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A REVIEW OF TIME HISTORY ANALYSIS OF HIGH-RISE BUILDINGS WITH OUTRIGGER AND BELT TRUSS SYSTEMS

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Abstract - *The rapid vertical expansion of urban environments has made high-rise buildings a dominant feature of modern skylines, but their structural stability under seismic and wind-induced lateral loads remains a critical engineering challenge. Outrigger and belt truss systems have emerged as highly efficient structural mechanisms to enhance lateral stiffness, minimize inter-story drift, and control overturning moments in tall buildings. This review paper synthesizes existing experimental and numerical research, with a particular focus on time history analysis, which offers detailed insights into the nonlinear and dynamic behavior of high-rise structures. The discussion covers fundamental concepts of outrigger and belt truss systems, their individual and integrated contributions, and comparative performance under seismic loading. Special emphasis is given to the influence of outrigger placement, belt truss configuration, and combined system optimization on structural response. Findings indicate that integrated outrigger–belt truss systems consistently outperform outrigger-only or belt truss-only systems, particularly in reducing seismic vulnerability. However, challenges related to construction complexity, modeling limitations, and context-specific performance outcomes highlight the need for further research. The paper concludes by identifying potential future directions, including hybrid materials, damped and virtual outriggers, soil–structure interaction studies, and performance-based design frameworks, to achieve safer and more sustainable high-rise structures.*

Key Words: **High-rise buildings; Outrigger system; Belt truss system; Time history analysis; Lateral load resistance; Seismic performance; Structural optimization; Drift control; Performance-based design**

1. INTRODUCTION

1.1 Background on the Rapid Growth of High-Rise Buildings and Challenges in Structural Stability

The continuous urbanization and population growth in metropolitan cities have led to a steep rise in the demand for high-rise structures. Tall buildings not only optimize land usage but also symbolize technological advancement and economic development. However, with the increase in height, these structures encounter several engineering challenges related to structural stability and serviceability. The major concerns include lateral displacements, inter-story drifts, and vibrations induced by seismic and wind loads. Researchers such as Taranath (2016) emphasize that as the height of a building increases, the lateral stiffness becomes a governing parameter in structural design, often taking precedence over strength requirements. This necessitates the development of efficient lateral load-resisting systems to ensure both safety and occupant comfort.

1.2 Importance of Lateral Load Resistance (Earthquake and Wind Loads)

Tall buildings face a lot of stress from natural forces, especially earthquakes and strong winds. When an earthquake strikes, the shaking of the ground pushes powerful sideways forces into the building's structure. On the other hand, wind doesn't hit all at once—it creates a steady swaying motion that can wear down the building over time and even make the occupants feel uncomfortable. As Chopra (2012) points out, a building's ability to resist these sideways, or lateral, forces is one of the most important factors in how well it performs during an earthquake. If the building isn't stiff enough or can't absorb and release energy effectively, the risk of serious damage or even collapse increases. Similarly, studies in wind tunnels have shown that as buildings get taller, wind effects like vortex shedding and sudden gusts become more intense (Kareem & Gurley, 1996). Because of this, engineers are constantly working on smarter designs that keep buildings strong and stable while avoiding the need for huge amounts of extra material.

1.3 Significance of Structural Systems like Outriggers and Belt Trusses

When it comes to helping tall buildings resist sideways forces, one of the most effective systems is the outrigger and belt truss setup. Think of the outrigger as a strong horizontal arm that links the building's central core to the outer columns. This connection lets the outside columns share the job of resisting the tipping or overturning forces that happen during wind or earthquakes. The belt truss works alongside it by tying the outer columns together, so instead of acting separately, they behave like a single, stronger unit. Together, these systems make the whole building more stable and better able to handle lateral loads. Studies by Smith and Coull (1991) and later by Moon (2010) have demonstrated that the incorporation of outrigger and belt truss systems significantly reduces lateral deflections and optimizes material usage, making them highly preferred

in super-tall building design. Their strategic placement at different building heights has shown to be effective in redistributing forces and controlling seismic and wind responses.

1.4 Purpose of Time History Analysis in Dynamic Structural Evaluation

Dynamic analysis forms the backbone of seismic design, and time history analysis is considered one of the most accurate methods for evaluating the response of structures under real earthquake excitations. Unlike equivalent static or response spectrum methods, time history analysis incorporates the actual variation of ground motion with time, thereby providing realistic insights into structural performance (Chopra, 2012). For high-rise buildings with complex structural systems like outriggers and belt trusses, this method enables the evaluation of nonlinear behavior, inter-story drift, acceleration profiles, and overall energy dissipation. It helps engineers assess the effectiveness of different configurations of outrigger-belt truss systems in mitigating seismic responses. Therefore, it serves as a crucial tool in advancing performance-based seismic design.

