

Dynamic Analysis of Reinforced Tall Structural Systems Connected in Series

Mahesh Kumar C L¹, Chandana C S², Basavana Gowda S N^{3,*}

Abstract

In recent years, there has been a notable surge in the development of multi-tower connected structures. This architectural phenomenon encompasses the creation of interconnected high-rise buildings that feature shared elements like podiums, sky bridges, or other forms of physical connection. These structures are designed to create a cohesive and functional complex that offers a range of amenities and promotes a sense of community. Dynamic analysis of horizontally connected reinforced concrete tall structures is an essential aspect of structural engineering to ensure their safety and stability under various loading conditions, including seismic events and wind forces. For this analysis Modelling of horizontally connected reinforced concrete tall structures as per IS 16700: 2017 provisions in ETABS software by varying the position and number of the horizontally connecting structure. The analysis involves assessing the dynamic response of the interconnected structures to vibrations and oscillations caused by external forces. And also, this analysis explores the influence of interconnection between individual structures on the overall response, considering factors like damping, stiffness, and mass distribution. For all of the models, similar variations in storey displacement, storey drift ratio and storey stiffness are observed in both the X and Y directions for both equivalent static method (ESA) and response spectrum analysis (RSA).

Keywords: Tall structure, horizontal connection, ETABS software, Response spectrum analysis, Equivalent static method.

INTRODUCTION

The evolution of multi-tower connected structures has indeed gained significant momentum in recent years. This architectural trend involves the construction of interconnected high-rise buildings that share common elements, such as podiums, sky bridges, or other means of physical connection. These structures are designed to create a cohesive and functional complex that offers a range of amenities and

promotes a sense of community. A structure that is at least 50 meters tall but not more than or equal to 250 meters. Tall structure is also referred to as skyscrapers, high rise buildings, and superstructures (towers). The proposed revolutionary structural solutions necessitate the use of high-strength materials, therefore modern tall and super-tall structures are often lighter, more flexible, and less heavily damped than those built in the past. Modern building methods are also available, and the tendency of ever-taller structures has been assisted and accelerated by the availability of recent construction materials with lighter cladding. In addition, modern structures now have more stories, especially in densely crowded places with limited space. As a result, when subjected to

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Received Date: January 15, 2024

Accepted Date: March 08, 2024

Published Date: May 18, 2024

Citation: Mahesh Kumar C L, Chandana C S, Basavana Gowda S N. Dynamic Analysis of Reinforced Tall Structural Systems Connected in Series. Journal of Polymer & Composites. 2024; 12(Special Issue 2): S224–S234p.

heavy wind and severe earthquake loads, modern buildings are more susceptible to dynamic excitation than older ones [1]. The proliferation of tall buildings is a response to escalating land costs and heightened population density in urban areas. The design of tall structures necessitates careful consideration of specific standards, particularly concerning lateral loads such as earthquakes and wind. The substantial forces imposed by lateral loads can render tall buildings unstable, posing safety risks if factors like wind, seismic activity, and fire safety are not adequately addressed in the design process. A skyway serves as an elevated pedestrian pathway connecting multiple buildings in urban settings or linking elevated spots within recreational alpine areas. Some footbridges are covered, providing protection from the elements, and modern open-top skyways in mountainous regions may incorporate glass bottoms. Enclosed skywalks are entirely constructed with glass, including ceilings, walls, and flooring. Additionally, certain skyways function as pedestrian-only linear parks, often connecting the initial levels above ground floors, although in some instances, like the Petronas Tower, they can extend to significantly higher levels. Studies made by Wang Z reveals that steel trusses, particularly with flexible connections, prove to be the most efficient composition in terms of both structure and material, demonstrating superior load-bearing capabilities and resilience against seismic effects [2]. The emergence of connected multi-tower structures has experienced notable acceleration in recent times. This architectural trend entails the development of high-rise buildings interconnected through shared elements like podiums, sky bridges, or other physical connections. The intention is to create a unified and practical complex, providing a variety of amenities and fostering a community-oriented environment. Baviskar and kalurkar focuses on the crucial application of structural dynamics in analysing the response of G+40 storey buildings to seismic effects. Tall structures, with their low natural frequency, are particularly vulnerable to dynamic loads such as earthquakes and winds, leading to significant lateral vibrations. The analysis involves G+40 storey buildings connected horizontally with a truss bridge at the 21st and 31st storeys, utilizing fluid viscous dampers (FVD) to compare the storey response curves with and without dampers in an ordinary moment resisting frame (OMRF) structure, employing ETABS V16 software [3]. Alomari J investigates the impact of connecting two regular reinforced concrete buildings with reinforced concrete sky bridges, revealing that such connections transform originally regular buildings into highly irregular structures. The study finds that traditional design procedures based on earthquake codes for regular buildings are no longer applicable to the connected structures, necessitating special treatment during earthquake excitation. The analysis, conducted with SAP2000 software, explores three models with different sky bridge connections, highlighting significant changes in structural behavior, including member forces, periods of vibration, storey drifts, and mode shapes. The findings provide recommendations for safely adding connections between buildings not originally designed for such linkages [4].

