

Research Article

Comparative Study of Adding Outrigger System to Supertall Building Using Static Pushover Analysis

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Abstract

Outrigger systems represent a range of contemporary structural solutions that have been employed to enhance the lateral performance of supertall buildings, a prime example of this being the Burj Khalifa. The systems under discussion consist of a central core which is connected to perimeter structural elements through outrigger walls located at selected stories. These systems are often complemented by a surrounding belt truss. The present study investigates the effectiveness of outrigger systems through the utilization of static pushover analysis. A comparative assessment is conducted in order to ascertain the optimum outrigger configuration. A comparative analysis is conducted on four models of a 136.8 m supertall building, incorporating varying outrigger arrangements, in contrast to a conventional baseline model devoid of outriggers. The performance of all models is evaluated in terms of the performance point obtained under response spectra derived from real earthquake records. The most effective outrigger configuration is identified for each loading case.

Keywords: Supertall Building; Outrigger System; Static Pushover Analysis; Performance Point.

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Introduction

The escalating demand for safe and resilient high-rise structures has led to a surge in research endeavours focused on structural systems that are capable of effectively resisting seismic and wind-induced lateral loads. Among these systems, outrigger-based configurations have emerged as one of the most efficient solutions for enhancing the global stiffness and stability of tall buildings. Outrigger systems function by establishing a connection between the central core and the perimeter columns, thereby enabling the entire structural system to function collectively in resisting lateral actions. This interaction has been shown to have a significant effect on the reduction of overturning moments, lateral displacements and internal force demands. This, in turn, has been demonstrated to improve the overall seismic performance of supertall structures.

A substantial corpus of research has been undertaken to evaluate the structural efficiency of outrigger systems under varying loading and configuration conditions. Numerical investigations using software such as ETABS have demonstrated that outrigger systems can substantially enhance lateral load resistance in high-rise buildings subjected to both seismic and wind actions (Kushwaha & Mishra, 2022; Tiwary et al., 2026). Comparative studies between conventional and hybrid outrigger systems have further highlighted the influence of building height and system configuration on structural performance (John & Kamath, 2024; Nissanka et al., 2023). Furthermore, pushover analyses have been extensively utilized to evaluate the nonlinear structural behaviour and performance-based design of buildings equipped with various lateral load-resisting systems (Anjum et al., 2026; Kasliwal et al., 2025; Keshava Murthy & L K, 2019).

The effectiveness of outrigger systems is influenced by several design parameters, including their stiffness, location along the building height, and interaction with belt trusses or shear walls. It has been demonstrated by earlier research that the optimal placement of outriggers, frequently guided by classical approaches such as the Taranath (2012) method, can considerably enhance structural efficiency (Hidayat & Wirabuana, 2025; Jankar et al., 2026). Furthermore, the integration of hybrid systems, such as steel-concrete composite outriggers or systems integrated with shear walls and steel plate elements, has been demonstrated to exhibit enhanced seismic behaviour and reduced column forces (Asadi et al., 2011; Kamble & Raut, 2024; Wang, 2019). These advancements underscore the continuous evolution of outrigger systems from conventional rigid elements to more sophisticated hybrid and composite configurations.

Recent research has also explored the integration of damping devices within outrigger systems to further enhance seismic resilience. The efficacy of viscous dampers, metallic fuse elements and other energy dissipation mechanisms in reducing dynamic responses and mitigating structural damage under strong ground motions has been demonstrated (Amin Afshar et al., 2026; Hope et al., 2026; Shehzad et al., 2025). Time-history analyses have confirmed that such damped outrigger systems are capable of capturing higher-mode effects and nonlinear behaviour with greater accuracy, thereby resulting in enhanced performance in comparison with traditional systems (Kumar Yadav & Kumar, 2025).

Concurrently, a growing body of research has underscored the significance of advanced analysis methodologies in the context of seismic performance of high-rise buildings. These methodologies encompass response spectrum analysis, nonlinear static pushover procedures, and time-history simulations (Zaher et al., 2024; Kuria et al., 2024; Ashwini et al., 2024). These approaches facilitate a more comprehensive understanding of structural response, particularly in the context of irregular or complex configurations (Chittiprolu and Kumar, 2014; Haque Ovi et al., 2025). Furthermore, hybrid structural systems combining reinforced concrete cores with composite frames have demonstrated enhanced seismic behaviour and damage control capabilities (Mahmoud et al., 2024; Xiong et al., 2016).

Notwithstanding the substantial corpus of research, there are still several challenges to be addressed in optimising outrigger system design, particularly with regard to configuration efficiency, material selection, and integration with contemporary performance-based design frameworks. Consequently, recent studies have concentrated on evaluating various structural arrangements, materials, and analysis techniques to identify optimal solutions for high-rise buildings under varying loading scenarios (Masrilayanti et al., 2023; Rathore et al., 2023; Regundwar, 2025).

The present paper analyses outrigger systems in terms of the position and number of hybrid outriggers, by means of nonlinear static pushover analysis. An investigation is conducted into the behaviour of different outrigger location systems under various seismic response spectra. In the instance of three probability levels being considered (2%, 5%, 10%), the probability of exceedance is taken into account. The objective is to obtain a performance matrix that ensures the model remains operational for earthquakes with a 10% probability of exceedance. Furthermore, the model should be transitioned to the Immediate Occupancy (IO) stage for earthquakes with a 5% probability of exceedance, and subsequently to the Life Safety (LS) stage for earthquakes with a 2% probability of

exceedance. Moreover, the objective of this research endeavour is to ascertain the minimum number of plastic hinges required in columns.

Methods

The present research employs analytical and comparative methodologies, utilising static pushover analysis via ETABS. A number of comparisons were conducted between the conventional core system and the core-outrigger system, with different outrigger numbers (see Fig. 5). The conventional model is presumed to be located in proximity to Aleppo in Syria. The design is undertaken in accordance with the dead load, live load and static equivalent load as delineated in UBC 97-zone 2B soil type S_D . The UBC97 model has been selected for use, given the absence of accurate seismic parameters (S_1 , S_s) and the 2% probability of exceedance (2,475 years) in Syria. This renders the application of ASCE 7 double-period response spectra unfeasible. In addition, the UBC97 seismic load combinations were taken into consideration (International Code Council, 1997). The hybrid system, comprising outrigger and belt components, is configured in a number of ways. The first configuration consists of one outrigger at 0.455L, with a second outrigger positioned at the top. The second configuration comprises two outriggers: one at 0.577L and the other at the top, while the third configuration features two outriggers, with one at 0.31L and the other at 0.7L. Finally, the fourth configuration involves three outriggers, with one at 0.31L, the second at 0.7L, and the third at the top, as recommended by Günel & Ilgin (2014).

