"Seismic Analysis of Industrial Pipe Racks with and without Buckling-Restrained Braces"

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Abstract

Industrial pipe racks are essential for supporting pipelines, cable trays, and auxiliary systems in petrochemical, power, and oil and gas facilities. Their seismic resilience is critical to ensuring uninterrupted operations and structural safety. This study presents a comparative seismic and buckling analysis of steel pipe rack structures using conventional hot-rolled bracing and Buckling-Restrained Braces (BRB), modelled and analyzed in STAAD. Unlike conventional braces that buckle under compression, BRB yield in both tension and compression, offering superior energy dissipation.

Two structurally identical models were analyzed under seismic loading. Results showed that the BRB-integrated frame achieved a 37.3% reduction in base shear, a 23% reduction in lateral deflection, and a 22% reduction in story drift compared to the conventionally braced system. The BRB model also exhibited a more uniform stress distribution and improved mode shape regularity. Additionally, the selected BRB configuration with a core area of 47.75 cm^2 These findings confirm that BRB significantly enhance seismic performance and support their integration into high-performance design strategies for industrial pipe racks in seismic-prone regions.

Keywords- *Pipe Rack Systems, Seismic Risk Mitigation, Buckling-Restrained Braces (BRB), Dynamic response.*

1. INTRODUCTION

In industrial and refinery operations, piping systems serve as vital conduits for transporting gases and liquids between process units. These systems—comprising interconnected pipes, fittings, flanges, pumps, valves, tanks, and heat exchangers—are often referred to as the lifelines of a facility, representing a substantial portion of the overall capital investment. Due to spatial constraints and the critical nature of process continuity, proper design and support of piping networks pose significant engineering challenges.

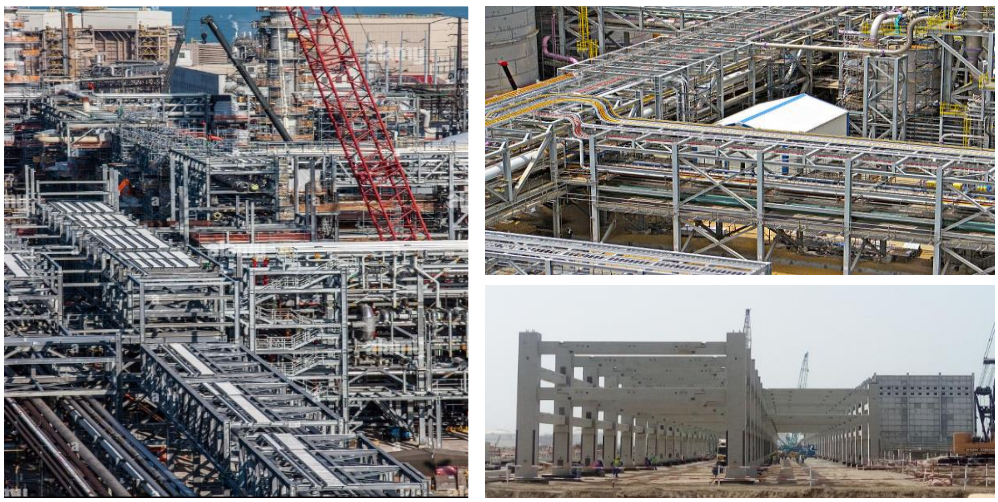

Fig 1.1: Snaps for Various Industrial Pipe Racks

Pipe support is integral to maintaining the structural integrity of piping systems. They carry the weight of pipes and their contents while safely transferring loads induced by pressure, temperature fluctuations, and external actions to the supporting structure. Pipe racks—also referred to as pipe bridges or pipe ways—are structural frameworks, typically composed of steel or reinforced concrete, designed to elevate and organize piping, cable trays, and occasionally mechanical equipment. These racks facilitate safe routing across process areas and help manage dead, live, and dynamic loads efficiently.

Given their exposure to lateral forces such as thermal expansion, wind, and seismic excitation, pipe racks must be designed to maintain structural stability under multi-hazard loading conditions. Failures due to pipe-support separation, excessive displacement, or inadequate ductility can lead to significant operational hazards. This is particularly critical in seismic-prone regions, where dynamic forces can induce large lateral displacements and buckling in conventional bracing systems.

