practice Periodical on Structural Design and Construction, Vol. 20, No. 2, pp. 04014002.
32. Bursi, O. S., Reza, M. S., Abbiati, G. and Paolacci, F., 2015, "Performance-based earthquake evaluation of a full-scale petrochemical piping system," Journal of Loss Prevention in the Process Industries, Vol. 33, pp. 10–22.
33. Firoozabad, E. S., Jeon, B. G., Choi, H. S. and Kim, N. S., 2015, "Seismic fragility analysis of seismically isolated nuclear power plants piping system," Nuclear Engineering and Design, Vol. 284, pp. 264–279.
34. Karapetrou, S. T., Fotopoulou, S. D. and Pitilakis, K. D., 2015, "Seismic vulnerability assessment of high-rise non-ductile RC buildings considering soil–structure interaction effects," Soil Dynamics and Earthquake Engineering, Vol. 73, pp. 42–57.
35. Mohamed, O. A. and Abbass, O. A., 2015, "Consideration of torsional irregularity in modal response spectrum analysis," Proceedings of the Earthquake Resistant Engineering Structures, Vol. 152, pp. 209–218.
36. Senthilkumar, G., Manikandan, H. and Shanmugasundaram, S., 2015, "Analysis of piping layout under static load in petrochemical industries," International Journal of Applied Sciences and Engineering Research, Vol. 4, No. 2, pp. 240–249.
37. Senthilkumar, G., Manikandan, H. and Shanmugasundaram, S., 2015, "Design of piping layout under static load in petrochemical industries," International Journal of Applied Sciences and Engineering Research, Vol. 4, No. 2, pp. 320–324.
38. Bisht, S. and Jahan, F., 2014, "An overview on pipe design using CAESAR II," International Journal on Emerging Technologies, Vol. 5, No. 2, p. 114.
39. More, B. U. and Kulkarni, S. S., 2014, "Development of steam piping system with stress analysis for optimum weight and thermal effectiveness," International Journal of Advance Engineering Research and Studies, pp. 108–113.
40. Saikia, R. and Pathak, J., 2014, "Seismic response of steel braced pipe racks and technological platforms in oil refineries," 15th Symposium on Earthquake Engineering, Indian Institute of Technology, Roorkee, pp. 11–13.
41. Takahashi, T. and Maekawa, A., 2014, "Impact of deformation stiffness beyond yield point of pipe support structures on nonlinear seismic response analysis," ASME Paper No. PVP2014-28371.
42. Barry, O., Oguamanam, D. C. and Lin, D. C., 2013, "Aeolian vibration of a single conductor with a Stockbridge damper," Journal of Mechanical Engineering Science, Vol. 227, No. 5, pp. 935–945.
43. Gokdemir, H., Ozbasaran, H., Dogan, M., Unluoglu, E. and Albayrak, U., 2013, "Effects of torsional irregularity to structures during earthquakes," Engineering Failure Analysis, Vol. 35, pp. 713–717.

44. Kidam, K. and Hurme, M., 2013, "Analysis of equipment failures as contributors to chemical process accidents," *Process Safety and Environmental Protection*, Vol. 91, No. 1–2, pp. 61–78.
45. Takahashi, T. and Maekawa, A., 2013, "Analytical study on effect of failure of pipe support structure on seismic response of piping system," ASME Paper No. PVP2013-97222.
46. George, S. S. and Varghese, V., 2012, "General concepts of capacity based design," *International Journal of Innovative Technology and Exploring Engineering*, Vol. 1, No. 2, pp. 211–215.
47. Takahashi, T. and Maekawa, A., 2012, "Seismic response reduction in piping systems using plastic deformation of pipe support structures," ASME Paper No. PVP2012-78052.
48. Urushadze, S., Pirner, M., Pospíšil, S. and Kral, R., 2012, "Experimental and numerical verification of vortex-induced vibration of hangers on the footbridge," *Engineering Mechanics*, p. 22.
49. Erduran, E. and Ryan, K. L., 2011, "Effects of torsion on the behavior of peripheral steel-braced frame systems," *Earthquake Engineering & Structural Dynamics*, Vol. 40, No. 5, pp. 491–507.
50. Karimi, M., Hosseinzadeh, N., Hosseini, F., Kazem, N. and Kazem, H., 2011, "Seismic evaluation of pipe rack supporting structures in a petrochemical complex in Iran," *International Journal of Advanced Structural Engineering*, Vol. 3, pp. 111–120.
