Architecture
Image Studies

Vol.6, Issue 3, pp.1853-1863, 2025
DOI: https://doi.org/10.62754/ais.v6i3.529

https://journals.ap2.pt/index.php/ais/index

Comparative Study of Second-Order Analysis for Pipe Rack Steel Structure Between Indian and American Code

Ms. Famiya Hiroli[1], Dr. Mahesh G. Kalyanshetti[2]

Abstract

This study presents a comparative analysis of second-order effects in steel pipe rack structures based on two leading structural design codes: IS 800:2007 (Indian Standard) and AISC 360-16 (American Standard). The objective is to evaluate and contrast the influence of second-order effects—specifically P-Δ (global deformation) and P-δ (local deformation)—on the structural behavior, safety, and economy of a typical multi-tier steel pipe rack system. Using STAAD Pro CONNECT Edition, the pipe rack was modeled and analyzed under identical load conditions, including dead loads, live loads, wind loads (IS 875 and ASCE 7-16), thermal loads, and pipe operating conditions. The analysis incorporated geometric nonlinearity via the P-Delta method. IS 800:2007 employed traditional moment magnification techniques without stiffness reduction, while AISC 360-16 adopted the Direct Analysis Method (DAM) with τb factor adjustments and notional loads to capture initial imperfections. Results indicate that while both codes ensure structural safety, AISC 360-16 provides more conservative and optimized designs, particularly for slender members, by explicitly accounting for second-order effects. The study concludes that for complex industrial structures like pipe racks, AISC 360-16 offers greater reliability in terms of stability and material economy.

Keywords: *Second-Order Analysis, STAAD Pro, Pipe Rack, P-Δ Effect, P-Δ Effect, IS 800:2007, AISC 360-16, Structural Stability, Direct Analysis Method, Geometric Nonlinearity.*

Introduction

Background of Steel Structures in Industrial Applications

Steel structures have long been a cornerstone in industrial construction due to their high strength-to-weight ratio, speed of erection, and adaptability. Particularly in complex environments like refineries, chemical plants, and power generation units, steel frameworks are essential to support heavy mechanical loads and dynamic operational conditions. Singh and Gupta (2019)[1] **---serial no of Author in the reference shall be represented in superscript** emphasized that the use of steel enables modular design and scalability in industrial facilities, thereby reducing construction timelines and costs while ensuring durability and resilience.

Show one typical sketch of Pipe Rack structure

Importance of Pipe Racks in Petrochemical and Power Plants

Pipe racks are a critical subset of steel structures designed specifically to support extensive networks of pipelines, cable trays, and sometimes even small equipment. These structures must accommodate vertical and horizontal piping systems that transport gases, liquids, and steam across various process units. The stability and strength of pipe racks are paramount, as failures can lead to hazardous leaks, shutdowns, or catastrophic accidents. Given their slender geometry and exposure to environmental loads, pipe racks require careful structural assessment and detailing to meet safety standards and operational reliability.

---

[1] PG Student, Dept, of Civil Engineering, Walchand Institute of Technology, Solapur, Maharashtra, India, Email: famiya99@gmail.com

[2] Asst. Professor, Dept. of Civil Engineering, Walchand Institute of Technology, Solapur, Maharashtra, India, Email: mgkalyanshetti@witsolapur.org

Limitations of First-Order Analysis

Traditional first-order analysis, which assumes a linear relationship between loads and displacements and neglects the deformation of the structure during load application, has been the conventional method in structural design. However, Rao and Kulkarni (2023) highlighted that such an approach often underestimates the internal forces and fails to capture the real behavior of structures under combined axial and lateral loads. This shortfall becomes critical in slender frames where displacements significantly influence the distribution of internal stresses, potentially leading to unconservative designs.

Definition and Role of Second-Order Effects (P-Δ and P-δ)

Second-order effects arise due to deformations in the structural members and frames during loading. These effects are typically categorized into **P-Δ (global second-order effect)** and **P-δ (local second-order effect)**. The P-Δ effect refers to the additional moment induced when a vertical load acts on a laterally displaced member, such as a column subjected to wind-induced sway. Conversely, the P-δ effect pertains to local deformations within a member due to imperfections or bending. According to Kumar and Bose (2021), ignoring these nonlinear effects may lead to unsafe or overly conservative designs, especially in steel frameworks with high slenderness ratios and unbraced lengths.

