Structural Design of High-Rise Buildings: Finite Element Modelling, Wind Response, and Stability Analysis

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Abstract — High-rise buildings are increasingly subjected to complex static and dynamic loading conditions, particularly wind-induced effects and stability-related challenges. The present manuscript investigates the structural behaviour of high-rise buildings using finite element modelling techniques and analytical approaches. Various modelling strategies are evaluated with respect to reaction forces, overturning moments, horizontal and vertical deflections, resonance frequencies, critical buckling loads, and acceleration responses. Analytical calculations based on Eurocode, SS-ISO standards, and empirical methods are compared with three-dimensional finite element analyses performed using Midas Gen software. The study highlights that a single numerical model is often insufficient to capture both global and local structural behaviour accurately. Different modelling approaches are necessary depending on whether the analysis concerns vertical loads, horizontal loads, dynamic response, or detailed force transfer mechanisms. The research further examines wind-induced along-wind and across-wind responses, occupant comfort criteria, and the influence of discretisation and element selection in finite element analysis. Results indicate that finite element modelling must be combined with engineering judgement and analytical verification to ensure reliable structural assessment and safe design of tall buildings.

Keywords: High-Rise Buildings, Finite Element Analysis, Wind Load, Structural Dynamics, Resonance Frequency, Acceleration, Stability, Buckling, Midas Gen

I. INTRODUCTION

A. Background

The design of high-rise buildings has evolved significantly with advancements in computational power and structural analysis software. Modern structural engineering practice frequently employs three-dimensional finite element models to evaluate the behaviour of tall buildings under static and dynamic loading conditions. However, despite the capabilities of advanced software, the complexity of numerical modelling often introduces uncertainties related to force distribution, stiffness representation, discretisation, and structural response interpretation.

High-rise buildings are particularly sensitive to lateral loading caused by wind and seismic actions. Their structural performance depends heavily on stiffness, damping, mass distribution, and the effectiveness of the lateral load-resisting system. Dynamic effects such as resonance, vibration, and occupant comfort become increasingly important as building height increases. Consequently, reliable modelling techniques and analytical verification methods are essential for ensuring structural safety and serviceability.

Finite element analysis enables detailed representation of structural systems, but the accuracy of results depends on appropriate modelling assumptions, mesh quality, material representation, and boundary conditions. Engineers must therefore critically evaluate numerical outputs and compare them with analytical calculations and code-based procedures.

B. Objectives

The primary objective of this study is to evaluate structural modelling approaches for high-rise buildings subjected to vertical and horizontal loading conditions. The study aims to:

- Investigate the influence of modelling techniques on structural response.
- Compare analytical methods with finite element analysis results.
- Examine resonance frequencies and acceleration responses.
- Evaluate overturning moments, reaction forces, and lateral deflections.
- Study the effects of wind-induced loading on structural behaviour.
- Assess occupant comfort criteria under dynamic excitation.

C. Scope and Limitations

The study focuses on the global structural behaviour of high-rise concrete buildings. Effects such as creep, shrinkage, cracking, and temperature variations are not included. The analyses assume linear elastic material behaviour and uncracked concrete sections. Time-history analysis is not performed; instead, wind-induced dynamic effects are evaluated using Eurocode-based procedures and modal analysis.

II. HIGH-RISE BUILDINGS

A. Structural Behaviour

A high-rise building is generally characterised by its considerable height relative to surrounding structures and its susceptibility to lateral loading effects. As building height increases, wind-induced forces become a governing design consideration. The structure behaves similarly to a cantilever fixed at the foundation, with overturning moments increasing significantly with height.

The primary structural challenge in tall buildings is achieving adequate lateral stiffness while maintaining architectural functionality and economic feasibility. Excessive deflections and accelerations can cause occupant discomfort and structural serviceability problems.

B. Structural Systems

Several structural systems are commonly used in high-rise buildings to resist lateral loads:

1) Framed Tube System

The framed tube system consists of closely spaced perimeter columns connected by deep spandrel beams, forming a stiff tubular structure capable of resisting lateral loads efficiently.

2) Bundled Tube System

Bundled tube structures combine multiple interconnected tubes, reducing shear lag effects and improving stiffness distribution.

3) Tube-in-Tube System

This system incorporates an exterior framed tube and an internal core working together to resist gravity and lateral loads.

4) Braced and Rigid Frame Systems

Diagonal bracing enhances lateral stiffness and reduces structural drift, while rigid frames rely on moment-resisting connections between beams and columns.

5) Outrigger System

Outrigger systems connect the central core to perimeter columns, significantly increasing overturning resistance and reducing lateral deflection.

6) Hybrid Systems

Hybrid systems combine multiple structural concepts to optimise stiffness, architectural flexibility, and structural efficiency.

