Seismic Performance Analysis of High-Rise Buildings Using ETABS

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Abstract- *Seismic load analysis of high-rise buildings is a critical field of study to assure structural safety and resilience during earthquakes. This research focusses on evaluating the effectiveness of diagrid lateral load-resisting systems in high-rise soft resist concrete buildings using ETABS software. The study looks at seismic behaviour in various seismic zones, analysing important characteristics such storey drift, displacement, natural time period, and storey shear. Various diagrid configurations are modelled and compared to traditional lateral load-resisting systems to determine the most effective design. The results demonstrate the superior performance of diagrid systems in managing seismic responses, highlighting its potential as a novel solution for earthquake-resistant high-rise structures. This research helps to generate safer and more efficient building designs, as well as valuable insights for structural engineers and designers.*

Keywords- Diagrid systems, Earthquake-resistant buildings, ETABS software, High-rise buildings, Lateral load-resisting systems, Seismic analysis, Seismic performance, Storey drift, Structural resilience.

I. INTRODUCTION

Seismic performance analysis is an essential component in evaluating the structural integrity and resilience of buildings, particularly those in regions prone to seismic activity. High-rise buildings, due to their height and complex structural requirements, are significantly impacted by lateral forces during earthquakes. These forces can be devastating if not adequately addressed in the design phase. This study focuses on a comprehensive seismic analysis of a high-rise steel building, evaluating its response to seismic forces using various types of bracing systems. Bracing systems are vital elements in the structural design of steel buildings, designed to resist lateral forces generated by earthquakes and other seismic events. Their role in enhancing the seismic performance of a building cannot be overstated, as they help mitigate the effects of dynamic loading by providing stiffness and strength. The seismic response of high-rise steel buildings varies significantly depending on the choice of bracing configuration. Steel is widely recognized for its high strength and ductility, making it an ideal material for constructing buildings that must withstand the dynamic forces of an earthquake. Different types of bracing systems, including diagonal, concentric, eccentric, and buckling-restrained braces, are strategically placed within buildings to resist lateral forces. Each type of bracing system has its own set of benefits and challenges, which are important to consider during the design process. The effectiveness of these systems in dissipating energy and providing stability during seismic events is a key area of research in structural engineering. The primary goal of seismic analysis in high-rise buildings is to understand how these structures will behave when subjected to seismic forces. Traditional methods of analysis, such as the linear static method, are often used for buildings up to 15 meters in height. However, for taller, more complex structures like high-rise buildings, more advanced techniques, such as linear dynamic analysis using the response spectrum method, are employed. These methods provide a more accurate representation of the building's behavior during an earthquake. When seismic activity occurs, the building undergoes dynamic motion, where the inertia forces of the structure counteract the acceleration caused by the earthquake. These forces, often referred to as seismic loads, are external forces that need to be accounted for in the building's design. High-rise buildings experience significant lateral forces during seismic events due to their height and the mass distribution within the structure. These lateral forces can cause the building to sway, and without adequate design, they can lead to severe structural damage. Therefore, it is crucial to accurately calculate and define these lateral forces to ensure the building is designed to withstand seismic events. The most important factor influencing seismic performance is the structure's ductility. Ductility allows a structure to undergo significant deformation without failing, which is critical during an earthquake. Well-designed structures with sufficient ductility tend to perform better during seismic events, as they can absorb and dissipate the energy generated by the shaking. The evolution of high-rise building design has seen significant advancements in recent years, particularly with the advent of more powerful computing capabilities and advanced software. Today, engineers can create comprehensive three-dimensional finite element models of buildings, allowing for more accurate simulations of seismic behavior. However, these models generate large amounts of data, and it is easy for small discrepancies or flaws in the model to be overlooked. It is important for engineers to be diligent and well-versed in structural behavior and finite element modeling to ensure the accuracy of the analysis. Additionally, the choice of modeling approach can significantly impact the distribution of forces and stresses within the building, potentially leading to discrepancies in the results obtained by different engineers. In conclusion, seismic performance analysis is crucial for ensuring the safety and stability of high-rise buildings during seismic events. The selection of the appropriate bracing system and the use of advanced seismic analysis techniques are essential in optimizing the structural design. With the development of more sophisticated modeling techniques and increased computational power, engineers are better equipped to design buildings that can withstand the forces of nature. However, careful consideration of the results and a thorough understanding of structural behavior remain essential for ensuring the reliability of seismic performance analysis.

II. LITERATURE REVIEW

Seismic performance evaluation is a critical component in the design and safety analysis of high-rise buildings, especially in regions prone to seismic activity. Over the years, numerous studies have been conducted to evaluate the seismic resilience of high-rise structures, particularly in response to irregularities in shape and design. The structural integrity of tall buildings under seismic forces not only influences the safety of occupants but also determines the economic and functional feasibility of the building post-earthquake. The complexities involved in designing and analyzing these structures necessitate advanced methods and tools that go beyond traditional seismic codes to ensure safety under dynamic loads.A significant body of research in this domain explores the impact of structural irregularities, such as plan and vertical irregularities, on the seismic performance of high-rise buildings. For instance, Chaudhary and Mahajan (2021) conducted a study analyzing the response of H, O, and C-shaped buildings using response spectrum analysis. Their research highlighted that H-shaped buildings exhibited the least lateral sway under seismic loads, suggesting that the geometry of the building plays a crucial role in its seismic performance. Furthermore, the study found that 12-storey buildings performed better compared to 16-storey buildings in terms of lateral displacement, emphasizing the importance of building height and its relationship with seismic behavior.