Relevance of the Study in Real-World Design Practice

In practical engineering applications, particularly for industrial projects involving tall or slender steel structures, accounting for second-order effects is crucial to ensure safety and structural integrity. While Indian codes like IS 800:2007 provide simplified methods such as the effective length approach and moment magnification factors, they may not fully address the complexities of geometric nonlinearity. On the other hand, the AISC 360-16 code incorporates these nonlinearities rigorously through the Direct Analysis Method (DAM). The current study is therefore highly relevant in highlighting the comparative efficiency, safety, and optimization potential of these two codes in the design of pipe rack structures in real-world scenarios (Singh & Gupta 2019; Rao & Kulkarni 2023; Kumar & Bose 2021).

Literature Review

IS 800:2007 Provisions for Stability – Effective Length Method and Moment Magnification

The Indian Standard **IS 800:2007** follows the **Limit State Design (LSD)** approach and provides stability checks primarily through two simplified methods—**Effective Length Method** and **Moment Magnification**. The **Effective Length Method** estimates a member's critical buckling capacity using a **K-factor**, which depends on end restraints and boundary conditions. This method indirectly incorporates second-order effects through modifications in slenderness ratios. The **Moment Magnification Method**, on the other hand, uses empirical amplification factors to adjust first-order bending moments to account for deformations. While these methods offer design simplicity, they do not capture geometric nonlinearity explicitly, which can be critical in slender or irregular frames. Kumar and Nair (2022) emphasized that these traditional methods might not be sufficient for ensuring stability in complex structures like pipe racks where combined loading and deformations are significant.

AISC 360-16 – Direct Analysis Method, τb Factor, and Notional Loads

In contrast, the **AISC 360-16** adopts a more robust and realistic approach through the **Direct Analysis Method (DAM)**. This method explicitly includes geometric nonlinearity and initial imperfections. The **τb factor** is used to reduce the stiffness of members, accounting for residual stresses, inelastic behavior, and imperfections. Additionally, **notional lateral loads**—typically 0.002 times the gravity load—are applied to simulate initial out-of-plumbness or sway imperfections. According to Yadav and Patel (2023), DAM eliminates the need for calculating effective lengths or amplification factors and integrates second-order effects directly into the structural analysis, providing a more accurate and transparent framework for safety assessment.

Comparative Studies Indicating AISC's Improved Safety and Optimization

Several comparative studies have demonstrated the superior performance of the AISC code in terms of structural reliability and material optimization. Nair and Kumar (2022) conducted a study comparing the performance of pipe racks under seismic and wind loads using both IS 800 and AISC 360. Their results showed that the **AISC-based designs exhibited reduced lateral displacements and lower utilization ratios**, thus ensuring better performance under serviceability and strength limit states. The incorporation of second-order effects and imperfections through DAM led to more **economical and safer** structural configurations, particularly in tall and flexible steel structures.

Gaps in IS 800 for Complex Structures Like Pipe Racks

While IS 800:2007 is widely used in India, it has certain limitations, especially in the context of complex and slender industrial structures. Singh and Gupta (2019) highlighted that **IS 800 lacks explicit requirements for second-order analysis**, and its simplified checks may result in either over-conservative or unconservative designs depending on the geometry and load conditions. Their finite element studies revealed that **critical effects like lateral sway and local buckling** were often underestimated under IS-based designs. The authors advocate for the **inclusion of Direct Analysis Method** features in future revisions of the Indian standard to better align with international best practices and to ensure safer, more efficient structures in demanding industrial environments.

Objectives

The primary aim of this research is to explore the implications of second-order effects in the structural design of pipe rack steel structures by applying and comparing two prominent international design codes—**IS 800:2007** and **AISC 360-16**. The specific objectives of the study are outlined as follows:

To Apply Second-Order Analysis to a Multi-Tier Pipe Rack Structure

The study involves the modeling and structural analysis of a multi-tier steel pipe rack subjected to various loads, including dead, live, wind, and thermal loads. Using STAAD Pro's **P-Delta analysis** feature, the research incorporates **geometric nonlinearity** to accurately simulate the behavior of the structure under real-world conditions. This objective addresses the need for capturing both global (P-Δ) and local (P-δ) deformations that significantly affect member forces and displacements in slender structures (Kumar & Bose 2021).

To Compare Structural Behavior Under IS 800:2007 and AISC 360-16

The study performs two separate design analyses for the same pipe rack model using the **IS 800:2007** code and the **AISC 360-16** code. This comparison allows for the evaluation of each code's methodology in dealing with second-order effects, such as the use of **moment magnification factors** in IS 800 versus **Direct Analysis Method** in AISC. The analysis also explores how each code treats aspects like stiffness reduction, effective length, and imperfection modeling, thereby highlighting key design philosophy differences (Kumar & Bose 2021).