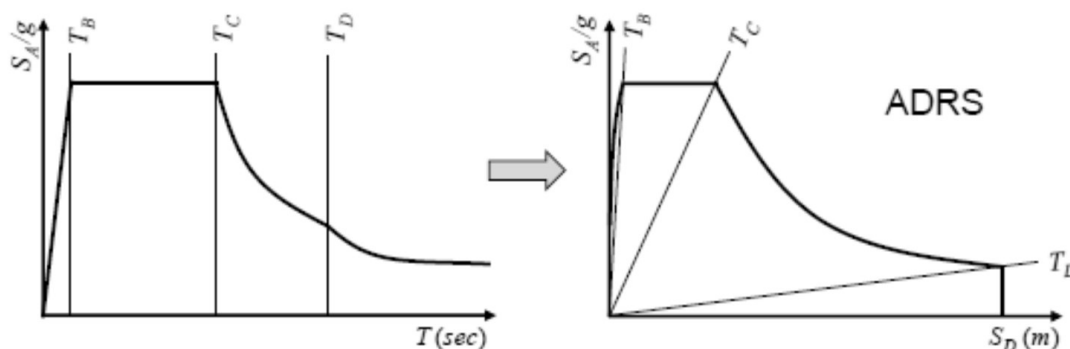


Figure 1. Converting Response Spectrum into ADRS

Secondly, the shear force-displacement curve is transformed into a capacity curve through several procedures. The shear force coordinate is converted into spectral acceleration, and the displacement coordinate is converted into spectral displacement.

The spectral acceleration is calculated from equation 2, in which it is related to a factor, W , i.e. the weight of the structure. The calculation of where is performed using equation 3, which is contingent upon

Capacity Spectrum Method

The analysis method that was ultimately adopted was the Capacity Spectrum Method (CSM), as outlined in FEMA (2005). The concept is predicated on the development of both a capacity curve and a demand curve. The combination of these two curves yields a performance point that signifies the behaviour of the structure under consideration. The capacity curve is derived from the shear force-displacement curve. However, it is important to note that the demand curve is an ADRS curve, i.e. the Acceleration Displacement Response Spectrum of the seismic zone under study.

Firstly, the push-over analysis technique is employed to generate a shear force-displacement curve. This is achieved by conducting a nonlinear analysis of a building model's behaviour. The structure under consideration is characterised by the presence of a single degree of freedom.

As illustrated in Figure 1, the transformation of the response spectrum into an ADRS curve is demonstrated. As demonstrated in equation (1), the spectral displacement S_D is obtained by multiplying the spectral acceleration, S_a , by $T^2 / 4\pi^2$. It is important to note that S_a remains constant in this equation.

$$T = 2\pi \sqrt{\frac{S_D}{S_a}} \quad (1)$$

T : fundamental period of the structure (sec).

S_a : Spectral acceleration

the first mode shape of the structure and the vertical distribution of its weight.

$$S_a = \frac{V/W}{\alpha_1} \quad (2)$$

Where:

$$\alpha_1 = \frac{(\sum W_i \phi_i / g)^2}{(\sum W_i / g)(\sum W_i \phi_i^2 / g)} \quad (3)$$

ϕ_i : first mode shape coordinate at level i .

The subsequent step in this process is to calculate the spectral displacement by means of equation 3. The function is contingent upon the displacement, the PF1 factor, and the maximum value of the first mode at the apex of the structure, denoted by ϕ_1 .

$$S_d = \frac{\Delta}{PF_1 \phi_1} \quad (4)$$

The PF_1 Factor is the participation factor of the first dynamic mode, calculated from equation 5.

$$PF_1 = \frac{\sum(W_i \phi_{i1})/g}{\sum(W_i \phi_{i1}^2)/g} \quad (5)$$

Accordingly, the SECANT period of the structure at any point on the capacity curve is calculated by equation 6.

$$T = 2\pi \sqrt{\frac{S_d}{S_a}} \quad (6)$$

As previously stated, identifying the performance point necessitates the integration of the capacity curve and the demand curve, as illustrated in Figure 3.

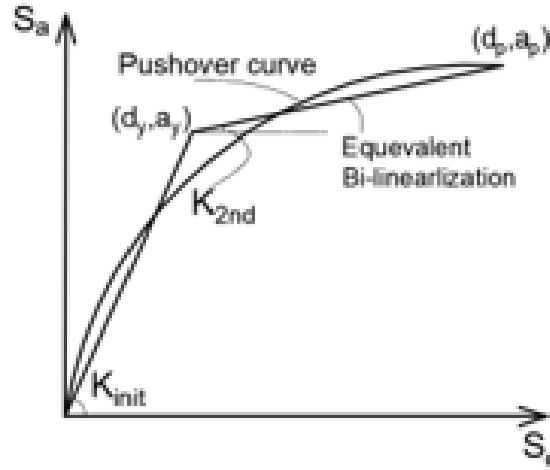


Figure 2. Capacity Curve Characteristics, FEMA 440

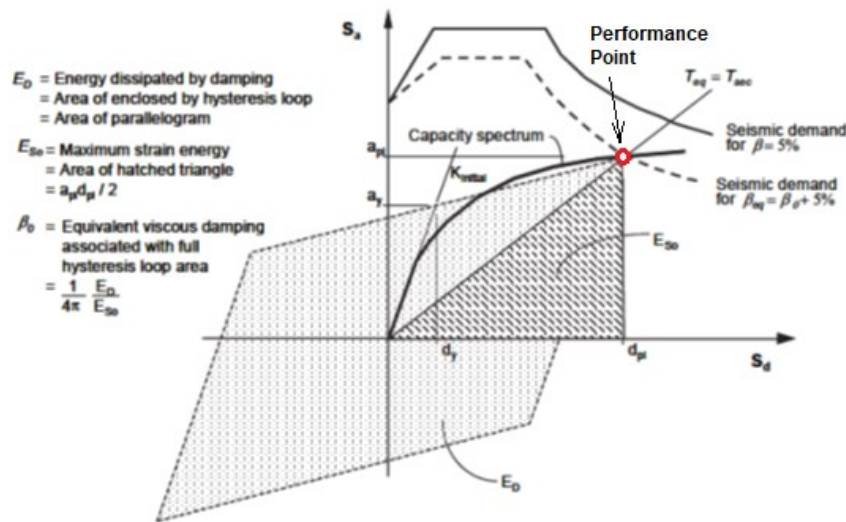


Figure 3. Graphical Representation of the Capacity-Spectrum Method of Equivalent Linearization

