

The Structural Behavior of Concrete Tall Buildings Using Rigid Frame Systems Under Wind Load

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Abstract

This study evaluates the structural behavior of a 20-story concrete office building with a rigid frame system under varying wind loads. The analysis is conducted using ETABS software at wind speeds of 40, 60, 80, and 100 mph. The internal forces, including deflection, shear, and overturning moments, are assessed under these conditions. The results demonstrate compliance with ACI318-19 code requirements and address critical factors like deflection limits and stability. The study further highlights environmental impacts, neighboring building effects, and wind movement in the width direction, ensuring safe and efficient high-rise building designs. It has been concluded that deflection, shear forces and overturning moments increase at a similar rate with the increase in wind speed. Additionally, the drift caused by wind does not pose a significant risk compared to that caused by earthquakes, for this reason, the American code does not specify a limit for wind induced drift as the $H/500$ limit is an approximate value derived from previous experiences. This study recommends that future studies on this system continue, taking into account seismic loads. It should also include a comparison between this system and other wind and seismic-resistant systems, focusing on construction cost and methodology in the context of Sudan

Key words—Wind; buildings; frame system; analysis; behavior

I. INTRODUCTION

With the rapid pace of urban development and the global trend toward vertical construction, high-rise buildings have become a central feature of modern cities. As buildings grow taller, lateral loads—particularly those induced by wind—become increasingly significant in structural design. Wind-induced forces can lead to substantial horizontal displacements, internal stresses, and stability concerns, making them a critical factor in the engineering and performance of tall structures. Among the various lateral load-resisting systems available to structural engineers, the Rigid Frame system is widely recognized for its simplicity, structural efficiency, and cost-effectiveness. This system relies on the rigid connections between beams and columns, enabling the frame to resist lateral loads through bending moments rather than bracing or shear walls. As a result, it offers designers greater architectural flexibility and ease of construction, while maintaining sufficient lateral stiffness, particularly in low- to mid-rise buildings. This study aims to analyze the structural behavior of a high-rise building designed with a Rigid Frame system under the influence of wind loads. The focus is on evaluating key internal responses such as lateral deflection, shear forces, and overturning moments. Advanced structural modeling software is utilized to simulate and assess the building's response to lateral loads, allowing for a comprehensive understanding of the system's performance at various heights and load intensities. Through this investigation, the paper seeks to demonstrate the effectiveness and limitations of the Rigid Frame system in tall building applications and The behavior of structures under wind-induced forces has been a subject of various investigations. It also aims to provide design insights that could contribute to more resilient, efficient, and safe high-rise structures, especially in wind-prone regions. The findings are intended to support engineers and designers in making in-

formed decisions when selecting structural systems for modern skyscrapers. Despite the widespread use of rigid frame systems in structural engineering, limited studies have explored their behavior under varying wind speeds, particularly in regions like Sudan where building practices and environmental conditions differ from Western contexts. this study not only aims to assess the typical increase in structural responses under wind loads but also investigates any nonlinear or unexpected trends in behavior, including the observed reductions in deflection and shear forces at certain wind speeds . "The study also aims to identify any unexpected trends in structural behavior under increasing wind speeds, which may reveal gaps in standard design assumption

A. Wind Load

Wind is the term used for air in motion and is usually applied to the natural horizontal motion of the atmosphere. Motion in a vertical or nearly vertical direction is called a current. Movement of air near the surface of the earth is 3D, with horizontal motion much greater than the vertical motion. Vertical air motion is of importance in meteorology but is of less importance near the ground surface. On the other hand, the horizontal motion of air, particularly the gradual retardation of wind speed and high turbulence that occur near the ground surface, is of importance in building engineering. In urban areas, this zone of wind turbulence is often referred to as the surface boundary layer extends to a height of approximately one-quarter of a mile above-ground. Above this layer, the horizontal airflow is no longer influenced by the retarding effect of the ground surface. The wind speed at this height is called gradient wind speed, and it is precisely within this boundary layer where most construction activity occurs. Therefore, how wind effects are felt within this zone is of concern in building design.

