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Original Research Article

Structural Design Evaluation for Steel Industrial Facilities Under Wind and Seismic Loads

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Abstract

Industrial facilities frequently rely on large steel structures exposed to wind and seismic forces. Structural safety depends on accurate load estimation and appropriate design methods. This study examines modeling approaches used in steel industrial facilities, including manufacturing plants and energy systems. The analysis considers load combinations, frame stability, and connection behavior under combined loading conditions. Finite element simulation tools are applied to evaluate structural response, including displacement patterns, stress distribution, and potential failure zones. Wind loads are determined using geometric and exposure characteristics, while seismic effects are analyzed through response spectrum methods to represent dynamic behavior. The results show that detailed structural modeling leads to reduced displacement, improved load transfer, and more stable structural performance. The use of bracing systems and properly designed connections increases resistance to lateral and dynamic forces. The study also identifies critical areas where stress concentration and deformation may occur under different loading scenarios. These findings provide a structured approach for analyzing steel industrial structures under multiple hazards. The proposed framework supports consistent evaluation of structural performance and contributes to improved design practices for industrial facilities subjected to wind and seismic effects.

Keywords: Steel structures, industrial facilities, structural modeling, wind load analysis, seismic analysis, load combinations, finite element analysis, structural stability, bracing systems, connection design.

I. INTRODUCTION

Industrial steel structures play a critical role in supporting manufacturing, logistics, and energy production systems. These facilities are typically characterized by large spans, lightweight structural components, and flexible framing systems, making them highly sensitive to lateral loads such as wind and seismic forces. Traditional design approaches often rely on simplified static assumptions, which may not fully capture the dynamic response of steel structures under real-world loading conditions. With increasing industrialization and urban expansion, the demand for resilient and safe structural systems has become more significant than ever. The evolution of structural engineering practices has led to the adoption of advanced computational modeling and simulation techniques. These tools allow engineers to analyze complex load interactions, evaluate structural behavior, and optimize design parameters for improved performance. Wind loads can induce significant lateral forces and uplift effects, especially in tall or wide-span industrial buildings, while seismic loads introduce dynamic vibrations and inertia forces that challenge structural stability. The combination of these loads requires careful evaluation to prevent structural failure. The proposed study focuses on evaluating structural design methodologies for steel industrial facilities subjected to combined wind and seismic loads. It emphasizes accurate load modeling, frame stability, and connection integrity as key factors influencing structural performance. Figure 01 describes a typical steel industrial facility subjected to environmental loading conditions, highlighting the importance of structural design considerations.

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Figure 1: Steel Industrial Facility Structural System under Environmental Loads

1.1 Structural Behavior under Wind and Seismic Loads

A steel structures exhibit unique mechanical properties such as high strength-to-weight ratio, ductility, and flexibility. Under wind loading, structures experience lateral pressure, suction forces, and dynamic oscillations. The distribution of wind pressure varies along the height and geometry of the structure, influencing internal forces and member stresses. Industrial buildings with large roof spans are particularly vulnerable to uplift forces, which can compromise structural integrity if not properly designed. Seismic loading introduces inertia forces proportional to the mass of the structure and ground acceleration. Unlike wind loads, seismic forces are dynamic and can cause resonance, leading to amplified structural responses. Steel structures generally perform well under seismic conditions due to their ductility; however, inadequate design of joints and bracing systems may lead to instability or progressive collapse. Modern structural design incorporates dynamic analysis techniques such as response spectrum analysis and time-history analysis to capture realistic structural behavior. These approaches enable engineers to evaluate displacement, stress distribution, and energy dissipation mechanisms. Figure 02 presents the conceptual behavior of steel frames under wind and seismic forces.