It is imperative to note that the demand curve should be modified by a new damping ratio that is specific to the structure at the performance point. This is calculated directly from the capacity curve (Figure 1). The subject is related to the ductility ratio (equation 7), the initial and second stiffness of the structure (equation 8).

$$\mu = \frac{d_p}{d_y} \quad (7)$$

$$K_{init} = \frac{a_y}{d_y} \quad K_{2nd} = \frac{(a_p - a_y)}{(d_p - d_y)} \quad (8)$$

$$\alpha = \frac{K_{init}}{K_{2nd}} \quad (9)$$

$$\beta_{eff} = \beta_0 + \kappa \frac{2(\mu - 1)(1 - \alpha)}{\pi\mu(1 + \alpha\mu - \alpha)} \quad (10)$$

The damping ratio is applied to the demand curve, represented by response spectra, by two factors, as demonstrated in equations 11 and 12:

$$SR_a = (3.21 - 0.681 \ln \beta_0) / 2.12 \quad (11)$$

$$SR_v = (2.31 - 0.41 \ln \beta_0) / 1.65 \quad (12)$$

The SR_a factor is applied to the maximum straight part of the response spectrum, while the SR_v factor is applied to the curve part of the response spectrum.

Model Description

The structure under consideration is a forty-storey building, measuring 32 x 32 m. The ground floor has a height of 4.2 m, while the typical floor is 3.4 m high. The total height of the building is 136.8 m. The life load has been established at 5.0 kN/m², while the flooring load has been determined to be 3.0 kN/m². The Slab is a monolithic structure composed of a 25-cm-

thick slab, which is supported by columns, shear walls and a mega-core. Spandrel beams are characterised by a section measuring 40 x 90 cm. In contrast, peripheral beams, as depicted in standard designs, possess a section measuring 25 x 60 cm. Table 1 provides a comprehensive overview of the various sections of vertical elements. Concrete grade C48 is to be used for vertical elements, while C32 is to be used for slabs and beams. The RC outrigger and belt, which have been added, have a thickness of 500 mm. As illustrated in Figure 4, the conventional plan and outrigger plan of the edifice are displayed. The expected yield strength that is considered in the backbone curve is as follows: It is imperative to note that (f_{ye}) is taken at 1.25 times the nominal yield strength (f_y) for braces and reinforcement. In accordance with the provisions stipulated in ASCE 41-13, it is anticipated that the compressive concrete strength (f'_c) will be equivalent to 1.3 times the lower-bound compressive strength ($f'_c=25\text{MPa}$).

Table 1. Sections of Vertical Elements

Storey	Columns Section (cm)	Core and Shear Walls Thickness (cm)
From 1 to 15	100x100	70
From 16 to 30	80x80	55
From 31 to 40	60x60	40