Similarly, studies like that of Apostolska et al. (2016) have identified the limitations of standard seismic codes for high-rise buildings, particularly in regions where building designs exhibit unique structural behaviors. Their case study on a 44-storey reinforced concrete building in Skopje revealed that traditional seismic design codes were insufficient for buildings of such scale and complexity. The study called for updated seismic guidelines to address the specific needs of high-rise structures. These findings are echoed in the works of other researchers such as Jia et al. (2018), who conducted a performance-based seismic analysis of high-rise buildings with irregular structural systems. Their study utilized advanced simulation techniques to predict the performance of buildings under varying seismic loads, showing that irregular buildings tend to have more pronounced seismic vulnerabilities.Moreover, the integration of modern tools and techniques, such as Artificial Neural Networks (ANN) and Performance-Based Seismic Design (PBSD), has significantly advanced the field of seismic performance evaluation. Ramaswami Mallarapu and Tarangini (2022) explored the use of ANN for seismic analysis, demonstrating its potential in improving predictive accuracy for structural displacements in high-rise buildings. This approach offers a more dynamic and adaptable method for assessing seismic risk, as it can account for the non-linear behaviors often observed in tall structures during an earthquake. ANN models can be trained on seismic data to predict how buildings will respond to different levels of seismic forces, providing more reliable safety assessments.

Another promising development in seismic performance evaluation is the use of hybrid structural systems, such as hybrid coupled walls (HCW), as discussed by Xiaodong Jia et al. (2018). Their research compared traditional reinforced concrete shear walls with HCWs, which incorporate replaceable steel coupling beams. The hybrid systems were found to offer enhanced energy dissipation and repairability post-earthquake, making them a cost-effective and efficient solution for high-rise buildings. Such innovations contribute significantly to improving the resilience of high-rise buildings to seismic forces, reducing both the immediate and long-term impacts of earthquakes.The seismic performance of modular steel constructions in mid-to-high rise buildings has also been an area of increasing interest, with studies like those of Deng et al. (2020) highlighting the potential for faster construction times and reduced environmental impact. While modular construction offers many advantages, the seismic behavior of these structures is still not fully understood, necessitating further research into lateral force-resisting systems and connection techniques. The performance of modular buildings under seismic loads remains a key challenge, as traditional seismic design methods may not always be suitable for the unique characteristics of modular steel systems.Additionally, researchers have emphasized the importance of considering both structural and non-structural elements in seismic analysis. Performance-Based Seismic Design methods, as proposed by Yuhong Ling et al. (2019), incorporate these elements to ensure that a building's response to seismic events is evaluated holistically. By using software like YJK and ETABS, these methods aim to meet performance objectives for both frequent and rare earthquakes, identifying potential vulnerabilities in complex building designs. This approach ensures that high-rise buildings are not only structurally sound but also safe in terms of functionality and usability after an earthquake, making it a crucial aspect of modern seismic design.

The integration of advanced computational tools and methodologies, such as ETABS and RSA software, has become standard practice in the seismic evaluation of high-rise buildings. Studies like that of Pechorskaya et al. (2021) have compared different seismic analysis software, revealing important insights into the selection of appropriate tools for analyzing complex high-rise structures. Their study found that software such as RSA tends to produce higher force and moment values compared to ETABS, which can influence the design and safety considerations for high-rise buildings. This highlights the importance of selecting the right software to ensure accurate seismic performance analysis and structural design. In recent years, seismic performance evaluation has also incorporated the concept of building resilience, which goes beyond structural integrity to include the time and financial losses that can result from a seismic event. Research by Dedeoğlu et al. (2020) introduced a new generation of risk assessment tools, such as the FEMA P-58 method, which evaluates not only the structural elements of a building but also the non-structural components, recovery time, and related financial loss. This holistic approach to seismic performance evaluation is essential for providing a comprehensive understanding of the impact of earthquakes on high-rise buildings and their occupants.Finally, recent advancements in damage detection and evaluation methods have further enhanced the ability to assess the seismic performance of high-rise buildings. Zhao (2023) introduced the concept of health detection and seismic performance evaluation using static elastic-plastic methods, which can offer more accurate results compared to traditional finite element analysis. This approach, which calculates the dissipated strain energy in structural columns, provides a better understanding of how buildings behave under seismic loads and helps in determining the structural damage index, offering a more precise evaluation of a building's seismic resilience.

III. RESEARCH METHOD

The seismic performance of high-rise buildings is a critical aspect of modern structural engineering, particularly in regions prone to earthquakes. This chapter outlines the methodology used in the study of seismic performance, with a particular focus on lateral load-resisting systems, including diagrid and traditional shear walls. The research process starts with an in-depth literature review to identify the existing knowledge and gaps in the design and analysis of high-rise buildings under seismic loads. This review forms the foundation for creating high-rise building models, which are then subjected to seismic analysis using ETABS software. These models are developed to include both diagrid and traditional lateral load-resisting systems, which are common in the construction of high-rise buildings. The goal of the study is to assess the behavior of these systems under various seismic conditions, considering parameters such as storey drift, displacement, natural time period, and storey shear.The seismic analysis is performed under different conditions, particularly varying seismic zones, to understand how these lateral load-resisting systems perform in response to seismic forces. The analysis is based on several critical factors, including the magnitude and distribution of seismic forces, the building's height and configuration, and the dynamic interaction between the structure and the seismic waves. The methodology follows a structured approach, beginning with the creation of building models, followed by the definition of load scenarios, simulations, and result analysis. This systematic process ensures that the research findings are reliable and provide meaningful insights into the seismic performance of high-rise buildings. Through this approach, the study aims to identify the most effective seismic design strategies for improving the resilience of high-rise buildings in earthquake-prone regions.