The evolution of structural systems for tall buildings has transitioned from the rigid frame to the tubular structure in the 1960s, enabling greater height with minimal material consumption. While the core-outrigger system gained popularity due to its design flexibility, conventional tubular structures persisted to a lesser extent but experienced a resurgence in modified forms. This study provides a comprehensive overview of various structural systems, aiding structural engineers and architects in collaboratively selecting suitable approaches for tall buildings in contemporary contexts [5].

This research involves a comprehensive investigation into the dynamic behavior of reinforced tall structural systems interconnected in series, focusing on how the interaction between multiple tall structures influences their collective response to dynamic loads, including seismic or wind forces. The study considers various configurations, arrangements, and factors like material properties, foundation types, and geometrical variations to provide a holistic understanding of the dynamic response in series-connected tall structures. The significance of this research lies in its potential to contribute valuable insights to structural engineering, enhancing the design, safety, and resilience of high-rise buildings. By unraveling the complexities of series-connected tall structures, the study aims to inform construction practices, design guidelines, and risk mitigation strategies, ultimately advancing knowledge and promoting the development of more robust tall structural systems.

METHODOLOGY

In this study, various analysis methods and parameters are used to obtain desired results. The following are the sequence of steps carried out in this study:

- Three towers in a series of RC tall building can be modelled using the ETABS software by changing the location and quantity of the horizontally connecting structure.
- Modal analysis and earthquake analysis for linear dynamic analysis of structures.
- For zone II Equivalent static load method and Linear Response Spectrum method is adopted.
- Results are evaluated for displacement, drift, stiffness, time period, frequency, base shear and acceleration.

Modelling

Modal analysis is used to examine the impacts that changing the position of the horizontal connection has on the dynamic performance of a tall building with three connected towers. An approximate technique for analyzing the dynamic characteristics of a structure system is modal analysis. Table.1 shows the location of connection in various models

Table.1. The location of connection in various models

Number	Model 1	Model 2	Model 3	Model 4	Model 5
Floor	-	10 th	10 th ,20 th	10 th ,20 th ,30 th	10 th ,20 th ,30 th ,40 th

Structural framing system

A commercial building employs a moment frame system featuring structural walls composed of columns, beams, and shear walls. The building comprises four towers, each 147.5 meters tall, with one car parking storey and 41 additional storeys. The parking storey has a floor-to-floor height of 4 meters, while the other storeys have a height of 3.5 meters. Each tower has a plan area of 30 × 30 meters, and the four towers are horizontally connected by a sky bridge with a clear span of 15 meters. Table 2 outlines the parameters considered for the structures.

Table 2. Parameters considered for the Structures

Tower	
Number of Storey	42
Floor to floor height of parking storey	4 m
Floor to floor height of typical storey	3.5 m
Total Height of four towers	147.5 m < 250 m (IS 16700: 2017 Table 1 Clause 5.1.1)
Floor area of one tower	30 m X 30 m
Slenderness ratio, (H/B)	4.92 < 9(IS 16700: 2017 Table 2 Clause 5.1.2)
Plan aspect ratio, (L/B)	1
CONNECTING STRUCTURE	
Clear Span	15 m (Abbood et al., 2018)
Reinforced Concrete Bridge	
MATERIAL PROPERTIES	
Grade of Concrete	M30 and M40
Column and Shear walls	M40
Slab and beams	M30
Grade of Reinforcement	Fe 550
LOADING DATA	
Dead load	Self-weight of structural members
Super Dead Load: IS 875 (Part 1): 1987	

Glazing of Glass load	1 kN/m
Partition load	1 kN/m ²
Floor finish load	1 kN/m ²
Live Load: IS 875 (Part 2): 1987	
Parking Storey	5 kN/m ²
Other Storey	4 kN/m ²
Seismic Load: IS 1893 (Part 1): 2016	
Seismic zone factor	Zone II – 0.1
Soil type	Medium or Stiff soil - II
Response reduction factor	SMRFs - 5
Importance factor	1.5
Natural period	2.487 s
Horizontal earthquake load	
Vertical earthquake load	

Figures 1 to 6 shows 3D Model of different positioning of horizontally connected structure.

