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Optimized Design and Analysis of Steel Pipe Rack for Oil and Gas Industries as Per Indian Standard Codes

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Abstract - Steel pipe racks are essential structural systems in oil and gas facilities, refineries and petrochemical plants. They support process pipelines, utility lines, cable trays and associated services while maintaining organized routing, access and operational continuity. Their design is challenging because the supporting frame is subjected to dead load, pipe operating and test loads, wind, earthquake, thermal effects, maintenance actions and other project-specific forces. The present study evaluates the structural behaviour and preliminary economy of a three-tier steel pipe rack having an overall length of 50 m, width of 6 m and height of 24 m. The adopted longitudinal column spacing is 10 m and the nominal vertical tier spacing is 3 m. The basic wind speed is 47 m/s and the project basis identifies the site as Seismic Zone V.

Three structural configurations are compared: a conventional moment-resisting frame, an X-braced frame and an A-type braced frame. The project report provides estimated steel quantities of 115 t, 90 t and 85 t, respectively. The corresponding reported maximum lateral deflections are 42 mm, 29 mm and 23 mm; reported wind base shears are 1,090 kN, 849 kN and 743 kN; and maximum member utilization ratios are 0.90, 0.83 and 0.82. On the basis of these supplied values, the A-type braced alternative has the lowest reported steel quantity, deflection, wind base shear and utilization ratio. Relative to the moment frame, its reported steel quantity is lower by 26.09% and its maximum deflection is lower by 45.24%.

The findings indicate that bracing can improve the lateral response and material efficiency of the studied pipe-rack model. The A-type arrangement is therefore identified as the preferred preliminary alternative within the reported comparison. This conclusion is conditional: the source report contains load-input and modelling details that require reconciliation, and the reported values should be verified against the final STAAD.Pro model, code checks, connection design, foundation reactions and piping flexibility requirements before construction or publication as a validated design.

Keywords: Steel pipe rack; oil and gas industry; structural optimization; moment-resisting frame; X-bracing; A-type bracing; wind load; seismic load; IS 800; IS 875; IS 1893.

1. INTRODUCTION

The oil and gas industry depends on extensive networks of pipelines for transporting crude oil, refined products, natural gas, steam, cooling water, compressed air and other process fluids. Refineries, petrochemical plants, fertilizer facilities and gas-processing installations also require electrical, instrumentation and communication services. An elevated pipe rack provides a common structural corridor for these services and reduces the need for independent supports or underground routes.

A typical pipe rack consists of columns, longitudinal and transverse beams, tier beams, pipe-support members, vertical and plan bracing, connections and foundations. Its framing is generally repeated along the plant route. Transverse frames support the rack across its width, while longitudinal members provide continuity and stability along its length. The load path must transfer gravity actions from the pipes and service systems through secondary members, primary beams and columns to the foundations.

Unlike a conventional building frame, a pipe rack is closely coupled to the arrangement and operating behaviour of the supported piping. Pipe anchors, guides, line stops, sliding supports and shoes transfer forces to the steelwork.

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Temperature changes can cause expansion and contraction, while operating, empty and hydrotest conditions can produce different vertical reactions. Wind acts on the steel frame and exposed pipes; earthquake action can be transmitted through both the rack and supported services.
The selected structural system influences member sizes, joint demands, lateral stiffness, deflection, foundation forces, access and constructability. A moment-resisting frame primarily resists horizontal actions through flexure in beams and columns and through moment-transferring joints. Braced frames introduce diagonal members that can transfer a significant portion of lateral force through axial action. X-bracing provides a direct diagonal load path but can obstruct the bay. A-type bracing can provide triangulation while potentially retaining more usable opening, depending on its detailed geometry.

1.1 Need for structural optimization

Optimization is not simply the minimization of steel tonnage. A useful pipe-rack solution must satisfy strength, stability and serviceability requirements while remaining compatible with piping flexibility, valve access, maintenance clearances, fabrication, transportation and erection. A reduction in primary member weight may be offset by additional bracing connections, more complex erection or pipe rerouting. The preferred system should therefore be selected using a multi-parameter comparison.