B. Rigid Frame System

Cast-in-place concrete has an inherent advantage of continuity at joints but the design and detailing of joints at the intersection of beams and columns may be of concern particularly in buildings assigned to SDC C [1] and above. This is because the column height within the depth of the girder, often referred to as a panel zone, is subjected to large shear forces. Horizontal seismic ties at very close spacing may be required to avoid uncontrolled diagonal cracking and disintegration of concrete and to promote ductile behavior. The intent is to have a system that can respond to earthquake loads without loss in gravity-load carrying capacity. A rigid frame is characterized by flexure of beams and columns and rotation at the joints. Interior rigid frames for office buildings are generally inefficient because (1) the number of columns in any given frame is limited due to leasing considerations and (2) the beam depths are often limited by the floor-to-floor height. However, frames located at the building exterior do not necessarily have these limitations. An efficient frame action can thus be developed by providing closely spaced columns and deep spandrels at the building exterior.

C. Research Objectives

- 1) Review the behavior of rigid frame systems.
- 2) Analyze lateral forces due to wind loads.
- 3) Conduct computational analysis using ETABS.
- 4) Provide conclusions and recommendations.



Fig. 1: plane of Building

II. METHODOLOGY

A. Case Study Building Details

- Plan Area: $13 \times 32 = 416 \text{ m}^2$
- Building Height: 60 m
- Ground Floor Height: 3 m
- Typical Story Height: 3 m
- Structural Components:
 - Columns: $400 \times 800 \text{ mm}$
 - Beams: $500 \times 250 \text{ mm}$
 - Slabs: 200 mm thickness

The plan of the studied building is shown in Figure(1)

B. Wind Load Parameters

- Basic wind speeds: 40, 60, 80, 100 mph.
- Analysis according to ASCE 7-16.
- Exposure category: D.
- Topographic factor (K_{zt}): 1.
- Direction factor (K_d): 0.85.
- Velocity pressure coefficients (K_z): Table
- 26.10.1 ASCE 7-16.[2]

The wind load was defined in the ETABS program as illustrated in Figure(2).

C. ETABS Modeling

D. Previous Studies

Rigid frame systems are widely used due to their high capacity to resist lateral loads particularly those induced by strong wind forces, which pose significant challenges in the design of high-rise buildings. Numerous studies have examined the behavior of these systems under wind loads, focusing on their flexibility, deformation tolerance, and ability to reduce lateral drift. Other research has investigated the influence of geometric configuration and material properties on the overall performance of the frame under varying wind pressures. Findings suggest that precise design and appropriate detailing can significantly enhance the system's resistance to wind forces, thereby reducing potential structural damage and improving the safety and stability of buildings. This study aims to deepen this understanding by evaluating the structural performance of moment-resisting frames under wind loads using advanced modeling and analytical techniques.

- 1) *SEG Plaza, China: A 79-story* : skyscraper experienced structural vibrations caused by wind-induced resonance, leading to its temporary evacuation in 2021.[3] This case is illustrated in Figure(3) This study emphasizes the importance of aerodynamic considerations in tall buildings.
- 2) *Tacoma Narrows Bridge Collapse*: This historical failure highlights the significance of accounting for dynamic wind effects such as vortex shedding.[4] The bridge is shown in Figure(4)
- 3) *Wind Tunnel Testing*: These studies underline the importance of accurately modeling wind loads for buildings exceeding 40 stories, where static methods may underestimate dynamic responses. An example of wind tunnel test results is shown in Figure(5).
- 4) *Shape building*: A rectangular-shaped building, regardless of its height, is less vulnerable. and suitable with respect to the C shape of building during the wind load. [5] The shape of the building's corners affects wind loads. Sharp corners create larger vortex shedding compared to rounded ones sharp corners tend to create larger vortex shedding, while rounded corners result in smaller, less intense vortices." This relationship is illustrated in Figure(6).