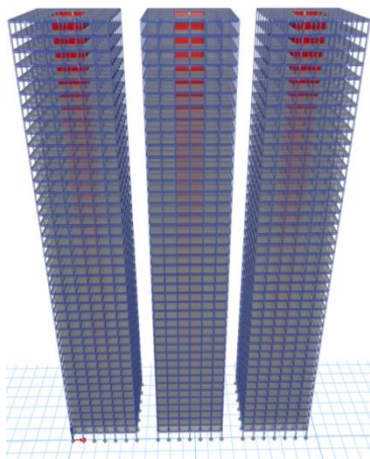


Figure 1. Without horizontal connection

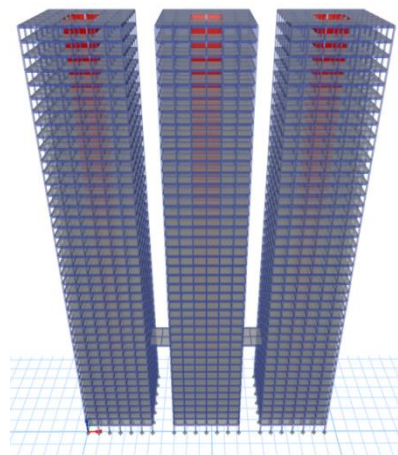


Figure 2. Building with connectivity at 10th level

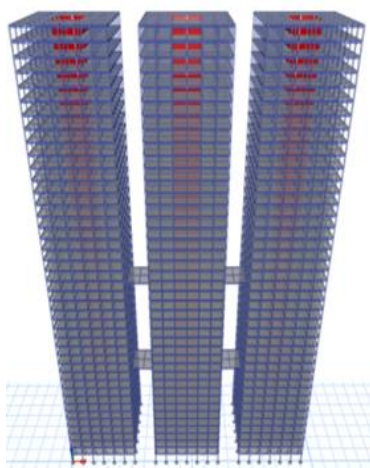


Figure 3. Sky corridors at 10th and 20th level

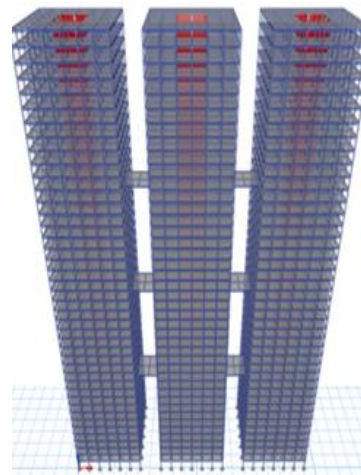


Figure 4. Sky bridges at 10th, 20th and 30th level

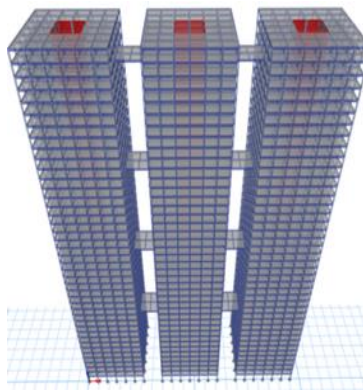


Figure 5. Sky Bridges at 10th, 20th, 30th and 40th level

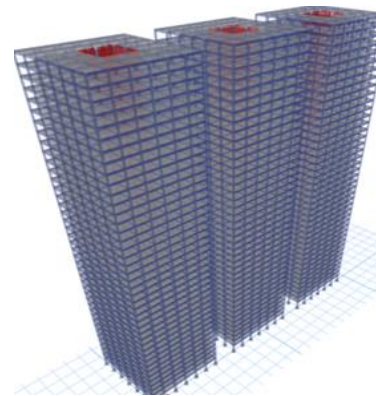


Figure 6. 3D Model of the Building

RESULTS AND DISCUSSIONS

The analysis involves the utilization of ETABS 2019 software to subject the models to both Equivalent Static Analysis and the Response Spectrum Method, adhering to the guidelines outlined in IS 1893–Part 1 (2016). Through this seismic analysis, various seismic parameters, including storey displacement, storey drift, and storey stiffness, are extracted for all the developed models. The study focuses on seismic zone II, aiming to comprehensively evaluate the structural response and behavior of the models under seismic loading conditions [6][7].

Time Period and Frequency

Figures 7 and 8 represents combined time period and frequency of all the five models.