1.2 Aim and scope

The aim of this study is to compare three lateral load-resisting arrangements for the same preliminary pipe-rack geometry and to identify the arrangement that provides the most favourable reported balance of steel consumption, lateral deflection, wind base shear and member utilization. The scope is limited to the data and results contained in the supplied project report. It does not constitute an independent re-analysis or a certified construction design.

1.3. Objectives and Study Framework

- Develop a comparative framework for a conventional moment-resisting, X-braced and A-type braced steel pipe rack.
- Maintain common overall geometry and comparable loading assumptions across the three alternatives.
- Review the structural response using the reported steel quantity, maximum lateral deflection, wind base shear and maximum utilization ratio.
- Interpret the influence of diagonal bracing on lateral stiffness and the distribution of member forces.
- Identify the preferred preliminary configuration while recording design checks and project information that require verification.

3. LITERATURE REVIEW

The project report's literature review identifies research on the design, assessment and optimization of industrial pipe racks. Drake and Walter (2010) discuss structural steel pipe-rack design as a distinct industrial framing problem. Singh and Ishtiyaque (2016) address optimized pipe-rack design using international codes and standards. Kawade and Navale (2019) examine the optimization of pipe racks through the study of braced bays. These topics establish the relevance of comparing alternative lateral systems rather than treating a pipe rack as a generic building frame.
Di Sarno and Karagiannakis (2020) are cited for critical assessment of design-code provisions and seismic assessment of pipe racks, including soil–structure interaction. Rajalingam and Srivastava (2020) consider analytical modelling and quantification of industrial pipe racks. Zakian, Ordoubadi and Alavi (2021) investigate optimization algorithms for steel pipe-rack structures. The project report also cites comparative studies of Indian and American standards and studies on wind loads for pipe-rack structures.
The reviewed work points to several recurring considerations: realistic representation of pipe and equipment loads, lateral system selection, code-consistent wind and seismic actions, connection behaviour, foundation flexibility and constructability. Optimization algorithms may be useful for systematic member selection, but the structural model and design constraints must first be reliable. A mathematically light frame is not necessarily the most practical industrial arrangement if bracing conflicts with process lines or access.
The present comparison is narrower than a full optimization study. It evaluates three preselected framing alternatives using the numerical results reported in the project document.

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4. DESIGN BASIS AND STRUCTURAL CONFIGURATION

The project considers a long, three-tier pipe rack. The dimensions and general design basis extracted from the project report are summarized in Table 1.

Table 1. Geometric Parameters

Parameter	Adopted project value
Overall length	50 m
Overall width	6 m
Overall height	24 m
Longitudinal column spacing	10 m
Number of pipe tiers	3
Nominal vertical tier spacing	3 m
Basic wind speed	47 m/s
Seismic classification	Zone V
Structural material	Hot-rolled structural steel; FE250 is stated in the modelling chapter

Six transverse frame lines are identified at 10 m intervals along the 50 m length. Each transverse frame has two column lines separated by 6 m. The model description states that all three alternatives use the same basic geometry and gravity loading, with the lateral-resisting arrangement varied between cases.
The stated 24 m overall rack height and the three tier levels spaced at 3 m should not be interpreted as the same dimension: the tier elevations describe the supported pipe levels, while the total structural height is separately stated as 24 m. The precise elevation schedule, top-of-steel height and bracing extents should be confirmed from the original model drawings.



Figure 1. Industrial multi-level pipe-rack arrangement

4.1 Structural alternatives

4.1.1 Conventional moment-resisting frame

The first alternative uses rigid beam-to-column connections and no vertical diagonal bracing. Wind and earthquake actions are resisted primarily through frame action, including bending in beams and columns and moment transfer at the joints. The absence of diagonal members leaves the bays relatively open for piping and access, but the main frame members and connections may attract larger flexural demands.