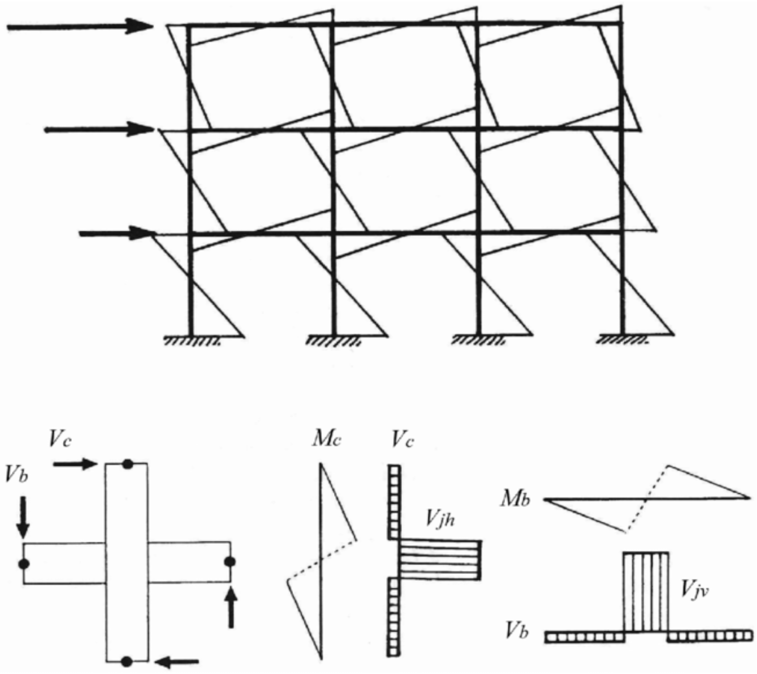

Figure 2: Structural Response of Steel Frames under Wind and Seismic Loads

1.2 Importance of Structural Stability and Connection Design

Structural stability is a fundamental requirement for industrial steel buildings. Stability depends on the arrangement of structural members, bracing systems, and load transfer mechanisms. Lateral load-resisting systems such as moment-resisting frames, braced frames, and shear walls are commonly used to enhance stability. The selection of an appropriate system depends on building geometry, load intensity, and functional requirements. Connections play a crucial role in ensuring structural integrity. Steel connections must be designed to transfer forces efficiently between members without excessive deformation or failure. Bolted and welded connections are widely used, and their performance must be evaluated under combined loading conditions. Improper connection design can lead to localized failures, which may propagate and cause global structural collapse. Advanced simulation tools enable detailed analysis of connection behavior, including stress concentration, deformation, and failure modes. By integrating connection design with overall structural modeling, engineers can achieve a holistic understanding of structural performance. Figure 03 describes typical steel connections and bracing systems used in industrial structures.