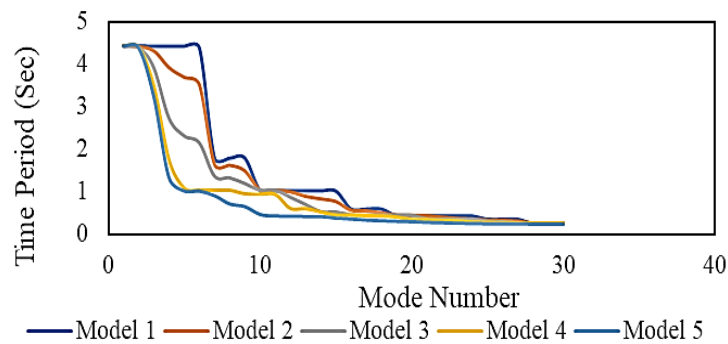


Figure 7. Time period of the models

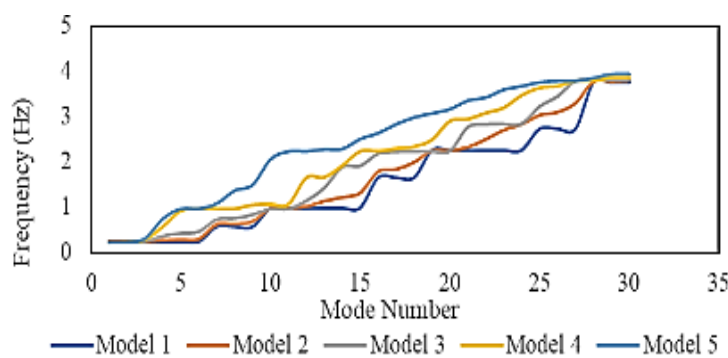


Figure 8. Frequency of the models

The time period of a building represents the duration required for it to complete one full cycle of oscillation. This crucial parameter is determined by the interplay of two fundamental properties: mass

and stiffness. The mass of the structure influences how much inertia it possesses, while stiffness governs the building's resistance to deformation. Together, these properties intricately shape the time period, offering insights into the dynamic behavior and response of the structure to external forces such as seismic or vibrational loads.

Equivalent Static Method

Figures 9 to 14 illustrate alterations in storey displacement, storey drift, and storey stiffness for all five models, as acquired through the equivalent static method. The presented data encompasses changes observed in both the X and Y directions. These visual representations offer a comprehensive overview of the dynamic responses of the models, providing valuable insights into the structural behavior in relation to lateral forces.

Displacements

Story displacement is a measure of the relative horizontal movement or drift occurring between consecutive floors within a building. This phenomenon is commonly triggered by lateral forces, such as those induced by earthquakes or wind. The extent of story displacement provides a clear indication of the building's deformation under the influence of these external forces, offering valuable insights into its structural response and integrity during dynamic events.

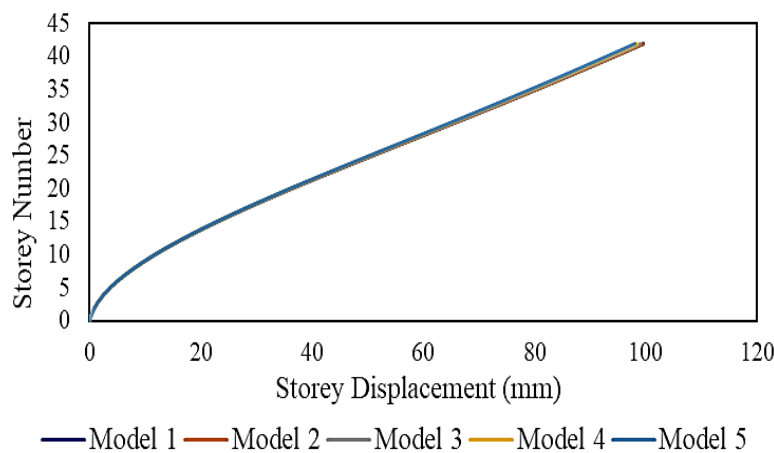


Figure 9. Storey displacement in X-direction

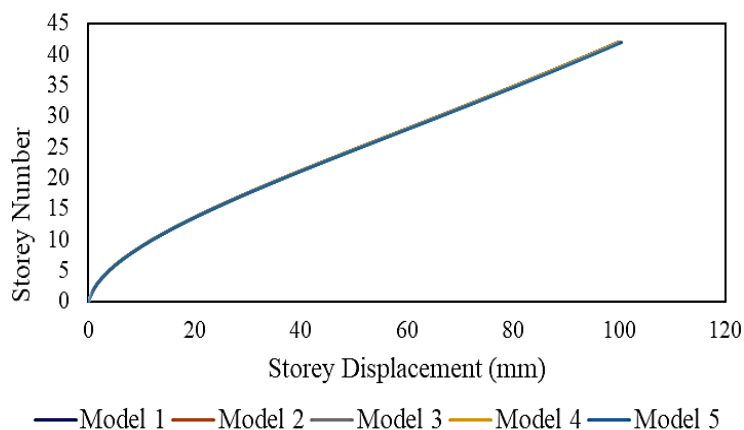


Figure 10. Storey displacement in Y-direction

Figures 9 and 10 depict a consistent pattern of storey displacement across all models, with notable differences observed between the Y and X directions. It is evident that the storey displacement is more prominent in the Y-direction compared to the X-direction. This discrepancy suggests that the structure exhibits greater stiffness, resulting in less deformation in the X-direction. The findings provide valuable