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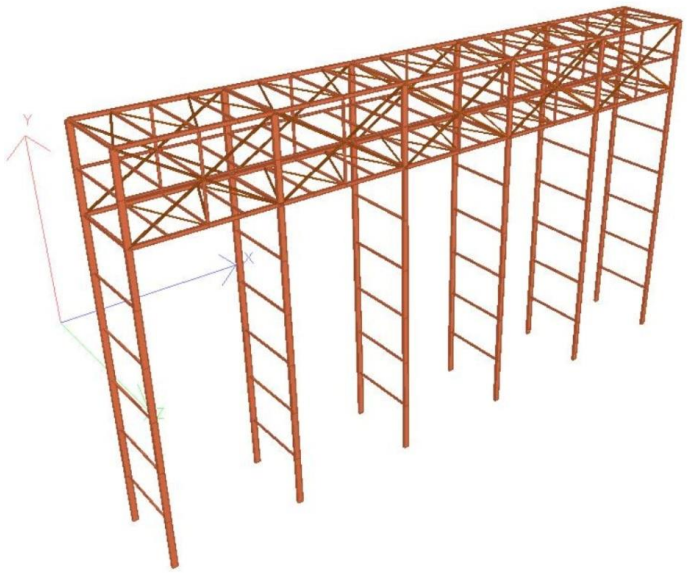

Figure 2. Three-dimensional steel pipe-rack model

4.1.2 X-braced frame

The second alternative introduces crossed diagonal members in the vertical bays. The bracing creates a direct lateral load path and increases the lateral stiffness of the frame. Depending on member slenderness and connection assumptions, the diagonals may participate in tension and compression or may be designed primarily as tension members. Crossed diagonals can reduce the unobstructed opening within a bay and must be coordinated with pipe routes, cable trays and access.

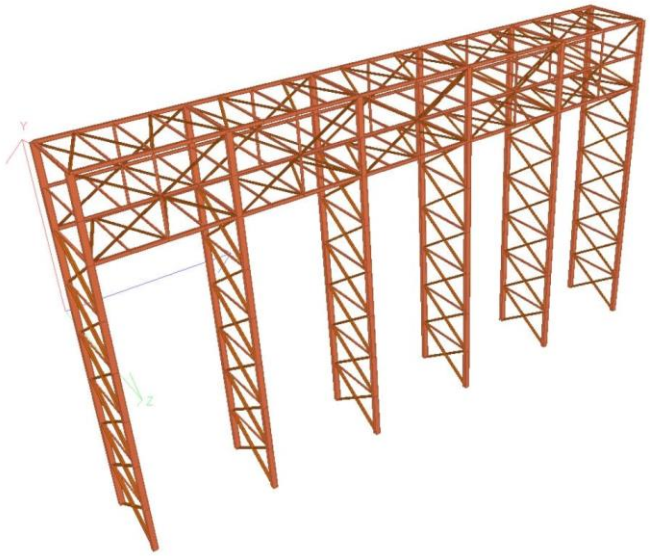

Figure 3. Three-dimensional braced pipe-rack model

4.1.3 A-type braced frame

The third alternative uses inclined members arranged in an A-type configuration. The diagonal arrangement provides triangulation and can transfer lateral forces through axial action while maintaining a different opening geometry from a full X-brace. Its suitability depends on the exact member arrangement, connection eccentricities and whether the bracing interferes with service corridors or maintenance access.

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Figure 4. Industrial pipe-rack steelwork illustrating an open framing arrangement.

5. MODELLING AND ANALYSIS METHODOLOGY

The project describes a three-dimensional analytical model developed in STAAD.Pro. The same general geometry, support assumptions, material basis and load cases are intended to be used for all alternatives. This common basis is important: a comparison is meaningful only if changes in results arise from the structural configuration rather than from inconsistent loading or boundary conditions.

