

# Buckling And Stability Analysis of Slender Steel Column in High Rise Building Under Axial and Lateral Loads

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**Abstract:** *The stability and buckling behaviour of slender steel columns play a vital role in the structural safety and performance of high-rise buildings. As the height of buildings increases, steel columns become more slender and are subjected to large axial compressive forces along with significant lateral loads caused by wind and seismic actions. Under such combined loading conditions, slender columns become highly susceptible to global and local buckling failures, which may lead to excessive deformation and structural instability. Therefore, accurate evaluation of buckling behaviour is essential for the safe and economical design of tall steel structures.*

**Keywords:** Buckling Analysis, Slender Steel Column, High-Rise Building, Axial Load, Lateral Load, Structural Stability, P- $\Delta$  Effect, ETABS, Seismic Load, Wind Load, Finite Element Analysis, Story Drift, Critical Buckling Load, Modal Analysis, Steel Structures.

## I. INTRODUCTION

Rapid urbanization and population growth have increased the demand for high-rise buildings in modern cities. Steel structures are widely preferred in tall buildings because of their high strength-to-weight ratio, faster construction speed, flexibility in design, and good seismic performance. In high-rise construction, steel columns act as the primary vertical load-carrying members and are responsible for transferring gravity and lateral loads safely to the foundation. As building height increases, the columns become more slender, making them more vulnerable to instability and buckling under combined loading conditions [1].

Buckling is a structural instability phenomenon that occurs when a compression member suddenly deforms laterally due to excessive axial load. Unlike material failure, buckling can occur even when the stress in the column is below the yield strength of steel. Slender steel columns are particularly sensitive to buckling because their large height-to-width ratio reduces their resistance to lateral deformation. The critical buckling load depends on several parameters such as column length, cross-sectional properties, end support conditions, and material stiffness [2].

In high-rise buildings, steel columns are subjected not only to axial compressive loads caused by dead and live loads but also to lateral forces generated by wind and earthquake effects. These lateral forces create additional bending moments and increase the deformation of columns. The interaction between axial compression and lateral displacement produces second-order effects, commonly known as P- $\Delta$  effects, which significantly influence the stability and load-carrying capacity of slender columns [3].

Modern structural engineering practice requires accurate analysis of buckling behaviour to ensure the safety and serviceability of tall structures. Traditional analytical methods based on Euler's buckling theory provide a simplified understanding of column instability; however, actual high-rise structures experience more complex behaviour due to geometric imperfections, residual stresses, nonlinear material properties, and dynamic loading effects [4]. Therefore, advanced numerical methods and finite element analysis software such as ETABS, ANSYS, and ABAQUS are commonly used to evaluate the real behaviour of steel columns under practical loading conditions [5].



The effect of slenderness ratio is one of the most important factors governing the stability of steel columns. Columns with higher slenderness ratios tend to experience larger lateral deflections and lower buckling resistance compared to short columns. Boundary conditions such as fixed, pinned, or semi-rigid supports also affect the effective length and critical buckling load of the column [6]. In addition, the presence of imperfections and fabrication tolerances further reduces the actual buckling capacity of steel members.

Wind and seismic forces are major design considerations in high-rise structures. Wind loads produce continuous lateral pressure on the building surface, while seismic forces generate dynamic inertial effects during earthquakes. These forces create sway in the structural system, increasing stress and displacement in slender steel columns. If not properly designed, excessive drift and instability may lead to structural failure [7]. Therefore, evaluating the combined influence of axial and lateral loads is essential for safe structural design.

Recent developments in performance-based design and computational analysis have improved the prediction of buckling behaviour in steel structures. Researchers have focused on nonlinear analysis, second-order analysis, and finite element modelling to better understand the interaction between local buckling, global buckling, and lateral stability effects [8]. These approaches help engineers optimize structural member sizes while maintaining adequate safety and serviceability.

This research focuses on the buckling and stability analysis of slender steel columns in high-rise buildings under combined axial and lateral loads. The study uses ETABS software to simulate realistic loading conditions and evaluate parameters such as story displacement, story drift, bending moments, deformation patterns, and buckling response. The investigation helps in understanding the structural behaviour of slender columns and provides recommendations for improving the safety and stability of steel high-rise buildings [9].