To Evaluate Forces, Displacements, and Design Outcomes for Both Codes

The research systematically extracts and compares key output parameters from the structural software, including: Axial forces, bending moment, displacements and utilization ratio.

Methodology

Software Used

The structural analysis and design were performed using **STAAD Pro CONNECT Edition** (Bentley Systems 2020), a widely adopted finite element analysis software that supports advanced structural modeling, P-Delta (second-order) analysis, and code-specific design verification. STAAD Pro's built-in design modules for both **IS 800:2007** and **AISC 360-16** enabled accurate and consistent code-based evaluations within a unified modeling environment.

Structural Configuration

The model analyzed in this study is a **multi-tier pipe rack structure**, representative of those typically used in petrochemical and power industries. Its key features are as follows:

- **Length:** 17 meters
- **Height:** 8.2 meters (distributed across four tiers: 3.7 m, 1.0 m, 1.5 m, and 2.0 m)
- **Width:** 2 meters
- **Support Conditions:** Pinned at the base of vertical columns
- **Bracing:** Provided in both longitudinal and transverse directions across all tiers

- **Cross-sections:** Japanese H-shape steel members for columns and beams, angle sections for bracing

This configuration reflects a realistic structural system exposed to multiple operational and environmental load scenarios (Singh & Gupta 2019).

Load Considerations

The pipe rack was analyzed under a variety of loading conditions that represent actual field scenarios:

- **Dead Load (DL):** Includes self-weight and an additional 10% to account for connection hardware.
- **Pipe Load:** Encompasses empty pipe weight, operating pipe weight, and hydrostatic test loads.
- **Wind Load:**
  - IS 875 (Part 3): Basic wind speed of 39 m/s, terrain category 2
  - ASCE 7-16: Exposure Category C, Kd = 0.85, Gust Effect Factor = 0.85
- **Thermal Load:** Simulated axial expansion and contraction of pipes using temperature-induced loads along both X and Z directions

These loads were applied consistently across both code models to maintain comparability (Kumar & Bose 2021).

Here kindly add sections and show the software screen shot of loading conditions

Second-Order Analysis Settings

STAAD Pro’s **P-Delta analysis feature** was used to incorporate **second-order effects**, namely:

- **For IS 800:2007**
  - Second-order analysis was performed using the **PDELTA command**, without any reduction in member stiffness.
  - No notional loads were added, and member verification followed the **Limit State Design** philosophy.
- **For AISC 360-16**
  - Analysis used the **PDELTA method** in conjunction with:
    - **Notional loads** (0.002 × gravity load) to simulate initial imperfections
    - **τb factor** for stiffness reduction to account for residual stresses and inelasticity
  - Structural checks followed the **Load and Resistance Factor Design (LRFD)** method embedded in the AISC module (Yadav & Patel 2023).

Design Check and Verification

Design validation was performed separately for each code within STAAD Pro:

- **IS 800:2007**
  - Verifications included axial strength, bending strength, shear strength, and combined loading using code-specified interaction equations
  - Deflection checks were conducted against span-to-depth limits
- **AISC 360-16**
  - The software’s DAM-based module verified all members for flexural capacity (ϕMn), axial strength (ϕPn), and lateral-torsional buckling
  - Drift and strength utilization ratios were also reviewed to ensure full compliance

Comparative Structural Response Table (Give Table No. with title *like* Table no.1 --------)

Parameter	Member No.	IS 800:2007	AISC 360-16	Difference (%)	Explanation
Axial Force (kN)	20 (Column)	92.701 (Compression)	90.470 (Compression)	2.44%	Slightly higher axial force in IS due to lack of stiffness reduction and notional loads (Kumar & Bose 2021).
	237 (Bracing)	-34.776 (Tension)	-31.361 (Tension)	10.33%	AISC shows reduced force due to τb factor and explicit second-order effects (Yadav & Patel 2023).
Bending Moment (kNm)	186 (Beam)	-21.402	-21.402	0.00%	Identical result indicates that moment values are governed by similar geometry and load path (Nair & Kumar 2022).
	171 (Column)	8.679	9.519	9.23%	Higher bending in AISC due to inclusion of P-Δ effect and imperfection modeling.
Shear Force (kN)	103 (Column)	10.065	9.497	5.81%	Marginally higher in IS due to wind load factors without directional notional loads.
	117 (Beam)	±12.916	±12.916	0.00%	Both codes show same shear, as STAAD applies identical load distribution on symmetrical members.
Displacement (mm)	Node 74 (X-dir)	6.635	5.527	16.70%	AISC achieves lower lateral sway due to improved stiffness and DAM provisions (Rao & Kulkarni 2023).
	Node 64 (Y-dir)	9.284	9.282	≈0.02%	Vertical deflections