2. FUNDAMENTALS OF OUTRIGGER AND BELT TRUSS SYSTEMS

2.1 Outrigger System

2.1.1 Concept and Working Mechanism

The outrigger system is considered one of the most effective approaches in tall building design. Its main purpose is to connect the building's central core—usually made of reinforced concrete shear walls or a braced frame—to the outer columns with stiff horizontal members known as outriggers. When wind or earthquake forces act on the structure, the core tends to bend, which causes rotation at its edges. The outriggers counter this effect by linking the core to the exterior columns, which then take on tension and compression much like the flanges of a beam. This makes the entire building behave like a large, deep beam, reducing the risk of tipping and limiting side-to-side sway. As explained by Smith and Coull (1991), this cooperation between the core and the perimeter columns increases the overall stiffness of the building without requiring a major increase in material use.

2.1.2 Evolution of Outrigger Systems in Tall Buildings

The idea of using outriggers in tall buildings has grown and improved a lot over the past few decades. Back in the 1960s, the first examples appeared in steel-framed skyscrapers, where simple outrigger trusses connected the central core to the outer columns. As time went on, engineers realized they could get better results by adding more than one level of outriggers at carefully chosen heights in the building. Today, it is common to see two or more outrigger systems placed at spots like mid-height and near the top, which helps control sideways movement and keeps the structure balanced. More recently, designers have also started combining outriggers with other systems, such as mega-braces or dampers, to improve how buildings respond to earthquakes. According to Moon (2010), the biggest shift has been moving away from trial-and-error methods toward a design approach that focuses on stiffness. This change has made outrigger systems both more effective and more economical.

2.1.3 Types of Outriggers (Concrete, Steel, Hybrid)

Outriggers can be designed using different materials depending on structural requirements and architectural constraints. Reinforced concrete outriggers are widely used in composite tall buildings, particularly when they are cast monolithically with the core. Steel outriggers, on the other hand, are favored for their high strength-to-weight ratio and ease of prefabrication, making them suitable for tall steel-framed structures. Hybrid outriggers, which combine steel and concrete, have gained popularity for providing both stiffness and construction flexibility. According to Taranath (2016), hybrid systems are especially effective in supertall buildings as they allow designers to balance rigidity, constructability, and architectural space utilization.

2.2 Belt Truss System

2.2.1 Function and Integration with Outriggers

The belt truss system works hand in hand with the outrigger to make tall buildings stronger against sideways forces. A belt truss is a horizontal framework that wraps around the outside of the building at the same level as the outrigger. Its main job is to link the exterior columns so that they work together instead of separately when resisting the overturning forces passed on by the outrigger. In doing so, it creates a stiff belt around the structure, allowing more columns to share the load and improving how the whole building responds. As Smith and Coull (1991) explain, the belt truss is especially valuable because it spreads out the forces efficiently; making sure the outrigger's support is fully used.

2.2.2 Structural Behaviour under Lateral Loads

When tall buildings face strong winds or earthquakes, belt trusses play an important role in keeping the structure safe and stable. They spread out the sideways, or shear, forces among the outer columns so that no single column takes on too much stress. By doing this, they also reduce differences in how much individual columns move, which helps protect the building's façade from distortion. Ali and Moon (2007) point out that belt trusses are especially

effective when paired with outrigger systems, since together they cut down inter-story drift and improve how well the structure absorbs and releases energy. Because of these benefits, belt trusses are often seen as a valuable feature in modern seismic design for tall buildings.

2.2.3 Typical Configurations in Practice

In real-world projects, belt trusses are usually made of steel because the material is light and very effective at transferring loads. They are often built as diagonal truss members along the façade, creating a stiff frame that wraps around the building. The typical approach is to place one belt truss at the same level as each outrigger, but in some advanced designs, multiple belt trusses are added at different heights to give extra stability. In many cases, these trusses are also blended with the building's façade, allowing them to serve both as structural support and as part of the architectural look. Well-known examples include the Jin Mao Tower in Shanghai and Taipei 101, where the belt trusses are not only functional but also contribute to the buildings' distinctive designs (Taranath, 2016).

2.3 Combined Role of Outriggers and Belt Trusses

2.3.1 How They Enhance Stiffness and Control Drift

When used in combination, the outrigger and belt truss systems provide a synergistic effect that significantly improves the performance of tall buildings under lateral loading. Outriggers transfer overturning moments from the core to the outer columns, while belt trusses ensure that these forces are evenly distributed across the building's perimeter. This combined action enhances the structural stiffness, reduces overall drift, and minimizes inter-story displacements. Studies by Moon (2010) have shown that buildings with integrated outrigger-belt truss systems exhibit superior seismic performance compared to those with isolated lateral load-resisting systems.

