



Seismic Response Analysis of High-Rise Reinforced Concrete Buildings Using Outrigger System

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Abstract For the past few years, the trend of construction of high-rise buildings has progressed due to rapid urbanization and lack of land for horizontal expansion, especially in metropolis. These buildings are uniquely characterized by the requirement of major design consideration under lateral loads, earthquakes, or wind. So, it becomes more difficult to control the drift and deflection with the increasing height of the structure. To this end, this study presents a few energy-dissipating techniques that can be used in buildings to increase their stiffness and stability under seismic forces, along with a comparative analysis of the appropriate system to dissipate the maximum energy induced by these forces. A total of one hundred twenty-three analytical models were created on finite element modeling software using two sets of models. The linear dynamic analysis was carried out in the reference building and building with three different outrigger systems. The best outrigger system was selected, and its optimum location was determined by comparing their results in terms of story drift and top story deflection. The seismic response analysis of the first set of models illustrates that the M3 system with belt truss and cap truss is the best outrigger system, and its position is nearly at the mid-height of the building. Furthermore, the research was extended to

the second set of models with ten more different systems with varying numbers of stories to investigate the effect of the slenderness ratio to locate the optimum position of the outrigger. The study highlights that it is more effective to place the outrigger at the upper heights of the building with a lower slenderness ratio to control the lateral displacement.

Keywords Dynamic analysis · High-rise buildings · Optimum location · Outrigger · Story drift

Background

Outriggers are rigid horizontal structures designed to improve the building's overturning stiffness, stability, and strength by connecting the building core or spine to distant columns, as shown in Fig. 1. Outrigger systems function by tying together two structural systems to yield the whole building's structural behaviors that are much better than those of the component systems. Outrigger system performance is affected by outrigger locations through the height of a building, the number of levels of outrigger provided, their plan locations, the presence of belt trusses, outrigger truss depths, and the primary structural materials used. Outriggers with belt trusses are a system in which the belts, such as trusses or walls encircling the building, add further stiffness to the structure, improving the lateral system efficiency. Outriggers with cap trusses are a system in which the top story is provided with outriggers as a hat. The tie-down action of the cap truss generates a restoring couple at the building top.

Outrigger systems are described in Clause 4.16 of IS1893:2016 [1] as a structural system with a core of perimeter columns and structural walls that can withstand both vertical and lateral loads. The desire for high-rise buildings

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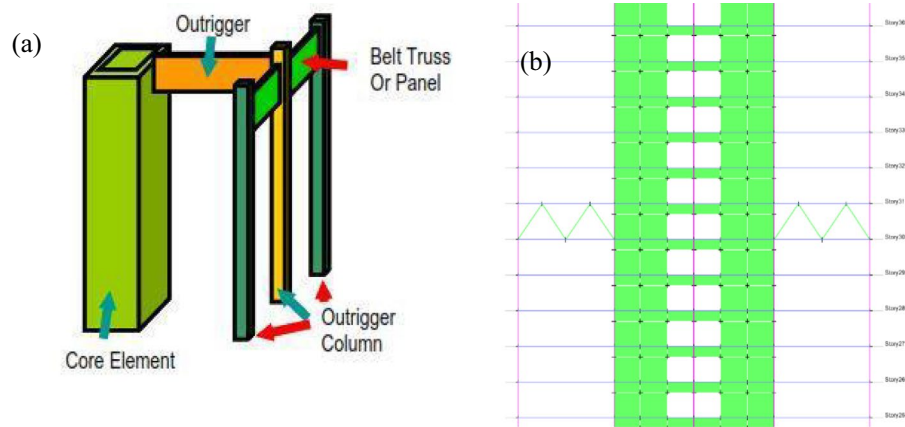
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Fig. 1 **a** Perspective view of the model with a central core and extended outrigger on all four sides with belt truss; **b** elevation of the system showing story outriggers with the central core



is not only invading the people's minds in seismically inactive countries but also in seismically active countries. The major design consideration for tall buildings is not always governed by the fully stressed state; it is usually controlled by displacement due to the lateral loads, such as winds and earthquakes, imposed on the structure. So, the structural challenges are raised with the increase in the height of the building, but it has also been settled with the new arising techniques to control the imposed drift requirements. The recent development of structural analysis and design software coupled with advances in the finite element method has allowed the creation of many innovative structural forms such as rigid frames, rigid frames with shear walls, coupled shear wall systems [2–6]. However, the design of tall structures using these systems becomes uneconomical due to the large size of structural members to meet the large lateral displacement criteria. Hence, it becomes necessary for alternative economic structural systems, such as braced tube systems and outrigger systems, which are effective in controlling lateral displacement.