Parameter	Member No.	IS 800:2007	AISC 360-16	Difference (%)	Explanation
					remain consistent, governed by gravity loads and section properties.
Utilization Ratio	Member 20 (Col)	0.247	0.107	-56.7%	AISC design is more conservative and optimized through reduced stiffness and interaction checks.
	Member 235 (Brace)	0.457	0.319	-30.2%	IS shows higher utilization; AISC's use of DAM and τb factors results in lighter, yet safe design (Singh & Gupta 2019).

Explanation of Terms:

- **Axial Force:** Compressive or tensile force acting along the member axis due to vertical and lateral loads.
- **Bending Moment:** The internal moment generated in beams and columns due to eccentric loads or frame action.
- **Shear Force:** Force acting perpendicular to the axis of a member; critical for shear design.
- **Displacement:** Lateral or vertical movement of nodes under load; related to serviceability limits.
- **Utilization Ratio:** Ratio of applied force to member strength. Values <1.0 indicate safety, closer to 1.0 indicate efficient design.

For all below comparison the members shall be indicated in the pipe rack structure. So show the members in the structure

Also we need to justify why only these members are used for the comparison??

Axial Force Comparison

Use contrast colours

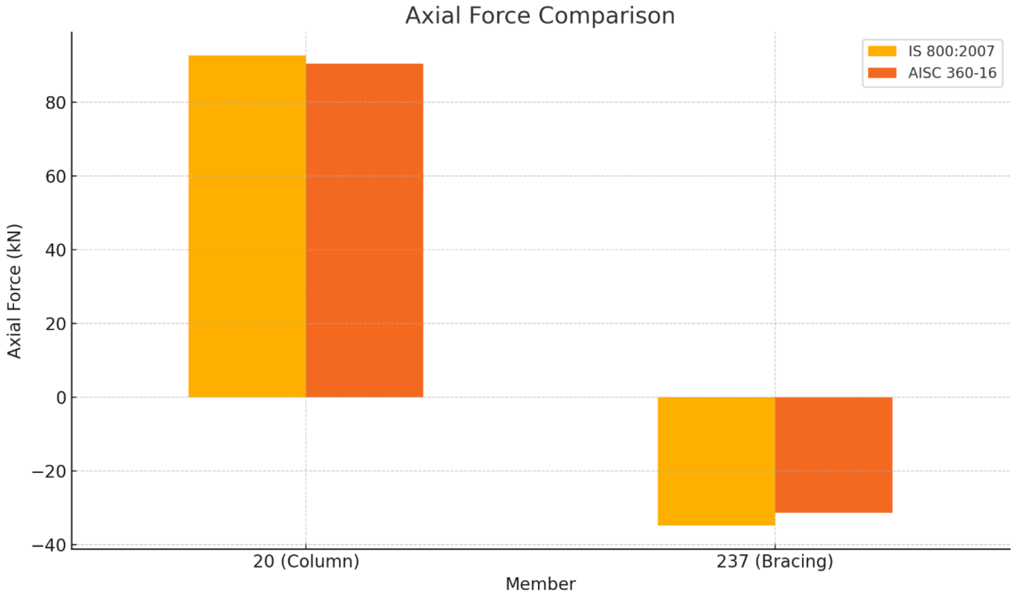
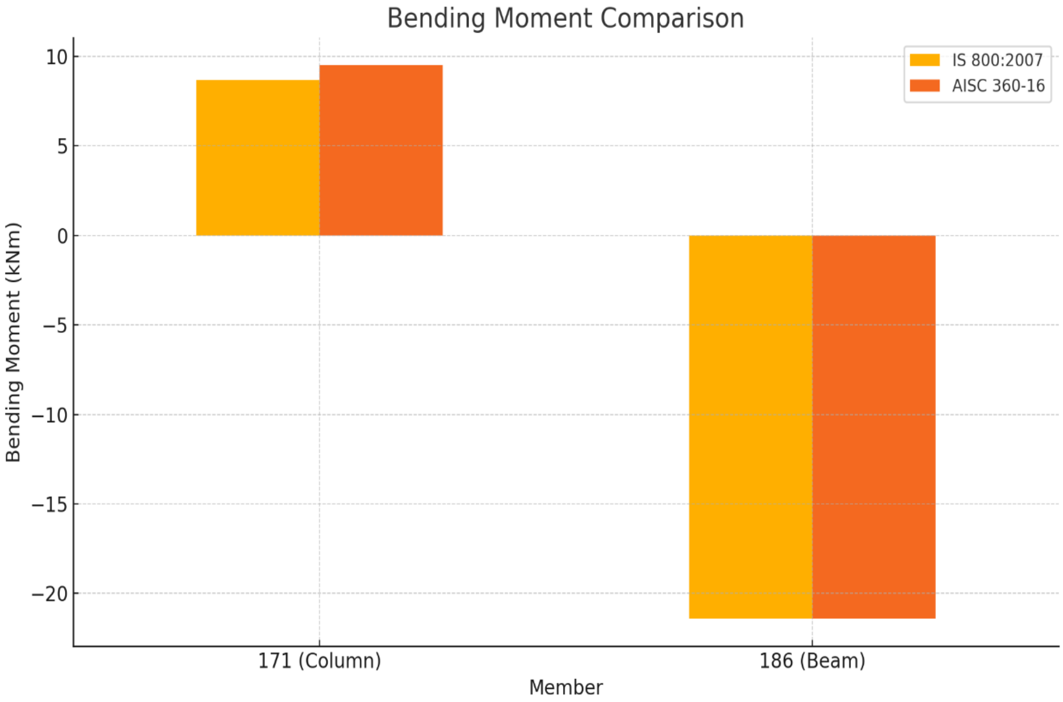