5.1 Model idealization

Table 2. Model Idealization

Item	Modelling basis reported
Structural system	Three-dimensional steel frame
Supports	Fixed at the bottom
Global axes	X: longitudinal; Y: vertical; Z: transverse
Main members	Beam-column line elements
Bracing	Axial-dominant diagonal members, with suitable connection assumptions
Gravity actions	Applied at appropriate member or support locations
Wind actions	Applied using exposed areas and applicable wind provisions
Seismic actions	Defined using the adopted seismic procedure
Design approach	Limit-state design as applicable under IS 800
Comparison basis	Same geometry and support assumptions for all three cases

5.2 Material and section properties

The modelling chapter identifies hot-rolled sections and states FE250 as the material grade. The project report also provides typical steel properties, including an elastic modulus of 2.0×10^5 N/mm², Poisson's ratio of 0.30 and density of 7,850 kg/m³. Actual yield and tensile strengths depend on the selected product thickness and the applicable material specification; these should be assigned from certified material data.

The section schedule above is transcribed from the project's alternative-specific tables. The complete schedule also includes secondary pipe-support beams, longitudinal stringers and plan bracing. Section naming and built-up box-member definitions must be checked against the actual STAAD.Pro property database and fabrication details.

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Table 3. Section Member Used

Member group	Moment frame	X-braced frame	A-type braced frame
Columns	ISMC 400 BOX	ISMC 250 BOX	ISMB 350 BOX (top columns stated)
Longitudinal main beams	ISMB 500	ISMB 300	ISMB 450
Transverse beams	ISMB 400	ISMB 200	ISMB 350
Tier beams	ISMB 350	ISMB 250	ISMB 300
Pipe-support beams	ISMC 300	ISMC 250	ISMC 250
Main diagonal bracing	—	ISA 110×110×10	ISA 100×100×10

5.3 Analysis workflow

Establish the rack geometry, member incidences, tier levels, frame spacing and global coordinate system.
Define steel material properties and assign the selected sections to the members in each alternative.
Apply support conditions and verify the intended restraint directions.
Define self-weight, pipe loads, imposed or maintenance loads, wind actions and earthquake actions.
Generate the strength and serviceability load combinations required by the adopted project design basis.
Run the analysis and review model stability, warnings, deformed shapes and force distribution.
Extract maximum lateral displacement, support reactions, member forces, wind base shear and design utilization ratios.
Perform member design checks and review bracing, beam-column and base connections separately.
Compare the three alternatives using identical acceptance criteria and document any differences in modelling assumptions.

The comparison parameters reported in the project are global steel tonnage, maximum lateral deflection, wind base shear and maximum member utilization ratio. These indicators are useful for screening alternatives, but they do not replace member-by-member design verification, connection design or piping stress assessment.

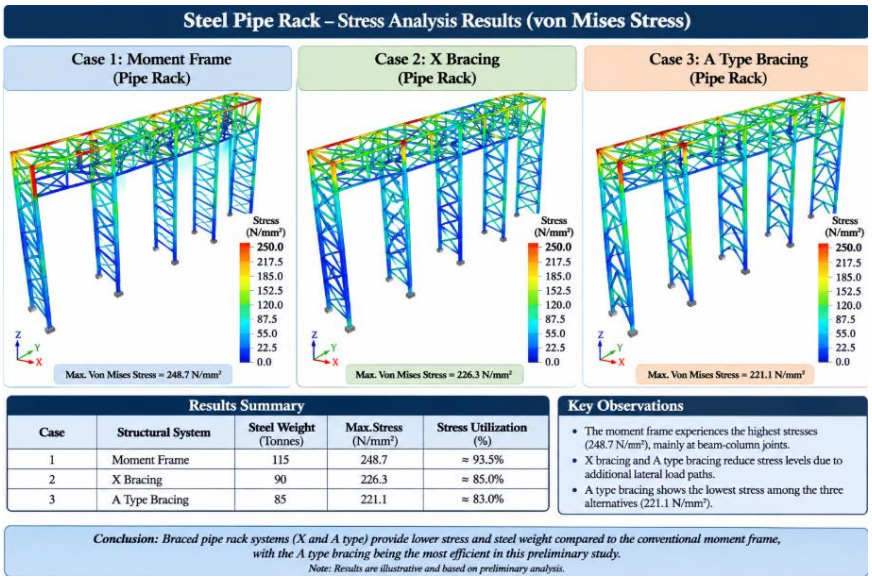

Figure 5. Comparative STAAD.Pro stress-analysis visual

5.4 Load cases and combinations

The project identifies dead load (DL), imposed load (IL), wind in the longitudinal and transverse directions, and earthquake actions in the principal directions. Pipe operating loads are also considered in the project load discussion. The report lists strength combinations including gravity with wind or earthquake action and reduced-dead-load

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combinations. The exact coefficients and signs must be confirmed against the adopted editions of the relevant Indian Standards and the project specification before final design.