Several studies have been performed to determine the performance and effective position of single as well as multiple outrigger systems in a high-rise building [7–10]. Additionally, currently artificial intelligence is being used to for optimizations [11]. Taranath [12] conducted research using wind loading for a single outrigger and concluded that its optimum location is 0.545 times the height of the structure, and McNabb et al. [13] suggested that the optimum location of the outrigger be at 0.685 and 0.312 of the total height of the building. Another study conducted by Taranath [14] showed the outrigger and belt truss system increases lateral stiffness by 30 percent, while Park et al. [15] concluded lateral drift could decrease up to 25–32%. Nair [16] studied the use of belt trusses and basements as virtual outriggers to eliminate the direct connection between the outriggers trusses and the core. His study highlighted the effectiveness of virtual outriggers is slightly lower than conventional outriggers. Likewise, Herath et al. [17] studied the behavior

of outrigger beams in high-rise buildings under earthquake loads for 50-story buildings with three different peak ground acceleration to peak ground velocity ratios. The author concluded that the structure is optimized when the outrigger is placed between 22 and 24 levels in 50-story building, which means 0.44–0.48 times the height. A similar study was conducted by Nanduri et al. [18] using a 90-m high-rise reinforced concrete building under wind and earthquake loading. They came up with the statement that the best result is shown by the use of outriggers with a belt truss system, and its best position is at the middle height of the building. Recent research carried out by Inam et al. [19] used the time history analysis to determine the optimum location of the single as well as double outrigger systems for a tall steel building. The research deduced that the best placement of a single outrigger to control lateral displacement is at the upper floors of the buildings and the location to be at 0.85 H, 0.69 H, and 0.72 with three earthquake records. Sattar et al. [20] examined the behavior of buildings with a shear core, outrigger, and belt truss. The study investigated the effect of effective depth of the structure when it flexes as a vertical cantilever by inducing tension in the windward ward direction and compression in the leeward columns. Similarly, Kazi et al. [21] carried out a dynamic analysis of a G + 44 story RCC structure using viscoelastic dampers. The study showed changes in the responses of displacement, velocity, acceleration, and drift for the damped structure. Also, Fawzia and Fatima [22] demonstrated that by effective utilization of belt truss and outrigger system on a 60-story composite building subjected to wind loads the deflection can be controlled from a numerical study. Beiraghi and Siahpolo [23] investigated the best position of the outrigger is 0.73H from the base of the building. Furthermore, Habrah et al. [24] proposed the analytical approach to determine the optimum location of four outrigger systems using three different lateral loadings; uniform, parabolic, and triangular and developed curves to select the number of outriggers. They also examined the required number of outrigger systems and the

maximum height of the building in terms of displacement limit criteria. In their study, it was concluded that the average position of the single outrigger system is $0.57H$ and top displacement is unaffected by the position of the second outrigger when the first system is placed at the upper half height of the building. They also illustrated the first outrigger is the most efficient system to control displacement, and its efficiency decreases with an increase in the number of outriggers.

The previous studies were mainly focused on determining the optimum location of the outriggers and considered the location of optimal outriggers depends merely on the height of the structure without considering the slenderness ratio. However, selecting the best outrigger system and locating its effective position are still the present need for research. So, the main purpose of this paper is to determine the effectiveness of using outrigger beams and determine the best outrigger system in the building from different outrigger arrangements. Moreover, the research also focuses on the evaluation of their appropriate positions along heights and the role of the slenderness ratio for the optimal position of the outrigger system. In this study, the optimum location of the outrigger is determined by considering the drift and displacement parameters of a 35-story prototype building based on dynamic analysis. The maximum deflection is at the top of the building, and providing a cap truss shall decrease the deflection, but the system is new and mostly limited to research works in developing countries. This study seems important to explore the possibility of introducing the system to practicing engineers while taking the local code of practice and actual ground conditions.

Materials and Methods

According to NBC 206: 2015 [25] architectural design requirement, a high-rise building is categorized as 9–39 stories based on the number of stories. Therefore, a regular 35-story building with the center core shear wall located in Kathmandu was chosen for the study as a representative structure with parameters summarized in Table 1. The designed building was safe under various load combinations as mentioned by IS1893:2016.