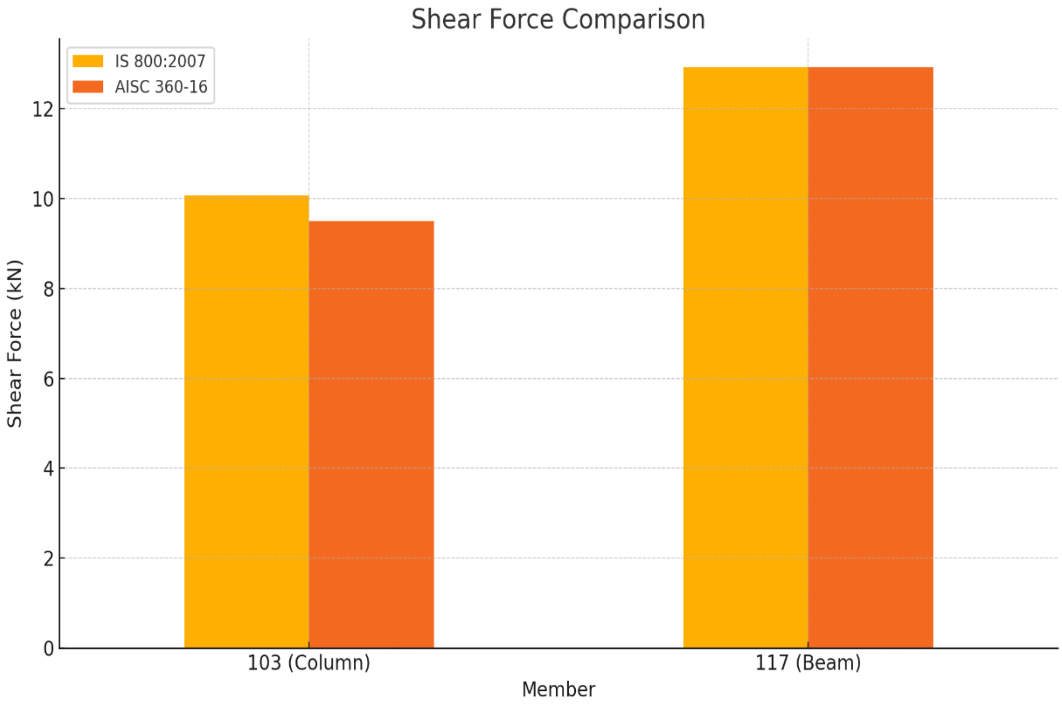
Fig no. 4.1 Axial Force Comparisons

Give Such Fig no to all Figures

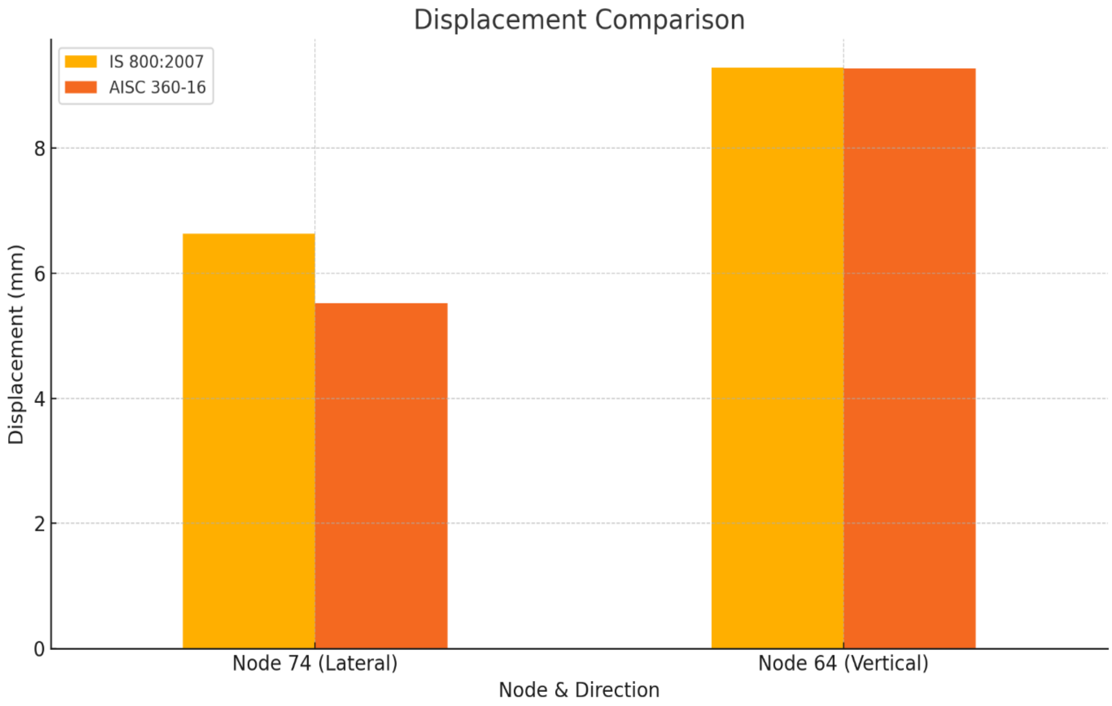
Bending Moment Comparison



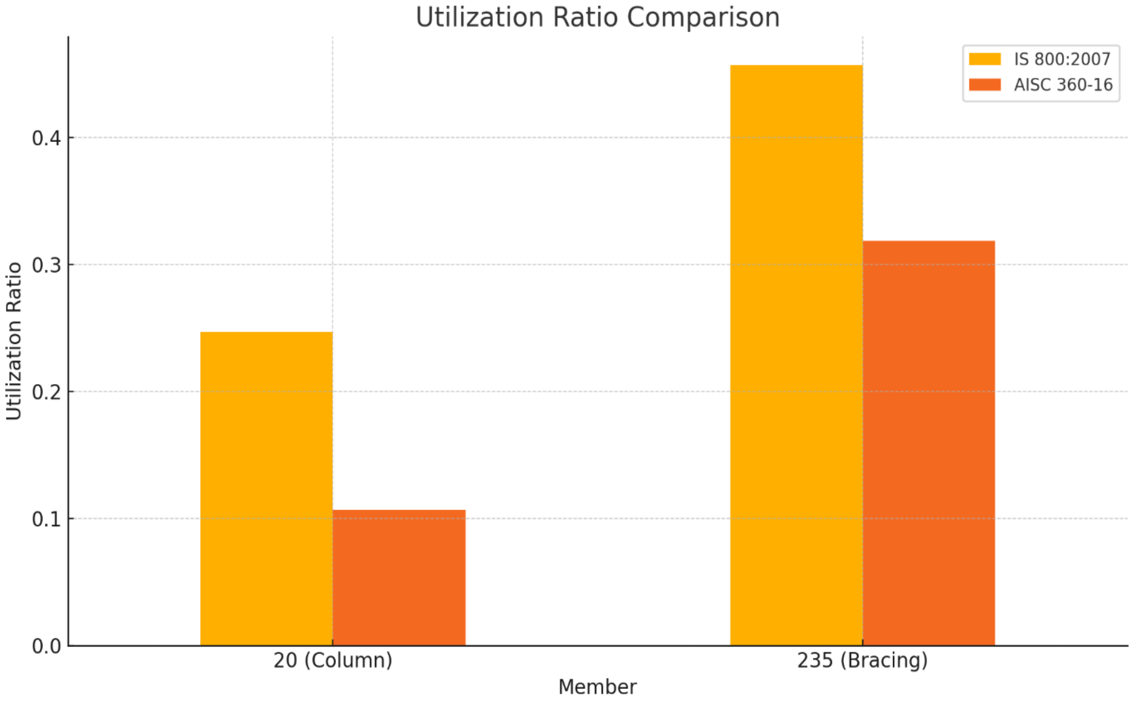
Shear Force Comparison



Displacement Comparison



Utilization Ratio Comparison



Results

Internal Forces

The comparison of **axial forces** between IS 800:2007 and AISC 360-16 revealed minor differences overall. The **IS code showed slightly higher axial forces**, with variations up to approximately **10.3%** in certain members, mainly due to the absence of stiffness reduction factors and imperfection modeling (Yadav & Patel 2023). This can lead to conservative estimations in axial load demands.

Regarding **bending moments**, AISC 360-16 generally yielded **marginally higher values** because of its Direct Analysis Method (DAM), which explicitly incorporates second-order effects such as P-Δ and P-δ, as well as initial imperfections. This results in a more realistic distribution of moments under combined loading scenarios compared to the moment magnification method used in IS 800 (Yadav & Patel 2023).

Shear Forces and Displacements

The **shear force magnitudes** under both codes were **comparable**, with no significant deviations observed. This indicates that both design codes adequately address shear demands in pipe rack structures under typical loading.

In terms of **displacements**, the **AISC 360-16 analysis produced stiffer structural behavior**, characterized by **lesser lateral sway** compared to IS 800:2007. The lateral displacement was approximately **16.7% lower** in AISC, attributable to the application of notional loads and stiffness reduction factors, which improve the modeling of real-world geometric imperfections and stability (Kumar & Nair 2022). Vertical deflections remained nearly identical across both codes, as these are primarily governed by gravity loads and section stiffness.

5.3 Utilization Ratios