6. LOAD ASSESSMENT

6.1 Pipe loading

The pipe load supplied in the project is 6.5 kN/m per tier. For a 50 m run, the line load gives 325 kN per tier. For three tiers, the direct arithmetic total is 975 kN (325 × 3). The 975kN is the arithmetic result of the stated line-load data.

Table 4. Pipe Load Calculation

Calculation item	Expression	Value
Pipe line load per tier	6.5 kN/m × 50 m	325 kN
Three-tier total from stated line load	325 kN × 3	975 kN
Total pipe load stated elsewhere in report	Reported value	2,475 kN
One support reaction per tier at 2.5 m spacing	6.5 kN/m × 2.5 m	16.25 kN
Equivalent support-beam UDL over 6 m	16.25/6	2.70 kN/m

6.2 Wind loading

The report adopts a basic wind speed Vb = 47 m/s and gives the design wind speed relation Vz = Vb × k1 × k2 × k3. Using k1 = 1.0, k2 = 1.14 and k3 = 1.0 gives Vz = 53.58 m/s. The corresponding pressure calculated using pz = $0.6Vz^2$ is approximately 1.722 kN/m².

Table 5. Wind Load Calculation

Wind parameter	Reported input / result
Basic wind speed, Vb	47 m/s
Risk factor, k1	1.0
Terrain/height factor, k2	1.14
Topography factor, k3	1.0
Calculated design wind speed, Vz	53.58 m/s
Calculated design pressure, pz	1.722 kN/m²
Transverse projected area	1,000 m²
Transverse force coefficient	1.6
Reported transverse wind force	2,755.2 kN
Longitudinal projected area	120 m²
Reported longitudinal wind force	330.364 kN

The report also calculates a pipe-wind force using a 150 mm pipe diameter, 50 m pipe length and force coefficient of 0.70, giving a reported force of 9.04 kN or 0.181 kN/m.

6.3 Earthquake loading

The project report presents an earthquake-load calculation using Zone Factor Z = 0.36, Importance Factor I = 1.5, Response Reduction Factor R = 4, average response acceleration coefficient Sa/g = 2.5 and an assumed seismic weight of 3,500 kN. It uses the relation Ah = (Z/2)(I/R)(Sa/g), obtaining Ah = 0.16875, and calculates a base shear of 591 kN from Vb = AhW.

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Table 6. Earthquake Load Calculation

Parameter	Value reported
Seismic zone	V
Zone factor, Z	0.36
Importance factor, I	1.5
Response reduction factor, R	4
Sa/g	2.5
Assumed seismic weight	3,500 kN
Calculated horizontal coefficient, Ah	0.16875
Calculated base shear	591 kN

7. RESULTS AND COMPARATIVE ANALYSIS

The numerical results below are taken from the comparative result tables and conclusion. They are presented as reported analysis outcomes.

Table 7. Parametric Comparison

Parameter	Moment frame	X-braced	A-type braced
Estimated steel weight (t)	115	90	85
Maximum lateral deflection (mm)	42	29	23
Wind base shear (kN)	1,090	849	743
Maximum utilization ratio	0.90	0.83	0.82

7.1 Structural steel consumption

The conventional moment-resisting alternative has the highest estimated steel weight at 115 t. The X-braced alternative is reported at 90 t, a reduction of 25 t or 21.74% relative to the moment frame. The A-type braced alternative is reported at 85 t, a reduction of 30 t or 26.09%. The A-type alternative is also 5 t, or approximately 5.56%, lighter than the X-braced alternative.