51. Nakamura, I., Otani, A., Sato, Y., Takada, H., Takahashi, K. and Shiratori, M., 2011, "Investigation of the seismic safety capacity of aged piping system—Shake table test on piping system with wall thinning by E-Defense," ASME Paper No. PVP2011-57560.
52. Paolacci, F., Reza, M. S. and Bursi, O. S., 2011, "Seismic design criteria of refinery piping systems," *Proceedings of the Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Corfu, Greece, pp. 2322–2329.
53. Takahashi, T. and Maekawa, A., 2011, "Effect of elastic-plastic property of support structure on seismic response of piping system," *Proceedings of the 21st International Conference on Structural Mechanics in Reactor Technology (SMiRT 21)*, New Delhi, India, November 6–11, Paper No. 282.
54. Drake, R. M. and Walter, R. J., 2010, "Design of structural steel pipe racks," *AISC Engineering Journal*, Vol. 47, No. 4, pp. 241–252.
55. Shirai, E., Yamada, T., Ikeda, K., Yoshii, T., Kondo, M., Okamoto, H. and Tai, K., 2010, "Seismic design margin of the piping and support system—Part 3: Evaluation of seismic margin of the piping system," ASME Paper No. PVP2010-25392.
56. Shirai, E., Yamada, T., Ikeda, K., Yoshii, T., Kondo, M., Tai, K. and Ogo, T., 2010, "Seismic design margin of the piping and support system—Part 1: Static loading test of the support," ASME Paper No. PVP2010-25524.
57. Azizpour, O. and Hosseini, M., 2009, "A verification study of ASCE recommended guidelines for seismic evaluation and design of 'On Pipe-Way Piping' in petrochemical plants," *Proceedings of the 2009 Technical Council on Lifeline Earthquake Engineering (TCLEE) Conference*, Oakland, CA, pp. 1–10.
58. JEA, 2009, "Seismic design using energy absorption of support structures of equipment and piping systems," *Technical Code for Seismic Design of Nuclear Power Plants*, The Japan Electric Association, Tokyo, Japan, Standard No. JEAC4601-2008.
59. Shirai, E., Eto, K., Umemoto, A., Yoshii, T., Kondo, M., Monde, M. and Tai, K., 2008, "Inelastic seismic test of the small bore piping and support system—Part 1: Seismic proving test of the small bore piping system," ASME Paper No. PVP2008-61342.
60. Shirai, E., Eto, K., Umemoto, A., Yoshii, T., Kondo, M., Shimizu, H. and Tai, K., 2008, "Inelastic seismic test of the small bore piping and support system—Part 2: Static failure test for piping support equipment," ASME Paper No. PVP2008-61351.
61. Gupta, P., Lal, A. K., Sharma, R. K. and Singh, J., 2007, "Analysis of reliability and availability of serial processes of plastic-pipe manufacturing plant: A case study," *International Journal of Quality & Reliability Management*, Vol. 3, pp. 63–69.
62. Kwon, O. S. and Elnashai, A. S., 2007, "Probabilistic seismic assessment of structure, foundation, and soil interacting systems," *MAE Center CD Release*, pp. 07–15.
63. Parulekar, Y. M., Reddy, G. R., Vaze, K. K., Ghosh, A. K., Kushwaha, H. S. and Babu, R., 2007, "Seismic response control of complex piping system using elasto-plastic dampers—Experiments and analysis," *International Workshop on Earthquake Hazards & Mitigations*, pp. 7–8.
64. Bakre, S. V., Jangid, R. S. and Reddy, G. R., 2006, "Optimum X-plate damper for seismic response control of piping systems," *International Journal of Pressure Vessels and Piping*, Vol. 83, No. 9, pp. 672–685.

65. Bakre, S. V., 2006, "Response of piping systems with supplemental devices," Doctoral dissertation, Indian Institute of Technology, Bombay, India.
66. Barbieri, R. and Barbieri, N., 2006, "Finite element acoustic simulation-based shape optimization of a muffler," *Applied Acoustics*, Vol. 67, No. 4, pp. 346–357.
67. ASME, 2006, "Code for pressure piping," B31.3-2006.
68. Parulekar, Y. M., Reddy, G. R., Vaze, K. K. and Muthumani, K., 2006, "Passive control of seismic response of piping systems," *International Journal of Pressure Vessels and Piping*, Vol. 128, No. 3, pp. 364–369.
69. Bakre, S. V., Jangid, R. S. and Reddy, G. R., 2004, "Seismic response of piping systems with isolation devices," *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, British Columbia, Canada, Paper No. 2676.