The outcomes of this study are expected to contribute to the development of efficient and economical steel structural systems capable of resisting complex loading conditions in modern tall buildings. The research also supports the application of advanced analytical techniques for evaluating the stability performance of slender steel columns in practical engineering design [10].

### **Motivation**

The rapid growth of urbanization and the increasing demand for high-rise buildings have created the need for efficient, lightweight, and strong structural systems. Steel structures are widely used in tall buildings because of their high strength-to-weight ratio, ductility, and faster construction process. However, as the height of buildings increases, steel columns become more slender and are subjected to large axial compressive forces along with lateral loads generated by wind and earthquakes. Under these combined loading conditions, slender steel columns become highly susceptible to buckling and instability, which may lead to excessive deformation or structural failure if not properly analyzed and designed. This creates a major challenge for structural engineers in ensuring both safety and economy in high-rise building construction.

### **Objectives**

1. To analyse the buckling behaviour of slender steel columns under combined axial and lateral loading conditions.
2. To develop a numerical model of high-rise steel structures using ETABS software for stability analysis.
3. To evaluate the effect of slenderness ratio and boundary conditions on the critical buckling load of steel columns.
4. To study the influence of P- $\Delta$  effects, wind load, and seismic load on column deformation and structural stability.
5. To identify safe and economical design approaches for improving the stability performance of slender steel columns in high-rise buildings., F1-score.



## **II. LITERATURE SURVEY**

### **1. Behzadi-Sofiani et al. (2023)**

Behzadi-Sofiani et al. (2023) investigated the buckling behaviour and design performance of cruciform steel columns subjected to axial compression. The study used finite element modelling to analyse local and global buckling effects in slender steel members. The researchers proposed improved design recommendations for enhancing column stability and load-carrying capacity in structural applications [1].

### **2. Aboukifa and Moustafa (2022)**

Aboukifa and Moustafa (2022) studied the structural and buckling behaviour of full-scale slender ultra-high-performance concrete (UHPC) columns under axial and eccentric loading conditions. The research highlighted the importance of moment magnification and second-order effects in slender column design. Experimental and numerical results showed that slenderness significantly affects the critical buckling load and deformation behaviour of columns [2].

### **3. Mousavi Davoudi and Naghipour (2021)**

Mousavi Davoudi and Naghipour (2021) analysed the effect of slenderness ratio on the compressive strength of concrete-filled steel tubular (CFT) columns using finite element analysis and experimental methods. The study concluded that increasing slenderness ratio reduces the load-carrying capacity and stability of composite columns. The research also emphasized the importance of considering buckling effects in high-rise steel structures [3].

### **4. Hussein and Hussein (2024)**

Hussein and Hussein (2024) investigated the structural behaviour of built-up cold-formed steel beams and columns under different loading conditions. The study focused on the influence of screw spacing and connection configuration on global buckling resistance and flexural strength. Results indicated that improved connection arrangements significantly enhanced the stability and load resistance of slender steel members [4].

### **5. Johannes Liljenherte et al. (2021)**

Johannes Liljenherte et al. (2021) studied the stability behaviour of periodically supported slender structures using finite element modelling and experimental validation techniques. The research examined how support conditions and geometric configurations influence buckling patterns and structural deformation. The study provided useful insights into improving the stability performance of slender structural systems subjected to axial and lateral loads [5].

## **Existing system**

### **1. Traditional Euler Buckling Theory**

Earlier buckling analysis methods for steel columns were mainly based on Euler's classical buckling theory, which predicts the critical load of ideal slender columns under axial compression. These methods assumed perfectly straight columns with ideal boundary conditions and elastic material behaviour. However, they were limited in accurately predicting the behaviour of real high-rise structural columns subjected to combined axial and lateral loads.

### **2. Conventional First-Order Structural Analysis**

Traditional structural analysis methods used first-order linear analysis to evaluate steel column behaviour in buildings. These methods considered only primary load effects and ignored second-order  $P-\Delta$  effects caused by lateral displacement. As a result, the actual instability and deformation behaviour of slender steel columns could not be accurately captured in tall structures.

### **3. Manual Design Based on Empirical Formulas**

Earlier steel column design approaches relied heavily on empirical formulas and simplified code-based calculations for determining column capacity and slenderness limits. Although these methods were simple and easy to apply, they often provided conservative or less accurate results for modern high-rise buildings subjected to dynamic loading conditions.