Various analytical studies have been conducted by different researchers using the finite element method to demonstrate the response of tall buildings with outrigger systems under seismic loading [17, 26, 27]. Kamgar and Rahgozar [28] studied the optimum location of the outrigger using concentrated, triangular, and uniform loading and demonstrated the result as $0.667H$, $0.49H$, and $0.441H$, respectively. In addition, Mousleh and Batikha [29] presented the 3D finite element analysis procedure for locating the optimum position of a single outrigger and the cost efficiency of

Table 1 Building modeling parameters adopted in the study

Parameter	Details
Concrete grade	M35
Reinforcement steel grade	Fe500
Structural system	RCC frame structure
Story height	3.6 m
Building height	126 m
Size of column	$0.9\text{ m} \times 0.9\text{ m}$
Size of beam	$0.3\text{ m} \times 0.7\text{ m}$
Size of brace	$0.3\text{ m} \times 0.7\text{ m}$
Core shear wall	0.23 m
Thickness of slab	0.14 m
Density of concrete	25 kN/m^3
Density of brick masonry	19.2 kN/m^3

this system and concluded the position is at $0.68H$, and the cost is reduced by 28%. In the present study, ETABS 2020 [30] was used to create the 3D finite element model (FEM) of the building. The validation of the model was carried out based on linear static and linear dynamic analysis. For instant, the time-period base shear of the numerical model was cross-verified based on the code requirements through manual calculations. The numerical modeling works and the methodology verification of the work are further illustrated in the research works of Bhusal and Paudel [31], Paudel and Bhusal [32], and Motra and Paudel [5]. The superimposed wall load was modeled as a uniform load equal to 6.5 kN/m . A uniformly distributed live load of 4 kN/m^2 was used in slab and floor finish, and the partition wall load assigned was 1.5 kN/m^2 and 5 kN/m^2 , respectively, as per the current practice using IS 875 part 1 [33] and part 2 [34]. Furthermore, the vertical and horizontal irregularities were not considered, the material is assumed to be linearly elastic, the connection between outriggers and core wall and core wall and foundation is rigid, and no wind load was considered. The study employed a three-dimensional model of a typical moment-resisting framing structure. The model is a 35-story reinforced concrete structure with a core wall in the middle and a frame around the outside. The structure is seen as a collection of vertical frames joined at each story level by diaphragm floor slabs, with the secondary beam lying across the main beam to limit the deflection of slab. Using the ETABS application, static and dynamic computer analysis were performed. Linear dynamic analysis which is commonly known as the response spectrum method was performed using IS 1893: 2016 [1]. Since the representative building was chosen from Kathmandu Valley which comprises very soft soil [35–38], soil type III (soft soil) was considered. The base shear required for the numerical study was calculated using the following relation:

Design Seismic Base shear $V_B = A_h * W$ in which A_h = design horizontal seismic coefficient, W = seismic weight of the building.

Design Horizontal Seismic Coefficient $A_h = Z/2 * I/R * Sa/g$

where Z = zone factor = 0.36 as applicable for structures built in zone V. I = Importance factor for the building, R = response reduction factor, Sa/g = average response acceleration coefficient is taken for soil type-3 and 5% damping.

The numerical study started with varying the size of the column and beams until the analyzed structure was safe under applied gravity and lateral loading. When the model was safe, four types of models were created, as summarized in Table 2.

The study commenced with the analysis of numerical models as shown in Fig. 2. When the position of outriggers was varied, two major response parameters, top story deflection and story drift, were observed in all four models to evaluate the effectiveness of outrigger systems and determine their best location in the building.

The research was further taken in another direction where ten different models were created with different numbers

Table 2 Initial set of models considered for the study (set I)

Type	Description
M0	A system with no outriggers
M1	A system with one-story outriggers and no belt truss
M2	A system with one-story outriggers and belt truss
M3	A system with one-story outriggers, belt truss, and one-story cap truss

Fig. 2 **a** Plan view of the model with a central core and extended outriggers on all four sides, **b** perspective view of the system without any outriggers (M0), **c** a system with one-story outriggers and no belt truss (M1), **d** a system with one-story outriggers and belt truss (M2), **e** 3D view of M0 system, **f** 3D view of M1 system, **g** a system with one story outriggers, belt truss, and one-story cap truss (M3)