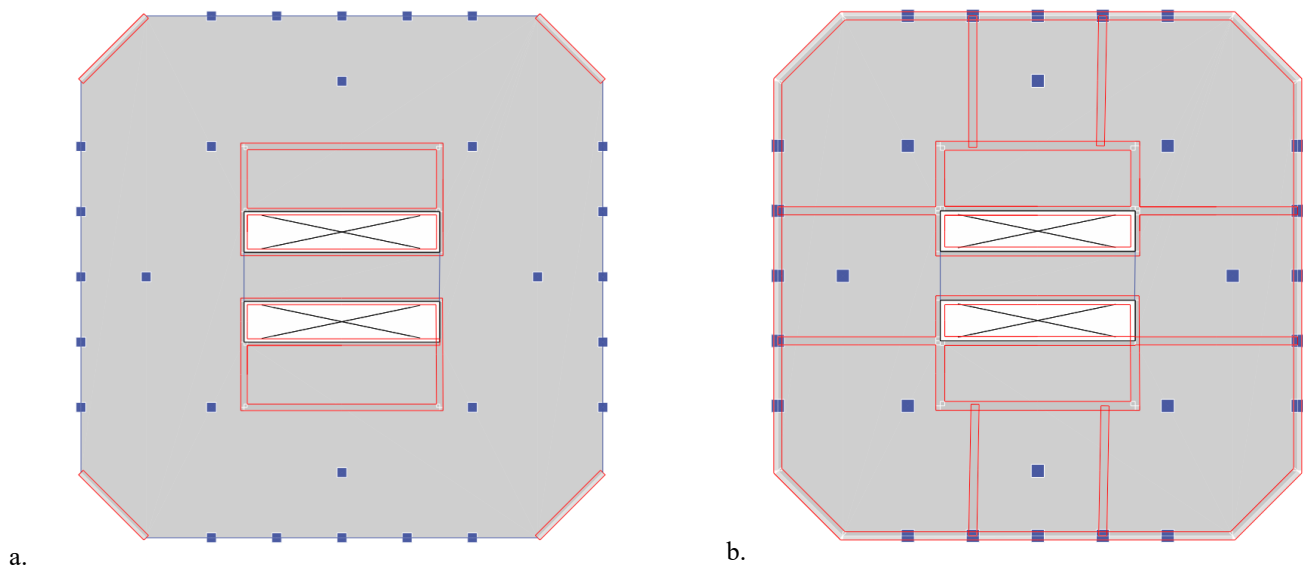


Figure 4. Models Plans: a. Typical Plan, b. Outrigger and Belt Plan

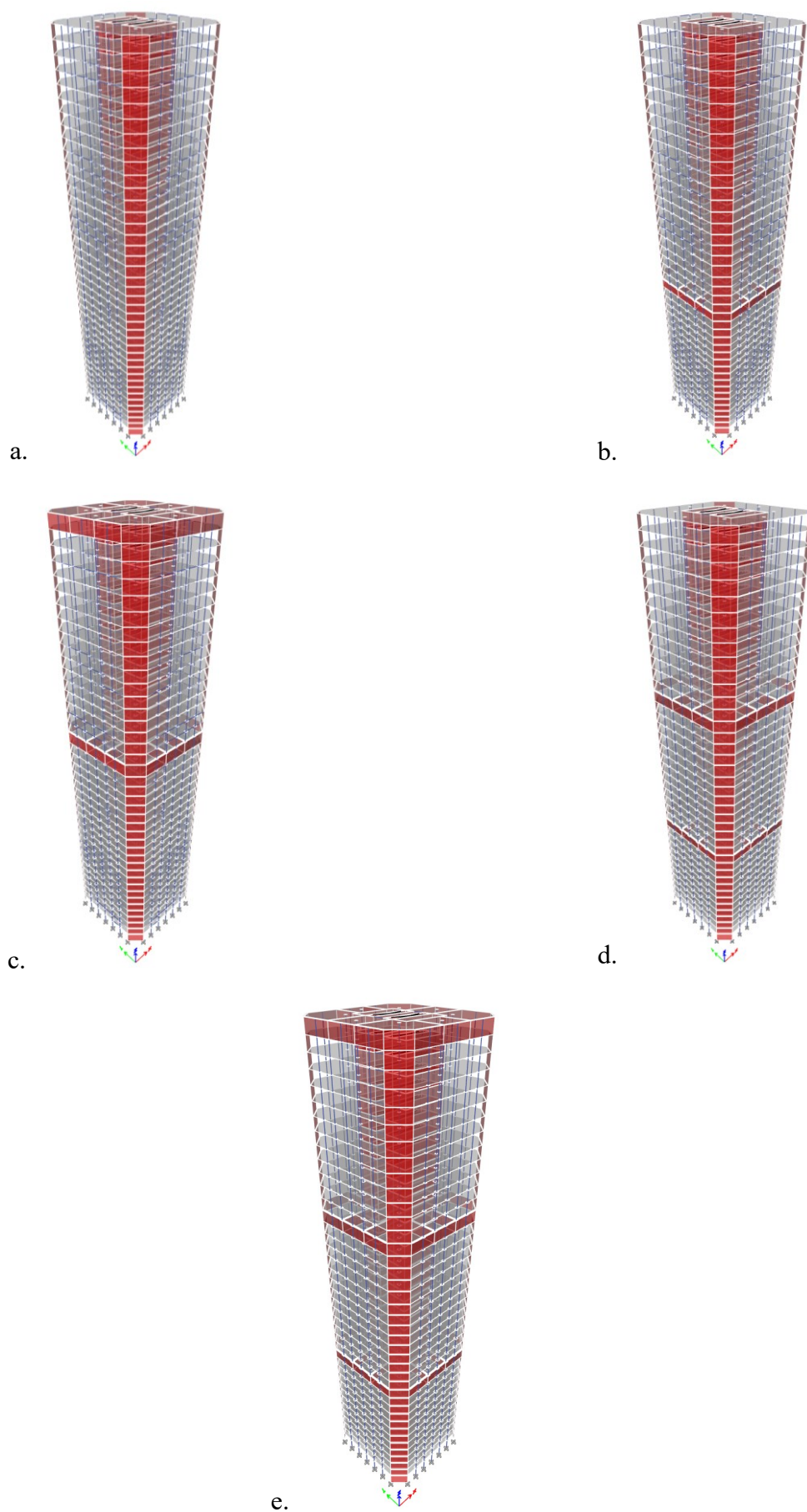


Figure 5. a. Conventional Model, b. One Outrigger - $0.455L$, c. Two Outriggers - $0.0L$ and $0.577L$, d. Two Outriggers - $0.31L$ and $0.7L$, e. Three Outriggers $0.0L$, $0.31L$ and $0.7L$

The primary objective of this study is to gain a comprehensive understanding of the behaviour of the core-outrigger system under earthquake response spectra. This will be achieved by employing nonlinear static pushover analysis as a methodological approach. In accordance with the provisions stipulated in ASCE 41-13 (2014), the definition of plastic hinge backbone curves was executed in a fully automated manner within the ETABS framework. As delineated in ASCE 41-13, "Concrete Beams: Flexure M3 Degree of Freedom," the beams hinges are defined as the points of articulation between the beam and its supporting structure, thereby enabling rotation around a single axis. These hinges are characterised by their resistance to flexure, with a maximum permissible deflection of M3, as specified in the aforementioned standard. As illustrated in the American Society of Civil Engineers (ASCE) 41-13, concrete columns are subject to a specific degree of freedom at the commencement and conclusion of their structure. The shear wall hinges in question are of the auto fibre P-M3 variety, in accordance with the specifications set out in the ASCE 41-13 standard. A meticulous examination of the vital parameters is conducted, encompassing the top displacement and the quantity of plastic hinges. In order to ascertain the performance point, the response spectra (ASCE 7-22, 2022) were applied as a seismic demand for three different probability of exceedance and return intervals, i.e. 10% (475 years), 5% (975 years) and 2% (2475 years). In the absence of accurate seismic parameters in Syria, particularly with regard to the 5% (975 years) and 2% (2475 years) probability of exceedance, the values of the seismic parameters of period one second, S_1 , and short period, S_s , are obtained from the USGS website (USGS.Gov | Science for a Changing World, n.d.) for a district in zone 2B according to UBC97 (International Code Council, 1997), which is Portland. Subsequently, the site modification factors, F_a and F_v , are obtained from ASCE 7-22 (2022) for site S_D . The complete set of values is enumerated in Table 2.

Analysis Procedure

The models were analysed by ETABS using nonlinear static pushover analysis, incorporating the P-delta effect given that the models under consideration were of supertall buildings.

It should be noted that the differences observed when comparing the analysis incorporating the P-delta effect and the analysis without P-delta effect were negligible, at approximately 1-2%. This is presumably due to the symmetry of the models. However, the analysis incorporating the P-delta effect was adopted since it is more accurate. The results of the analysis are presented in Table 3 for all models under the response spectrum, with a 2% probability of exceedance. As demonstrated in Figure 6, the capacity curves were obtained in terms of base shear and displacement. It is evident that the response initially exhibits characteristics of stiff linear elasticity, where the base shear increases in proportion to the displacement. Subsequently, the curve intersects the second stage, at which point it becomes flat, indicating a reduction in stiffness and an increase in ductility. It is evident that the maximum force capacity increases with the number of outriggers.

The capacity curves are converted into spectral form by the equations (2, 3, 4, 5). As illustrated in Table 2, the demand curves correspond to the three response spectra that have been tabulated. These spectra are characterised by three different return intervals and exceedance probabilities. The transformation of these curves into ADRS curves is achieved through the utilization of equation (1). Figure 7 provides a visual representation of the adopted three response spectra, accompanied by their respective return intervals and the corresponding ADRS curves. The generation of performance points is achieved through the intersection of the demand curves with the capacity curves. The figure illustrates the performance of the model in question when subjected to the specified earthquake parameters. For example, Figure 8 demonstrates the intersection procedure for the model (3)-two outriggers (A) model.