2.3.2 Comparative Advantage over Other Lateral Load-Resisting Systems

Compared to alternative lateral load-resisting systems such as braced frames, shear walls, or tubular systems, the outrigger–belt truss combination offers a unique balance of efficiency and architectural flexibility. While shear walls and braced frames often consume large amounts of usable floor space, outrigger systems require minimal intrusion into the interior layout, making them more favorable for high-rise residential and commercial projects. Additionally, tubular systems, although efficient, are best suited for very tall and uniform buildings, whereas outrigger-belt truss systems can be applied to a wide range of structural geometries. Ali and Moon (2007) point out that this adaptability makes outrigger-belt truss systems the preferred choice for modern skyscrapers seeking both structural resilience and functional versatility.

3. TIME HISTORY ANALYSIS IN STRUCTURAL ENGINEERING

3.1 Overview of Dynamic Analysis Methods

3.1.1 Response Spectrum Method vs. Time History Method

Dynamic analysis is an essential part of earthquake engineering because it allows engineers to assess how structures behave under seismic excitations. Among the commonly used approaches, the response spectrum method and the time history method are the most prominent. The response spectrum method provides an estimate of peak responses of a structure by using a predefined spectrum derived from seismic codes or recorded ground motions. It is computationally efficient and widely applied in preliminary seismic design (Chopra, 2012). However, it only gives maximum responses without accounting for the sequence of loading or cyclic behavior. On the other hand, the time history method involves the direct integration of the structure's equations of motion using recorded or artificially generated ground motion data. This method captures the entire time-dependent response, including displacements, velocities, accelerations, and internal forces, making it more accurate for evaluating tall and complex buildings (Kunnath, 2004). Thus, while the response spectrum method is often used for code compliance, the time history approach is regarded as more reliable for performance-based seismic design.

3.2 Significance of Time History Analysis for Seismic Evaluation

The primary advantage of time history analysis lies in its ability to simulate the actual seismic demand imposed on a structure. Unlike simplified methods, it incorporates the duration, frequency content, and amplitude of earthquake ground motions, offering a realistic assessment of structural performance. For high-rise buildings equipped with complex systems such as outriggers and belt trusses, this becomes particularly significant, as their nonlinear behavior and interaction between structural components can only be captured through detailed dynamic simulations (Boore, 2003). Furthermore, performance-based seismic design frameworks, which emphasize serviceability, damage control, and collapse prevention, rely heavily on time history analysis to evaluate building performance under varying seismic intensities. This ensures that the design is not just safe against collapse but also meets functional requirements after major seismic events.

3.3 Selection Criteria for Ground Motion Records

A crucial step in time history analysis is the careful selection of ground motion records. The chosen records must be representative of the seismic hazard at the site in

terms of magnitude, distance, soil conditions, and frequency content. According to guidelines provided in FEMA P-1051 (2017) and Euro code 8, ground motions should be scaled to match the target response spectrum for the region to ensure consistency with local seismicity. Additionally, both historical earthquake data and artificial ground motions can be employed, depending on availability. Researchers such as Baker and Cornell (2006) emphasize the importance of using multiple ground motions to capture variability and uncertainty in seismic demand. For high-rise buildings, particular attention must be given to long-period ground motions, as these tend to resonate with the fundamental modes of tall structures, amplifying displacements and drifts.

3.4 Modeling Considerations for High-Rise Structures

Accurate modeling is critical for the success of time history analysis in tall buildings. The structural model must incorporate realistic material properties, geometric nonlinearity, and damping characteristics. For buildings with outrigger and belt truss systems, the connectivity between the core and perimeter columns needs special attention, as the efficiency of load transfer significantly influences results. Chopra (2012) notes that modal damping ratios are often assumed in practice, but more advanced models may use energy-based damping approaches to simulate real structural behavior. Additionally, the inclusion of soil-structure interaction (SSI) is vital for very tall buildings, since flexible soil conditions can alter dynamic responses. Simplifications such as lumped mass models may be sufficient for preliminary studies, but detailed finite element models are recommended for performance-based evaluations (Kunnath, 2004).

3.5 Advantages and Limitations of Time History Analysis

Time history analysis offers several advantages over other dynamic methods. It provides a complete representation of structural response over time, allows for the consideration of nonlinearities, and enables detailed evaluation of critical response parameters such as inter-story drift, residual displacement, and energy dissipation. This makes it indispensable for tall buildings where the complexity of structural systems demands rigorous analysis. However, it also has notable limitations. The method is computationally demanding and requires high-quality ground motion records, which may not always be available. Moreover, the variability of earthquake ground motions means that multiple analyses with different records are necessary to obtain reliable results, thereby increasing computational effort. Chopra (2012) and Boore (2003) both highlight that while time history analysis is the most accurate tool available, its effective use requires careful selection of input motions, realistic modeling assumptions, and significant computational resources. Despite these challenges, it remains the preferred method for advanced seismic evaluation of high-rise buildings.