The principal objectives of pipe rack design include:

- Maintaining allowable stress levels and joint integrity.
- Controlling vibrations and dynamic responses.
- Mitigating seismic and wind-induced displacements.
- Preventing uplift and pipe sagging.
- Accommodating thermal expansion and protecting sensitive instrumentation.

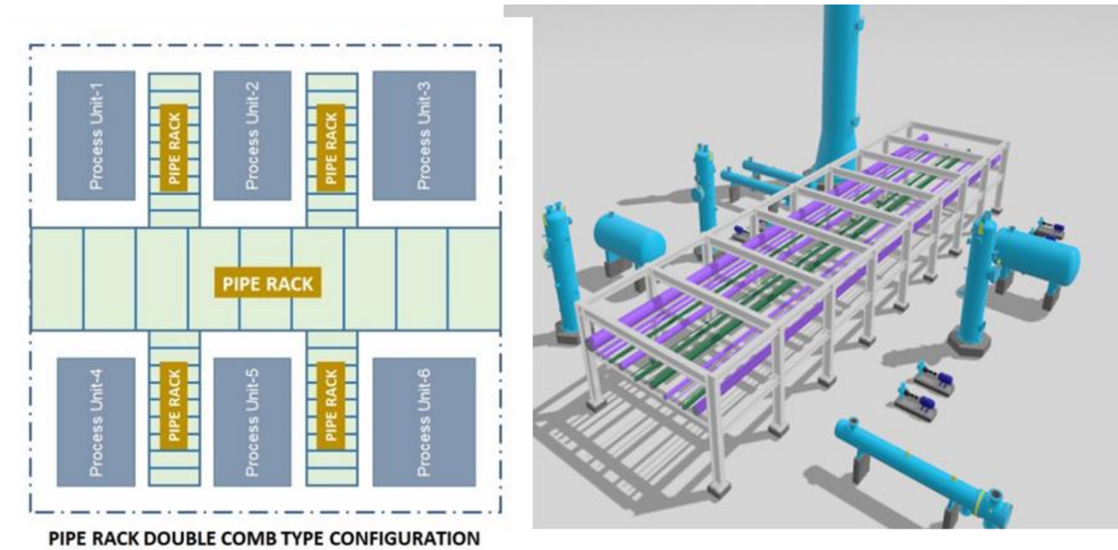

Fig 1.2: Piperack layouts and 3D view of rack with equipment

To address these challenges, this study explores the integration of Buckling-Restrained Braces (BRB) into industrial pipe rack systems as a means of seismic risk mitigation. BRB are advanced structural devices that provide stable, symmetric hysteretic behavior under cyclic loading by allowing the steel core to yield in both tension and compression without buckling. Originating in Japan in the late 1980s, BRB have since been adopted globally and are governed by seismic design standards such as AISC 341.

This research investigates the comparative seismic performance of pipe rack systems with conventional hot-rolled steel bracing and BRB-integrated configurations using STAAD.Pro. The analysis includes evaluation of critical parameters such as base shear, lateral displacement, story drift, and stress distribution. Additionally, the study highlights the material characteristics, axial capacity, and composite action of BRB, validating their ductile behavior under seismic excitation.

A. Buckling-Restrained Braces (BRB)

A typical BRB consists of:

Steel Core – The main energy-dissipating element, designed to yield in axial tension and compression.

Debonding Layer – Prevents shear or bending transfer between the core and the casing, ensuring axial deformation.

External Restraining Unit – Usually a concrete-filled steel tube (CFST) that prevents lateral buckling of the core.

