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Analysis and Design of a Multi-Storey Building Incorporating Belt Truss and Outrigger Systems: A Review

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Abstract: The outrigger and belt truss system is a widely used structural mechanism for controlling excessive lateral drift in high-rise buildings subjected to wind and seismic forces. This study evaluates the effectiveness of outrigger and belt truss systems in a G+12 commercial building with different structural configurations, including conventional concrete, steel, and composite materials. A three-dimensional finite element analysis is conducted using STAAD.Pro to assess the impact of outriggers on lateral displacement, storey drift, base shear, and bending moments. The study considers seismic loading as per IS 1893 (Part 1): 2002 and investigates the optimal placement of outriggers for maximum efficiency. The results indicate significant improvements in deflection control and structural stability with the inclusion of outrigger and belt truss systems. The findings provide insights into the selection of optimal structural configurations for high-rise buildings in seismic and wind-prone zones, ensuring enhanced safety and serviceability.
Keywords: Single under-reamed friction pile, Isolated footing, Sub-structure, Storey displacement, Building frame etc.

I. INTRODUCTION

High-rise buildings are increasingly being constructed worldwide due to rapid urbanization and the need for optimized land use. However, as buildings grow taller, they become more susceptible to lateral loads induced by wind and earthquakes. These forces can lead to excessive drift, structural instability, and discomfort for occupants. To mitigate these effects, various structural systems have been developed, one of the most effective being the outrigger and belt truss system. This system enhances the lateral stiffness of high-rise buildings, thereby reducing deflection and improving overall stability.

The design of high-rise buildings is often governed more by serviceability criteria than by strength. Structural engineers continuously strive to control lateral displacement, storey drift, and the self-weight of structures. The outrigger and belt truss system is an advanced lateral load-resisting system that significantly enhances the performance of tall buildings. It consists of a central core, typically made of reinforced concrete or steel, connected to perimeter columns through rigid horizontal elements called outriggers. These outriggers act as stiff arms, distributing lateral forces between the core and the exterior columns, thereby increasing the overall stiffness of the building. Additionally, belt trusses are incorporated to connect exterior columns, further enhancing structural integrity.

The concept of outriggers is inspired by the stability mechanisms of sailing ships. In traditional ships, a slender mast is stabilized by horizontal spreaders connected to shrouds or stays, which distribute the forces exerted by wind. This analogy has been translated into building structures, where the central core represents the mast, outriggers function as spreaders, and exterior columns act as shrouds. This system effectively reduces excessive sway in high-rise buildings, making it an ideal choice for structures located in seismic-prone and wind-dominated regions.

One of the primary advantages of using the outrigger and belt truss system is its ability to control lateral deflection efficiently. Conventional moment-resisting frames or shear walls alone may not provide adequate stiffness for very tall buildings, leading to excessive inter-storey drift. By introducing outriggers at strategic locations, the lateral displacement of the building is significantly reduced. Studies have shown that the inclusion of one, two, or three outrigger levels can lead to reductions in lateral deflection of approximately 34%, 42%, and 51%, respectively. This demonstrates the effectiveness of this structural system in improving the overall stability of high-rise buildings.

This research focuses on a G+12 commercial building, analyzing different structural configurations, including conventional concrete, steel, and composite materials. The study is conducted using STAAD.Pro software to evaluate the building's response under seismic loading as per IS 1893 (Part 1): 2002. The analysis aims to determine the optimal placement of outriggers and belt trusses to achieve maximum deflection control. The building, designed for exhibition and showroom purposes, has an open interior layout with external shear walls providing additional lateral stability.

By comparing different structural configurations, this study aims to provide insights into the efficiency of the outrigger and belt truss system in controlling deflection and enhancing structural resilience. The findings will help engineers optimize the design of high-rise buildings, ensuring improved safety, serviceability, and cost-effectiveness in seismic and wind-prone regions.

II. PROBLEM STATEMENTS

1) Excessive Lateral Displacement – High-rise buildings experience significant lateral displacement under wind and seismic loads, leading to instability and discomfort for occupants.
2) Storey Drift Control – Conventional moment-resisting frames and shear walls alone may not effectively control inter-storey drift in tall structures.
3) Serviceability Issues – Excessive sway and vibrations can impact the functionality of high-rise buildings, making them unsuitable for commercial and residential use.
4) Structural Efficiency – Optimal placement of outriggers and belt trusses is essential to maximize stiffness and reduce structural deformation.
5) Material Selection – The performance of conventional concrete, steel, and composite structures needs to be compared to determine the most effective system.
6) Seismic and Wind Resistance – Buildings in seismic-prone and wind-dominated areas require advanced lateral load-resisting systems for enhanced stability.