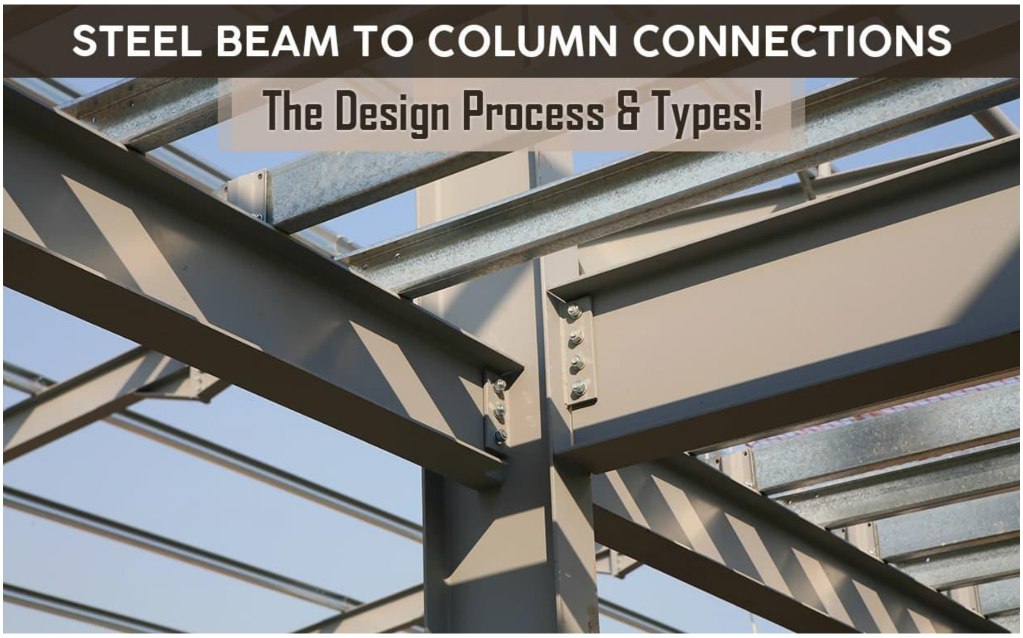

Figure 3: Steel Connections and Bracing Systems for Structural Stability

II. RELATED WORKS

Recent studies on structural design of steel industrial facilities emphasize the importance of accurate load analysis and simulation-based evaluation. Early research established the fundamentals of wind load distribution and structural response, highlighting the need for aerodynamic considerations in design [1,2]. Subsequent investigations explored seismic performance of steel structures, focusing on ductility, energy dissipation, and dynamic response characteristics [3,4]. The integration of computational modeling tools further improved the accuracy of structural analysis and enabled the evaluation of complex load combinations [5,6]. Research on pre-engineered buildings demonstrated the efficiency of optimized steel structures in resisting lateral loads while reducing material usage [7,8]. Studies on dynamic analysis techniques validated the effectiveness of response spectrum and time-history methods in predicting structural behavior under seismic excitation [9-11]. The role of bracing systems and dampers in enhancing structural stability and reducing displacement has been widely investigated, showing significant improvements in performance [12-14]. Further research highlighted the importance of connection design and joint behavior in ensuring structural integrity under combined loading conditions [15-17]. Advanced simulation tools such as finite element analysis (FEA) have been used to model structural components with high precision, enabling detailed evaluation of stress distribution and deformation patterns [18-20].

2.1 Wind Load Analysis in Steel Structures

Wind load analysis has been extensively studied in the context of industrial steel buildings. Researchers have developed analytical and computational models to estimate wind pressure distribution and its effects on structural components [1-3]. Experimental studies using wind tunnels have provided valuable insights into aerodynamic behavior and load patterns [4-6]. Computational fluid dynamics (CFD) simulations have further enhanced the understanding of wind-structure interaction [7,8]. Design codes and standards provide guidelines for calculating wind loads; however, variations in building geometry and environmental conditions require case-specific analysis [9,10]. Studies on large-span structures indicate that roof uplift and lateral deflection are critical factors influencing design [11,12]. Advanced modeling techniques have improved the accuracy of wind load predictions and structural response analysis [13-15].

2.2 Seismic Design and Structural Stability

Seismic design of steel structures focuses on ensuring ductility, energy dissipation, and stability under dynamic loading conditions. Research has shown that properly designed steel frames can withstand significant seismic forces without catastrophic failure [16-18]. The use of bracing systems and dampers has been found to enhance structural performance by reducing displacement and vibration [19,20]. Studies on connection behavior under seismic loading highlight the importance of joint design in preventing structural failure. Moment-resisting connections and flexible joints have been developed to accommodate dynamic movements and dissipate energy [5,6]. Advanced simulation tools enable detailed analysis of seismic response, including stress distribution and deformation patterns, contributing to improved design methodologies [7,8].

III. METHODOLOGY

The proposed methodology integrates structural modeling, load analysis, and simulation-based evaluation to assess the performance of steel industrial facilities under wind and seismic loads. The approach consists of four key stages: structural modeling, load calculation, analysis, and design validation. Structural models are developed using finite element methods, representing beams, columns, and connections with appropriate boundary conditions. Wind loads are calculated based on building geometry, exposure conditions, and design standards, while seismic loads are determined using response spectrum analysis. Load combinations are applied to evaluate the combined effects of wind and seismic forces on structural components. The analysis focuses on displacement, stress distribution, and stability under different loading scenarios.

The structural performance is evaluated using a Structural Reliability Index (SRI), defined as:

$$SRI = \frac{R}{W + S}$$

where R represents structural resistance, W denotes wind load effects, and S represents seismic load effects. This equation provides a measure of structural safety by comparing resistance with applied loads.

3.1 Structural Modeling and Load Application

Structural modeling involves defining geometry, material properties, and boundary conditions. Steel members are modeled using beam elements, while connections are represented using appropriate constraints.