In the design of high-rise buildings, one of the most critical structural components is the shear wall. These walls serve as the primary element for resisting lateral forces induced by wind and seismic loads. Shear walls are typically designed to provide a rigid resistance to these forces, and their effectiveness depends significantly on their orientation and the direction of the forces. The shear wall's role is to resist both axial and lateral forces, which results in the wall undergoing complex stress distributions, including axial, shear, flexural, and torsional stresses. The distribution of these stresses is a key factor in the overall seismic performance of a building. The analysis of failure mechanisms in shear walls is essential for designing resilient structures. These mechanisms include axial compression failure, flexural failure, torsional distortion, and shear failure. Each of these failure modes must be carefully considered in the design process to ensure that the shear wall can withstand the loads imposed by an earthquake. Furthermore, the slenderness ratio of the shear walls is a crucial design parameter. The slenderness ratio, which is the ratio of the effective height to the effective thickness or radius of gyration, determines the potential for buckling failure. High slenderness ratios make shear walls more prone to out-of-plane buckling and lateral torsional buckling, which can compromise the wall's stability during seismic events. Engineers must account for these failure modes when designing shear walls to ensure that they can resist the combined effects of axial, shear, and bending stresses during an earthquake.

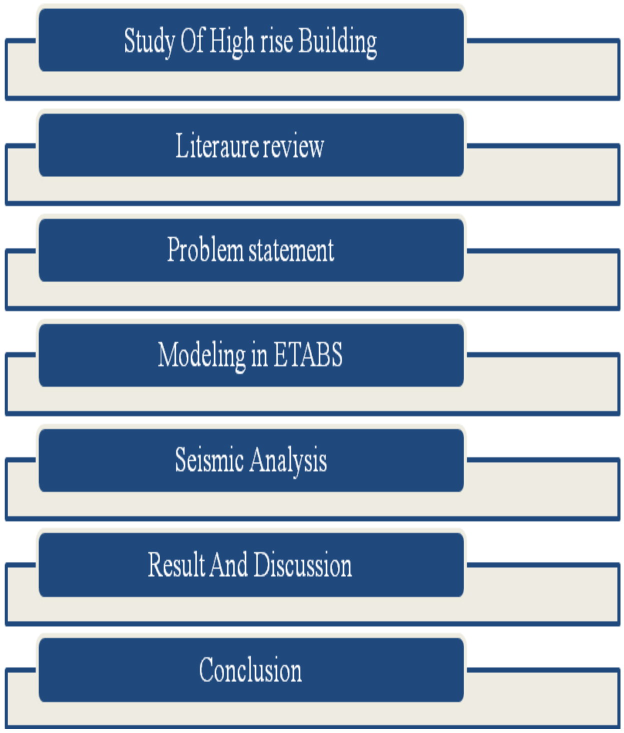


Fig 1 Flowchart

In addition to the failure mechanisms, the interaction between shear walls is another important consideration. In most real-world applications, shear walls are often not isolated but function as coupled systems. Coupling occurs when adjacent shear walls transmit forces to each other, resulting in enhanced overall stiffness. This coupling can reduce shear deformations and improve the building's stability under lateral loads. The effectiveness of the coupling depends on the stiffness of the connecting components. If the coupling is strong, the shear walls behave more like a single, unified component, resulting in a more stable structure. Conversely, weak coupling leads to independent behavior of the walls, which can increase the risk of shear deformations and instability. Seismic analysis is a critical step in the design process of any structure, especially high-rise buildings, as it ensures that the building can withstand the forces generated by an earthquake. There are two primary methods for seismic analysis: equivalent static force analysis and dynamic analysis. Each method has its advantages and applications, depending on the complexity of the structure and the nature of the seismic loads. The equivalent static force analysis is a simplified approach used primarily for low-rise buildings or buildings with relatively simple geometries. This method assumes that the building responds uniformly to seismic forces and estimates the seismic forces using a static load.

In contrast, dynamic analysis is more appropriate for high-rise buildings, as it accounts for the dynamic behavior of the structure during an earthquake. Dynamic analysis is crucial for structures with multiple degrees of freedom, such as high-rise buildings, where higher modes of vibration play a significant role in the overall seismic response. The dynamic analysis methods include response spectrum analysis, time history analysis, and pushover analysis, among others. Each of these methods provides valuable insights into the structure's performance under seismic loads. Response spectrum analysis is particularly useful for buildings with multiple modes of vibration, as it calculates the response of the building by considering the contribution of each vibration mode to the overall seismic response. Time history analysis provides a more detailed simulation of the building's response to a specific ground motion, while pushover analysis helps assess the nonlinear behavior of the building under increasing seismic forces. In seismic analysis, it is essential to understand how seismic forces are distributed across a building. The total seismic force, or base shear, is calculated based on the mass of the building and its distribution.