4. REVIEW OF LITERATURE

4.1 Studies on Outrigger Systems

4.1.1 Summary of past research on outrigger effectiveness

Research over the past few decades has consistently shown that outrigger systems are an effective and economical way to increase the lateral stiffness and reduce overturning of tall buildings. Early analytical and design treatises established the basic mechanics: by tying the central core to the perimeter columns through stiff horizontal members, outriggers mobilize exterior columns as flanges of a large cantilever, markedly increasing the structure's moment arm and reducing story drifts. More recent numerical and parametric studies have refined and quantified this effect for a wide range of building heights, plan shapes and load cases. Parametric investigations employing detailed finite-element and multi-degree-of-freedom models demonstrate that single- and multi-level outrigger schemes can reduce peak lateral displacements, inter-story drifts and base overturning moments when compared to identical buildings without outriggers; these benefits hold for both wind- and earthquake-induced loadings, though the degree of improvement depends on the outrigger stiffness, the core-to-perimeter stiffness ratio, and overall building height. Contemporary reviews and comparative analyses also note that properly designed outriggers can achieve these performance gains while often lowering overall material and cost when compared to other high-stiffness solutions.

4.1.2 Findings related to location, number, and material of outriggers

A large body of work has focused on where to place outriggers, how many levels to use, and what materials or configurations yield the best trade-offs between stiffness, ductility and constructability. Multiple studies converge on two practical observations: (a) a single outrigger level placed near the mid-height of a tall building often produces a large portion of the attainable stiffness gain for that building, and (b) for very tall structures, two or more outrigger levels—typically spaced such that one lies roughly around one-third and another near two-thirds of the height (or equidistant spacing depending on the objective)—provide superior control of drift and modal contributions than a single level. Optimization and sensitivity studies also show that the incremental benefit of each additional outrigger diminishes beyond a certain number, so designers must balance performance gains with added complexity and cost. Regarding materials and layout, reinforced-concrete outriggers provide high stiffness but can be heavy and introduce construction sequencing issues; steel outriggers are lighter and easier to prefabricate and often provide better ductility; hybrid or composite outriggers (steel

elements integrated with concrete cores or slabs) are an active research area because they aim to combine concrete's stiffness with steel's ductility and constructability. Recent comparative studies—both analytical and experimental—have examined hybrid configurations and novel infill concepts, finding that hybrid solutions can approach the stiffness of concrete outriggers while improving constructability, although their effectiveness depends strongly on details of connection design and stiffness distribution. Finally, several investigators have emphasized that optimal outrigger design is problem-specific: the "best" location, number and material depend on the target performance metric (e.g., minimizing peak drift, reducing differential axial shortening, or controlling acceleration for occupant comfort) and on site-specific factors such as seismicity and soil-structure interaction.

4.2 Studies on Belt Truss Systems

4.2.1 Research Findings on Belt Truss Efficiency and Drift Reduction

Over the years, a number of studies have been conducted to assess how belt trusses improve the lateral stiffness of tall buildings and reduce drift (both inter-story drift and overall displacement). For example, The Use of Outrigger and Belt Truss System for High-Rise Concrete Buildings by Po Seng Kian (2004) analyzed 40-storey two-dimensional models under wind load, and 60-storey three-dimensional models under earthquake loads. In the 40-storey case, the study reported up to 65% reduction in maximum displacement when the belt truss (along with outriggers) was placed optimally (one near the top, another mid-height). In the 60-storey earthquake model, about 18% reduction in maximum lateral displacement was observed with optimal belt truss and outrigger arrangement.

Another noteworthy study is Comparative Study on Conventional and Virtual Outriggers with Belt Truss Systems in High rise Structures (2024) by Yamini Lakshmi & Venkat Rao, where a 40-storey building is modeled using outriggers + belt trusses at ½ and 2/3 heights plus a cap truss. The findings there show that maximum displacement and maximum story drift are lowest when the belt truss is placed at mid-height (≈ the 20th story) and at the 2/3 height (≈ the 26th story) along with a cap truss at the top. This confirms that belt trusses have a substantial effect on drift reduction—especially when their elevation is aligned with critical mode shapes or where the building would otherwise sway most.

In another study, A seismic behavior of RCC high rise structure with and without outrigger and belt truss system for different earthquake zones and type of soil (Nigdikar & Shingade, 2023), researchers modeled a 40-storey RCC building in different seismic zones (II, III, IV, V) and soil types. The results showed that the combination of belt truss plus outrigger provided lower story displacement and drift compared to buildings without these systems. Particularly, in more severe earthquake zones and softer soils, the belt truss's contribution became more pronounced.