### **4. Simplified Frame Analysis Methods**

Conventional frame analysis techniques assumed ideal support conditions and neglected the influence of geometric imperfections, residual stresses, and connection flexibility. These simplified methods were unable to represent the



actual interaction between axial load, bending moments, and lateral forces in slender steel columns used in tall building systems.

### 5. Basic Finite Element Modelling Approaches

Initial finite element analysis methods for steel structures used simplified beam models and limited nonlinear analysis capabilities. These systems could analyse basic buckling behaviour but lacked advanced features for accurately evaluating local buckling, global buckling, dynamic response, and realistic high-rise building loading combinations.

### III. PROPOSED SYSTEM

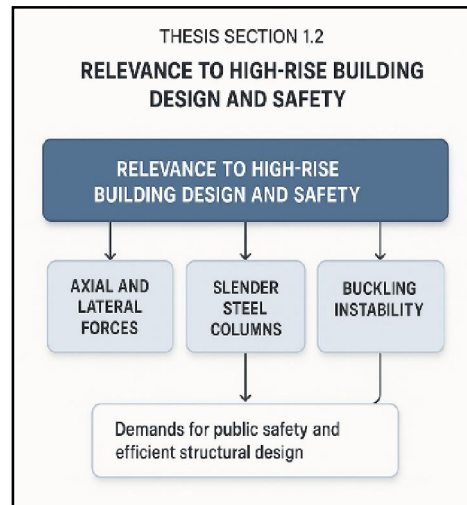


Figure 1: Relevance to High-Rise Building Design

#### 1. Combined Axial and Lateral Load Analysis

The proposed system analyses the behaviour of slender steel columns under the simultaneous action of axial compressive forces and lateral loads such as wind and earthquake forces. This combined loading approach helps in understanding the actual structural response and stability performance of high-rise buildings under realistic conditions.

#### 2. Stability Evaluation of Slender Steel Columns

The system focuses on evaluating the stability behaviour of slender steel columns used in tall structures.

#### 3. Buckling Instability Detection

The proposed system identifies local and global buckling instability in steel columns using advanced numerical analysis techniques.

#### 4. Advanced ETABS-Based Structural Modelling

The system uses ETABS software for modelling and analysis of the high-rise structure. Advanced finite element analysis

#### 5. Safe and Economical Structural Design

The proposed system aims to achieve a safe and economical structural design by optimizing column sections, reducing excessive displacement, and improving structural stability.

#### 6. Combined Loading Analysis Using Advanced Approaches

The proposed system incorporates advanced analysis approaches such as Linear Buckling Analysis, Direct Analysis Method, and Finite Element Analysis to evaluate the behaviour of slender steel columns under combined axial and lateral loading conditions.



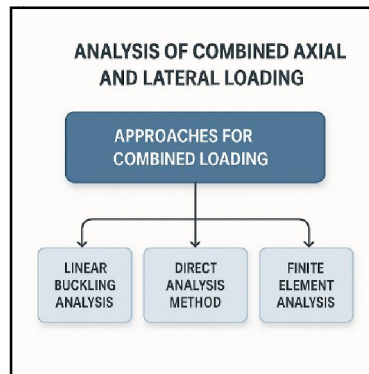


Figure 2 : Analysis of combined axial and lateral loading

**IV. SYSTEM DESIGN**

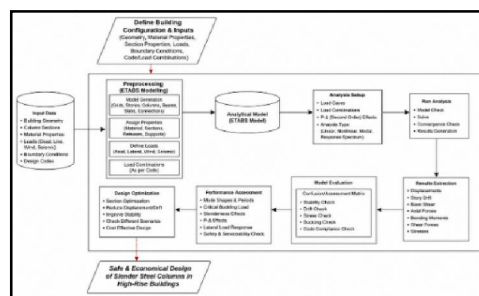


Figure 3. Block Diagram

**System Design**

The proposed system is designed to analyse the buckling and stability behaviour of slender steel columns used in high-rise buildings under combined axial and lateral loading conditions. The system integrates structural modelling, preprocessing, numerical analysis, result evaluation, and optimization processes using ETABS software and design code provisions. The complete workflow ensures accurate prediction of structural behaviour, deformation patterns, and buckling response under realistic loading scenarios.