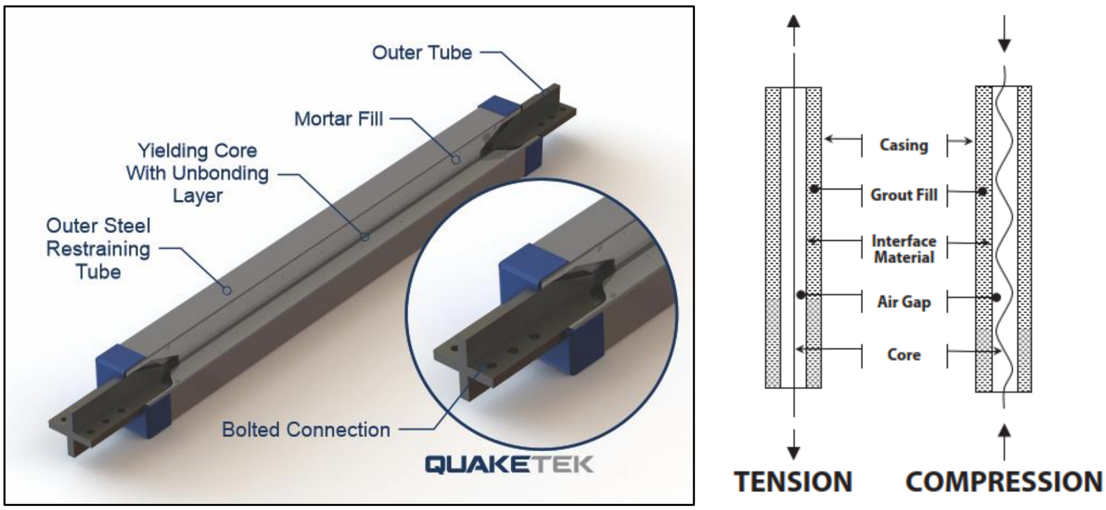

Fig 1.3: Components of & Behaviour of BRB

This composite system ensures high energy dissipation, minimized residual deformation, and improved cyclic stability. BRB not only enhance ductility and reduce base shear but also extend the fundamental period and behavior factor (R), optimizing seismic design. However, they require robust connections and post-earthquake inspection due to possible force amplification from strain hardening.

This paper presents a detailed analysis comparing the seismic performance of BRB-integrated and conventionally braced pipe racks to support their application in performance-based seismic design strategies for industrial structures.

2. LITERATURE REVIEW

A comprehensive review of prior research was conducted to establish the current understanding and identify gaps in the seismic performance of industrial pipe racks with and without Buckling-Restrained Braces (BRB). The review is structured into four key domains: (1) analytical studies on piping systems, (2) seismic stability enhancement strategies, (3) performance assessment of pipe racks, and (4) the role of BRB in structural resilience.

In the domain of analytical studies, Maghrabi et al. [1] provided a detailed review of pipe rack design methodologies, emphasizing the lack of standardized guidelines for seismic conditions. Similarly, Drake and Walter [15] outlined practical design approaches for structural steel pipe racks, highlighting the need for robust frameworks to address dynamic seismic loading. Parulekar et al. [16], [18], [20], [21] conducted extensive experimental and analytical studies on elasto-plastic dampers, demonstrating their effectiveness in dissipating seismic energy in complex piping systems. Their work showed that such dampers significantly reduce stress concentrations in critical components under cyclic loading. Note: A previously cited study by Kunieda et al. [45] could not be verified as it is absent from the provided reference list and has been excluded pending further details.

Seismic stability enhancement strategies have been explored through various damping and isolation techniques. Erduran and Ryan [13] investigated the effects of torsion on peripheral steel-braced frame systems, revealing that torsional irregularities amplify seismic demands, necessitating advanced damping mechanisms. Bakre et al. [17], [19] proposed X-plate dampers and isolation devices to control seismic responses in piping systems, achieving significant reductions in displacement and acceleration. Soong and Spencer Jr. [22] reviewed supplemental energy dissipation techniques, including viscous and hysteretic dampers, which enhance the seismic resilience of industrial structures by mitigating dynamic amplifications.

Performance assessment of pipe racks under seismic loading remains a critical area with limited research. Borkar and Daule [2] conducted dynamic analyses of pipe rack systems, emphasizing the importance of incorporating seismic drift, torsional effects, and P-Δ considerations to ensure structural integrity. Karimi et al. [14] evaluated pipe rack supporting structures in a petrochemical complex, identifying vulnerabilities due to inadequate lateral stiffness under seismic excitations. Studies on modular and soil-interactive systems, such as Di

Roseto et al. [7] and Mitropoulou et al. [11], underscored the significant influence of soil–structure interaction and foundation flexibility on seismic response, advocating for performance-based design approaches to account for these effects.

The integration of BRB into pipe racks represents a promising advancement in enhancing structural resilience. Kanyilmaz et al. [10] performed full-scale push-over tests on braced steel storage racking systems, demonstrating that BRB effectively enhance energy dissipation and prevent buckling under lateral loads. Chen et al. [3] explored the multidirectional stability of prefabricated modular steel structures, finding that BRB improve ductility and reduce collapse risks during seismic events. Saikia and Pathak [12] analyzed steel-braced pipe racks in oil refineries, recommending strategic bracing layouts to optimize lateral stiffness and minimize seismic damage. These studies collectively highlight the potential of BRB to transform pipe rack design by providing reliable energy dissipation and enhanced stability under seismic loading.