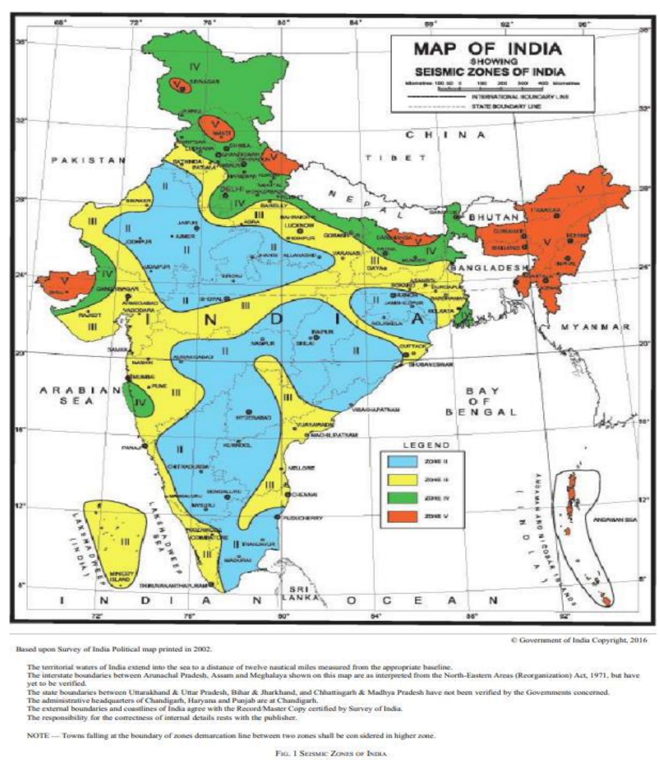


Fig 2 Representation of Seismic Zone of India

The base shear is then distributed to different floors based on the height and stiffness of the building. This distribution is crucial for determining the lateral forces acting on each floor and assessing the building's overall seismic performance. The calculation of the base shear and its distribution across the height of the building is typically done using seismic coefficients, which are defined by building codes such as IS 1893:2016. The seismic load combinations, as outlined in IS 1893:2016 and IS 456:2000, are also an essential aspect of the design process. These load combinations account for various scenarios, including dead load, live load, and earthquake load, to ensure that the building is designed to handle the worst-case conditions. The load combinations help ensure that the building can withstand both normal and extreme loading conditions, including seismic events. The load combinations incorporate different factors to account for variations in the severity of seismic forces and the response of the building to these forces. In conclusion, the seismic performance of high-rise buildings is influenced by a variety of factors, including structural design, shear wall configuration, coupling effects, and the type of seismic analysis method used. By carefully considering these factors and using advanced software tools such as ETABS, engineers can model and analyze the behavior of high-rise buildings under seismic loads. The results of these analyses provide valuable insights into how buildings respond to earthquakes and help identify the most effective design strategies for ensuring the safety and stability of high-rise structures in earthquake-prone regions. This methodology aims to improve the seismic resilience of high-rise buildings and contribute to the development of more earthquake-resistant buildings worldwide.

IV. PROBLEM STATEMENT AND MODELING

High-rise buildings are often subjected to significant lateral forces, especially from seismic events, which can compromise their stability. To mitigate these forces, a system of coupled shear walls is typically used, as they are effective in resisting lateral loads. However, in taller structures, such as G+20 buildings, shear walls alone may not provide sufficient resistance, and additional systems are necessary. One such system is the outrigger beams, which are placed between the shear walls and external columns. These beams enhance the building's ductility and rigidity, ensuring that the structure can absorb seismic energy while minimizing lateral displacement. In this study, a G+20 story RCC building equipped with an outrigger system is analyzed to understand its response to seismic forces. The key structural responses, including lateral displacement, storey drift, and base shear, will be computed. Additionally, the optimal location of outriggers within the high-rise building will be determined to ensure maximum seismic performance. The building under study features an X-type outrigger bracing system, designed with square tube sections. The dimensions of the beams and columns, set at 300x600 mm and 1000x1000 mm respectively, ensure that the structure can handle substantial loads. Material properties like the modulus of elasticity of steel (20,000 MPa) and concrete (27,386.12 MPa) are also crucial in providing the necessary stiffness. The study will examine the building's response to different loading conditions, including dead, live, and super dead loads, which together form the total load acting on the slabs. The modeling and analysis of the structure will be performed using ETABS software, which will allow for a detailed examination of four different models: a conventional model without additional lateral load-resisting elements, a model with belt trusses only, a model with outriggers only, and a combined model with both belt trusses and outriggers. The goal of this analysis is to determine which configuration provides the best seismic performance, minimizing lateral displacements while ensuring the building's stability during an earthquake.