**1. Input Data and Building Configuration**

The system begins with defining the building geometry and structural input parameters. These include column dimensions, beam sections, material properties, loading conditions, support conditions, and design code specifications. Different load cases such as dead load, live load, wind load, and seismic load are considered. Boundary conditions and load combinations are also specified according to IS codes and structural design standards. These inputs form the foundation for generating the analytical model.

**2. Preprocessing and ETABS Modelling**

In the preprocessing stage, the complete structural model is developed in ETABS software. Grid systems, storey data, beams, columns, slabs, and structural connections are defined. Material properties and sectional properties are assigned to all structural members. Support conditions such as fixed or pinned restraints are applied to represent realistic structural behaviour. The model is then prepared for analysis by assigning load patterns and load combinations as per design requirements.



### 3. Boundary Conditions and Effective Length Factors

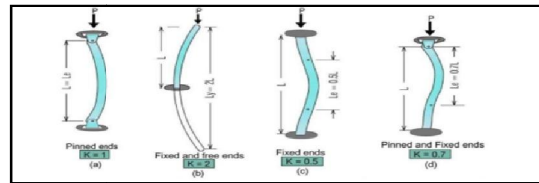


Figure 5. Boundary Conditions and Effective Length Factors

Boundary conditions representing various end restraints are implemented through specification of displacement and rotation constraints.

### 4. Analysis Setup and Structural Analysis

The analysis setup includes defining linear, nonlinear, modal, and response spectrum analysis procedures. Second-order P-Δ effects are included to account for additional moments caused by lateral displacement of columns under axial compression. ETABS performs structural analysis for different load combinations and generates results related to displacements, bending moments, shear forces, axial forces, and stresses. Modal analysis is also performed to evaluate vibration characteristics and dynamic response of the structure.

### 5. Results Extraction and Evaluation

The output results obtained from the analysis are evaluated to study the stability behaviour of slender steel columns. Important parameters such as story displacement, story drift, critical buckling load, stress distribution, and mode shapes are analysed. Stability checks, drift checks, stress verification, and code compliance evaluations are carried out to determine the safety and performance of the structure under combined loading conditions.

### 6. Performance Assessment

The system further assesses the performance of the structure by examining the effects of slenderness ratio, lateral loads, and P-Δ effects on column stability. The influence of seismic and wind loads on deformation behaviour and structural safety is studied. This stage helps identify critical regions in the structure where buckling or excessive displacement may occur.

### 7. Design Optimization

Based on the analysis results, optimization techniques are applied to improve structural performance and reduce material consumption. Section sizes, stiffness, and load-resisting systems are modified to achieve safe and economical structural design. Different structural configurations and loading scenarios are compared to obtain the most stable and efficient design for high-rise buildings.

### 8. Types of Steel Columns Used in High-Rise Structures

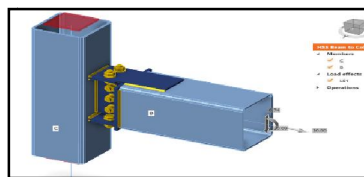


Figure 4 Steel Columns

High-rise buildings use different types of steel columns based on loading conditions, architectural needs, and structural requirements. Hollow Structural Sections (HSS), such as square, rectangular, and circular tubes, are widely used because of their high torsional rigidity, uniform buckling resistance, and attractive appearance.



**V. OUTCOMES FROM THE SYSTEM**

**1. Maximum Story Displacement Diagram**

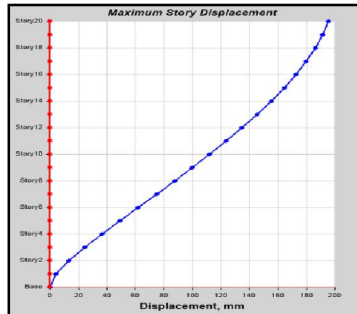


Figure 5 Maximum Story Displacement Diagram

This diagram shows the variation of lateral displacement along the height of the building. The displacement increases gradually from the base to the top storey, indicating that upper floors experience greater movement under wind and seismic loading conditions. It helps evaluate the lateral stiffness and serviceability performance of the structure.