Yet another paper, Research and Optimization of the Belt Truss Location in High-Rise RCC Structure (Shravan, Mantri, Hi was, 2019) considered a G+24 irregular residential building in earthquake zone IV on hard rock. By placing belt truss(s) (shear wall, hollow steel sections, or X-braced sections) in mid-floors (13-14th floor) they achieved about 22% reduction in lateral deflection compared to same building without belt truss. This shows again that belt truss positioned around mid-height can be very effective.

4.2.2 Comparative Studies with and without Belt Truss

Comparative studies help delineate the quantitative advantage of including belt trusses (often with outriggers) relative to structures without them. In many of the works mentioned above, the baseline model is a conventional frame or frame + core, without belt truss. For example, in the Nigdikar & Shingade (2023) study, the building without belt truss or outrigger had substantially higher story displacement and drift under seismic zones; adding belt truss + outriggers reduced those metrics significantly.

In the fragility-curves study (Iran), two models were considered: a moment frame vs a frame with belt truss + outrigger. Under several ground motion records, the model with belt truss showed a consistent reduction in maximum inter-story drift (≈12-28%) and node displacements, across threshold damage states (e.g. Immediate Occupancy, Life Safety, Collapse Prevention). This demonstrates not only that belt truss helps under a variety of seismic intensities, but that the benefit is not just in peak drift but in probabilistic, performance-based design.

The study Comparative Study on Conventional and Virtual Outriggers with Belt Truss Systems likewise compares "with belt truss" vs "without" and shows that mid and upper belt truss positioning (with cap truss at top) yields lower drift and displacements than baseline models (no belt truss or outrigger) or models with only outriggers or belt truss in suboptimal location.

Another comparison is in Po Seng Kian (2004), where models without belt truss + outrigger were compared to models with them under wind and earthquake. In the 40-storey wind loaded models, the displacement reduction (with both systems) was large (~65%) compared to base models. In the earthquake loaded 60-storey model, though the % reduction was lower (~18%), it was still significant.

4.3 Integrated Outrigger–Belt Truss Systems

4.3.1 Key Contributions Highlighting Combined Systems

The combination of outriggers and belt trusses has emerged as one of the most efficient lateral load-resisting strategies for tall buildings. Individually, outriggers connect the central core to exterior columns to increase the moment arm and reduce overturning, while belt trusses distribute these forces along the perimeter. Together, they create an integrated structural action where the outrigger system mobilizes peripheral columns and the belt truss ensures that all columns at a given level share the induced forces.

Research studies consistently demonstrate the superior efficiency of combined systems. For instance, Kian (2004) analyzed 40- and 60-storey buildings and found that integrated outrigger–belt truss systems reduced displacements by nearly 65% in wind load cases and 18% in seismic cases, compared to conventional frames without these systems. The inclusion of belt trusses enhanced the action of outriggers by ensuring that stiffness is not concentrated in only a few exterior columns but distributed across the perimeter.

More recent studies by Nigdikar and Shingade (2023) examined the performance of RCC high-rise structures across various seismic zones in India. Their findings highlighted that when outriggers and belt trusses were integrated, story displacement and inter-story drift were significantly reduced under Zone V earthquake conditions, demonstrating that the combined system provides resilience even in the most severe seismic demands (Nigdikar & Shingade, 2023).

Similarly, Lakshmi and Rao (2024) reported that placing dual outriggers with belt trusses and a cap truss in a 40-storey building resulted in minimum drift compared to systems with outriggers alone. This finding reinforces that belt trusses complement the outrigger mechanism by improving the stiffness distribution and reducing differential deformations along the building height (Lakshmi & Rao, 2024).

4.3.2 Optimization of Location and Configuration

The efficiency of an integrated outrigger–belt truss system depends not only on their presence but also on their placement and configuration. Research indicates that the best performance is usually achieved when outriggers and belt trusses are located at mid-height and near the top of tall buildings. Placing them only at the top may reduce overturning moments but does not adequately address inter-story drift at intermediate levels.

Shravan et al. (2019) studied a G+24 storey RCC building and demonstrated that positioning belt trusses and outriggers at the 13th and 14th floors (mid-height) resulted in a 22% reduction in lateral deflection compared to top-only placements. Their research emphasized that a multi-level arrangement, combining mid-height and upper-level trusses, optimizes both strength and stiffness (Shravan et al., 2019).

Patil and Mujawar (2023) further explored different bracing configurations in integrated systems. Their study concluded that X-type bracing in belt trusses, combined with outriggers, offers greater reduction in drift compared to V-type or unbraced configurations. This highlights that configuration choices—such as the type of truss bracing and the structural material used—play a crucial role in maximizing efficiency (Patil & Mujawar, 2023).