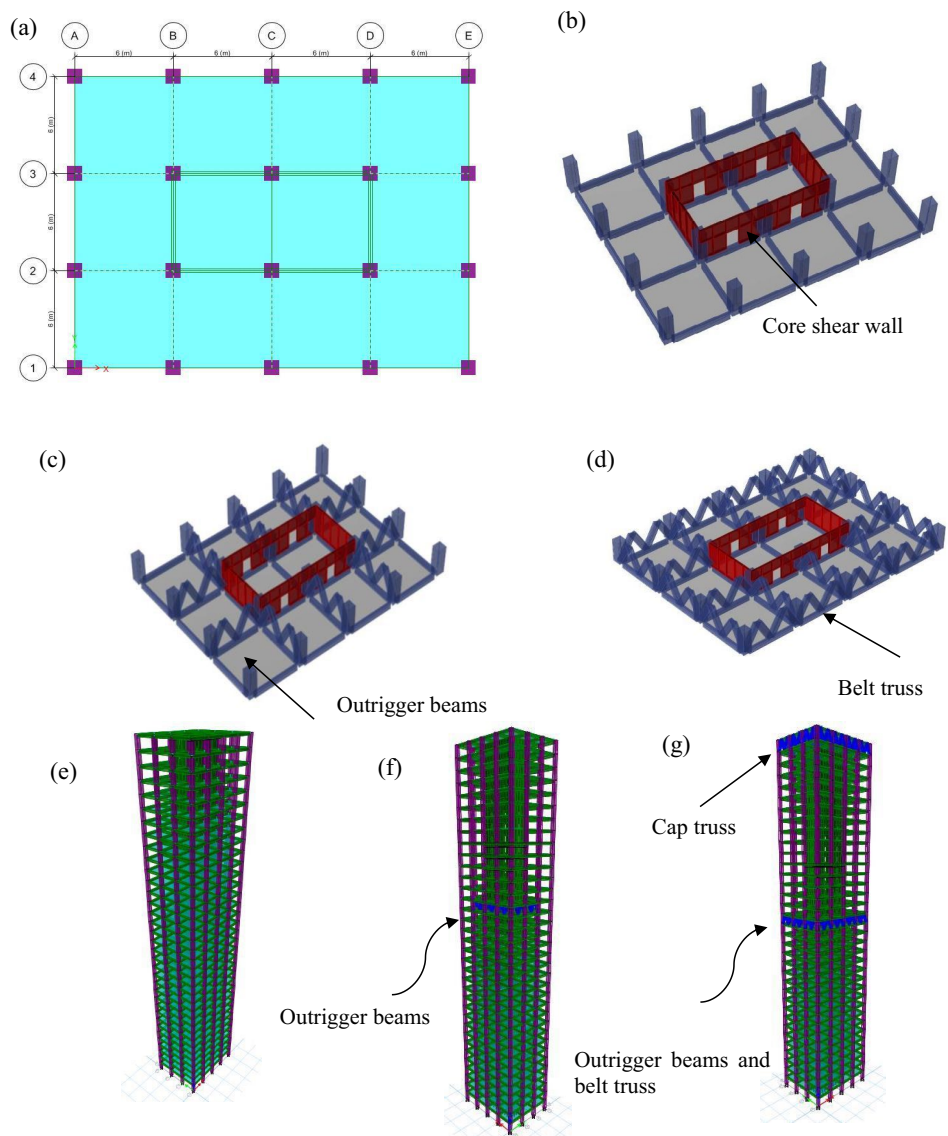


Table 3 New sets of models used for validation purposes (set II)

Type	Description
M4	A system with 30 story and outriggers as in M2
M5	A system with 25 story and outriggers as in M2
M6	A system with 20 story and outriggers as in M2
M7	A system with 18 story and outriggers as in M2
M8	A system with 16 story and outriggers as in M2
M9	A system with 14 story and outriggers as in M2
M10	A system with 12 story and outriggers as in M2
M11	A system with 40 story and outriggers as in M2
M12	A system with 45 story and outriggers as in M2
M13	A system with 50 story and outriggers as in M2

of floors to validate the result as seen in the previous models and to study the effect of building height to locate the optimum position of the outrigger systems as tabulated in Table 3.

The whole methodology is briefly presented in the following flowchart as shown in Fig. 3.