**2. Axial Force Distribution Diagram**

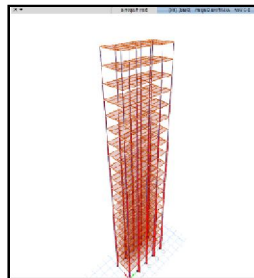


Figure 6. Axial Force Distribution Diagram

The axial force diagram shows the distribution of compressive forces in the steel columns due to dead load and combined loading conditions. Higher axial forces are concentrated in the lower storeys because these columns support the cumulative load from upper floors. This diagram helps identify critical columns that are more susceptible to buckling failure.

**3. Bending Moment Diagram (2-2 Direction)**

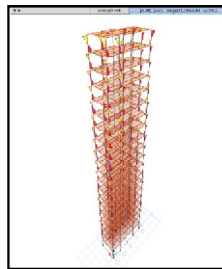


Figure 7. Bending Moment Diagram (2-2 Direction)

This diagram represents the bending moments acting about the local 2-2 axis of beams and columns. Higher bending moments are observed near beam-column joints and lower storeys due to increased structural demand. It helps evaluate moment transfer behaviour and member stability in the structural frame.



#### 4. Bending Moment Diagram (3-3 Direction)

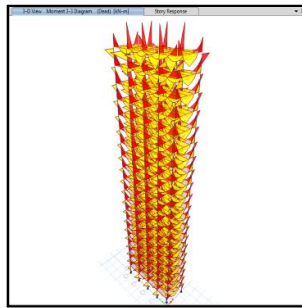


Figure 8. Bending Moment Diagram (3-3 Direction)

The 3-3 bending moment diagram illustrates moments acting about the local 3-3 axis of structural members. The diagram highlights regions experiencing high bending stresses under gravity and lateral loading conditions, which are important for column design and buckling analysis.

#### 5. Shear Force Diagram

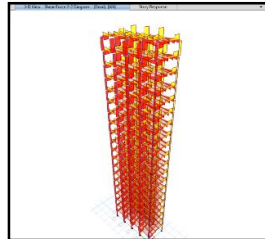


Figure 8. Shear Force Diagram

The shear force diagram shows the internal shear forces developed in beams and columns due to applied loads. Higher shear force values are generally observed in lower storeys and near beam-column connections where load transfer occurs. This diagram helps assess structural safety and load distribution.

### VI. CONCLUSION

The present study focused on the buckling and stability analysis of slender steel columns used in high-rise buildings under combined axial and lateral loading conditions. As modern buildings become taller and more slender, structural stability becomes one of the most critical aspects in ensuring safety and serviceability. The study successfully investigated the behaviour of slender steel columns subjected to gravity loads, wind loads, seismic loads, and second-order  $P-\Delta$  effects using ETABS structural analysis software. The analysis provided detailed information regarding displacement behaviour, story drift, stress distribution, bending moments, shear forces, and buckling response of the structural system.

The results obtained from the numerical analysis revealed that lateral loads significantly influence the stability performance of slender steel columns. It was observed that the increase in slenderness ratio leads to larger lateral displacement and reduced critical buckling load capacity. The study also showed that  $P-\Delta$  effects play a major role in amplifying bending moments and deformation in tall structures, especially in lower storeys where axial forces are maximum. Modal and response spectrum analysis helped in understanding the dynamic behaviour of the building, including natural time periods, vibration modes, and seismic response characteristics.

### VII. FUTURE SCOPE

The present study mainly focused on the numerical analysis of slender steel columns under combined axial and lateral loading conditions using ETABS software. In future research, the work can be extended by performing



detailed experimental investigations on full-scale steel column specimens to validate the numerical analysis results. Advanced finite element software such as ANSYS, ABAQUS, and OpenSees can also be used for more detailed nonlinear and dynamic stability analysis. Future studies may include the effect of different steel grades, composite columns, bracing systems, and innovative structural materials on buckling resistance and overall structural performance.

Further research can also focus on the influence of real-time dynamic loading conditions such as blast loads, impact loads, progressive collapse, and near-fault earthquake effects on slender steel columns in super-tall buildings. The implementation of artificial intelligence, machine learning techniques, and optimization algorithms can help predict structural instability and improve automated design processes. In addition, future investigations may include the study of soil-structure interaction, connection flexibility, residual stresses, corrosion effects, fire resistance, and sustainability aspects in high-rise steel structures.

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