III. RESULTS AND DISCUSSION

A. Wind Speed Effects on Deflection

Maximum deflection increased proportionally with wind speed. At 100 mph, the deflection exceeded allowable limits

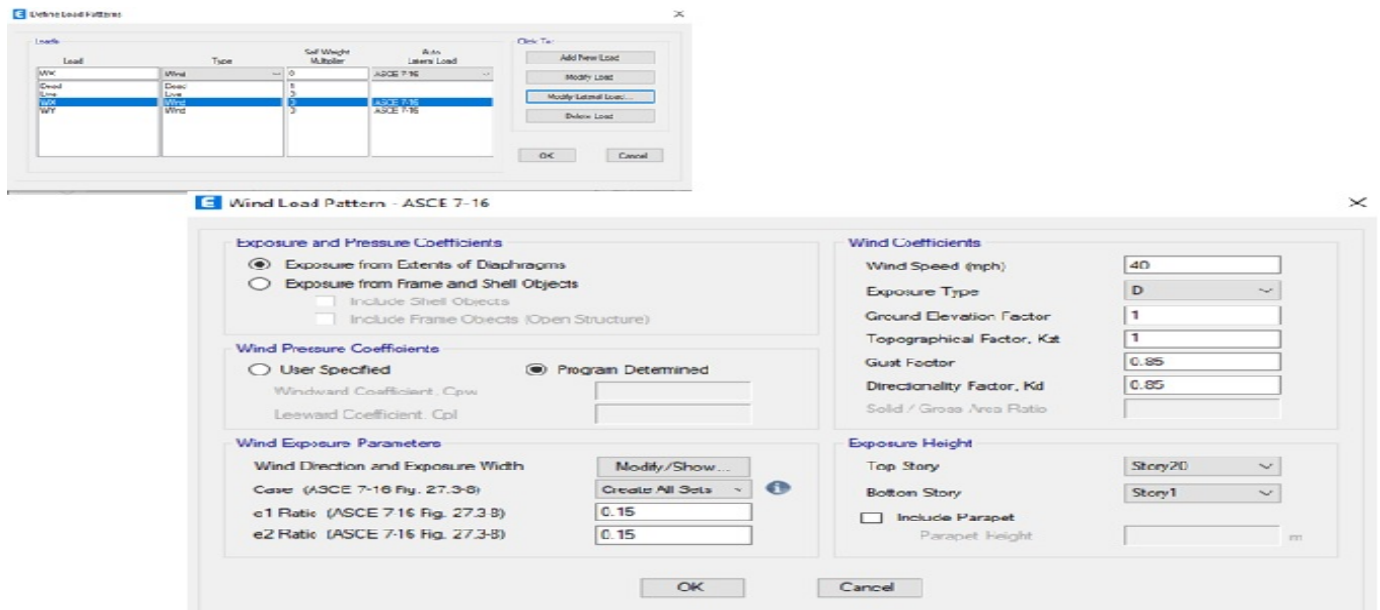


Fig. 2: Define wind load in ETABS program

Structure in General	
Building type	skyscraper
Building status	existing [completed]
Structural material	concrete
Facade material	glass
Facade system	curtain wall
Architectural style	modernism

Technical Data	
Height (tip)	355.80 m
Height (architectural)	291.60 m
Height (roof)	291.60 m
Floors (above ground)	70
Floors (below ground)	4
Construction end	2000



Fig. 3: high rise building SEG Plaza

Wind Comfort Criteria Lawson, wind criteria.



Pedestrian wind comfort simulation of Central London

Fig. 5: wind tunnel test result



Fig. 4: Tacoma Narrows Bridge

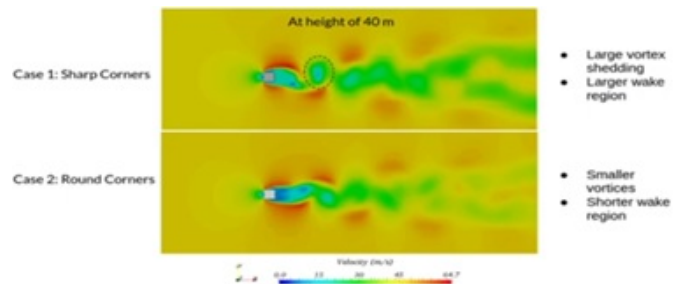


Fig. 6: relationship between building corner shape and vortex shedding

(H/500), particularly in upper stories. The variation of deflec-

tion with wind speed is shown in Figure(7). This necessitates structural reinforcements or alternative design adjustments.