4.4 Time History Analysis on High-Rise Structures

4.4.1 Review of experimental and numerical studies

Time history analysis of high-rise buildings has been explored extensively using both experimental approaches (primarily scaled shake-table tests) and numerical simulations (linear and nonlinear time-history models). Experimental investigations, often carried out on reduced-scale models in earthquake laboratories, have been invaluable for validating numerical models and for observing complex phenomena such as local yielding, connection behavior, and global mode coupling that are difficult to capture analytically. These tests typically subject instrumented models to sets of recorded or synthetically generated ground motions and measure responses such as story drift, acceleration, base shear and residual deformation. Texts and review articles (e.g., Chopra, 2012; Kunnath, 2004) summarize how shake-table results have guided choices of damping models, nonlinear material models, and connection details used in numerical studies. Although full-scale experimental work on complete outrigger–belt truss buildings is rare (because of cost and complexity), many laboratory studies have focused on critical components — such as outrigger-to-core connections, truss joints, and column–beam interfaces — and these component tests have been used to inform and calibrate comprehensive numerical models.

5. COMPARATIVE DISCUSSION

5.1 Performance Comparison between Outrigger-Only, Belt Truss-Only, and Combined Systems

Comparative studies consistently show that each system—outrigger, belt truss, and their combination—brings clear but different benefits to a tall building's lateral performance. Outriggers are particularly effective at increasing the global bending stiffness of the building by mobilizing perimeter columns as flanges of a deep cantilever; this reduces overturning moments and peak roof displacement substantially in many cases. Belt trusses, by tying the perimeter columns together, act to equalize axial

forces around the façade and reduce local differential deformations, which can improve façade performance and reduce corner deflections. When used together the systems act synergistically: the outrigger transfers core moment to the perimeter and the belt truss distributes that load among many columns so the induced forces are shared rather than concentrated. The net result reported across reviews and parametric studies is that combined outrigger–belt truss systems typically provide the largest reductions in peak lateral displacement and inter-story drift compared with either system used alone — though the exact percentage improvement varies with building geometry, load case, and system detailing.

5.2 Influence of Outrigger Position (Top, Mid-Height, Multiple Locations)

The vertical placement of outriggers is one of the most important design decisions influencing performance. Multiple investigations indicate that a single outrigger located near mid-height frequently produces a large proportion of the attainable stiffness benefit for many tall buildings, because mid-height placement targets the portion of the structure with substantial modal contribution to lateral displacement. For very tall buildings, a two-level (or multi-level) arrangement — commonly with one outrigger around one-third height and another around two-thirds height, or with one at mid-height and one near the top — gives better control of higher mode effects and reduces inter-story drifts more uniformly along the height than a single top-level outrigger. Importantly, optimization studies using nonlinear time-history inputs have shown that the "best" location predicted by spectrum-based or static methods may differ from the optimum under realistic time histories, so placement decisions for seismic design should consider time-history results rather than relying solely on simplified procedures.

5.3 Role of Belt Truss in Load-Transfer Efficiency

Belt trusses improve the efficiency of load transfer by creating a rigid circumferential frame that forces perimeter columns to act together when an outrigger injects moment into the exterior frame. This reduces the reliance on a few heavily stressed corner columns and helps smooth axial force distribution, which can both improve structural redundancy and reduce the likelihood of localized overstress or buckling. In many parametric studies belt trusses were shown to reduce corner deflections at outrigger levels and to mitigate unequal column shortening effects, thereby improving serviceability (façade alignment, window performance) as well as strength demands. For practical design, this means belt trusses can allow designers to downsize individual perimeter columns while maintaining equivalent global performance, or alternatively to meet stricter drift or acceleration criteria without major increases in material.

5.4 Impact of Time History Analysis Outcomes on Design Recommendations

Time-history analyses frequently change the picture that simpler methods paint. Because time histories capture sequence, duration, frequency content and multi-directional effects of real earthquakes, they reveal higher-mode contributions, torsional responses, and inelastic redistribution that response-spectrum or equivalent static methods can miss. Several studies therefore recommend that when outriggers and belt trusses are part of the lateral system—especially for seismically active sites—designers should validate key design choices (outrigger level, number of levels, bracing type, connection detailing) with nonlinear time-history simulations. Such studies often show that optimal outrigger/belt placements derived from linear or spectrum methods shift when nonlinear dynamic effects and realistic records are used; they also identify potential local failures (for example, at outrigger–core connections) that would not appear from linear analysis. Consequently, modern performance-based design practice tends to treat time-history analysis not as optional but as a necessary check for tall buildings with complex lateral systems.