insights into the structural behavior, emphasizing the significance of directional stiffness in influencing the overall deformation response of the building.

Story Drift

Story drift, alternatively termed inter-story drift, characterizes the relative displacement occurring between successive floors of a building when subjected to lateral forces like earthquakes or wind. This parameter quantifies the vertical displacement or deformation of one floor in relation to its adjacent floor, providing a crucial measure of the building's flexibility and response to lateral loading. Understanding story drift is essential in assessing the structural integrity and performance of a building under dynamic conditions, offering valuable insights into its behavior during seismic or wind-induced events.

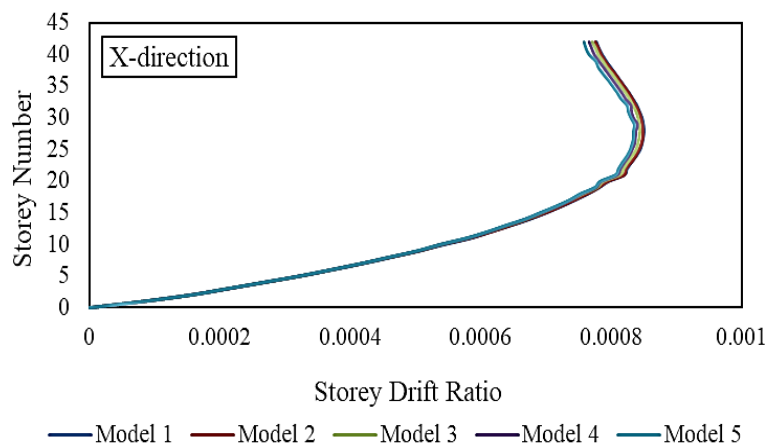


Figure 11. Storey drift in X-direction

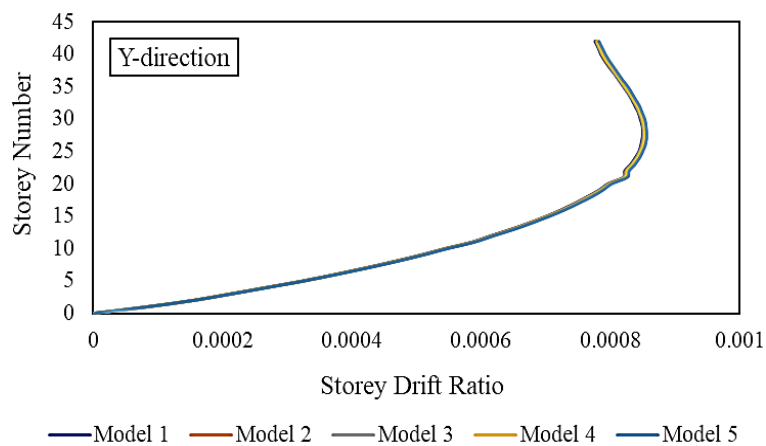


Figure 12. Storey drift in Y-direction

Figures 11 and 12 reveal a consistent pattern of storey drift variation across all models, with a notable distinction observed between the Y and X directions. The storey drift in the Y-direction is observed to be greater than that in the X-direction. It is noteworthy that, in accordance with IS code 1893–2016, the storey drift for any storey should not exceed 0.004 times the storey height. The analysis demonstrates that the storey drift values for all five models fall within the prescribed limits, ensuring compliance with the seismic design code [4].

Story Stiffness

Storey stiffness refers to a building's resistance to lateral deformation or sway between floors, crucial for stability and load distribution during seismic or wind events.