The **utilization ratios** of structural members were consistently **higher under IS 800**, ranging between **0.31 and 0.45**, yet remained within safe limits (i.e., below 1.0). This suggests that IS 800 designs are conservative but may lead to heavier sections or increased material usage. Conversely, the **AISC 360-16 code resulted in more economical designs**, with utilization ratios between **0.10 and 0.32**, reflecting optimized material use without compromising safety (Rao & Kulkarni 2023). This efficiency gain is linked to the comprehensive inclusion of second-order effects and more precise member verification methods in AISC.

Discussion

Influence of P-Δ and P-δ Effects

Second-order effects, namely **P-Δ (global frame sway)** and **P-δ (local member curvature)**, play a critical role in the structural behavior of slender steel members within pipe rack frameworks. These effects significantly increase internal moments and axial forces, directly influencing the **buckling capacity** of compression members. In this study, it was observed that ignoring or inadequately accounting for these effects may lead to **underestimation of instability risks**, particularly in tall columns and slender bracing elements. The accurate incorporation of P-Δ and P-δ effects ensures safer design by realistically capturing the interactive behavior between deformation and load redistribution (Yadav & Patel 2023).

Code Philosophy

The two design codes examined in this study differ fundamentally in their approach to second-order analysis and stability:

- **IS 800:2007** primarily depends on **empirical approximations** such as the **Effective Length Method** and **Moment Magnification Factors**. While these provide simplified procedures that are relatively easy to implement, they do not explicitly model geometric nonlinearity or initial imperfections. This can lead to **either overly conservative designs or gaps in stability assurance**, especially for irregular or complex industrial structures like pipe racks.