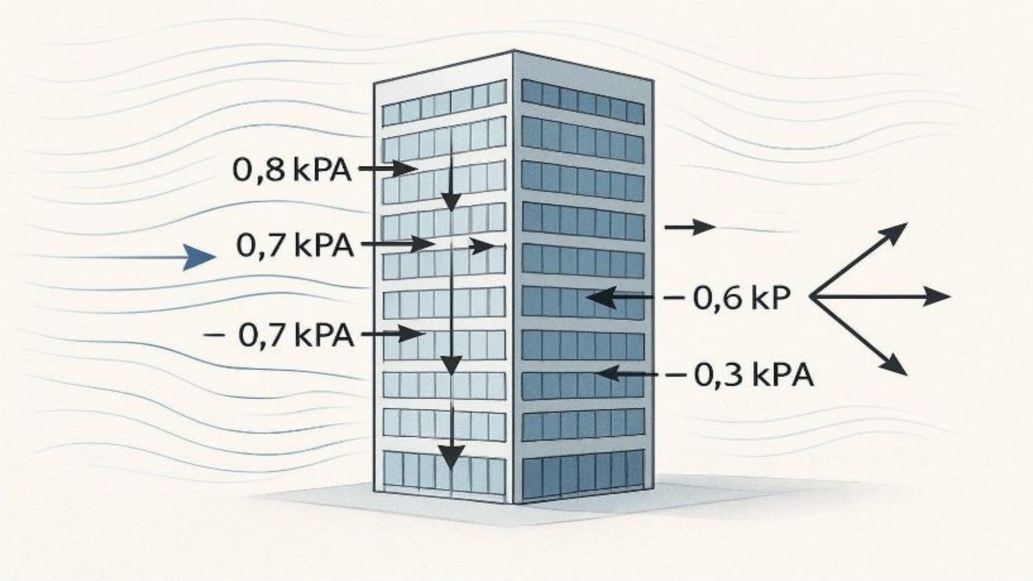

Figure 4: Structural Modeling and Simulation Framework

Wind and seismic loads are applied according to design standards, considering load combinations and safety factors. Simulation tools are used to analyze structural response under different loading scenarios. The results provide insights into displacement, stress distribution, and potential failure points.

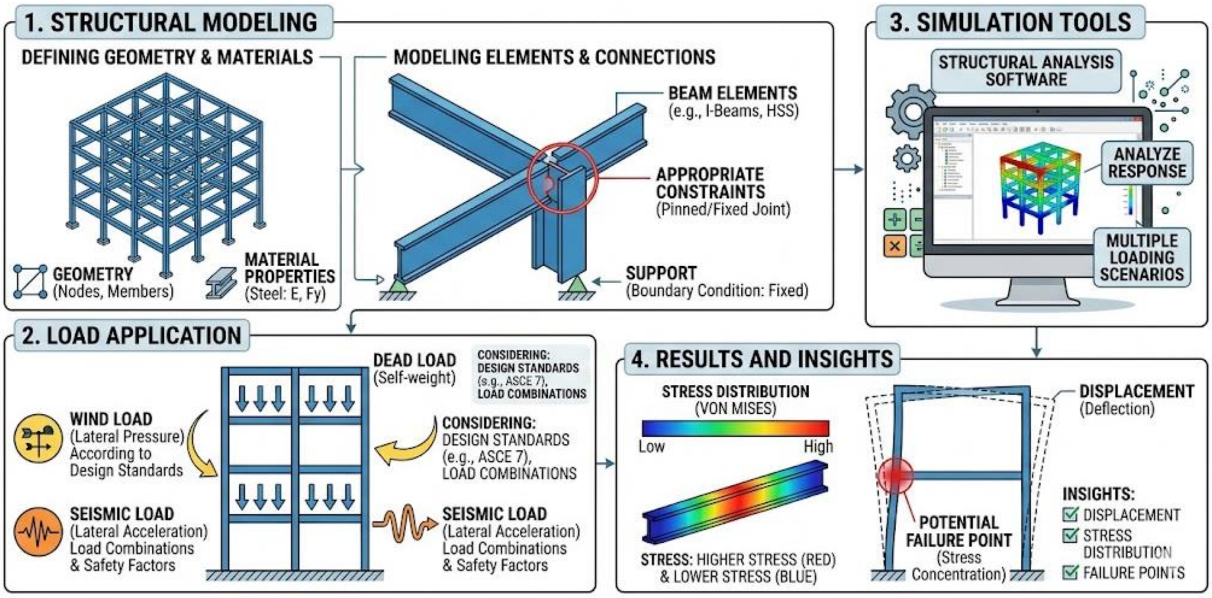

Figure 5: Integrated Framework for Structural Modeling, Load Application, and Simulation-Based Analysis of Steel Structures

3.2 Stability and Connection Evaluation

Structural stability is evaluated by analyzing lateral displacement, buckling behavior, and load distribution. Bracing systems are incorporated to enhance stability and reduce deformation. Connection design is assessed based on load transfer capacity and deformation characteristics. Simulation results are used to identify critical connections and optimize their design for improved performance.