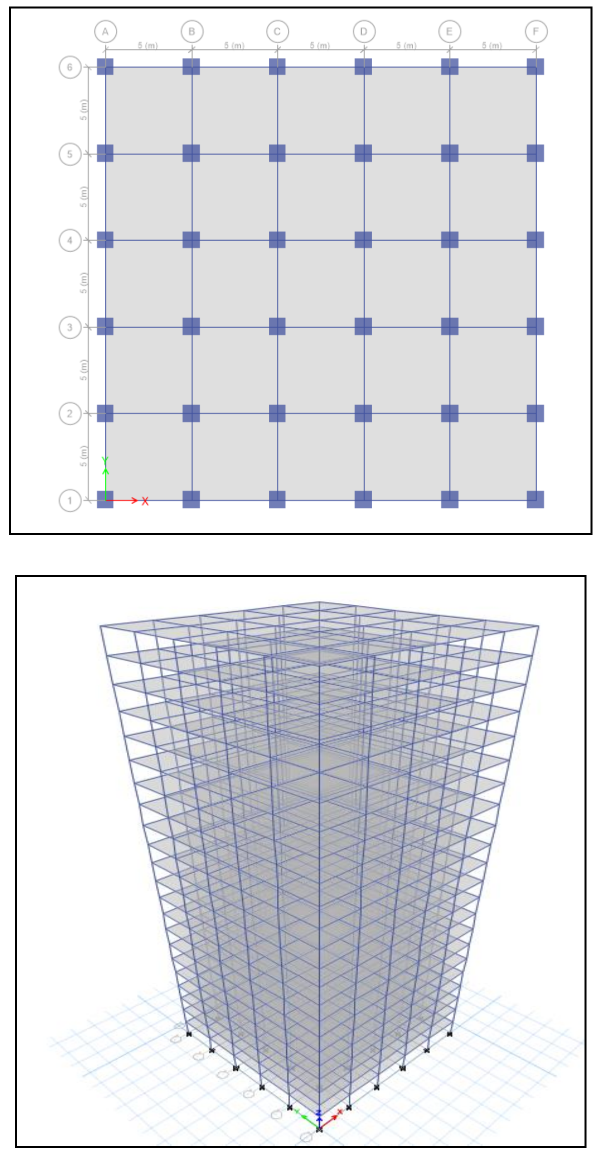
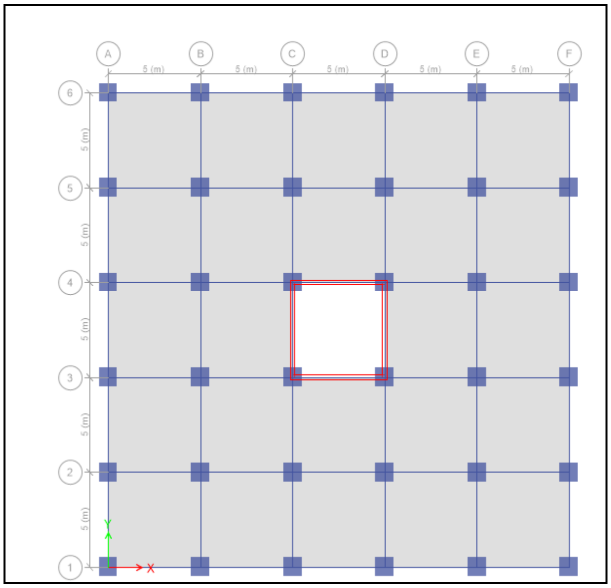


Fig 3 Conventional model



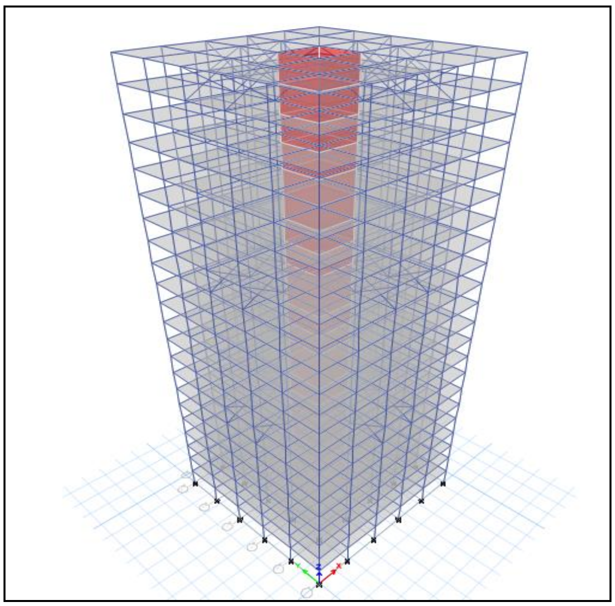
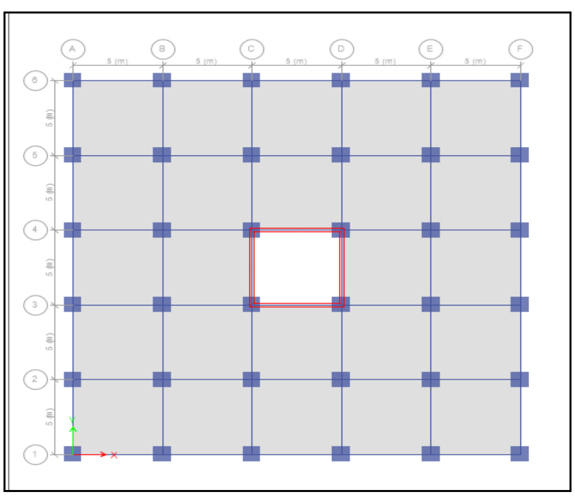