Results and Discussion

The fundamental period and mode are shown in Table 4. Additionally, the base shear for the selected models is also shown in Table 4. For the general comparison, we can consider M0, M1, M2, and M3. The comparison is made between the best location of the outrigger structure with no belt truss, with belt truss, and with belt truss + cap truss, which is at the 15th, 18th, and 18th story. The fundamental period was observed to be the lowest in the M3 model. The maximum base shear is for M3, as expected from the extra weight of trusses. The difference between this maximum value and minimum is only 9.5%.

The results from the numerical study carried out by relocating the outrigger at various stories of the M2 system are shown in Fig. 4. Similar results were also studied for the other two systems (M1 and M3), but the result herein is plotted only for the M2 system as a representative work. Figure 4a shows the lateral displacement of the system in which outriggers with a belt truss (OBT system) were provided for the M2 system. Furthermore, Fig. 4b illustrates story drift for outriggers provided at the base, 3rd story, 6th story, 9th story, 12th story, 15th story, 18th story, 21st story, 24th story, 27th story, 30th story, 33rd story, and 34th story for the M2 system.

The summary of the results in terms of story displacement while varying the outrigger positions along the height of the buildings for the M1, M2, and M3 systems and the reference building M0 is shown in Fig. 5.

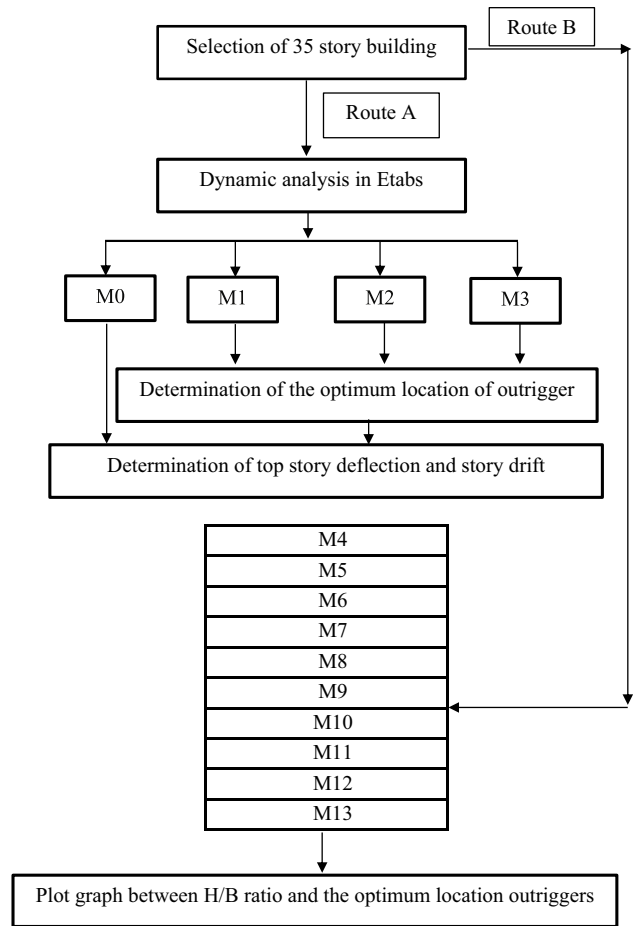


Fig. 3 Outline of the research methodology

From Fig. 5, it is evident that the M3 system has the minimum top story displacement of 361 mm which may be due to its higher stiffness value resulting from the cap truss and belt truss. The figure also indicates the optimum location of outrigger systems is roughly 40–50% of the building height for all three systems.

In addition, a comparison of top story displacement, optimum location of the outrigger system, and percentage reduction to reference model M0 is shown in Table 5. The minimum top story deflection is obtained when the location of the outrigger is at 48.6% and 42.8% for M1 and M3 systems, respectively, while its position is the same for M1 and M2 systems. The effect of the cap truss lowered the position of the belt truss in the M3 system. So, the optimum position of the outrigger in the M3 system is lower than in the other two systems. Moreover, the reduction of top story deflection is 14.56% of the M3 system to that without an outrigger system (M0). Table 5 also shows the top story deflection in the M0 system is 422.5 mm which is equal to 0.335% of the total height of the structure.