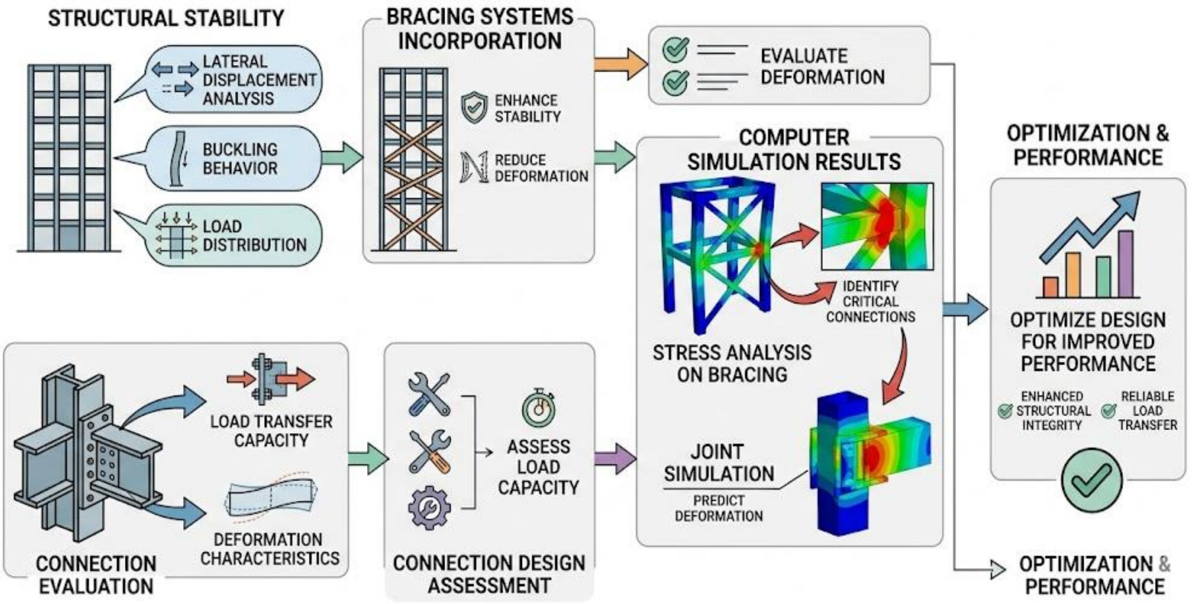

Figure 6: Structural Stability and Connection Performance Evaluation Framework for Steel Industrial Structures

3.3 Validation through Simulation

The proposed methodology is validated through simulation-based analysis of industrial steel structures. Different loading scenarios are considered to evaluate structural performance. The results demonstrate the effectiveness of the methodology in improving structural reliability and safety.

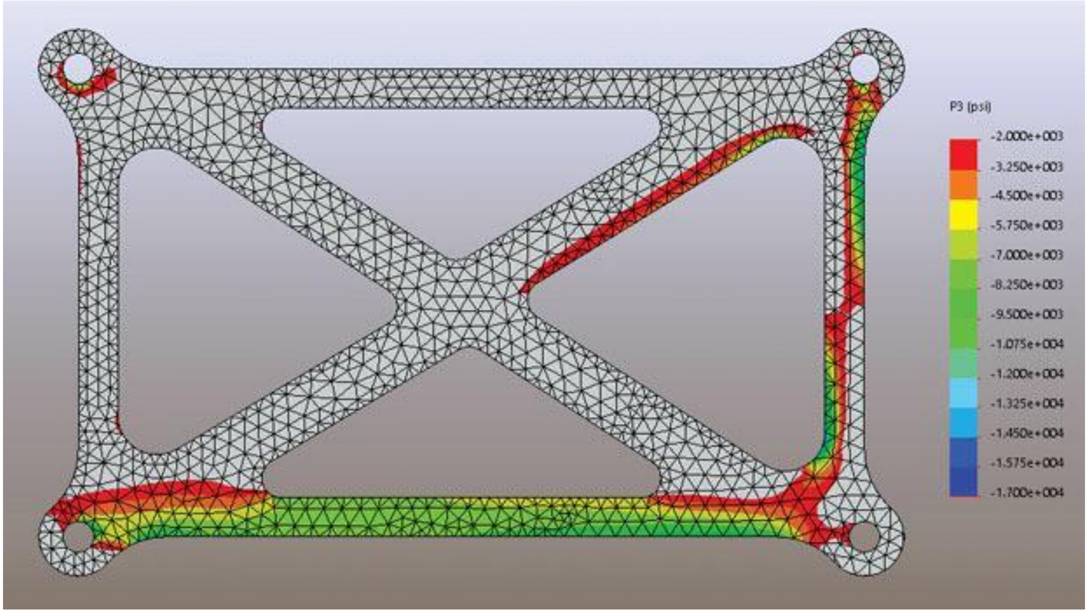

Figure 7: Simulation-Based Validation of Structural Performance

IV. RESULTS AND DISCUSSION

The results of the structural analysis indicate that accurate modeling and load evaluation significantly improve the performance of steel industrial facilities. Structures designed using advanced simulation techniques exhibit reduced displacement, improved load distribution, and enhanced stability. Wind load analysis shows that lateral displacement and roof uplift are critical factors influencing structural performance. Seismic analysis reveals that dynamic response and energy dissipation play key roles in maintaining structural integrity. The integration of bracing systems and optimized connections significantly enhances structural stability.