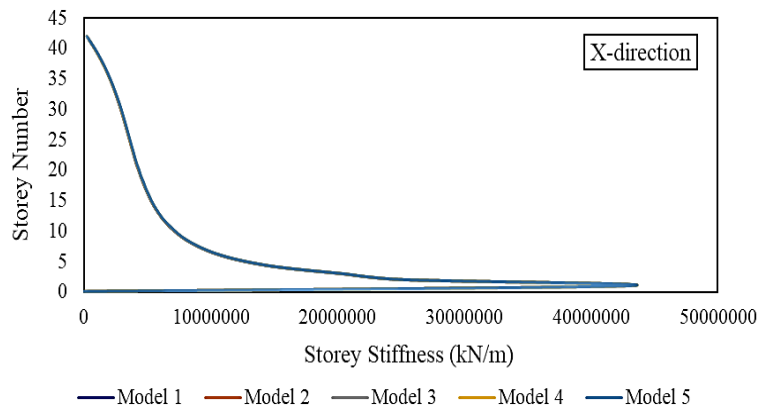


Figure 13. Storey stiffness in X-direction

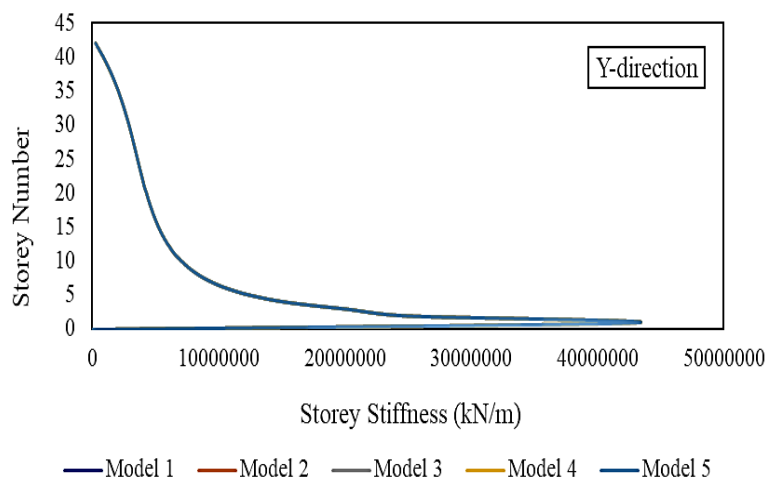


Figure 14. Storey stiffness in Y-direction

Figures 13 and 14 exhibit consistent patterns of variations in storey stiffness across all models. Notably, there are similar types of variances observed in the storey stiffness values. It is noteworthy that the storey stiffness in the X-direction is identified to be greater than that in the Y-direction. This distinction in directional stiffness provides valuable insights into the structural behavior of the models, indicating a greater resistance to deformation in the lateral X-direction compared to the Y-direction

Response Spectrum Method

Figures 15 to 20 represents the change in storey displacement, storey drift and storey stiffness of all the five models in both X and Y directions obtained by response spectrum method.

Displacements

Story displacement refers to the relative horizontal movement or drift between consecutive floors of a building, often caused by lateral loads such as earthquakes or wind, indicating the building's deformation under these forces.

Figures 15 and 16 reveal a consistent pattern of storey displacement variation across all models, with a notable distinction in the Y-direction having greater displacement than the X-direction (except for Model 2). This observation indicates that, in general, the structure exhibits greater stiffness and consequently experiences less deformation in the X-direction. However, it's important to note that in Model 2, the structure displays greater stiffness in the Y-direction, deviating from the overall trend observed in the other models. This insight into directional stiffness is essential for understanding the structural response and deformation characteristics of each model under lateral loads [8].