Table 2. Seismic Parameters of Adopted Response Spectra

	2475 Years 2% Probability Exceedance	975 Years 5% Probability Exceedance	475 Years 10% Probability Exceedance
S_1	0.91	0.57	0.37
S_s	0.35	0.21	0.13
F_a	1.48	1.6	1.6
F_v	1.5	1.5	1.74

Table 3. Performance Points Results for all Models Under Response Spectrum: Probability of Exceedance 2%

Model	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)
Shear (kN)	96968	115585	112343	158713	138477
Displ. (mm)	625	509	441.5	584	464
S_a/g	0.223	0.259	0.235	0.334	0.289
S_D (mm)	406	322	299.8	376	308.25
B_{eff}	0.117	0.081	0.0718	0.1554	0.1
W (kN)	658727	665515	673905	682190	688970
T_0 (sec)	2.74	2.594	2.518	2.35	2.352

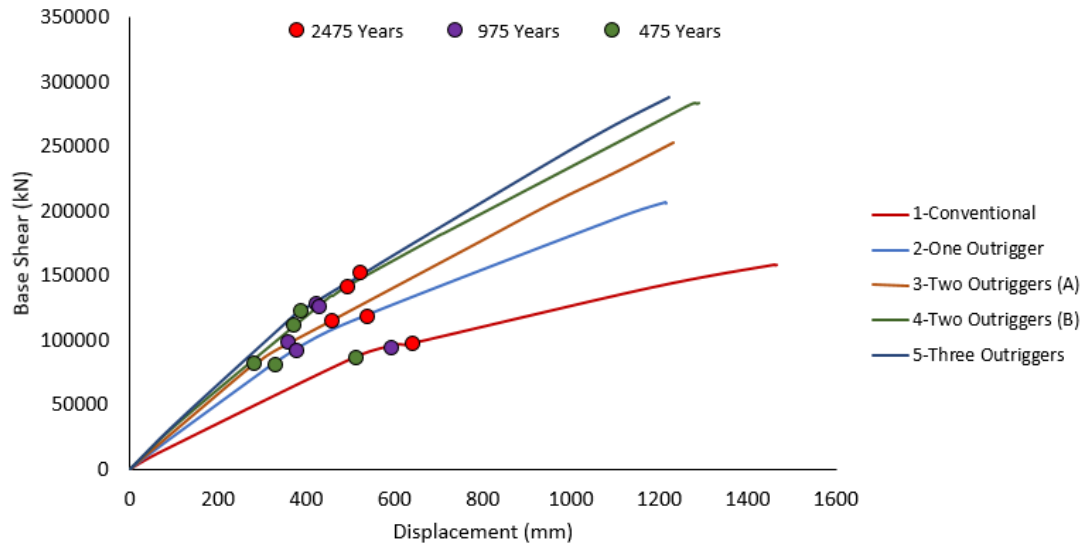


Figure 6. Base Shear-Displacement Curves with the Performance Points of Models

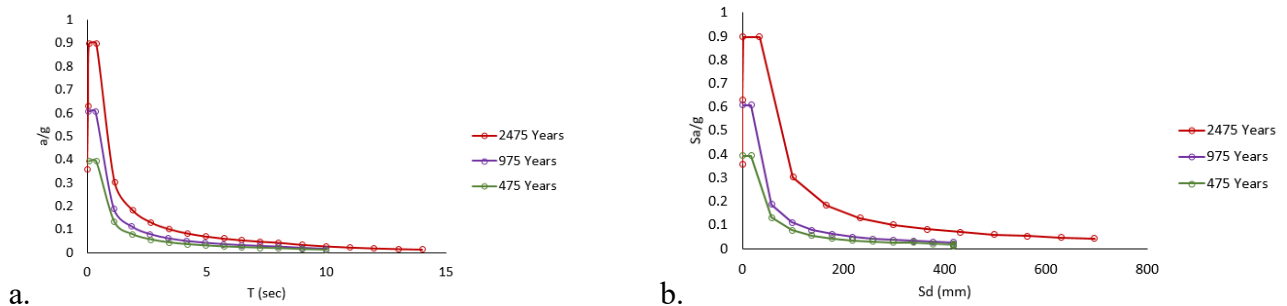


Figure 7. Demand Curves: a. Response Spectra. b. ADRS Curves

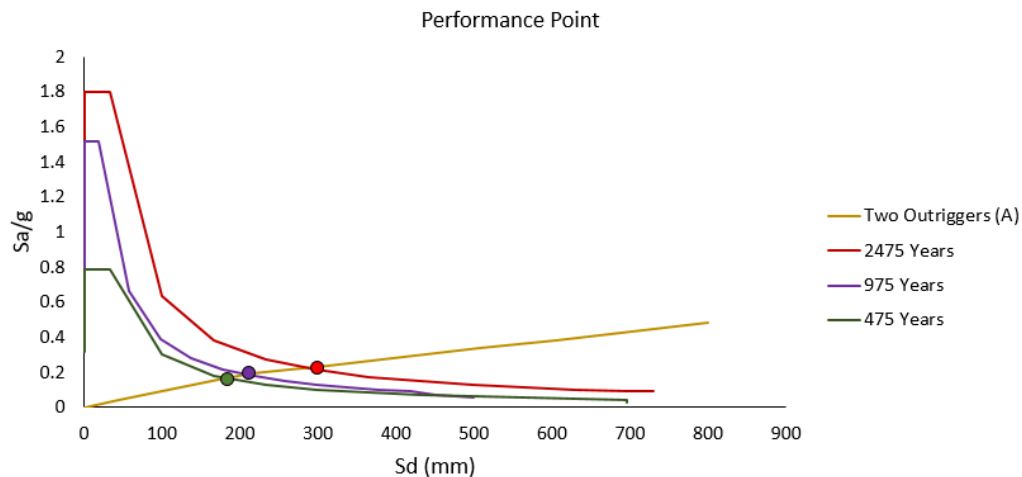


Figure 8. Demand Curves- Capacity Curve Intersection of the Two Outriggers (A) Model

As illustrated in Figure 6, the performance of the five models is demonstrated across the three demand curves. The conventional model, with a return interval response spectrum of 475 years, provides a performance point at the onset of the yielding stage, designated as Immediate Occupancy (IO). In contrast, outrigger models exhibit linear elastic performance, also referred to as operational performance. However, this phenomenon occurs at an earlier point for the model (3)