Fig 4 Model with outrigger



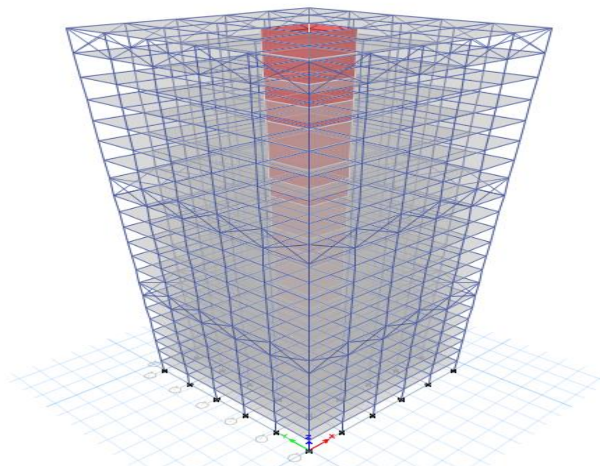
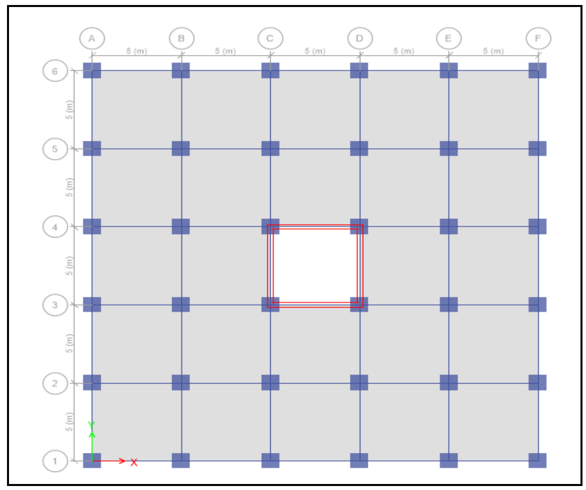


Fig 5 Model with belt truss



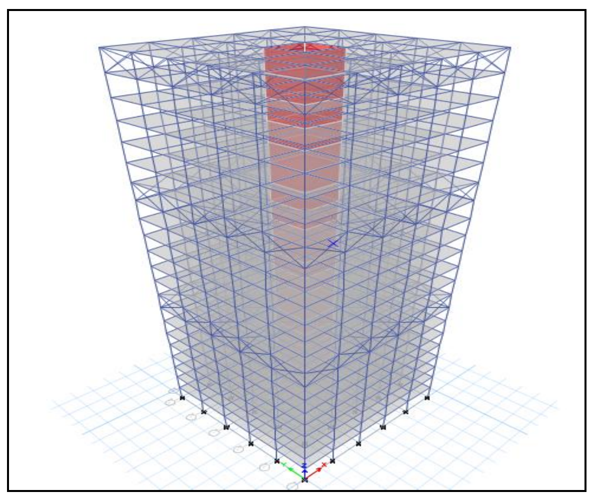
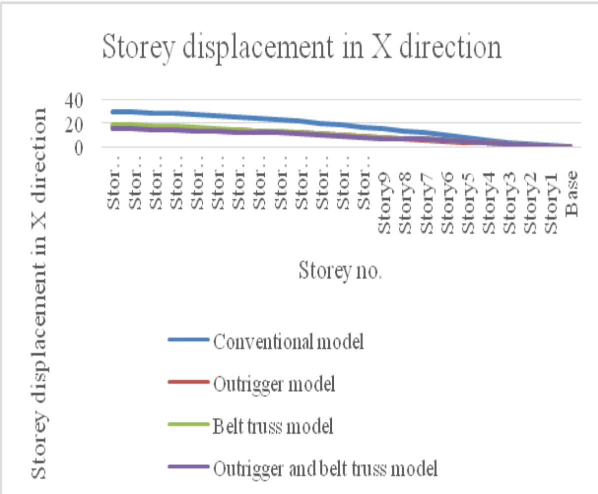


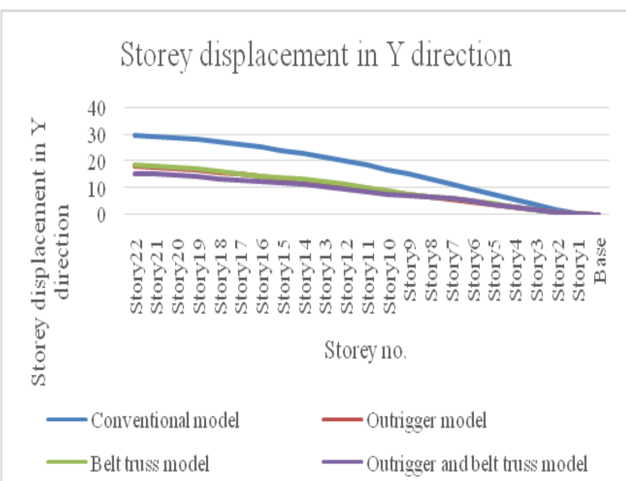
Fig 6 Model with outrigger and belt truss