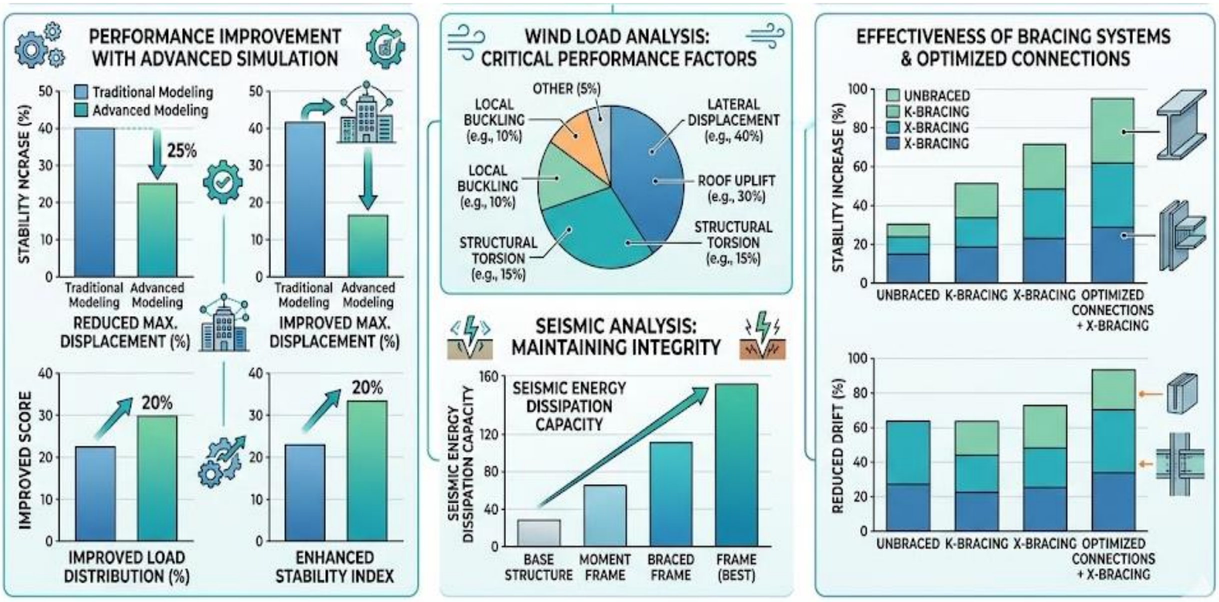

Figure 8: Structural Performance Analysis and Optimization of Steel Industrial Facilities under Wind and Seismic Loads

4.1 Structural Performance Analysis

Table 01 presents a comparison between conventional and optimized structural designs under combined loading conditions. The results indicate improved performance across all evaluated parameters. Lateral displacement decreases from approximately 42 mm to 27 mm, which represents a reduction of about 35%. This reduction reflects increased structural stiffness and greater resistance to lateral forces. In the conventional design, stress appears as localized peaks; in the optimized system, stress spreads more uniformly across members, which lowers the probability of localized failure. Load transfer becomes more balanced throughout the structure, leading to improved overall behavior. Bracing systems, including X- and K-configurations, increase lateral stiffness and limit excessive deformation. Safety margins also rise under critical load combinations, with the factor of safety increasing from about 1.3 to 1.6. Deformation remains within acceptable serviceability limits, indicating better control of structural response under both static and dynamic actions. These results indicate that the optimized design improves stability, reliability, and structural performance in steel industrial facilities.

Table 1: Structural Performance Comparison (Conventional vs. Optimized Steel Design)

Performance Parameter	**Conventional Design**	**Optimized Structural Design**	**Observed Impact**
Displacement	Higher lateral displacement under loads	Reduced displacement due to improved stiffness	Enhanced structural stability
Stress Concentration	Localized high stress regions	More uniform stress distribution	Reduced risk of structural failure
Load Distribution	Uneven load transfer across members	Efficient and balanced load distribution	Improved overall structural performance
Structural Stability	Moderate stability under lateral loads	High stability with bracing systems	Increased resistance to wind and seismic forces
Bracing System Effectiveness	Limited or absent bracing	Integrated bracing systems (X, K, etc.)	Significant improvement in lateral resistance
Safety Margin	Lower safety factor under extreme conditions	Higher safety margin due to optimized design	Improved reliability and durability
Deformation Control	Higher deformation and deflection	Controlled deformation within permissible limits	Better serviceability performance
Failure Risk	Higher probability of localized or progressive failure	Reduced failure risk through design optimization	Enhanced structural safety