– the two outriggers (A) model. The behaviour exhibited within the 975-year return interval response spectrum is indicative of the initial yield stage, which is designated as Immediate Occupancy (IO). The observed behaviour is more closely aligned with the 2475-year return interval response spectrum of the conventional model, while it is more closely aligned with the 475-year return interval response spectrum of the outrigger models. The models' behaviour under the 2475-year return interval response spectrum is characterised by a

greater propensity to yield, as evidenced by the Life Safety (LS) metric. It is evident that the three points are in close proximity in the conventional model, whereas they diverge for outrigger models. This indicates that outrigger models possess a superior safety margin. It is evident from Figure 9 that Model (3) is in accordance with the recommendations set out in ASCE 7-22. This figure illustrates the performance level stipulated in the latest version of ASCE 7-22, which stipulates that the performance level should be shifted to the left on the performance matrix according to the high risk category. This approach entails the design of essential facilities in a manner that enhances the structural integrity of the building and minimises the demand for ductility on the structure. The objective for an essential facility is to achieve immediate occupancy in the event of the building site experiencing ground-shaking intensity equal to the design ground-shaking intensity (2/3 MCER), i.e. a probability of 10% of exceeding the intensity. The same objective is to achieve life safety if

the building site experiences ground-shaking intensity equal to the MCER, i.e. a probability of 2% of exceeding the intensity.

It has been demonstrated that the addition of outriggers to the model results in a decrease in top displacement, owing to the concomitant increase in model stiffness. However, it subsequently began to increase in tandem with the rise in mass. As illustrated in Figure 10, the top displacement values of the three models under the three response spectra are presented. It is evident that the conventional model demonstrates the greatest displacement value. Nevertheless, the model (3)-two outriggers (A) model has the lowest displacement value, with a reduction ratio of 29% (2475-year return interval response spectra), as illustrated in Table. 4. In addition, the model (2, 4) yielded the lowest values for the reduction ratio, with 18.5% and 6.5%, respectively.

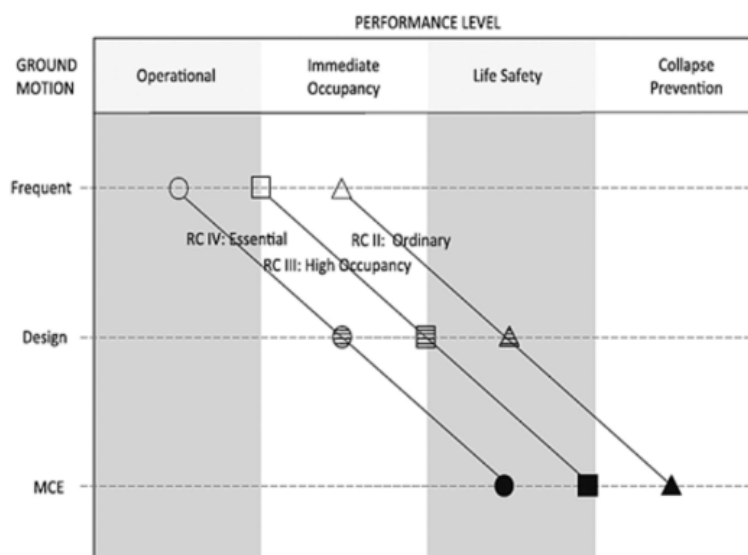


Figure 9. Expected Performance as Related to Risk Category and Level of Ground Motion (ASCE 7-22, 2022)

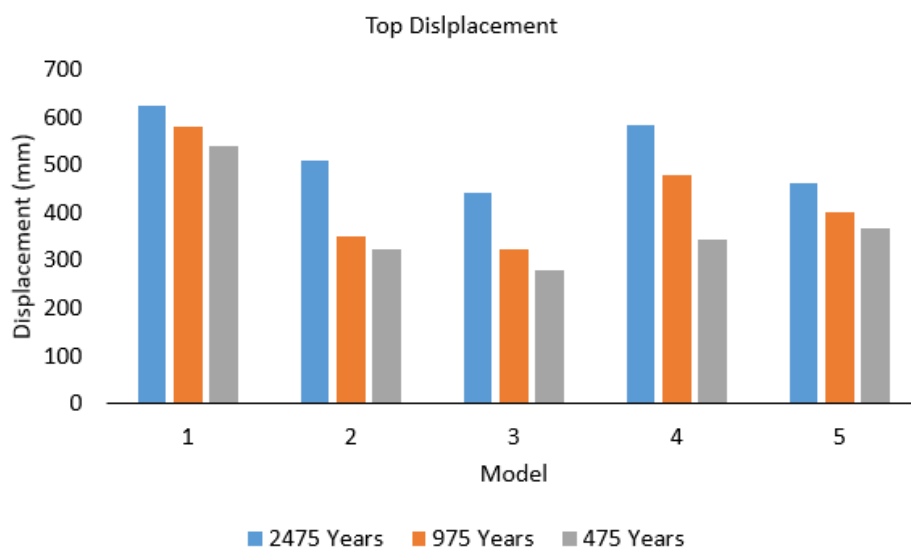


Figure 10. Top Displacement of the Five Models Under the Three Response Spectra Return Interval

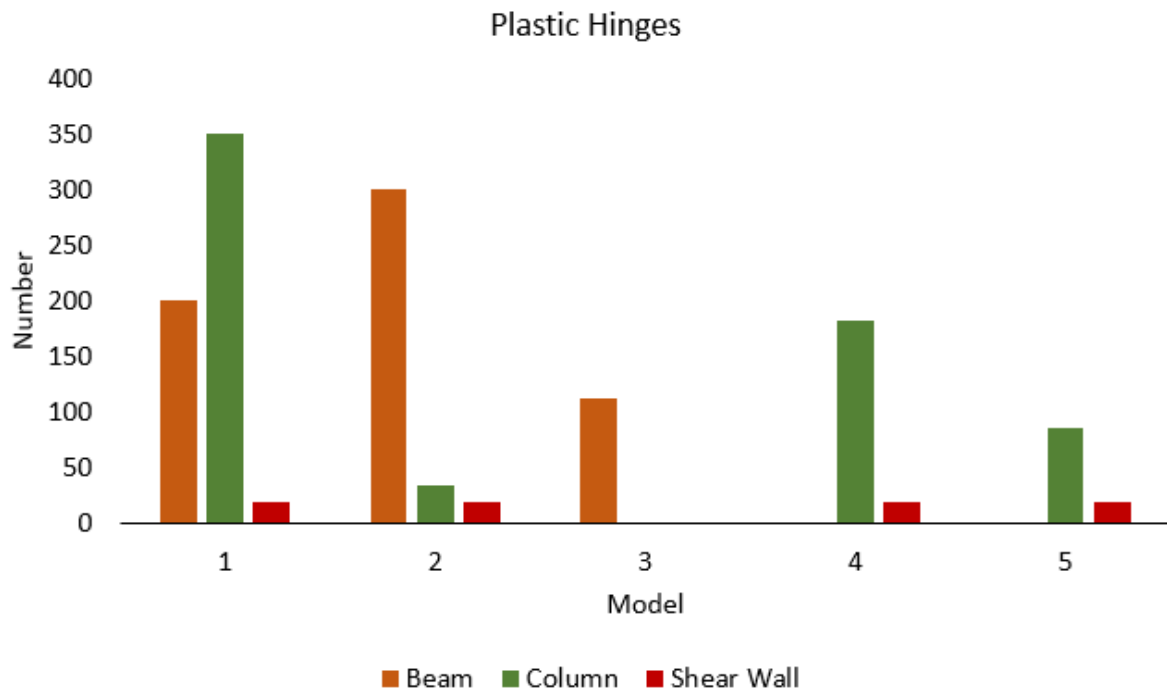
Table 4. Displacement Reduction of Models