Table 4 Tabular representation of fundamental period and base shear

Type	Mode	T (sec)	Outrigger position	x -direction(kN)	y -direction(kN)
M0	1	4.567	None	7983.98	6843.43
	2	3.425			
	3	1.968			
M1	1	4.281	15th story	8517.08	6861.90
	2	3.223			
	3	1.961			
M2	1	4.27	18th story	8644.04	6887.75
	2	3.187			
	3	1.944			
M3	1	4.27	18th story	8742.85	6932.06
	2	3.172			
	3	1.9			

Fig. 4 **a** Lateral displacement and **b** story drift for varying outrigger positions of the M2 system

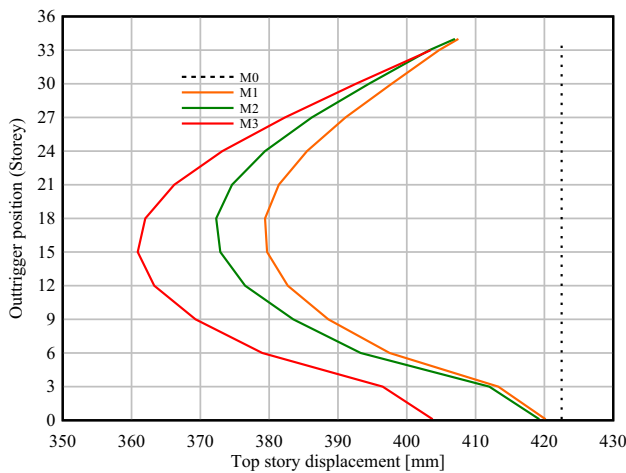
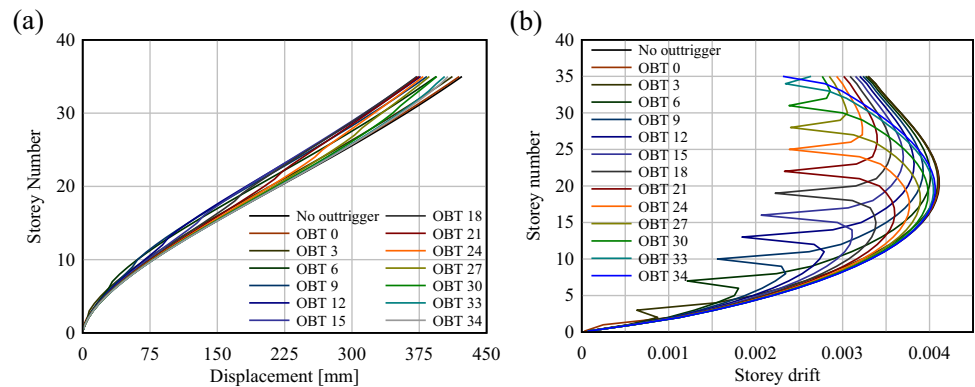


Fig. 5 Summary of M0, M1, M2, and M3 systems

When the drift of the M0 system was recorded, its value at the 20th story was slightly higher than the allowable value as per the Indian code IS1893:2016 [1], which recommends the allowable drift to be equal to 0.4% of the building height. Therefore, system M0 was redesigned with outrigger

Table 5 Tabular representation of the optimum location of outrigger beams with respect to top story deflection

Options	M0	M1	M2	M3
Top deflection (Δ , mm)	422.5	379	372	361
Location of outrigger in % of the total height of the building	–	48.6	48.6	42.8
Reduction Δ (%)		10.30	11.95	14.56

systems, and a comparison of top story drift, optimum location of outrigger system, and percentage reduction compared to basic model M0 is shown in Table 6.

The drift lies within the allowable value in the case of buildings with outrigger systems (M1–M3). The reduction of the drift is up to 15.2% in the case of M3 with the outrigger system located at the 18th story. The story drift in all three sets of models (M1–M3) showed the optimum location of the outrigger system at the middle height of the building. This parametric study provides the conclusion that the optimum location of the outrigger system in this 35-story building is at 50% of the height, i.e., at the 18th story. The result also shows that the M3 system is the best option to choose

Table 6 Tabular representation of the optimum location of outrigger beams with respect to story drift

Options	M0	M1	M2	M3
Maximum drift	0.00411	0.003618	0.003557	0.003486
Location of outrigger in % of the total height of the building	–	51	51	51
Reduction drift (%)		11.97	13.48	15.20

from the outrigger systems, indicated by the maximum reduction in top story drift as well as top story displacement.