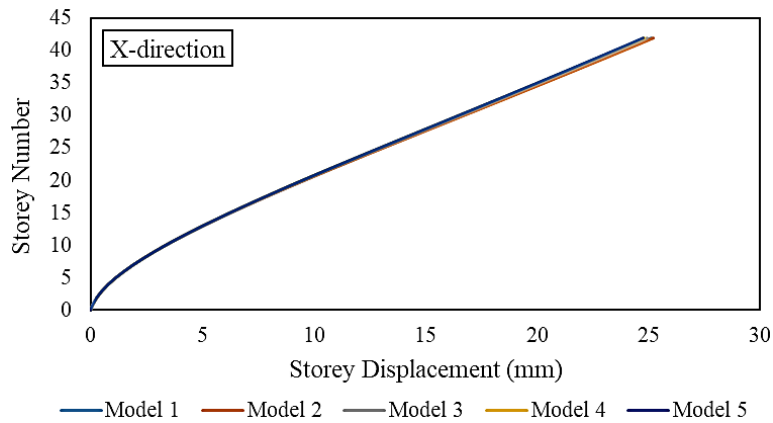


Figure 15. Storey displacement in X-direction

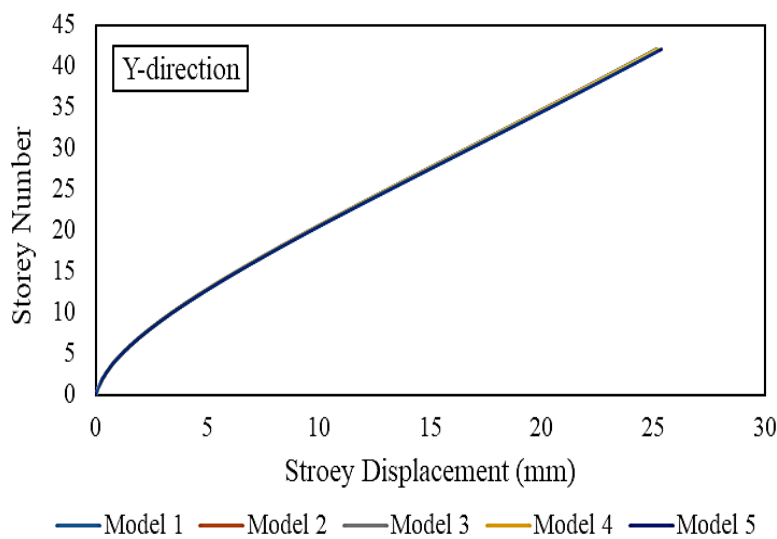


Figure 16. Storey displacement in Y-direction

Story Drift

Story drift, also known as inter-story drift, refers to the relative displacement between adjacent floors of a building during lateral loads such as earthquakes or wind.

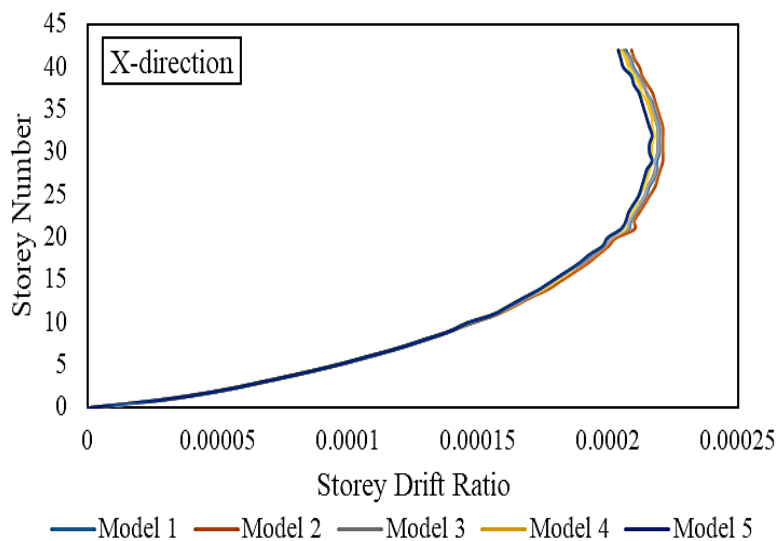


Figure 17. Storey drift in X-direction

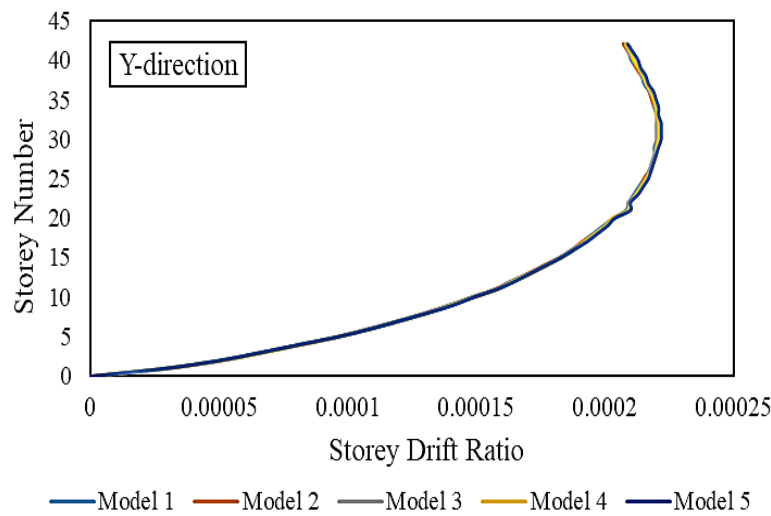


Figure 18. Storey drift in Y-direction

From Figures 17 and 18, we observed variation in storey drift across all models is of a similar kind. But it is noticed that storey drift in Y-direction is greater than X-direction 55 in model 3,4,5. Where as in model 2 storey drift in X-direction is found be more. However, for model 1 it is found to be same in both the X and Y direction. But as per IS code 1893 – 2016, Storey drift for any storey shall not be higher than 0.004 times the storey height. From the analysis storey drift of all the 5 model are within the limits [8].