Displacement Reduction	2475 Years	975 Years	475 Years
Model (2)	0.1856	0.44032	0.4808
Model (3)	0.2936	0.47936	0.551904
Model (4)	0.0656	0.2336	0.44824
Model (5)	0.2576	0.3552	0.41232

An analysis of the plastic hinges at the performance point reveals that the conventional model exhibits a higher number of column hinges, with 350 hinges identified. The figure for model (2) with one outrigger is 34, and this decreases for model (3). In the context of shear wall hinges, it is evident that the values for models 1, 2, 4 and 5 are closely aligned, with a range of approximately 19 to 22 plastic hinges, as illustrated in Figure 11. However, for model 3, this value is observed to be reduced to zero. Consequently, the incorporation of outriggers leads to a substantial reduction in the number of plastic hinges within the columns. As illustrated in Figure 12, the model

incorporating two outriggers, one positioned at the top and the other at 0.577L, is also devoid of a shear wall plastic hinge.

As illustrated in Table 5, a comprehensive performance check summary is provided for the five models. The plastic hinges were found to be in the Initial Occupancy stage (IO). However, it is evident that the maximum value of the demand capacity ratio for (IO) differs between the elements of the models. For instance, Model (4) exhibits the highest ratio in columns with 0.983, while Model (3) demonstrates the lowest ratio in beams with 0.285.

**Figure 11. Plastic Hinges of the Five Models****Table 5. Plastic Hinges of the Five Models**

Model	Model (1)		Model (2)		Model (3)		Model (4)		Model (5)	
Element	No.	Max DC Ratio for IO	No.	Max DC Ratio for IO	No.	Max DC Ratio for IO	No.	Max DC Ratio for IO	No.	Max DC Ratio for IO
Beam	200	0.318	300	0.373	112	0.285	0	0	0	0
Column	350	0.611	34	0.373	0	0	182	0.983	86	0.642
Shear Wall	20	0.262	20	0.23	0	0	19	0.372	19	0.285

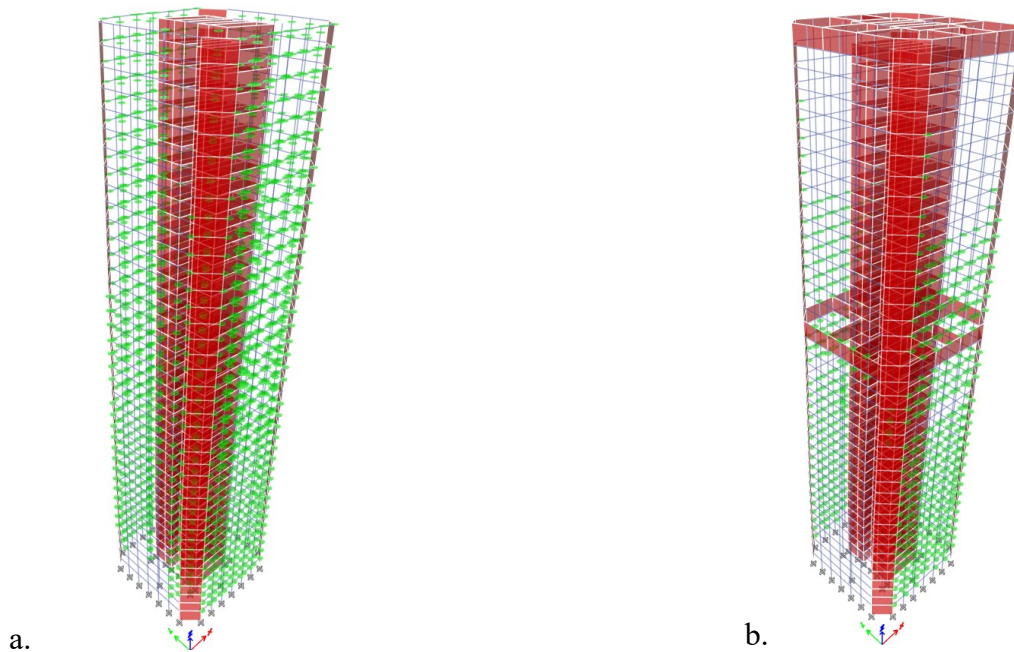


Figure 12. Plastic Hinges at the Performance Point Under 2475 Years Response Spectra

a. Conventional Model, b. Model (3)

Results and Discussion

The incorporation of outriggers serves to reduce the top displacement, thereby shifting the performance point towards higher base shear and lower displacement. This, in turn, enhances the overall stiffness and stability of the building.

Displacement

The conventional model provides a top displacement of 625 mm under a return interval of 2475 years and a 2% exceedance probability. Conversely, the model (3), which incorporates two outriggers (one at the top and another at 0.577L), exhibits a reduced displacement of 442 mm. However, it should be noted that the top displacement in model (4) is 584mm. The model is equipped with two outriggers: one at 0.31L and another at 0.7L. The model (5) with three outriggers – one at the top, the second at 0.31L and the third at 0.7L – has a top displacement of 464mm. This model has been shown to be superior to the conventional model and the models (2, 4). However, the model (3) that has two outriggers, one at the top and another at 0.577L, has a reduced value of top displacement. This phenomenon can be attributed to the increase in mass, which exerts a counteracting force on the enhancement of stiffness.

Therefore, it can be concluded that the top outrigger configuration demonstrated superior performance in comparison to the other configurations, and that the dual outrigger configuration represented the optimal solution. It is evident that all models equipped with outriggers exhibited a reduction in top

displacement, exhibiting varying ratios. However, Model (3) demonstrated the most significant reduction ratios, with 29% under 2475 years return intervals, 48% under 975 years return intervals, and 55% under 475 years return intervals earthquake. It has been observed that the reduction in displacement increases with decreasing return interval for seismic events.