In Set II, the number of stories was varied, keeping the plan of the building the same to see whether the result is similar to that observed in 35 story building. The numerical study was further carried out with ten different models created with different numbers of floors to validate the result as

tabulated in Table 3. Before performing the overall study to investigate the performance of the building with the variation of the story, a numerical study was performed by varying the location of the outrigger system for the M2 model, and the results of the studied models are shown in Fig. 6.

The results from the numerical study are further illustrated in Table 7 in terms of story displacement and drift, respectively. It was observed that the more the number of outriggers was used more the deflection was controlled, which was as expected due to the increase in stiffness of the structure. The maximum deflection is at the top of the building, and providing a cap truss shall decrease the deflection due to the introduction of additional lateral load-resisting systems, such as belt trusses and outriggers to attain the requisite stiffness of tall buildings. The results based on top story deflection showed that while decreasing the number of stories from 35 story to 12 story, the optimum location

Fig. 6 Story displacement for varying outrigger positions of various studied systems

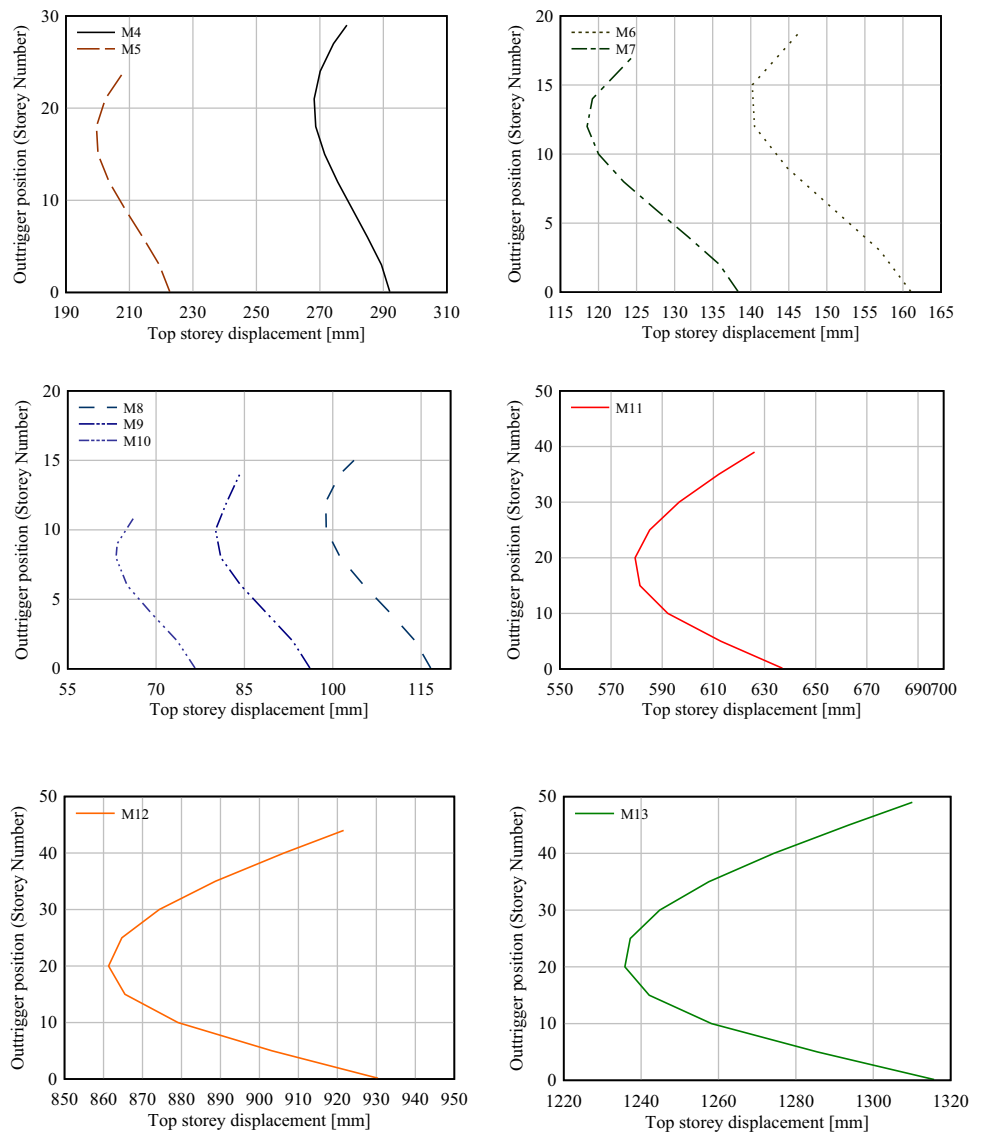
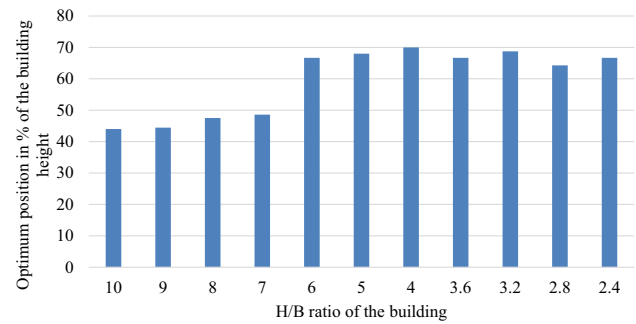