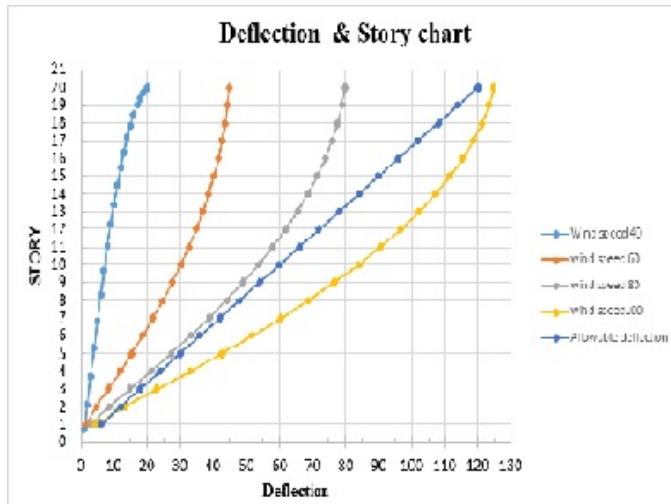


Fig. 7: Deflection chart of wind speeds

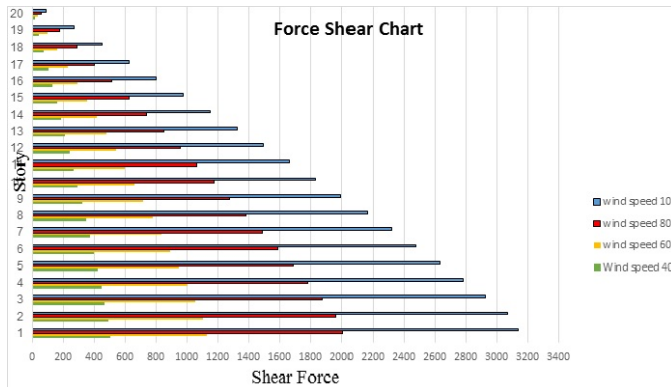


Fig. 8: Shear force chart of various wind speeds

B. Shear Force Distribution

Shear forces were significantly higher at the base under increasing wind speeds. At 100 mph, the base shear approached the critical design threshold,[1] requiring robust foundation systems. As shown in Figure(8), the shear force at the base increases significantly with wind speed.

C. Overturning Moments

Overturning moments increased substantially with wind speed. Safety factors remained above the required limit ($F_s \geq 1.5$), but at higher wind speeds, the structure approached critical stability conditions. Figures(9 and 10) present overturning moments in the X- and Y-directions, respectively.

D. Extended Discussion

- The results of the analysis indicate that deflection, shear force, and overturning moment increase steadily as wind speed increases from 40 mph to 100 mph. This behavior aligns with fundamental structural principles, where higher wind loads induce greater lateral forces and moments.
- Table(I) summarizes the relationship between wind load and internal forces, showing the proportional increase in