Table 7. Consumption of Steel

Configuration	Steel weight (t)	Reduction vs. moment frame
Moment-resisting frame	115	0.00%
X-braced frame	90	21.74%
A-type braced frame	85	26.09%

The reduction is consistent with the expected role of bracing: diagonal members provide an additional lateral load path and can reduce the flexural demand on the principal beams and columns. However, steel weight alone does not capture connection plates, gussets, bolts, welds, corrosion protection or fabrication complexity.

7.2 Maximum lateral deflection

The reported maximum lateral deflection decreases from 42 mm for the moment frame to 29 mm for the X-braced frame and 23 mm for the A-type braced frame. Relative to the moment frame, the X-braced system reduces the reported maximum displacement by 30.95%, while the A-type system reduces it by 45.24%.

The trend indicates that the braced alternatives provide greater lateral stiffness in the reported analysis. This is mechanically consistent with the additional axial load path formed by the diagonal members. Reduced rack movement can be beneficial to pipe-support alignment and serviceability; nevertheless, allowable rack displacement and support movement must be established from the piping flexibility and equipment interface requirements.

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Table 8. Deflection Comparison

Configuration	Maximum deflection (mm)	Reduction vs. moment frame
Moment-resisting frame	42	0.00%
X-braced frame	29	30.95%
A-type braced frame	23	45.24%

7.3 Wind base shear

The reported wind base shear is 1,090 kN for the moment frame, 849 kN for the X-braced frame and 743 kN for the A-type braced frame. The X-braced configuration is reported to reduce wind base shear by 22.11% relative to the moment frame. The A-type configuration is reported to reduce it by 31.83% relative to the moment frame and 12.48% relative to the X-braced configuration. Base shear represents the resultant horizontal action transferred to the supports for the specified analysis case. Its value depends on the applied wind pressure, exposed area, force coefficients, shielding assumptions, load distribution and structural model.

Table 9. Base Shear Comparison

Configuration	Wind base shear (kN)	Reduction vs. moment frame
Moment-resisting frame	1,090	0.00%
X-braced frame	849	22.11%
A-type braced frame	743	31.83%

7.4 Member utilization ratio

The maximum reported utilization ratio is 0.90 for the moment frame, 0.83 for the X-braced frame and 0.82 for the A-type braced frame. The ratio is described as the relationship between design demand and design capacity. All three reported values are below 1.0, but this alone does not establish overall structural adequacy.

Table 9. Capacity of Member Used

Configuration	Maximum utilization ratio	Reduction vs. moment frame
Moment-resisting frame	0.90	0.00%
X-braced frame	0.83	7.78%
A-type braced frame	0.82	8.89%

7.5 Consolidated interpretation

Across the four reported comparison measures, the A-type braced alternative has the lowest values. The X-braced alternative also improves all four measures relative to the moment frame. The result suggests that the introduction of diagonal bracing is beneficial for the specific model and load assumptions used in the project. It does not establish that A-type bracing will be universally superior for every pipe rack; bay openings, pipe routing, connection detailing, erection access and actual load paths can change the preferred arrangement.

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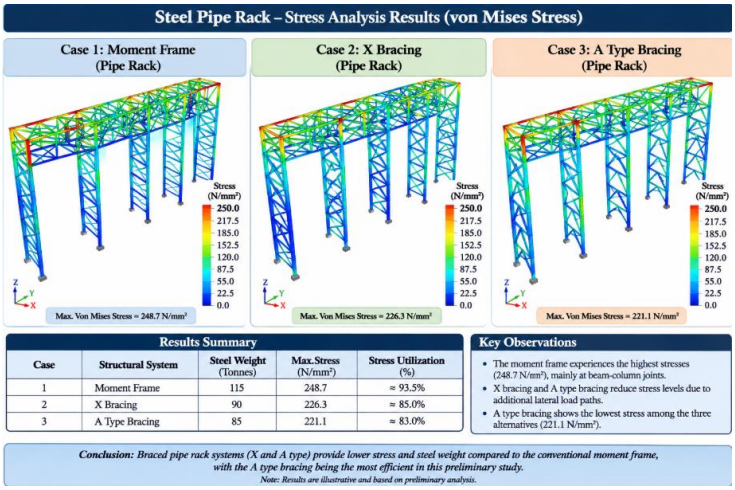

Figure 6. Project-file stress-analysis comparison image; used as a qualitative illustration only.