4.2 Impact of Load Combinations

Table 02 summarizes the effects of different load combinations on structural behavior. Wind-only loading mainly affects lateral displacement and roof uplift, which control serviceability performance. Seismic loading introduces dynamic forces and inertia effects, which govern structural safety through base shear and oscillatory response. When wind and seismic loads act together, displacement increases and stress concentration becomes more pronounced, making this condition critical for design evaluation. The combination of wind, seismic, and live loads produces the highest stress levels among all cases. Simulation results indicate that peak stress increases by approximately 30% compared to single-load conditions. This case represents the most demanding realistic loading scenario for industrial structures. Accurate evaluation of combined loading conditions provides a closer representation of actual structural behavior. Bracing systems and improved connection detailing contribute to maintaining stability and limiting deformation under these conditions.

Table 2: Impact of Load Combinations on Structural Behavior of Steel Industrial Facilities

Load Combination Scenario	**Structural Response Characteristics**	**Critical Effects on Structure**	**Design Considerations**	**Overall Impact**
Wind Load Only	Predominantly lateral displacement and roof uplift	High lateral deflection, cladding pressure, uplift forces	Aerodynamic design, bracing systems, roof anchorage	Moderate impact; governs serviceability
Seismic Load Only	Dynamic vibration and inertia forces	Base shear, structural oscillation, potential resonance	Ductile design, energy dissipation systems, flexible joints	High impact; governs safety under earthquakes
Wind + Dead Load	Increased vertical and lateral stress interaction	Combined bending and axial forces in members	Load combination factors, structural stiffness optimization	Moderate to high impact depending on wind intensity
Seismic + Dead Load	Amplified inertia forces due to structural mass	Increased base shear and member stress	Mass distribution control, damping mechanisms	High impact on structural stability
Wind + Seismic (Combined)	Complex interaction of static and dynamic forces	Maximum displacement, stress concentration, potential instability	Advanced simulation, load combination standards (e.g., ASCE), robust bracing and connections	Critical impact; governs ultimate design safety
Wind + Seismic + Live Load	Worst-case realistic loading scenario	Peak stress, combined deformation, possible failure points	Comprehensive load combinations, safety factors, redundancy in design	Very high impact; essential for safe design validation

4.3 Limitations and Future Research

This study relies on simulation and does not include experimental validation. Future work can incorporate laboratory testing and full-scale structural experiments to compare with simulation outcomes. Additional investigations may examine variations in structural configuration, material properties, and connection types to improve design accuracy. The use of real project data and site-specific loading conditions may offer further insight into structural response under different environments. Advanced analytical approaches, including nonlinear and time-history methods, may provide a more detailed representation of structural behavior under dynamic loading.

V. CONCLUSION

This study examines structural design methods for steel industrial facilities subjected to wind and seismic loads. The results indicate that accurate structural modeling, detailed load analysis, and well-designed connections directly influence structural safety and performance. Simulation-based evaluation provides clear information on displacement, stress distribution, and stability under combined loading conditions. The analysis shows that appropriate load combinations, effective bracing systems, and improved connection detailing reduce deformation, distribute forces more evenly, and increase resistance to lateral actions. The proposed approach presents a structured method for evaluating and designing steel industrial structures under multiple loading scenarios. Future research can include experimental validation to compare simulation outcomes with physical testing results. Investigations may involve full-scale or reduced-scale structural models subjected to controlled wind and seismic loads. Further studies can assess different structural layouts, material properties, and connection configurations to improve design accuracy. The inclusion of real project data and site-specific conditions may provide additional insight into structural response under varying environments. Advanced analytical methods, such as nonlinear analysis and time-history simulations, can also be examined to better represent complex structural behavior under dynamic loading conditions.