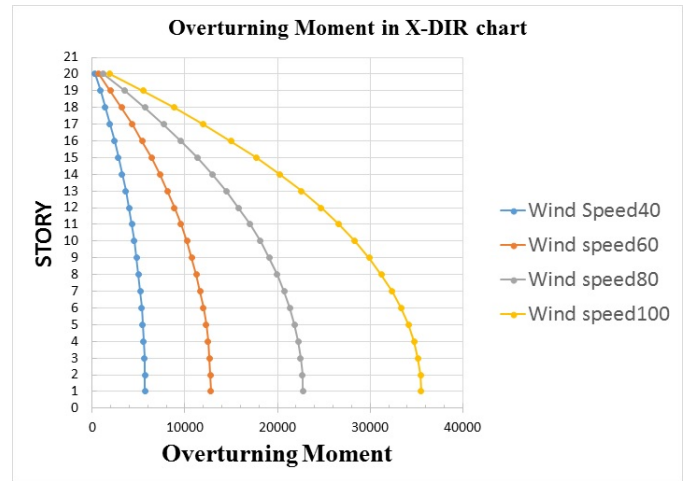


Fig. 9: comparison overturning chart in X-direction of various wind speeds

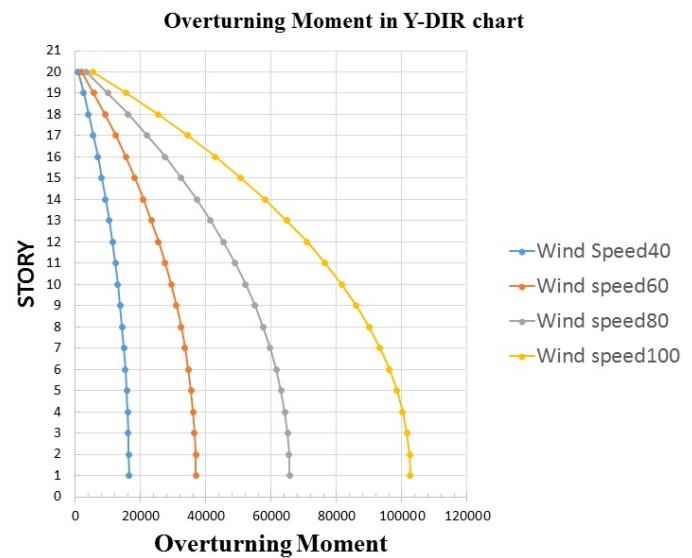


Fig. 10: comparison overturning chart in Y-direction of various wind speeds

deflection, shear, and overturning moments with wind speed.

- Key Observations and Interpretations:**
- Overturning Moment:** The overturning moment is not critical for this structure. The building's self-weight provides significant resistance, as shown by the minimum factor of safety of 7.68 at a wind speed of 100 mph — approximately five times greater than the required minimum of 1.5.
- Lateral Deflection/Drift:** Wind-induced deflection does not represent a critical failure mode. The ACI Code does not define strict deflection limits for wind loads,[1] unlike seismic loads. The commonly referenced $H/500$ limit is based on practical experience and offers sufficient safety. For example, at 80 mph, the deflection values remained approximately 25% below the critical limit, indicating acceptable performance.

- Suitability of Rigid Frame System: The rigid frame system becomes unsuitable for areas with wind speeds exceeding 80 mph, as it leads to deflection values that exceed allowable limits and may affect serviceability.
- Shear Force Behavior: Wind-induced shear forces are mainly resisted by the columns. Given the building's location in a non-seismic zone (not Zones D, E, or F), no special reinforcement detailing is required in this context.
- Wind Directional Effect: The Y-direction experiences greater wind effects than the X-direction due to the larger surface area exposed to wind loads, making this direction more critical in the structural response.
- Height Dependency: Wind-induced forces increase significantly with building height, stressing the importance of vertical geometry and mass distribution in the structural design process.
- Occupant Comfort and Sway: The swaying of tall buildings may cause occupant discomfort. Potential signs include vibrating objects, falling books, leaning pictures, and unusual noises. This makes serviceability and human comfort a vital consideration in design.
- Comfort and Serviceability: Accelerations due to sway may affect occupant comfort. Although not directly analyzed, these criteria should be included in future studies for a holistic approach.
- Recommendations for Reinforcements: Enhanced lateral stiffness through shear walls or braced frames could mitigate excessive deflection observed at higher wind speeds.