8. DISCUSSION

The comparison indicates a consistent ranking in the reported numerical results: A-type bracing, followed by X-bracing, followed by the conventional moment frame. The moment frame relies more heavily on bending resistance in the beams and columns. This can increase member sizes and joint demands when lateral actions govern. The braced configurations introduce axial load paths that can improve lateral stiffness and reduce flexural demand in the primary frame.

The A-type system combines the lowest reported steel quantity with the lowest reported maximum displacement and wind base shear. Its reported utilization ratio is also marginally lower than that of the X-braced system. This combination makes it the leading preliminary option in the current comparison. The X-braced system remains a competitive alternative where a clear diagonal load path is desirable and the crossed members can be accommodated without unacceptable interference with process services.

Industrial functionality must remain part of the selection process. A-type bracing can preserve some access openings depending on the configuration, but it may still conflict with large-bore pipes, valves, cable trays, lifting paths or maintenance platforms. X-bracing may obstruct the bay at the crossing. Moment frames may preserve openings but require heavier members and more demanding moment connections.

8.1 DATA CONSISTENCY, LIMITATIONS AND REQUIRED VERIFICATION

Table 9. Observations and Necessary Actions

Item requiring verification	Observation from the supplied project file	Required action
Pipe-load total	6.5 kN/m per tier over 50 m and three tiers gives 975 kN, while another line reports 2,475 kN.	Confirm whether additional pipe, equipment, platform or other loads are included.
Rack geometry	Overall height is 24 m; tier spacing is 3 m and the three tier elevations are listed as 0, 3 and 6 m.	Confirm full elevation schedule and exact bracing extents.
Seismic period calculation	A period expression uses h = 20 m despite the stated 24 m rack height; the report also references more than one IS 1893 part/edition.	Confirm the correct industrial-structure provisions, height, period method and code edition.
Wind actions	Calculated transverse and longitudinal wind forces are much larger than the reported comparative base-shear values.	Reconcile applied projected areas, force coefficients, load factors, pipe shielding and extracted output case.
Material and section data	FE250 is stated; several section	Verify material certificates, section

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	designations include box members whose construction is not fully described.	properties, built-up details and section database entries.
Utilization ratios	Only maximum values are supplied, without member IDs or governing combinations.	Provide STAAD.Pro design output with member, section, load combination and code check.
Steel tonnage	Reported totals are 115, 90 and 85 tonnes; the scope of included bracing, plates and connection steel is not defined.	Provide quantity take-off and confirm whether connection steel and secondary steel are included.

10. CONCLUSION

A comparative study of three structural configurations for a 50 m long, 6 m wide and 24 m high, three-tier steel pipe rack has been presented using the geometry, design basis and analysis results contained in the supplied project report. The alternatives considered were a conventional moment-resisting frame, an X-braced frame and an A-type braced frame.

1. The conventional moment frame has the highest reported steel quantity (115 t), maximum lateral deflection (42 mm), wind base shear (1,090 kN) and maximum utilization ratio (0.90).
2. The X-braced alternative reduces the reported steel quantity to 90 t, maximum deflection to 29 mm, wind base shear to 849 kN and utilization ratio to 0.83.
3. The A-type braced alternative has the lowest reported values: 85 t of steel, 23 mm maximum deflection, 743 kN wind base shear and a maximum utilization ratio of 0.82.
4. Compared with the moment frame, the A-type braced arrangement reduces reported steel consumption by 26.09%, maximum lateral deflection by 45.24% and wind base shear by 31.83%.
5. The results support the use of bracing as an effective means of improving lateral response and reducing the reported structural steel requirement for the studied model.
6. A-type bracing is the preferred preliminary configuration. The X-braced option remains a viable alternative where the bay arrangement and service routing can accommodate the diagonal members.

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[20] Note: References above are transcribed or normalized from the project report's bibliography. Verify publication metadata, page ranges, titles, DOI details and the current status of each Indian Standard against authoritative records before journal submission.

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