Research Gap

Despite existing work on BRB in general steel structures, their specific application to industrial pipe racks—considering the coupled interaction between piping and supporting frames—remains limited. Moreover, probabilistic assessments incorporating soil-structure interaction and nonlinear behavior are largely absent. This study aims to fill this gap through comparative analysis of BRB and non-BRB pipe rack configurations using STAAD, focusing on base shear, displacement, drift, and stress behavior under seismic excitation

3. METHODOLOGY

This paper reports on the investigations conducted to assess the seismic performance of industrial steel pipe rack systems with and without Buckling-Restrained Braces (BRB). In recent years, BRB have emerged as an effective structural solution for seismic retrofitting and performance enhancement of non-building structures due to their symmetric yielding characteristics under tension and compression. The present study aims to evaluate and compare the dynamic response of unbraced and BRB-integrated pipe rack systems in terms of displacement, velocity, acceleration, and torsional moments under seismic loading.

- Static and Dynamic Loading: Evaluating pipe rack performance under both static and dynamic load cases to understand structural behavior under varied operational and environmental conditions.
- Modelling with and without BRB: Creating two structural models one with Buckling-Restrained Braces (BRB) and one without comparing their performance and assessing the impact of BRB integration.
- Dynamic Analysis: Conducting modal and response spectrum analyses to evaluate how the BRB influence dynamic characteristics such as natural periods and mode shapes.
- Seismic Performance: Studying the behavior of the pipe rack structure during seismic events, including evaluation of parameters such as base shear, lateral deflection, and story drift.

4. PERFORM ANALYSIS & RESULT DISCUSSION

Dynamic analysis was conducted in STAAD using Response Spectrum Analysis (RSA) to evaluate seismic performance under three orthogonal components—ELX, ELY, and ELZ. The natural periods were computed via modal analysis, considering up to 100 mode shapes to capture at least 90% of the total mass participation. The Complete Quadratic Combination (CQC) method was adopted due to closely spaced modes, while SRSS was not used.

P–Δ effects were included in the analysis. As the structure falls under Category 2 per IS 1893 (Part 4), accidental torsional eccentricity was not considered. BRB were modelled as truss elements with equivalent stiffness and damping. The STAAD models reflect accurate 3D geometry, boundary conditions, and load applications, including static, wind, and seismic loads, ensuring compliance with IS design standards.

This study adopts a finite element-based analytical approach using STAAD CONNECT Edition to compare the seismic performance of industrial steel pipe racks with conventional hot-rolled bracing and Buckling-Restrained Braced (BRB). The methodology involves structural modeling, material selection, load definition, and dynamic analysis as per relevant Indian Standards (IS).

A. Structural Modeling

Two pipe rack configurations were modeled:
Model A: Conventional concentric bracing system
Model B: BRB-integrated frame