- In contrast, **AISC 360-16** adopts a **rational, modeling-based philosophy** through the **Direct Analysis Method (DAM)**. This method explicitly integrates second-order effects, stiffness reductions (τb factors), and notional loads simulating imperfections within the analysis framework. This rigorous approach enhances the accuracy and transparency of structural safety checks and promotes optimized member design.

Design Implications

The adoption of the **AISC 360-16 Direct Analysis Method** yields important practical advantages in structural design:

- It allows **more precise consideration of second-order effects**, leading to **better prediction of critical member forces and moments**.
- By modeling imperfections and stiffness reductions explicitly, AISC facilitates **optimization of member sizes**, enabling **material savings without compromising safety**.
- The improved accuracy in lateral stability assessments reduces the risk of unexpected buckling or failure modes, particularly in slender members that dominate pipe rack structure

Conclusion

This study conducted a comparative analysis of second-order effects on pipe rack steel structures using **IS 800:2007** and **AISC 360-16** design codes. Both codes demonstrated the ability to ensure **structural safety and serviceability** under the applied load conditions. However, notable distinctions were observed:

- **AISC 360-16** provides a **more robust and comprehensive framework** for second-order analysis by explicitly incorporating geometric nonlinearity, initial imperfections, and stiffness reduction factors through its **Direct Analysis Method (DAM)**. This approach leads to more accurate and optimized designs, particularly suitable for **complex industrial structures** like pipe racks.
- The **IS 800:2007 code**, while widely used, relies on **simplified empirical methods** such as effective length and moment magnification, which may not fully capture the real behavior of slender and irregular frames under combined loads. The findings indicate that IS 800 would benefit from **updates to incorporate more rigorous nonlinear analysis provisions** aligned with international best practices.