V. RESULT AND DISCUSSION



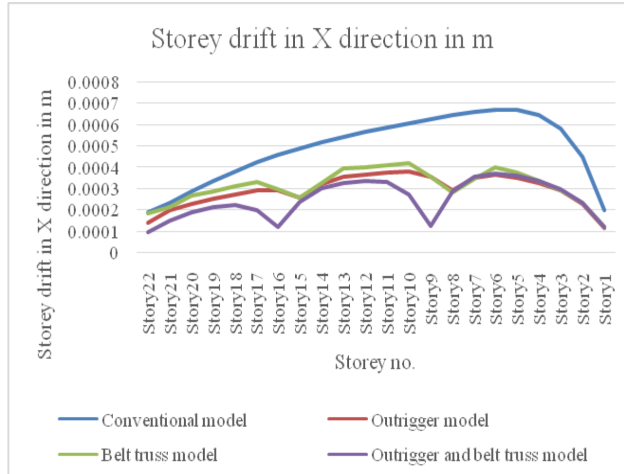
Graph 1Storey displacement in X direction in mm

The storey displacement in the X direction indicates that the displacement values decrease from the structure's base to its top in all models. The conventional model has the biggest displacement at each storey level, with a maximum of 29.584 mm at Story 22 and a minimum of 0.587 mm at Story 1. The use of structural upgrades considerably lowers displacement. The outrigger model decreases displacement at the top storey by almost 40%, while the belt truss and combined outrigger-belt truss models cut displacement even further, with the outrigger and belt truss combination having the lowest top-storey displacement of 15.419mm.



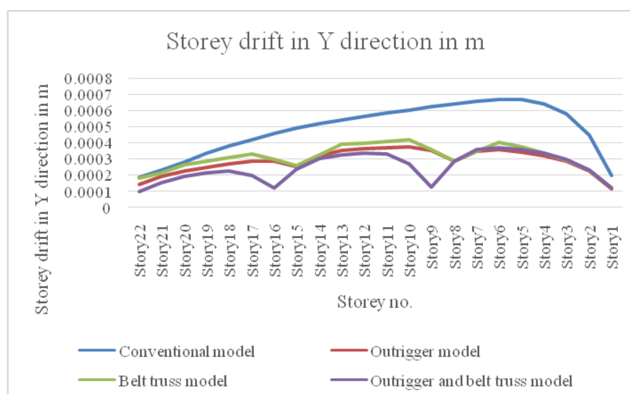
Graph 2 Storey displacement in Y direction in mm

The tendency for storey displacement in the Y direction (mm) is the same as in the X direction. The conventional model once again produces the greatest results, but displacement reduces with the use of outrigger and belt truss systems. The combined model yields the biggest decrease, lowering the top-storey displacement from 29.584 mm in the conventional model to 15.419 mm. This continuous trend indicates that the structural modifications increase the building's lateral stiffness and resistance to forces in both primary directions.



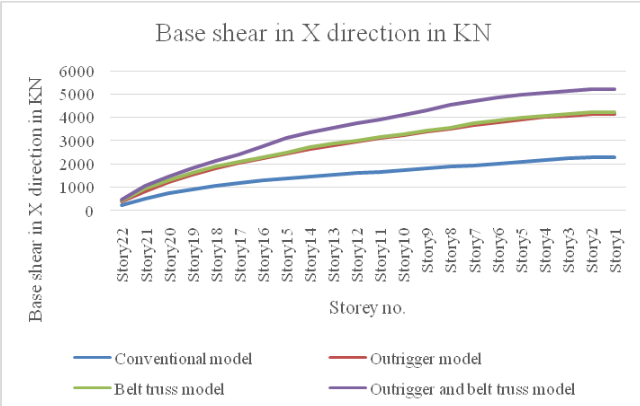
Graph 3 Storey drift in X direction in m

Storey drift, which measures inter-storey displacement, shows comparable patterns among models. The conventional model has the largest drift values, notably in the middle storeys, reaching a peak of 0.000668 m at Story 6. The drift is significantly reduced with the inclusion of structural systems. The combined outrigger and belt truss model has the least drift, with values consistently below 0.000371 m across all levels. Drift decrease shows increased inter-storey stability and deformation resistance.



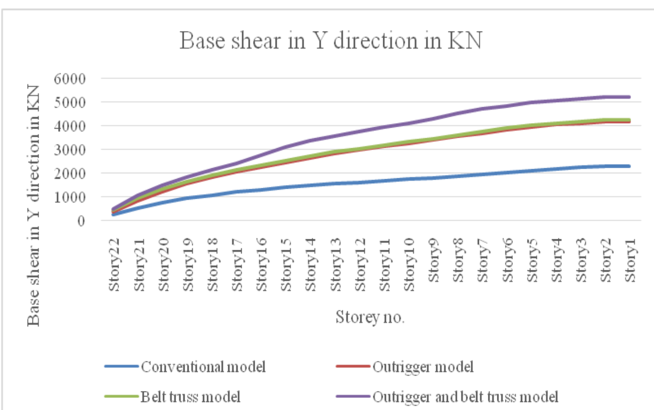
Graph 4 Storey drift in Y direction in m

All models show a decreasing tendency for storey drift in the Y direction. The conventional model records a high drift of 0.000668 m, but the combined outrigger and belt truss model decreases it to less than 0.000371 m. The use of outriggers and belt trusses greatly decreases lateral deformation, improving overall structural performance under lateral stress in both X and Y directions.