III. Wind Effects on High-Rise Buildings

Wind loading is one of the most critical design considerations for tall buildings. Wind effects may be classified as:

- Static wind effects
- Dynamic wind effects

Dynamic wind loading produces along-wind, across-wind, and torsional responses. These responses depend on building geometry, stiffness, mass distribution, damping characteristics, and surrounding terrain conditions.

A. Along-Wind Response

Along-wind response primarily results from fluctuating wind pressure and turbulence. The dynamic amplification depends on the building's natural frequency and damping ratio.

B. Across-Wind Response

Across-wind response is mainly associated with vortex shedding phenomena. In some cases, across-wind effects may exceed along-wind responses and govern structural design.

C. Resonance

Resonance occurs when the frequency of external loading approaches the natural frequency of the structure, leading to amplified vibrations.

$$u(\omega) = \frac{f}{k}\frac{1}{1-(\omega/\omega_n)^2}$$

The amplification of structural response near resonance frequencies highlights the importance of modal analysis and dynamic evaluation in high-rise building design.

IV. Finite Element Method

A. Fundamentals

The finite element method (FEM) is widely used to analyse complex structural systems by discretising the structure into smaller interconnected elements. Structural behaviour is determined through numerical approximation of governing differential equations.

The general equation of motion for structural dynamics is:

$$M\ddot{u} + C\dot{u} + Ku = f$$

where:

M= mass matrix
C= damping matrix
K= stiffness matrix
u= displacement vector
f= external load vector

B. Element Types

Different element types are used in finite element modelling:

- Beam elements
- Plate elements
- Shell elements
- Plane stress elements

Selection of appropriate element types is essential for obtaining accurate structural behaviour.

C. Modelling Challenges

Several challenges arise during finite element modelling:

- Mesh sensitivity
- Material idealisation
- Numerical singularities
- Load discretisation
- Boundary condition assumptions
- Computational limitations

Improper modelling assumptions may lead to misleading results and unsafe structural designs.

V. Structural Dynamics

Structural dynamics investigates the response of structures subjected to time-dependent loading.

A. Single Degree of Freedom System

The equation of motion for a single degree of freedom system is:

$$m\ddot{u} + c\dot{u} + ku = f$$

where:

m= mass
c= damping coefficient
k= stiffness
u= displacement

B. Natural Frequency

Natural frequencies are fundamental properties governing structural response. Accurate estimation of modal characteristics is critical for evaluating wind-induced vibrations and occupant comfort.

VI. Stability and Buckling Analysis

The stability of tall buildings is strongly influenced by axial forces and lateral displacements. The global critical load may be estimated using the Vianello method:

$$N_{cr} = k_v\frac{EI}{L_h^2}$$

where:

N_{cr}= critical load
E= Young's modulus

I= moment of inertia
L_h= building height
k_v= stability coefficient

Buckling analysis is necessary to evaluate the overall stability of slender high-rise structures.

VII. Occupant Comfort Criteria

Dynamic motion in high-rise buildings affects occupant comfort and perception. Excessive accelerations may lead to discomfort, nausea, or reduced productivity.

International standards such as SS-ISO 10137 provide acceptable acceleration limits based on building occupancy type and vibration frequency. Residential buildings generally require stricter comfort criteria than office buildings.

VIII. Results and Discussion

The analyses demonstrate that:

– Different modelling approaches produce significantly different results.
– Coarse finite element meshes may fail to capture local stress concentrations.
– Global structural behaviour can be evaluated using simplified models, while detailed analyses require refined meshes.
– Wind-induced accelerations are highly sensitive to stiffness and damping assumptions.
– Construction stage analysis improves prediction of realistic displacement behaviour.
– Dynamic analyses are essential for evaluating serviceability and occupant comfort.

The comparison between analytical calculations and finite element analyses shows good agreement for global behaviour; however, local stress distributions require more refined numerical modelling.

IX. Conclusions

This study highlights the importance of appropriate modelling techniques in the structural analysis of high-rise buildings. Finite element analysis provides powerful capabilities for evaluating structural response, but results must always be validated through engineering judgement and analytical methods.

The following conclusions can be drawn:

– High-rise buildings require careful evaluation of both static and dynamic behaviour.
– Wind-induced accelerations and resonance effects significantly influence structural performance and occupant comfort.
– Different finite element models are often necessary for global and local analyses.
– Analytical calculations remain essential for verification of numerical results.
– Construction stage analysis improves prediction accuracy for vertical displacements and force redistribution.
– Proper selection of structural systems greatly enhances lateral stiffness and overall stability.

Future research should focus on nonlinear material behaviour, time-history analysis, soil-structure interaction, and performance-based design approaches for tall buildings.

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