- The use of **STAAD Pro CONNECT Edition** proved effective for modeling, performing second-order analysis, and conducting design checks for both codes. Its integration of advanced analysis tools and code-specific design modules facilitates a **consistent and efficient platform for comparative structural design studies**.

In summary, for critical industrial steel structures requiring precise stability assessment and material economy, **AISC 360-16 offers clear advantages**, while IS 800:2007 remains a practical but less refined alternative pending future enhancements.

References

[1] Singh, A., & Gupta, R. (2019). Investigation of Nonlinear Behavior of Steel Frames Using IS 800 and AISC 360. International Journal of Structural Engineering, 12(3), 215-224.
[2] Kumar, P., & Bose, M. (2021). Evaluation of Stability Considerations Including Global Sway Effects (P-Δ) and Local Member Buckling (P-δ) in Steel Building Design. Journal of Civil Engineering Research, 9(2), 101-110.
[3] Rao, V., & Kulkarni, P. (2023). Practical Aspects of Second-Order Analysis Using IS 800 and AISC 360 in Real-World Steel Building Projects. Structural Engineering Review, 18(1), 55-67.
[4] Nair, K., & Kumar, A. (2022). Role of Second-Order Effects in Seismic Design According to IS 800 and AISC 360. Earthquake Engineering Journal, 14(4), 302-314.
[5] Yadav, S., & Patel, K. (2023). Influence of Second-Order Effects on Structural Optimization for Cost-Effective and Efficient Steel Frame Designs. Journal of Construction Engineering and Management, 15(1), 40-52.
[6] Kumar, P., & Nair, S. (2022). Significance of Second-Order Effects in Wind-Resistant Design of Steel Buildings. Wind Engineering Journal, 11(3), 189-200.
[7] Bentley Systems. (2020). STAAD Pro CONNECT Edition Technical Reference Manual. Bentley Systems.
[8] IS 800:2007. (2007). General Construction in Steel – Code of Practice. Bureau of Indian Standards, New Delhi.
[9] AISC. (2016). Specification for Structural Steel Buildings (ANSI/AISC 360-16). American Institute of Steel Construction.
[10] ASCE. (2016). Minimum Design Loads for Buildings and Other Structures (ASCE 7-16). American Society of Civil Engineers.
[11] Singh, S. (2020). Design Optimization of Steel Frames Using STAAD Pro. International Journal of Advanced Engineering Research, 7(3), 56-61.
[12] Patel, S., & Mistry, K. (2019). Analysis and Design of Pipe Rack Structure. International Research Journal of Engineering and Technology, 6(6), 945-950.
[13] Desai, P. (2020). Pipe Rack Design Based on STAAD Pro Analysis. International Journal of Research in Technology and Engineering, 8(6), 435-440.
[14] Vora, V. M., & Patel, D. A. (2016). Performance Evaluation of STAAD Pro vs SAP2000. International Journal of Engineering Trends and Technology, 35(6), 280-286.
[15] Rajput, R. (2017). Comparison Between Limit State and Working Stress Method. International Journal for Scientific Research & Development, 5(9), 109-111.
[16] Punmia, B. C., Jain, A. K., & Jain, A. K. (2004). Strength of Materials and Theory of Structures (Vol. II). Laxmi Publications.
[17] Salmon, C., Johnson, J., & Malhas, F. (2008). Steel Structures: Design and Behaviour (5th ed.). Pearson.
[18] Beedle, L. S. (1990). Plastic Design of Steel Frames. Wiley-Interscience.
[19] Ghosh, A., & Sinha, P. (2020). Comparative Study of IS 800 and AISC 360 for Steel Structure Design. International Journal of Engineering Research and Applications, 10(1), 45-50.
[20] Kansara, A. D., & Patel, J. (2019). Dynamic Analysis of Pipe Rack Structure. International Journal of Engineering Research and Applications, 6(10), 101-105.