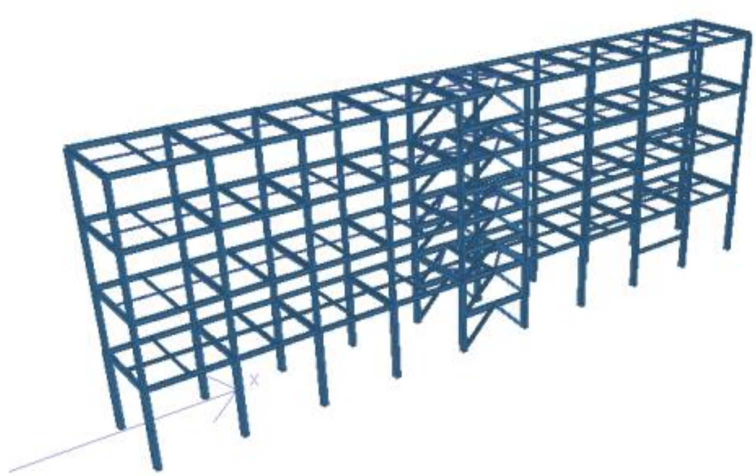

Fig 4.1: 3D snap from STAAD for Piperack module for Both BRB and without BRB

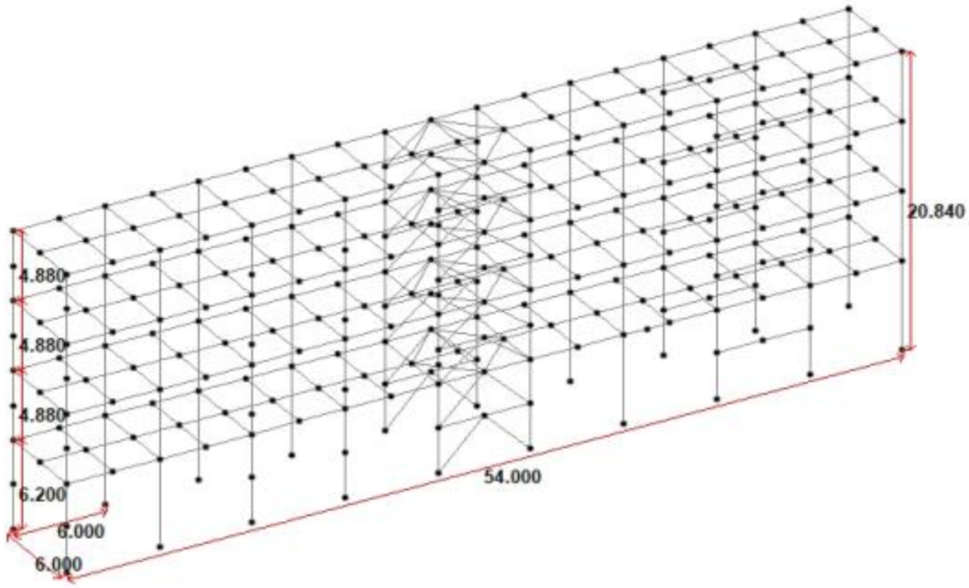

Fig 4.2: Geometry STAAD for Piperack module for Both BRB and without BRB

Both models consist of 9 bays, 4 tiers, and a total length of 54 m, with a maximum height of 20.84 m. Each bay spans 6 m, and inter-tier spacing ranges from 4.88 m to 6.5 m. Columns and beams were modeled using rolled steel sections conforming to IS 2062 and BSEN 10365.

STAAD's TRUSS and BEAM elements were used, with BRB defined via parametric stiffness values and damping properties derived from manufacturer data and literature. BRB material characteristics included a core area of 97 cm² and enhanced damping (5%) compared to conventional braces (2%).

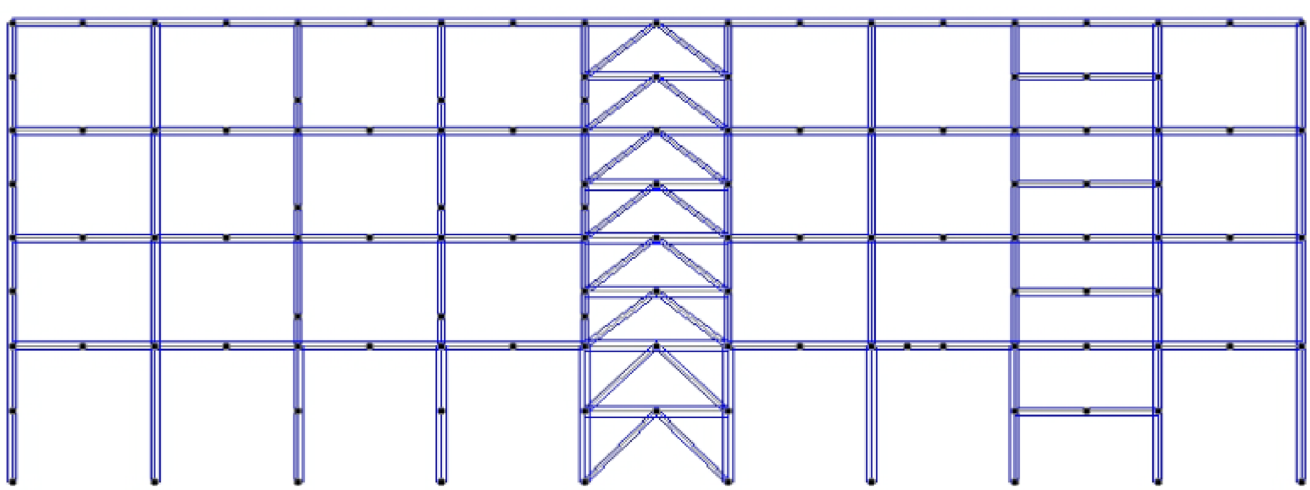

Fig 4.3.: Elevational Section and Plan for Piperack module for Both BRB and without BRB