70. Fujita, K., Kimura, T. and Ohe, Y., 2004, "Seismic response analysis of piping systems with nonlinear supports using differential algebraic equations," *Journal of Pressure Vessel Technology*, Vol. 126, No. 1, pp. 91–97.
71. Suzuki, K., Abe, H. and Suzuki, K., 2004, "Seismic proving test of ultimate piping strength: Design method confirmation test," *ASME Paper No. PVP2004-2952*.
72. Abe, H., Ichihashi, I., Kuroda, K., Iwatsubo, T. and Tai, K., 2003, "Seismic proving test of heavy component with energy absorbing support," *Proceedings of the International Conference on Global Environment and Advanced Nuclear Power Plants*, Atomic Energy Society of Japan, p. 1675.
73. Namita, Y., Suzuki, K., Abe, H., Ichihashi, I., Shiratori, M., Tai, K., Iwata, K. and Nebu, A., 2003, "Seismic proving test of eroded piping: Status of eroded piping component and system test," *ASME Paper No. PVP2003-2097*.
74. Satish Kumar, K., Muthumani, K., Gopalakrishnan, N., Sivarama Sarma, B., Reddy, G. R. and Parulekar, Y. M., 2003, "Reduction of large seismic deformations using elastoplastic passive energy dissipators," *Science Defense Journal*, Vol. 53, No. 1, pp. 95–103.
75. Hanawa, Y. and Shimizu, N., 2002, "Statistical seismic response analysis of piping system with a Teflon friction support," *International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, Vol. 45, No. 2, pp. 393–401.
76. Satish Kumar, K., Muthumani, K., Gopalakrishnan, N., Sivarama Sarma, B., Reddy, G. R. and Parulekar, Y. M., 2002, "Seismic response reduction of structure using elastoplastic passive energy dissipation," *Indian Society for Earthquake Technology Journal*, Vol. 39, No. 3, pp. 85–99.
77. Soong, T. T. and Spencer Jr, B. F., 2002, "Supplemental energy dissipation: State-of-the-art and state-of-the-practice," *Engineering Structures*, Vol. 24, No. 3, pp. 243–259.
78. Vecchiarelli, J., Currie, I. G. and Havard, D. G., 2000, "Computational analysis of Aeolian conductor vibration with a Stockbridge-type damper," *Journal of Fluids and Structures*, Vol. 14, No. 4, pp. 489–509.
79. Chopra, A. K., 1998, "Dynamics of structures, theory and application to earthquake engineering," Prentice Hall of India Pvt. Limited, New Delhi.
80. Goel, R. K., 1998, "Effects of supplemental viscous damping on seismic response of asymmetric-plan systems," *Earthquake Engineering & Structural Dynamics*, Vol. 27, No. 2, pp. 125–141.
81. Suzuki, K., Sasaki, Y., Abe, H., Kuroda, K., Namita, Y. and Ono, S., 1998, "Proving test on seismic reliability of piping system with energy absorbing supports," *JSME International Journal, Series C*, Vol. 41, No. 2, pp. 192–198.
82. Lopez, O. A. and Torres, R., 1997, "The critical angle of seismic incidence and the maximum structural response," *Earthquake Engineering & Structural Dynamics*, Vol. 26, No. 9, pp. 881–894.
83. Namita, Y., Ono, S., Suzuki, K., Sasaki, Y., Abe, H. and Kuroda, K., 1997, "Proving test on the seismic reliability of the main steam piping system: Part 3—Analytical evaluation of BWR feed water piping supported by energy absorbing support," *Seismic Engineering Conference Proceedings*, Vol. 345, pp. 125–131.
84. Park, Y. J., DeGrassi, G., Hofmayer, C., Bezler, P. and Chokshi, N., 1997, "Analysis of nuclear piping system seismic tests with conventional and energy absorbing supports," *Brookhaven National Lab, BNL-NUREG-64173, CONF-970826-7*, Upton, NY, United States.
85. Park, Y. J. and Hofmayer, C. H., 1995, "Practical application of equivalent linearization approaches to nonlinear piping systems," *Seismic Engineering Conference Proceedings, ASME PVP*, Vol. 312, pp. 187–200.
86. De la Llera, J. C. and Chopra, A. K., 1994, "Evaluation of code accidental-torsion provisions from building records," *Journal of Structural Engineering*, Vol. 120, No. 2, pp. 597–616.