Story Stiffness

Storey stiffness is a key attribute denoting a building's capacity to resist lateral deformation or sway between floors, playing a pivotal role in ensuring stability and effective load distribution during seismic or wind events. Figures 19 and 20 illustrate consistent patterns of variations in storey stiffness across all models. Despite similar variances, the analysis highlights that the storey stiffness in the X-direction surpasses that in the Y-direction. This directional difference in stiffness underscores the building's ability to withstand lateral forces more robustly in the X-direction, providing crucial insights into its structural behavior under dynamic loads.

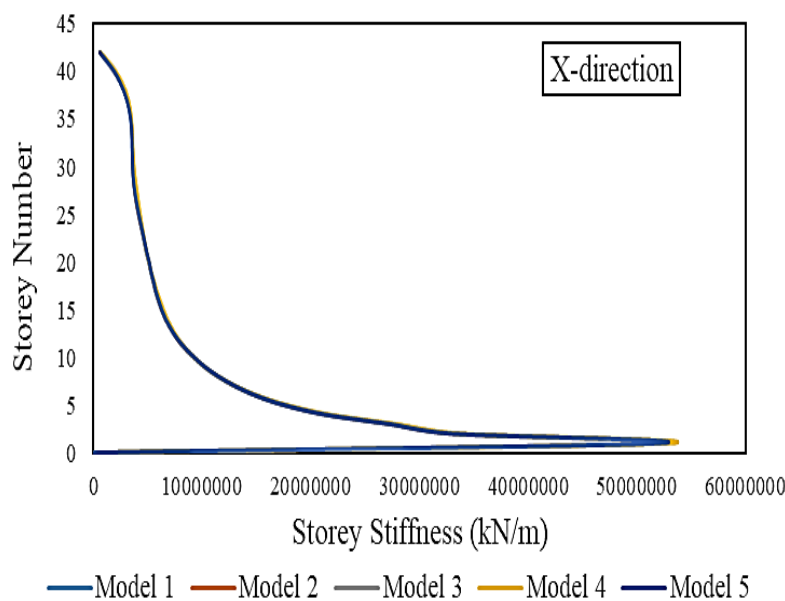


Figure 19. Storey stiffness in X-direction

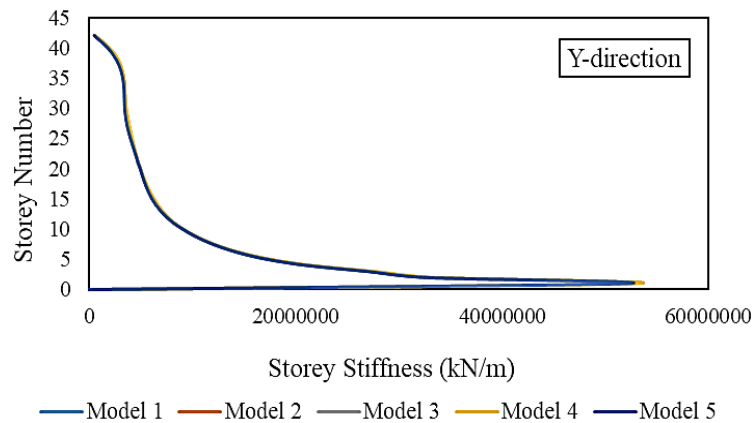


Figure 20. Storey stiffness in Y-direction

CONCLUSIONS

Using ETABS software, the present study analyzes the dynamic analysis performance of tall horizontally connected structures. In seismic zone II, seismic parameters such as storey displacement, drift ratio, storey stiffness and modal analysis and response spectrum method are gathered in both X and Y directions according to IS 1893- Part 1 (2016). For all of the models, similar variations in storey displacement, storey drift ratio and storey stiffness are observed in both the X and Y directions for both equivalent static method (ESA) and response spectrum analysis (RSA).

1. The observed variation in storey displacement is consistent among all models. Nevertheless, in both the cases of ESA and RSA, it is observed that the storey displacement in the Y-direction exceeds that in the X-direction.
2. When the displacement values compared in both the methods it was determined that response spectrum analysis resulted in lower value.
3. The noted variation in storey drift is consistent across all models. However, an observation reveals that in both ESA and RSA, the storey drift in the Y-direction surpasses that in the X-direction.
4. Similar types of variances in storey stiffness are seen across all models. The storey stiffness in the Y-direction, however, is found to be larger than that in the X-direction for both ESA and RSA methods.
5. The storey stiffness values in equivalent static method are negligible in comparison to response spectrum analysis method.
6. Time period and frequency almost retains same for all the five models.

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