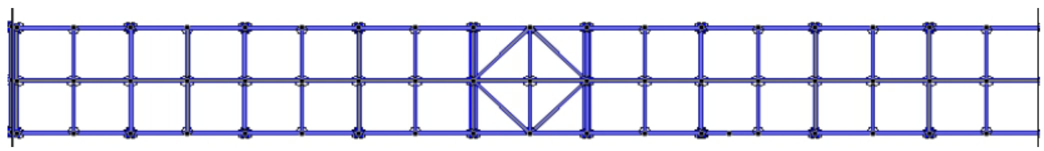

Fig 4.4: Plan for Piperack module for Both BRB and without BRB

B. Load Considerations

Loading was applied as per IS 875 (Parts 1–3), IS 800:2007, IS 1893 (Part 4:2024) & PIP for seismic design of industrial structures. The following load types were considered:

Dead Load & Live Load: Based on structural self-weight and equipment loads

Pipe Loads: Including empty, operating, and test conditions, obtained from the mechanical discipline

Thermal Loads: Applied based on pipe expansion forces

Wind Loads: Calculated for a basic wind speed of 44 m/s per IS 875-3

Seismic Loads: Applied for Zone V (Z = 0.36), with Importance Factor = 1.5 and Response Reduction Factor R = 4.5 (conventional) and R = 7 (BRB)

Load Combinations: Included gravity, thermal, wind, and seismic cases following IS 800 & IS 1893-4 (e.g., ELX ± 0.3ELY ± 0.3ELZ)

Load case Envelopes were created for along with repeat Load cases

Serviceability (LC 101–172)

Strength and Stress Checks (LC 301–408)

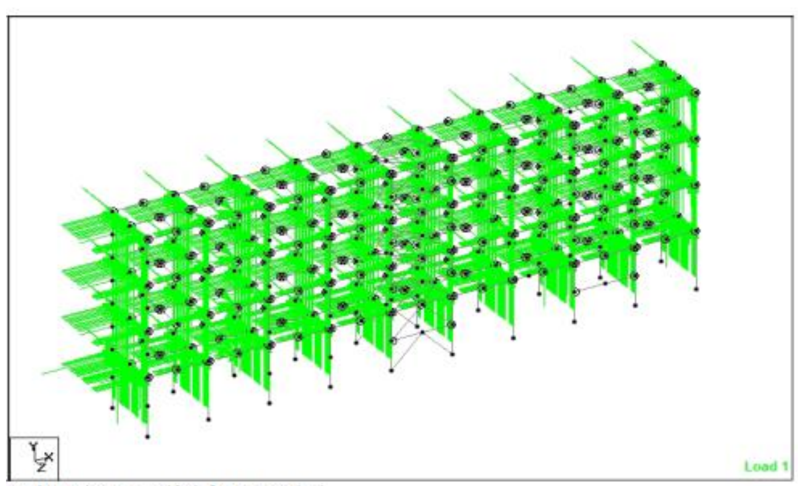

Fig 4.5: EQX/Y/Z Loading Application for Piperack module for Both BRB and without BRB

C. Material Properties

Sr.No.	Parameter	Non-BRB (Hot-Rolled Steel Brace)	BRB (Buckling-Restrained Brace)
1	Material Grade	IS 2062 E250 / E350	As Per CoreBrace
2	Modulus of Elasticity (E)	2.0 × 10^5 MPa (2.0e8 kN/m²)	2.05 × 10^5 MPa (2.05e8 kN/m²)
3	Yield Strength (Fy)	250 MPa	262 MPa
4	Ultimate Tensile Strength	410 Mpa	414 Mpa
5	Designed section	UC203x203x89	Bolted Connection Core equal to 15in^2 (97cm2)
6	Buckling Behavior	Buckles in compression; strength degradation	Buckling restrained; same capacity in tension & compression
7	STAAD Element Type	BEAM (TRUSS)	Parametric properties (TRUSS)
8	STAAD Material Example	IS2062_E250	BRB_STEEL
9	Failure Mode	Buckling or yielding	Core yielding; casing prevents buckling
10	Damping Ratio	0.02	0.05
11	Use in STAAD	Hot-rolled profiles with moment/axial properties	Defined with core area + releases or spring properties
12	Density	78.5 Kn/m3	76.97kN/m3
13	Coefficient of Thermal Expansion	6.5×10^{-6} /°C	12×10^{-6} /°C (or 1.2e-5 /°C)
14	Yield strength overstrength factor	1.5	1.1
15	Tensile rupture overstrength factor	1.2	1.04

All bracing members were modeled to capture their stiffness, strength, and post-yield characteristics accurately. BRB were assigned ductile behavior with buckling restraint and symmetric yield in compression and tension.