III. LITERATURE REVIEW

A. Literature Survey

The outrigger and belt truss system is a structural mechanism employed in high-rise buildings to mitigate excessive lateral displacements caused by wind or seismic forces. This system enhances the building's stiffness and stability by connecting the central core to peripheral columns using stiff outriggers and belt trusses at strategic levels. Over the years, numerous studies have investigated the effectiveness, optimal configurations, and design considerations of this system.

Alhaddad, M. M., & Halabi, et al. (2020), This paper present This comprehensive review delves into the design principles of outrigger and belt-truss systems in tall buildings. The authors discuss various configurations, material considerations, and the impact of these systems on building performance under lateral loads. They also provide guidelines for optimal topology and size design, emphasizing the importance of integrating exterior and interior structural systems through rigid horizontal beams.

Kian, P. S., & Siahaan, F. T. et al. (2020) This study examines the application of outrigger and belt truss systems in 40-storey and 60-storey concrete buildings subjected to wind and earthquake loads, respectively. The findings indicate that strategic placement of outriggers can lead to significant reductions in lateral displacement, with a 65% reduction observed when the first outrigger is at the top and the second at mid-height in the 40-storey model.

Sharma, R., & Kumar, P. (2021) This paper reviews the behavior of high-rise buildings equipped with outrigger and belt truss systems under seismic and wind forces. The authors highlight the system's effectiveness in enhancing building stiffness and reducing lateral displacements, emphasizing the need for optimal positioning and design to achieve desired performance levels.

Patel, D., & Shah, B. (2021) The authors present a review of various techniques used to investigate the effectiveness of belt truss and outrigger systems in tall buildings. They focus on parameters such as lateral displacement, storey drift, core moment, and optimal outrigger positioning, providing insights into design considerations for controlling deflection in high-rise structures.

Yılmaz, M., & Öztürk, B. (2023) This study investigates the impact of outrigger systems on the structural performance and cost of high-rise buildings. The findings suggest that buildings with outrigger systems have a 7.2% lower cost rate compared to frame systems, highlighting the economic benefits alongside structural advantages.

Singh, A., & Gupta, R. (2022) This literature review compiles recent contributions related to outrigger systems, focusing on their role in enhancing the lateral load resistance of multistorey buildings. The authors discuss various design strategies, including the depth variations of outriggers and their impact on structural performance.

Zhang, L., & Li, Q. et al. (2022) This study explores the effect of different outrigger placements on the seismic performance of reinforced concrete (RC) high-rise buildings. The authors use finite element analysis (FEA) to compare various outrigger positions and conclude that placing outriggers at 0.4H and 0.7H (where H = total height) provides optimal structural performance in reducing inter-story drift and increasing base shear resistance. The study also suggests that dual outrigger configurations are more effective than single outrigger systems in improving lateral stiffness.

Kim, J., & Eom, T. (2021), This paper compares the performance of conventional outrigger systems, damped outrigger systems, and hybrid outrigger configurations in high-rise buildings. Using dynamic response spectrum analysis, the study finds that damped outrigger systems (incorporating tuned mass dampers) reduce lateral displacement by 20-30% compared to conventional outrigger systems. The authors highlight that energy dissipation mechanisms within the outrigger structure significantly enhance seismic resistance.

Abbas, H., & Rizwan, M. (2023), This study evaluates the effectiveness of outriggers in high-rise buildings under varying soil conditions (hard, medium, and soft soils). The results indicate that the effectiveness of the outrigger system decreases in soft soil conditions, with lateral displacement being 15-25% higher compared to hard soil cases. The authors recommend foundation modifications and soil-structure interaction analysis to enhance the efficiency of the outrigger system in flexible soil conditions.

B. Gap Identified

Despite extensive research on outrigger and belt truss systems in high-rise buildings, several gaps remain. Many studies focus on lateral stiffness enhancement, but limited research explores the real-time adaptability of outrigger systems under dynamic loads like earthquakes and wind. Additionally, most existing analyses use static or simplified dynamic simulations, whereas machine learning-based predictive models for outrigger placement and stiffness optimization remain underexplored.