Performance Point

In consideration of the performance point behaviour, it has been determined that the conventional model performance point is in the Immediate Occupancy stage for a 475-975-year return interval response spectrum and in the Life Safety stage for a 2475-year return interval response spectrum. However, the incorporation of outriggers resulted in the performance point being shifted to an earlier stage. That is to say, the performance point was shifted to the linear elastic stage for a return interval response spectrum of 475–975 years and to the immediate occupancy stage for a return interval response spectrum of 2475 years. Model (3) demonstrates optimal performance, characterised by the presence of two outriggers: one situated at the upper extremity and the other positioned at 0.577L. This configuration results in the performance points being shifted to the left, accompanied by a reduction in displacement values.

Plastic Hinges and Dissipated Energy

The incorporation of outriggers has been demonstrated to result in a substantial reduction in the number of plastic hinges required. In consideration of

the performance aspect, plastic hinges demonstrate a decrease in effectiveness over a 2475-year return interval response spectrum. Specifically, column hinges exhibit a decline from 350 to 34 for model (2) with one outrigger, and a corresponding diminution is observed for model (3). As demonstrated in Figure 1, shear wall hinges exhibit close values for all models, with the exception of model (3), for which the value is diminished. Consequently, model (3) dissipates energy through beam hinges as opposed to vertical element hinges.

This paper posits that static pushover analysis and the response spectrum method have enhanced their accuracy and are considered a reasonable tool with which to understand a structure's behaviour during an earthquake. This assertion is supported by the findings of Anjum et al. (2026), Masrilayanti et al. (2023), JKHSI & SABER (2025) and Ashwini L et al. (2024). The findings of this study underscore the efficacy of reinforced concrete outriggers, a conclusion that aligns with the observations reported by Tiwary et al. (2026) and Kushwaha & Mishra (2022). The effectiveness of the structure is enhanced by the addition of belts walls to its perimeter (John & Kamath, 2024; Kasliwal et al., 2025; Nissanka et al., 2023). In addition, Kumar Yadav and Kumar's (2025) study indicated that outrigger-belt systems demonstrate consistent superiority over outrigger-only or belt-only systems through time-history analysis. The aforementioned elements are in accordance with the static pushover analysis that has been conducted in this paper.

Lateral Stiffness

As demonstrated in Figure 2, 3, 4 and 5, the outrigger models exhibit higher lateral stiffness in comparison to the conventional model (1). This observation indicates that the lateral system becomes more ductile and effective in terms of energy absorption, provided that it possesses sufficient stiffness in both directions (Mahmoud et al., 2024).

As illustrated in Table 3, 4 and 5, the addition of outriggers leads to a decrease in the fundamental period, concurrent with an increase in stiffness. This phenomenon occurs as a result of the interplay between stiffness and the seismic mass of the structure model. This assertion is corroborated by the findings of Kare & Safdari (2022).

Conclusion

The static pushover analysis of supertall buildings equipped with outrigger and belt systems has highlighted the critical role these structural arrangements play in improving lateral stiffness and reducing displacement. Outrigger systems serve as effective connections between the central core and perimeter columns, while belt walls distribute forces

uniformly along the perimeter of the building, thereby enhancing load-sharing efficiency.

Five distinct models were subjected to a static pushover analysis. A three-dimensional finite element analysis is conducted using static pushover analysis under three demand response spectra with different return intervals and exceedance probabilities. ETABS is used to consider P-delta effects, with the aim of studying the effect of adding outriggers at different levels to a supertall model.

The initial structure under consideration is a conventional supertall building, characterised by a mega core and peripheral columns that constitute its primary structural system. The remaining four systems incorporate an outrigger belt system, which is present at various levels. These levels are as follows: one outrigger, two outriggers at 0.31L-0.7L, two outriggers, one at the top and another at 0.577L, and three outriggers, one at the top and two at 0.31L-0.7L. It has been demonstrated that outrigger models exhibit superior performance in comparison to their conventional counterparts. However, the third model, which featured two outriggers, one positioned at the top and another at 0.577L, demonstrated superior performance.

It is evident that a substantial reduction in displacement was observed, with a 29% decrease recorded for earthquakes occurring at intervals of 2475 years, a 48% decrease for earthquakes occurring at intervals of 975 years, and a 55% decrease for earthquakes occurring at intervals of 475 years.

In terms of performance, model (3) exhibited the lowest number of plastic hinges, leading to a significant reduction in the total number of plastic hinges in the vertical element and the energy dissipated by beam hinges. The novel aspect of this study was its focus on behaviour under different return period response spectra. The difference between the conventional model and the outrigger model is as follows. The conventional model exhibited behaviour in two distinct phases. Firstly, in the Immediate Occupancy phase, characterised by a return interval of 475-975 years, and secondly, in the Life Safety stage, with a return interval of 2475 years. However, the behaviour of the outrigger models was found to be in linear elastic under both the 475-975 year return interval response spectra and the Immediate Occupancy stage for the 2475 year return interval response spectrum.

The findings indicated a clear correlation between the location of the outrigger truss system and the nonlinear behaviour of the structure. This observation aligns with the findings reported in the literature (Husain et al., 2021; Jankar et al., 2026; Kare & Safdari, 2022; Kushwaha & Mishra, 2022).

Future Work

The impact of higher modes, as opposed to the fundamental period, was not addressed in the present study. Further analysis and inspection is required in this research area, with a particular emphasis on high-rise buildings. The development of innovative hybrid materials, including composite steel-concrete outriggers and advanced damped steel truss systems, offers significant potential to enhance the structural capacity and constructability of outrigger systems. Furthermore, the advent of innovative concepts such as virtual outriggers and embedded damping devices, which function as structural fuses, offers a compelling alternative to conventional heavy systems. These novel approaches facilitate effective displacement control and energy dissipation. Further investigations are required into the interaction between soil and structure, as well as torsional response, in the context of real earthquake records. This is particularly important for irregular and asymmetrical high-rise configurations. It is imperative that future studies incorporate life-cycle cost analysis and sustainability assessments. This will ensure that outrigger–belt truss systems achieve not only structural efficiency but also long-term environmental and economic viability. This will contribute to the development of safer and more sustainable supertall buildings.

Declarations

Authors' Contributions

R.K: Conceptualization, Methodology, Data curation, Writing of the original draft.

M.A.A: Resources, Writing –review & editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration on the Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Ethics

This study did not involve human participants or animals; hence, no ethical approval was required.

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