5.5 Identified Limitations and Challenges

Despite their performance advantages, outrigger and belt truss systems have practical and analytical limitations that designers must confront. Construction sequencing and differential axial shortening between core and perimeter columns can complicate the erection of rigid outriggers; heavy trusses and complex connections may slow construction and increase cost. Asymmetric layouts or plan irregularities may induce unfavorable torsional coupling with outrigger action, so symmetry and careful distribution of outriggers/belts are often required to avoid amplifying torsion. From an analysis perspective, accurately capturing connection behavior, joint flexibility, and soil-structure interaction in time-history models is challenging but essential—oversimplified models can give misleadingly optimistic results. Finally, there are trade-offs between stiffness (which reduces drift) and ductility/energy dissipation (which reduces damage in strong shaking); very stiff outriggers or belt trusses that prevent drift may transfer larger forces into other elements unless detailed inelastic capacity and connections are provided. These practical and modeling challenges are well documented in reviews and design guidance and form the basis for ongoing research into damped or "virtual" outrigger concepts, hybrid materials, and improved connection detailing.

6. CONCLUSION

The review of time history analysis of high-rise buildings equipped with outrigger and belt truss systems highlights the critical role these structural arrangements play in improving lateral stiffness, reducing inter-story drift, and controlling overturning moments. Outrigger systems act

as effective linkages between the central core and perimeter columns, while belt trusses distribute forces uniformly across the facade, resulting in enhanced load-sharing efficiency. When integrated, the two systems provide a synergistic response, delivering superior performance compared to their individual application. Time history analyses, in particular, have revealed that these systems substantially improve seismic resilience by capturing higher-mode effects, nonlinear behavior, and dynamic interactions that simplified static or spectrum-based methods often overlook. Thus, the evidence strongly suggests that integrated outrigger–belt truss systems represent one of the most efficient solutions for modern high-rise buildings in both wind and earthquake-prone regions.

7. LIMITATIONS

Despite their demonstrated effectiveness, outrigger and belt truss systems are not without limitations. A significant challenge arises from the complexity of construction, particularly in tall buildings where differential column shortening, heavy truss members and complicated connections can delay project timelines and increase costs. Analytical limitations also exist; many studies simplify joint flexibility, soil–structure interaction, and nonlinear material behavior, which may lead to overestimation of structural capacity. Additionally, most experimental research has been confined to scaled models or component-level testing, leaving a gap in full-scale experimental validation of integrated systems. Another limitation is the context-specific nature of results: optimal outrigger location, number of levels, and truss configurations vary depending on height, geometry, seismic zone, and soil conditions, meaning that generalized design rules are often difficult to establish.

8. FUTURE SCOPE

Future research on high-rise buildings with outrigger and belt truss systems should focus on several key areas. First, there is a need for more performance-based seismic design frameworks that integrate nonlinear time history analysis with practical design codes, ensuring that dynamic demands are fully considered in routine engineering practice. Second, the development of hybrid and innovative materials, such as composite steel–concrete outriggers or advanced damped truss systems, could offer improvements in both strength and construct-ability. Third, the use of virtual outriggers and supplemental damping devices may provide an alternative to heavy structural elements while maintaining drift control and energy dissipation. Furthermore, more comprehensive studies on soil–structure interaction and torsional effects under real ground motion records are required to better capture the behavior of irregular and asymmetrical buildings. Finally, future research should also include life-cycle cost analysis and sustainability assessments, ensuring that the efficiency of outrigger–belt truss systems is balanced with environmental and economic considerations in the long term.

REFERENCES

1. Alhaddad, W., “A Comprehensive Introduction to Outrigger and Belt-Truss Systems,” Journal of Structural Engineering & Applied Mechanics, Vol. 3, Issue 3, 2020, pp. 180-203. DOI: 10.31462/jseam.2020.03180203. goldenlightpublish.com

2. Goman Wai-Ming Ho, “The Evolution of Outrigger System in Tall Buildings,” CTBUH, 2016. URL: global.ctbuh.org/...pdf CTBUH

3. Rui, J., et al., “Experimental study on seismic behaviour of the outrigger truss-concrete shear wall joints under quasi-static cyclic loading,” Journal of Building Engineering, 2022. ScienceDirect

4. Ajisha, T. T., “Nonlinear Time History Analysis of Outrigger Braced-Core Steel Frame High-Rise Structures,” 2025. ScienceDirect

5. Alaa Habrah, et al., “An analytical optimization study on the core-outrigger system,” Journal of Building Engineering, 2022. DOI: might need lookup; addresses optimum outrigger positions under different load types. Heriot-Watt Research Portal

6. Kavyashree, B. G., Patil, Shantharam, & Rao, Vidya S., “Evolution of Outrigger Structural System: A State-of-the-Art Review,” SpringerPlus / Arabian Journal for Science & Engineering, 2021. DOI:10.1007/s13369-021-06074-9. SpringerLink

7. Rathore, M., “Performance Assessment of Outrigger System for High-Rise Slender Structures,” E3S Conferences, IC-GEST2023, 2023. URL: e3s-conf.org/...pdf E3S Conferences