Furthermore, studies evaluating soil-structure interaction effects on outrigger performance in soft soil conditions are scarce. There is also a lack of comprehensive research on hybrid outrigger systems that combine energy dissipation mechanisms with traditional outrigger designs. Future research should focus on smart outrigger systems with real-time monitoring, optimizing stiffness distribution, and integrating damped outrigger technology for seismic resilience.

C. Summary of Literature Survey

The literature review highlights the effectiveness of outrigger and belt truss systems in enhancing the lateral stiffness of high-rise buildings. Several studies confirm that outriggers significantly reduce lateral displacement and inter-storey drift, making them ideal for buildings in seismic-prone and wind-dominated regions. Researchers have explored different outrigger configurations, including single, double, and multiple outriggers, to determine the optimal placement for structural efficiency.

However, gaps exist in the study of real-time adaptability, soil-structure interaction effects, and hybrid outrigger systems with damping mechanisms. Most analyses rely on static simulations, with limited exploration of machine learning-based predictive models for optimized outrigger placement. Future research should integrate advanced computational methods to enhance the efficiency of outrigger systems in seismic design.

IV. RESEARCH METHODOLOGY

A. Criteria for selecting this study

A G+12 storey building for a commercial complex has plan dimensions (35M x 28M). The building is Studied for all seismic zone on a site with medium soil. Design of building for seismic loads as per IS 1893 (Part 1): 2002.

1) The example building consists of conventional concrete Building, Steel Structure building, & Composite building with outrigger and Belt truss included Shear Wall caved in center of building in outer periphery. Analysis and design is to be performed in Staad-pro Structural software.
2) The building will be used for exhibitions, as an art gallery or show room, etc., so that there are no walls inside the building. Only external walls 230 mm thick with 12 mm plaster on both sides are considered. For simplicity in analysis, no balconies are used in the building.
3) At ground floor, slabs are not provided and the floor will directly rest on ground. Therefore, only ground beams passing through columns are provided as tie beams. The floor beams are thus absent in the ground floor.
4) Secondary floor beams are so arranged that they act as simply supported beams and that maximum number of main beams get flanged beam effect.
5) The main beams rest centrally on columns to avoid local eccentricity.

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6) For all structural elements, M30 grade concrete will be used.
7) The floor diaphragms are assumed to be rigid.
8) Centre-line dimensions are followed for analysis and design.
9) Preliminary sizes of structural components are assumed by experience.
10) For analysis purpose, the beams are assumed to be rectangular so as to distribute slightly larger moment in columns. In practice a beam that fulfils requirement of flanged section in design, behaves in between a rectangular and a flanged section for moment distribution.
11) Seismic loads will be considered acting in the horizontal direction (along either of the two principal directions) and not along the vertical direction, since it is not considered to be significant.
12) Plan aspect ratio is taken constant for all the models which is (35m x 28m).
13) All dimensions are in meter, unless specified otherwise.

B. Method of analysis:

1) The analysis of the G+12 storey commercial building is performed using STAAD.Pro software, considering different structural configurations under seismic loads as per IS 1893 (Part 1): 2002. The study involves three structural systems: reinforced concrete (RC) moment-resisting frame, steel structure, and composite structure with belt truss and outrigger systems.
2) The analysis is conducted using the linear static method for preliminary assessment and the response spectrum method for detailed seismic evaluation. The models are analyzed under different support conditions (fixed and semi-rigid supports) to observe structural behavior. The displacement, base shear, and inter-storey drift are recorded for each model to assess seismic performance.
3) Various configurations, including models with and without belt trusses, outriggers, and shear walls, are compared. The optimal outrigger placement is determined by running multiple simulations to minimize displacement and enhance lateral stiffness. The results help in selecting the most efficient structure for seismic resistance.

C. Comparison and Analysis

The comparative study of the G+12 storey commercial building involves analyzing three structural configurations: RC frame, steel structure, and composite structure with belt truss and outriggers, using STAAD.Pro under seismic loads as per IS 1893 (Part 1): 2002. The analysis considers fixed and semi-rigid supports, with parameters like maximum displacement, base shear, and inter-storey drift used for evaluation. The RC moment-resisting frame exhibits the highest lateral displacement, making it the least effective in resisting seismic forces. The steel structure, while lighter, also shows significant displacement due to its reduced stiffness. The composite structure with belt trusses, outriggers, and shear walls demonstrates the best seismic performance, as outriggers enhance lateral stability by distributing forces efficiently. The optimal placement of outriggers is observed at the 4th, 8th, and 12th floors, significantly reducing lateral displacement. Among all models, the composite structure with shear walls in the outer periphery provides the best structural efficiency, reducing drift and increasing stiffness. The response spectrum analysis confirms that the belt truss-outrigger system significantly enhances seismic resistance, making it the preferred choice for high-rise buildings in earthquake-prone regions. This comparison highlights the importance of hybrid structural systems for improved seismic resilience.