REFERENCES

1. Akhter, T. (2025, October 6). MIS-enabled workforce analytics for service quality & retention. *TechRxiv*. https://doi.org/10.36227/techrxiv.175978943.38544757.v1
2. Saikat, M. H., Shoag, M., Akter, E., Bormon, J. C. (October 06, 2025.) Seismic- and Climate-Resilient Infrastructure Design for Coastal and Urban Regions. *TechRxiv*. DOI: 10.36227/techrxiv.175979151.16743058/v1
3. Saikat, M. H. (October 06, 2025). AI-Powered Flood Risk Prediction and Mapping for Urban Resilience. *TechRxiv*. DOI: 10.36227/techrxiv.175979253.37807272/v1
4. Akter, E. (September 15, 2025). Sustainable Waste and Water Management Strategies for Urban Civil Infrastructure. Available at *SSRN*: https://ssrn.com/abstract=5490686 or http://dx.doi.org/10.2139/ssrn.5490686
5. Karim, M. A., Zaman, M. T. U., Nabil, S. H., & Joarder, M. M. I. (2025, October 6). AI-enabled smart energy meters with DC-DC converter integration for electric vehicle charging systems. *TechRxiv*. https://doi.org/10.36227/techrxiv.175978935.59813154/v1
6. Al Sany, S. M. A., Rahman, M., & Haque, S. (2025). Sustainable garment production through Industry 4.0 automation. *World Journal of Advanced Engineering Technology and Sciences*, 17(1), 145–156. https://doi.org/10.30574/wjaets.2025.17.1.1387
7. Rahman, M., Haque, S., & Al Sany, S. M. A. (2025). Federated learning for privacy-preserving apparel supply chain analytics. *World Journal of Advanced Engineering Technology and Sciences*, 17(1), 259–270. https://doi.org/10.30574/wjaets.2025.17.1.1386
8. Rahman, M., Razaq, A., Hossain, M. T., & Zaman, M. T. U. (2025). Machine learning approaches for predictive maintenance in IoT devices. *World Journal of Advanced Engineering Technology and Sciences*, 17(1), 157–170. https://doi.org/10.30574/wjaets.2025.17.1.1388
9. Akhter, T., Alimozzaman, D. M., Hasan, E., & Islam, R. (2025, October). Explainable predictive analytics for healthcare decision support. *International Journal of Sciences and Innovation Engineering*, 2(10), 921–938. https://doi.org/10.70849/IJSCI02102025105
10. Rahman, M. (October 15, 2025) Integrating IoT and MIS for Last-Mile Connectivity in Residential Broadband Services. *TechRxiv*. DOI: 10.36227/techrxiv.176054689.95468219/v1
11. Islam, R. (2025, October 15). Integration of IIoT and MIS for smart pharmaceutical manufacturing. *TechRxiv*. https://doi.org/10.36227/techrxiv.176049811.10002169
12. Hasan, E. (2025). Big Data-Driven Business Process Optimization: Enhancing Decision-Making Through Predictive Analytics. *TechRxiv*. October 07, 2025. 10.36227/techrxiv.175987736.61988942/v1
13. Rahman, M. (2025, October 15). IoT-enabled smart charging systems for electric vehicles. *TechRxiv*. https://doi.org/10.36227/techrxiv.176049766.60280824/v1
14. Alam, MS (2025, October 21). AI-driven sustainable manufacturing for resource optimization. *TechRxiv*. https://doi.org/10.36227/techrxiv.176107759.92503137/v1

15. Alam, MS (2025, October 21). Data-driven production scheduling for high-mix manufacturing environments. *TechRxiv*. https://doi.org/10.36227/techrxiv.176107775.59550104/v1
16. Ria, S. J. (2025, October 21). Environmental impact assessment of transportation infrastructure in rural Bangladesh. *TechRxiv*. https://doi.org/10.36227/techrxiv.176107782.23912238/v1
17. Akter, E., Bormon, J. C., Saikat, M. H., & Shoag, M. (2025), "AI-Enabled Structural and Façade Health Monitoring for Resilient Cities", *Int. J. Sci. Inno. Eng.,* vol. 2, no. 10, pp. 1035–1051, Oct. 2025, doi: 10.70849/IJSCI02102025116
18. Haque, S., Al Sany (Oct. 2025), "Impact of Consumer Behavior Analytics on Telecom Sales Strategy", *Int. J. Sci. Inno. Eng*., vol. 2, no. 10, pp. 998–1018, doi: 10.70849/IJSCI02102025114.
19. Sharan, S. M. M. I (Oct. 2025)., "Integrating Human-Centered Design with Agile Methodologies in Product Lifecycle Management", *Int. J. Sci. Inno. Eng*., vol. 2, no. 10, pp. 1019–1034, doi: 10.70849/IJSCI02102025115.
20. Alimozzaman, D. M. (2025). Explainable AI for early detection and classification of childhood leukemia using multi-modal medical data. *World Journal of Advanced Engineering Technology and Sciences*, 17(2), 48–62. https://doi.org/10.30574/wjaets.2025.17.2.1442