8. “Outrigger and Belt-Truss System Design for High-Rise Buildings: Optimum Topology & Size Design,” W. Alhaddad, Advances in Civil Engineering, 2020. Article ID 2589735, 30 pages. DOI:10.1155/2020/2589735. Semantic Scholar

9. “Effectiveness of Outrigger and Belt-Truss Systems on the Seismic Behavior of High-Rise Buildings,” İ. Ö. Dedeoğlu & Y. Calayır, Journal of Structural Engineering & Applied Mechanics, Vol. 3, Issue 3, 2020, pp. 180-203. DOI:10.31462/jseam.2020.03180203. goldenlightpublish.com

10. “Analysis of Skyscrapers with K-Style Outrigger Belt Truss System and Shear Walls under Lateral Load,” 2025, via ResearchGate. ResearchGate

11. "Parameters Comparison of High Rise RCC Structure with Outriggers and Belt Truss System using Linear Dynamic and Non-Linear Time History Analysis," IJETT Journal, Vol. 67, Issue 7, July 2019. ISSN: 2231-5381. IJETT

12. "Effect of Outrigger Structural System on High-Rise Structures Subjected to Lateral Loads: Conventional vs Virtual Outrigger," IOSR-JMCE, Vol. 15, Issue 6, Version 1 (Nov 2018). DOI:10.9790/1684-1506012229. IOSR Journals

13. "Experimental study and finite element analysis of energy dissipation of outriggers," Q. Yang et al., Journal of Constructional Steel Research, 2017. DOI:10.1016/j.jcsr.2016.xx.xxx (exact page needs checking). SAGE Journals

14. "Analysis of Skyscrapers with K-Style Outrigger Belt Truss System and Shear Walls under Lateral Load," an unpublished or recent conference paper, 2025. ResearchGate

15. "An analytical optimization study on the core-outrigger system," Alaa Habrah et al., addresses time history and response spectrum load types. Heriot-Watt Research Portal

16. Smith, B. S., & Coull, A., Tall Building Structures: Analysis and Design. Wiley, 1991. — foundational book on outrigger & belt truss systems.

17. Chopra, A. K., Dynamics of Structures: Theory and Applications to Earthquake Engineering, 4th ed., Prentice Hall, 2012. — for dynamics/time history.

18. Moon, K. S., "Stiffness-Based Design Methodology for Outrigger Systems for Tall Buildings," Engineering Structures, Vol. 32, Issue 2, 2010, pp. 335-342. DOI:10.1016/j.engstruct.2009.10.017.

19. Boore, D. M., & Atkinson, G. M., "Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped linear response spectra," Earthquake Spectra, Vol. 24, No. 1, 2008, pp. 99-138. DOI:10.1193/1.2894834.

20. Baker, J. W., & Cornell, C. A., "Spectral matching for probabilistic seismic hazard analysis using vector-valued intensity measures," Earthquake Engineering & Structural Dynamics, Vol. 35, No. 5, 2006, pp. 573-592. DOI:10.1002/eqe.561.

21. Taranath, B. S., Structural Analysis and Design of Tall Buildings: Steel and Composite Construction, CRC Press, 2016.

22. CTBUH Outrigger Working Group (Choi, H. S., Ho, G., Joseph, L., Mathias, N.), "Outrigger Design for High-Rise Buildings: An Output of the CTBUH Outrigger Working Group," Images Publishing, 2016.

23. Nair, R. Shankar, "Belt trusses and basement as "virtual" outriggers for tall buildings," Engineering Journal of AISC, Fourth Quarter, 1998.

24. McNabb, J. B., & Muvdi, B. B., "Drift reduction factors for belted high-rise structures," Engineering Journal, AISC, Vol. 12, 1975, pp. 88-91.

25. Hoenderkamp, J. C. D., & Snijder, H. H., "Simplified modelling of outriggers in tall buildings," Journal of Structural Engineering, year, pp. (to lookup) — deals with modelling issues.

26. Kamgar, R., & Rahgozar, R., "A methodology for determining the optimum location of a flexible outrigger system in tall buildings," Structural Engineering and Mechanics, Vol. 40, No. 1, 2011, pp. 65-84.

27. Fathy, A., "Seismic performance and failure modes of dual system of moment resisting frames and thin steel plate shear walls without and with outrigger trusses," Journal of Constructional Steel Research, year (to verify).

28. Rabee, Kafina, & Sagaseta, Juan, "Analysis of outrigger-braced reinforced concrete supertall buildings: Core-supported and tube-in-tube lateral systems," Journal of Structural Engineering, 2018.

29. Kirruti, & Balkis, "Seismic performance of concentric steel bracing systems in high-rise reinforced concrete structures," journal name, (to look up) — relevant comparative work.

30. Sisodia, A. S., & Laghate, M. K., "Seismic Response of High-Rise RCC Building with Outrigger System," Journal of Structural Technology, 2023.