D. Evaluation of methodologies used:

The proposed work is planned to be carried out in the following manner –
For the study reinforced concrete structure is considered, having G+12 stories. Each floor is considered as 3 m height.
For the reference base model, a regular reinforced concrete moment resisting bare frame model is considered. One Structure modelled with Fixed support and other with SS with reference to base model by using STADD PRO Software.

The floor height is kept constant for all models in order to get consistent results.
1) Model without belt truss and outrigger.
2) Model with one belt truss and outrigger.
3) Model with belt truss outrigger including shear-wall in composite structure.

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This model has three belt truss at 4th, 8th and 12th floor and outrigger fixed at all four corner side, and shear wall is provided in the centre of building outer periphery. Whereas many models has been run to find the optimum placement of outrigger and Observation of Max. Displacement.

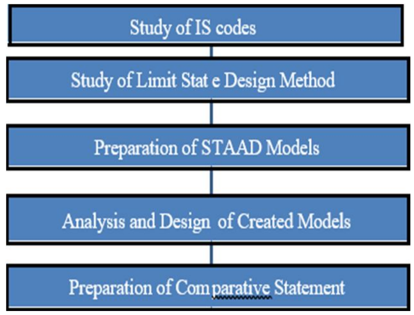

Fig.1. Work Planning

E. Highlighting trends, advancements, and challenges

1) Trends in High-Rise Structures

The demand for high-rise buildings has significantly increased due to rapid urbanization and space constraints. Modern structural systems such as outriggers, belt trusses, shear walls, and composite structures are widely adopted to improve lateral stability and seismic performance. Additionally, performance-based seismic design (PBSD) and energy dissipation devices like tuned mass dampers (TMDs) are emerging as effective solutions to enhance building resilience. Sustainable construction with high-strength materials and prefabricated components is also gaining popularity, reducing material consumption and improving efficiency.

2) Advancements in Structural Analysis and Design

Advanced structural modeling and simulation tools like STAAD.Pro, ETABS, and ANSYS have transformed high-rise building design by providing precise analysis of seismic and wind loads. The integration of Building Information Modeling (BIM) enables seamless collaboration among engineers and architects, optimizing the design process. Additionally, the use of hybrid structural systems, combining reinforced concrete, steel, and composite materials, has improved the strength-to-weight ratio, reducing overall structural mass while maintaining robustness.

1) Challenges in High-Rise Construction

Despite advancements, several challenges remain in designing high-rise structures. Seismic vulnerability, especially in high-risk zones, necessitates innovative lateral load-resisting mechanisms. The optimum placement of outriggers and belt trusses remains a critical challenge in enhancing structural stability. Additionally, construction cost and material optimization are major concerns, requiring efficient use of high-performance concrete and steel. Deflection and drift control pose another challenge, demanding precise analysis and implementation of stiffness-enhancing elements.

While technological advancements continue to drive innovation in high-rise structures, challenges such as seismic performance, cost efficiency, and construction complexity require continuous research and development for sustainable and resilient building solutions.

V. CONCLUSION

The review of this study highlights the significant role of outrigger structural systems in enhancing the lateral stiffness and overall stability of high-rise buildings subjected to seismic and wind forces. The integration of belt trusses, perimeter columns, and core structural walls significantly improves resistance against lateral loads, as outlined in IS 1893-2016 (Part 1). The study confirms that the positioning of outriggers greatly influences structural performance, with optimal placement found at 0.9H and 0.5H from the base in a two-outrigger system. Comparative analysis of structural responses reveals that buildings without outriggers exhibit higher displacements under both seismic and wind load conditions. Specifically, for seismic loads in Zone III, X-axis displacements are 4.25% higher, and Y-axis displacements are 7.56% higher in structures without outriggers compared to those incorporating the system. Similarly, for wind loads, X-axis displacements increase by 9.23% in buildings lacking outrigger belt trusses.

Overall, the study underscores the efficiency of outrigger-belt truss systems in reducing lateral deflections, thereby enhancing building performance under extreme conditions. Future research can explore alternative outrigger configurations and material optimizations to further improve structural resilience while ensuring cost-effectiveness and practical feasibility.

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