The Buckling-Restrained Braces (BRB) in this study were designed based on axial demands derived from modal response spectrum analysis in STAAD.Pro. The BRB were arranged in a chevron configuration and modeled as truss elements with equivalent axial stiffness, representing the combined behavior of the yielding core, transition zone, and non-yielding segments.

Design input parameters included axial forces obtained from beam end reactions under seismic loading. The design followed a manual procedure using manufacturer data (CoreBrace®), accounting for yield strength, core area, stiffness, and strain-hardening effects. A Response Modification Factor (R) of 7 was used for BRBF systems.

Table -4.1: Detail Base shear for BRB vs without BRB

Height in m	Level	without BRB Shear kN	with BRB Shear kN
21.14	8	372.64	238.17
18.7	7	391.77	251.12
16.26	6	663.77	422.43
13.82	5	678.75	432.06
11.38	4	854.11	538.43
8.94	3	862.7	543.76
6.5	2	963.92	604.39
3.5	1	969.88	608.01
0.3	0	969.88	608.01

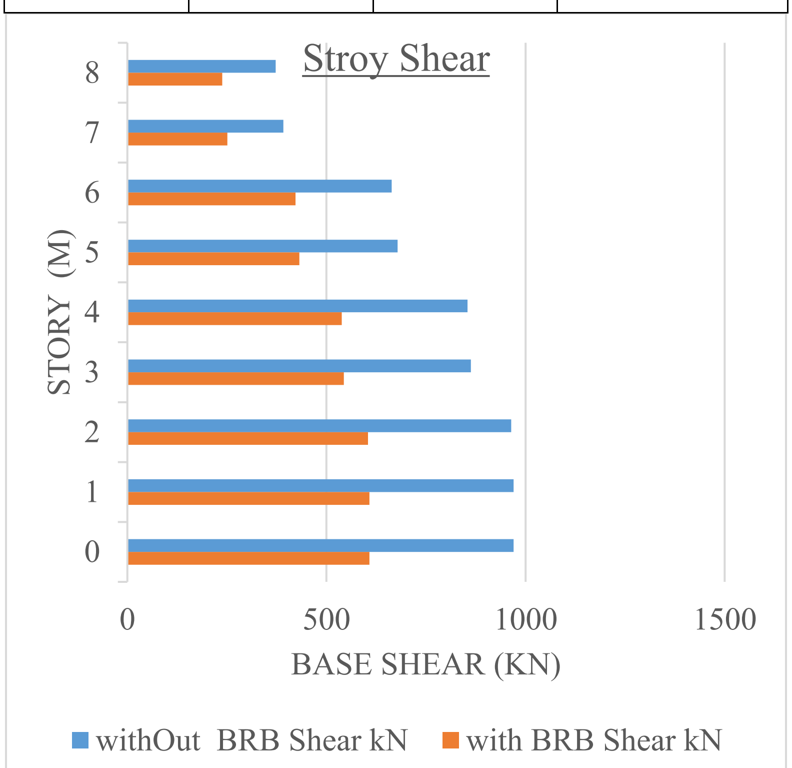

Fig 4.6: Snap for Storey Shear for braced area frame without BRB and with BRB

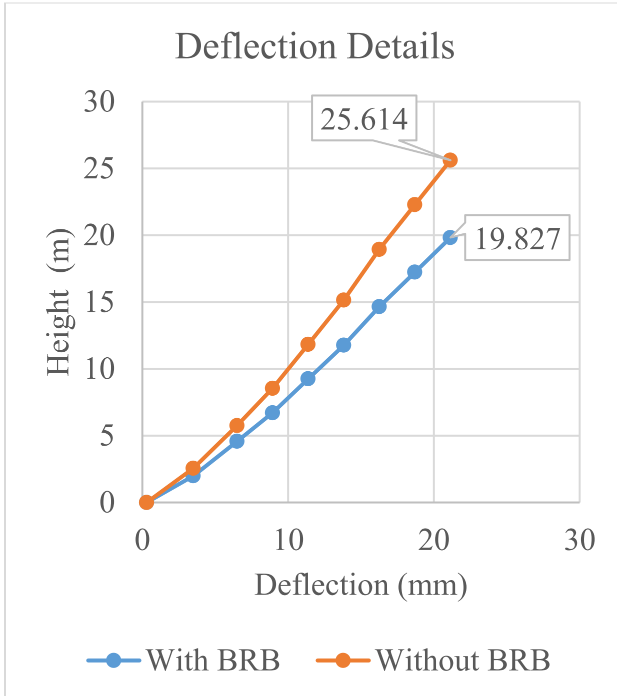

Fig 4.2: Snap for Frame deflection for braced area frame without BRB and with BRB

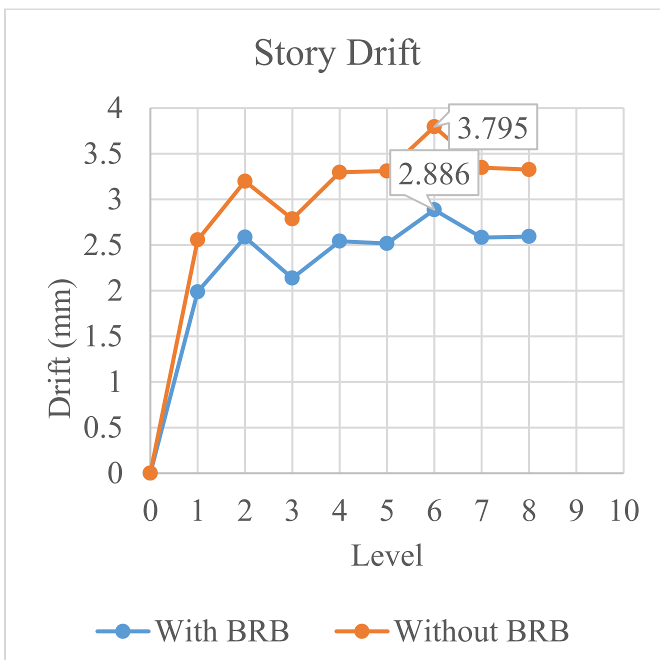

Fig 4.3: Snap for story drift frame without BRB and with BRB

Key Design Steps:

- Core Area Estimation (Asc)
- Stiffness Verification & Adjustment
- Brace Size Selection
- Strength Adjustment via Interpolation for non-standard lengths

Table -4.2.: Design summary for BRB bracing

Parameter	**Results**
Minimum Yield Strength (Fy_min)	262 MPa
Maximum Yield Strength (Fy_max)	414 MPa
Brace Angle (θ)	46.85°
Core Area (Asc)	47.75 cm²