TABLE I: Relationship between Wind Load and Internal Forces

Wind Speed	40 mph	60 mph	80 mph	100 mph
Deflection (mm)	19.98	44.95	79.91	124.86
Shear(KN)	502.67	1131	2010.66	3141.66
Overturning Moment (X-Direction) (KN.m)	5681.21	12782.72	22724.85	35507.58
Overturning Moment (Y-Direction) (KN.m)	16420.89	36947.01	65683.57	102630.59

E. Comparative Analysis of Previous Studies and Current Findings

- Several previous studies have investigated the wind-induced response of tall buildings. For instance, the SEG Plaza incident in China (2021) highlighted the impact of resonance under steady wind conditions, leading to significant lateral vibrations. Wind tunnel studies, such as those by Davenport (1961), emphasize the importance of aerodynamic design and rounded building shapes to mitigate vortex shedding. Compared to these studies, our findings confirm that rigid frame systems exhibit increasing lateral forces with height and wind intensity, but the performance remains within acceptable safety

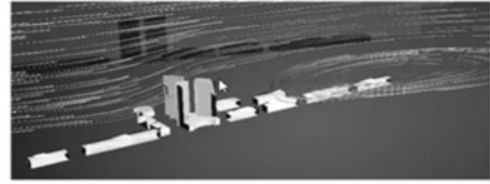


Figure 1a. Distribution of wind flows to existing buildings during the construction of multi-storey and high-rise buildings at a height of 77.5 m

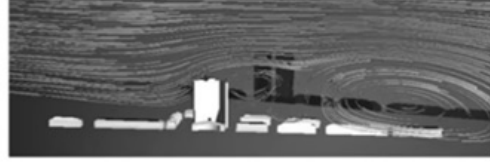


Fig. 11: impact of surrounding buildings on wind induced response

margins up to wind speeds of 80 mph. Beyond that, serviceability concerns—particularly deflection—become critical. Unlike buildings with aerodynamic modifications or hybrid systems, our model lacked damping enhancements, which partly explains the larger deflection values at upper stories

- According to the SEG Plaza report[3], lateral displacements reached 180 mm at the top floor, while our study recorded 124.86 mm under 100 mph wind load

F. the impact of surrounding buildings on wind induced response

- With increasing height there is an increase in pressure from the windward side and an increase in eddy flows from the leeward side of a high-rise building, which affect not only high-rise buildings, This effect is illustrated in Figure(11). but also low existing buildings.
- The proximity of other structures can exacerbate wind turbulence, leading to amplified forces. This study assumes isolated conditions but recommends further investigation of urban contexts

IV. CONCLUSIONS

The findings affirm that rigid frame systems can effectively resist wind loads in high-rise structures, provided that their design parameters are optimized for severe wind conditions. Furthermore, it is crucial to address deflection limits and ensure full compliance with structural codes such as ACI 318 and ASCE 7. Incorporating aerodynamic design elements and performing advanced dynamic analyses is recommended to improve overall structural performance and serviceability.

V. RECOMMENDATIONS

Dynamic Wind Nature: Wind loads are not static. They change rapidly, generating larger effects than if the loads were applied gradually. This dynamic nature must be accounted for in design. Key Design Considerations:

- Structural strength and stability under lateral loads.
- Fatigue in structural members due to cyclic wind loading.

- Excessive lateral deflection, which may affect cladding, partitions, and doors.
- Amplitude of sway, which can cause human discomfort; structural engineers must design within acceptable human tolerance levels.
- Environmental impact, particularly the influence of surrounding buildings.
- Annoying vibrations and acoustic disturbances, especially in upper floors.
- Consideration of a cross-wind motion and torsional responses in tall buildings.
- Vortex Shedding and Building Shape:
 - To prevent vortex shedding, it is recommended to design for wind speeds greater than 1.25 times the critical speed, calculated from the building's natural frequency.
 - Selecting a building shape with rounded corners is advisable, as it helps reduce vortex formation and minimizes dynamic wind effects.
- Rigid Frame Limitations: Based on this study, the rigid frame system is not recommended in areas subject to high wind speeds.
- Wind Tunnel Testing: It is strongly recommended to conduct wind tunnel tests for buildings taller than 50 stories, especially in urban areas where wind behavior is influenced by the surrounding environment.
- Optimize beam and column dimensions for high wind speeds.
- Incorporate wind tunnel testing for critical projects.
- Consider environmental impacts on neighboring structures.
- Investigate advanced materials and damping systems to improve resilience.



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