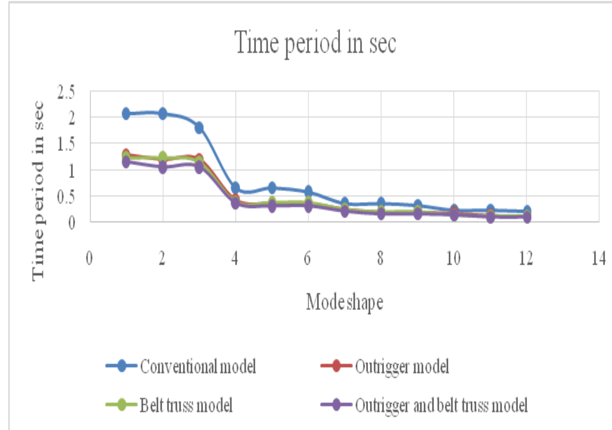
Graph 5 Base shear in X direction in KN

Introducing structural systems significantly improves base shear, which measures the total horizontal force exerted at the structure's base. The conventional model has lower base shear values, peaking at 2,300.385 kN in Story 1. However, the combined model withstands the largest base shear of 5,205.082 kN, suggesting that the increased stiffness provided by the outrigger and belt truss systems improves the structure's ability to tolerate horizontal forces.



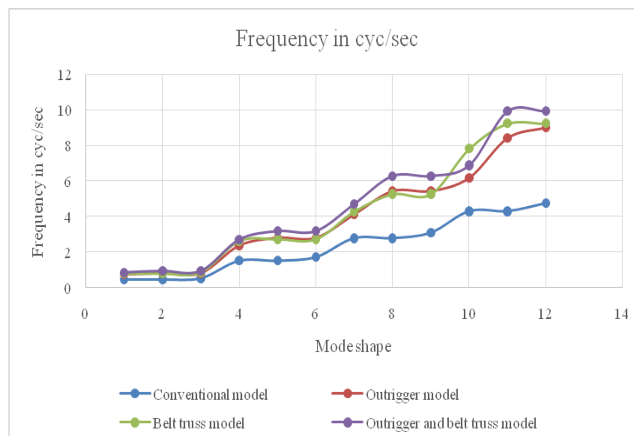
Graph 6 Base shear in Y direction in KN

The base shear in the Y direction shows comparable rates of improvement to the X direction. The conventional model indicates a peak base shear of 2,300.385 kN, but the combined outrigger and belt truss model has a substantially larger peak of 5,205.082 kN. This increase demonstrates the structural changes' enhanced ability to withstand seismic or wind stresses in both directions.



Graph 7 Time period in sec

Adding structural systems dramatically reduces the natural periods of the structure, which are influenced by mode forms. The conventional model's basic mode takes the largest time of 2.058 seconds, whereas the combined model decreases it to 1.148 seconds. Lower time periods imply enhanced rigidity and decreased structural flexibility, resulting in improved performance under dynamic stress.



Graph 8 Frequency in cyc/sec

The frequency results exhibit an inverse connection with the time period. The conventional model has the lowest fundamental frequency of 0.486 cycles/sec, while the combined model has the highest frequency of 0.871 cycles/sec in the first mode. The rise in frequency represents the improved structural rigidity and dynamic stability gained by outrigger and belt truss integration. The potential for resonance effects is reduced by higher frequencies, which suggest quicker structural response to dynamic loads.

VI. CONCLUSION

The purpose of this research study was to evaluate the seismic performance of a high-rise G+20 RCC structure, with an emphasis on the effectiveness of structural upgrades using outrigger and belt truss systems. The analysis included essential structural parameters such as storey displacement, storey drift, base shear, time period, and frequency. According to the results, the conventional model, which is based primarily on moment-resisting frames, is ineffective at mitigating the impacts of lateral loads, especially under seismic load conditions. This model saw the largest storey displacements and drifts, with values that potentially jeopardise the building's structural stability and serviceability. The outrigger and belt truss model systems, on the other hand, demonstrated a significant decrease in displacement and drift. The combined outrigger and belt truss model fared the best, reducing top-storey displacement by roughly 50% and significantly improving base shear resistance. The outrigger system efficiently dispersed lateral stresses by connecting the building's core to the exterior columns, minimizing core overturning moments while boosting lateral stiffness. The belt truss system strengthened the perimeter structure, increasing its resistance to deformation from seismic stresses. The storey drift results revealed that inter-storey deformation was most apparent in the conventional model's mid-levels, possibly causing severe levels of structural instability and damage to non-structural features such as walls and facades. The incorporation of structural systems brought drift values well below allowed limits, resulting in increased structural safety and performance during seismic events. The base shear analysis revealed a considerable improvement in the building's ability to bear horizontal forces using the upgraded models. The combined system model has the greatest base shear values, emphasizing the importance of extra lateral stiffness in high-rise buildings. This shows that buildings using outrigger and belt truss systems may better absorb and disperse energy under dynamic loads, such as earthquakes and wind forces, while maintaining structural integrity. The study of natural time periods and frequency responses demonstrated the structure's better dynamic behaviour. The natural time period was reduced with the addition of structural systems, showing increased stiffness and quicker structural reaction. The upgraded models' higher frequency values represent a lower sensitivity to resonance, which is crucial for averting structural collapse during prolonged seismic excitation. Overall, this study demonstrates the importance of including outrigger and belt truss systems into the design of high-rise structures in order to enhance their seismic performance. These systems not only decrease lateral displacements and inter-storey drift, but also improve load redistribution, resulting in increased stability and less damage from seismic loads. Findings provide a good platform for formulating design standards for tall buildings in seismically prone locations.

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