Strain Hardening Factor (ω)	1.44
Compression Overstrength (β)	1.13
Yield Strength used (Fy)	262 MPa
Brace Length (Lwp)	4390 mm
Required Axial Force (Pu_ required)	1126.30 kN
Calculated Ultimate Axial Force	2280 kN
Strain at Drift	1.31%
Deformation (ΔL)	3.03 mm
Axial Stiffness Adjustment Factor KF Prime	1.65
Geometry adjustment factor	0.9
Axial Stiffness Adjustment Factor KF Final	1.84

5. CONCLUSION

The This study presents a comparative seismic evaluation of industrial pipe rack systems with conventional hot-rolled bracing and Buckling-Restrained Braces (BRBs), using finite element analysis in STAAD The results demonstrate that BRB integration significantly enhances the seismic performance of pipe rack structures.

Key structural parameters showed substantial improvements with BRBs: base shear was reduced by approximately 37.3%, lateral deflection by 23%, and story drift by 22%, ensuring compliance with IS 1893:2016 drift limits. These improvements indicate increased stiffness, energy dissipation capacity, and overall structural resilience under seismic excitation.

The BRB-integrated model maintained all members within permissible stress limits and exhibited more uniform stress distribution. The BRB configuration, designed with a core area of 47.75 cm^2 and axial capacity of 2280 kN, safely exceeded demand (1126.3 kN), offering a conservative design margin and controlled deformation.

These findings confirm that BRBs are an effective solution for enhancing the seismic resilience of industrial pipe racks, especially in high seismic zones. Their inclusion supports performance-based seismic design strategies, promoting safer and more reliable structural systems.

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