87. De la Llera, J. C. and Chopra, A. K., 1994, "Accidental and natural torsion in earthquake response and design of buildings," *Report No. UCB/EERC-94/07*, Earthquake Engineering Research Center, University of California at Berkeley.

88. Han, S. W. and Wen, Y. K., 1994, "Method of reliability-based calibration of seismic structural design parameters," University of Illinois Engineering Experiment Station, College of Engineering, University of Illinois at Urbana-Champaign.
89. Endo, R., Murota, M., Kawahata, J.-I., Sato, T., Mekomoto, Y., Takayama, Y., Kobayashi, H. and Hirose, J., 1993, "The development of the design method of nuclear piping system supported by elasto-plastic support structures—Part 1," Proceedings of the 12th International Conference on Structural Mechanics in Reactor Technology (SMiRT 12), Stuttgart, Germany, August 15–20, pp. 193–198.
90. Fujita, K., Ito, T., Kajii, S., Kokubo, E., Nakagawa, T. and Kato, T., 1991, "Study on a rotary type lead extrusion damper as a high damping support for nuclear piping systems," Proceedings of the 11th International Conference on Structural Mechanics in Reactor Technology (SMiRT 11), Tokyo, Japan, August 18–23, pp. 475–480.
91. Namita, Y., Shibata, H., Hara, F., Ichihashi, I., Matsuda, T., Yoshinaga, T., Kunieda, M., Suzuki, K., Iiyama, K. and Murota, M., 1991, "A study on application of energy absorber to piping system in nuclear power plant," Proceedings of the 11th International Conference on Structural Mechanics in Reactor Technology (SMiRT 11), Tokyo, Japan, August 18–23, pp. 499–504.
92. Namita, Y., Yoshinaga, T., Shibata, H., Kunieda, M., Hara, F., Suzuki, K., Ichihashi, I., Iiyama, K., Matsuda, T. and Murota, M., 1991, "Development of energy absorber and its application to piping system in nuclear power plants," ASME PVP, Vol. 211, pp. 51–57.
93. Shibata, H., Hara, F., Suzuki, K., Kunieda, M., Ichihashi, I., Fukuda, T., Satoh, A., Takada, K., Furukawa, S. and Kobayashi, H., 1991, "Development of the elasto-plastic damper and its application to the piping system in nuclear power plants," Proceedings of 11th International Conference on Structural Mechanics in Reactor Technology (SMiRT 11), Tokyo, Japan, August 18–23, pp. 487–492.
94. Shibata, H., Kunieda, M., Hara, F., Suzuki, K., Ichihashi, I., Fukuda, T., Satoh, A., Takata, K., Furukawa, S. and Kobayashi, H., 1991, "Development of elasto-plastic damper as a seismic support for piping system in nuclear power plants," ASME PVP, Vol. 211, pp. 63–69.
95. Chiba, T. and Kobayashi, H., 1990, "Response characteristics of piping system supported by visco-elastic and elasto-plastic dampers," Journal of Pressure Vessel Technology, Vol. 112, No. 1, pp. 34–38.
96. Nomura, T., Kojima, N., Shimoda, I., Tsuruya, C., Fujita, K., Ito, T., Nakatogawa, T. and Takayama, Y., 1989, "Study on lead extrusion damper as a seismic support," Proceedings of the 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Anaheim, CA, August 14–18, pp. 733–737.
97. Sone, A. and Suzuki, K., 1989, "An experimental study of an energy absorbing restrainer for piping systems," Proceedings of the 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Anaheim, CA, August 14–18, pp. 721–726.
98. Olson, D. E. and Tang, Y. K., 1988, "Decreasing snubber in-service inspection costs through snubber reduction and improved test limits," Nuclear Engineering and Design, Vol. 107, No. 1–2, pp. 183–199.
99. Kunieda, M., Chiba, T. and Kobayashi, H., 1987, "Positive use of damping devices for piping systems—Some experiences and new proposals," Nuclear Engineering and Design, Vol. 104, No. 2, pp. 107–120.
100. Paulay, T. and Goodsir, W. J., 1986, "The capacity design of reinforced concrete hybrid structures for multistorey buildings," Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 19, No. 1, pp. 1–17.
101. Jennings, P. C., 1968, "Equivalent viscous damping for yielding structures," Journal of the Engineering Mechanics Division, Vol. 94, No. EM1, pp. 103–116.
102. Caughey, T. K., 1960, "Sinusoidal excitation of a system with bilinear hysteresis," Journal of Applied Mechanics, Vol. 27, No. 4, pp. 640–643.



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details