Table 7 Optimum location of outrigger beams with respect to top story deflection and story drift

Options	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13
Total number of stories	30	25	20	18	16	14	12	40	45	50
Displacement top (mm)	268.1	199.5	140.1	118.5	98.5	80.1	63.2	579	861.3	1235
Location of outrigger in % of the total height of the building (top story deflection)	66.7	68	70	66.7	68.7	71.4	66.7	47.5	44.44	42
Maximum drift	0.0031	0.0027	0.0023	0.0022	0.0022	0.002	0.0018	0.0048	0.006	0.008
Location of outrigger in % of the total height of the building (drift)	60	60	60	55	50	57	50	50	55	60

**Fig. 7** Variation of the optimum location of outrigger system with varying H/B ratio based on top story deflection

ranged from 66 to 71%, as shown in Fig. 6 and Table 7. Whereas increasing the number of stories from 35 story to 50 story, the optimum location of the outrigger system ranged between 40 and 50%. The result of this set of works finally suggested that the optimum location of the outrigger is not always at 40–60%, as suggested by previous researchers [17, 19]. The fact that the optimum location of the outrigger also depends on the slenderness ratio of the building was not mentioned in previous studies.

Therefore, the dependency of the optimum location of outrigger beams with the slenderness ratio (H/B) was noticed and plotted. It was found that a building with a H/B ratio greater than 6.5 showed the expected result of optimum location approximately at 50% of building height to guide the designers about the placement of outrigger systems along the building height based on the H/B ratio of the building. To reduce the lateral displacement for lower values of the H/B ratio, it is more effective to place the outrigger at the upper height of the building, which lies around 70% of the building height. Hence, from this study, it was observed that the optimum location of the outrigger is dependent on the shape of the building as shown in Fig. 7.

The result based on the story drift (see Fig. 8 and Table 7) shows the optimum location of the outrigger system is approximately at the middle height varied from 0.5 to 0.6 H of the building in all cases despite varying H/B ratios which are similar to 0.61 H as a result obtained by Park et al. [15].

Conclusion and Recommendations

The present study investigated the optimum position of a single outrigger system in a regular high-rise building using numerous analytical models created on FEM software. In each model, the results in terms of story drift and top story deflection were compared. The research was further extended to evaluate the effect of the number of a story while determining the optimum location of the outrigger. The result highlights that its optimum position

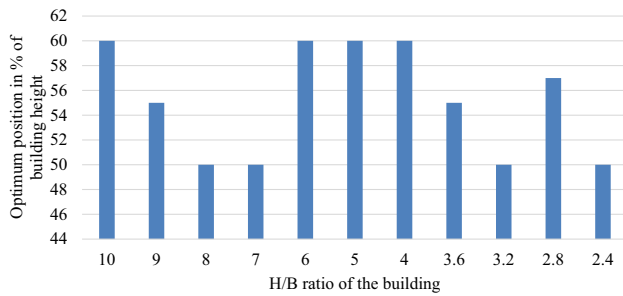


Fig. 8 Variation of the optimum location of the outrigger system with varying *H/B* ratio based on story drift

is also dependent on the slenderness ratio. In addition, the following conclusions can be generated from this study:

1. The outrigger system with belt truss and cap truss, i.e., M3 is the best system among the other two systems under study.
2. The percentage reduction of the top story deflection in M1, M2, and M3 is 10.3%, 11.95%, and 14.56%, respectively, while in the case of story drift, the reduction as compared to the system without the outrigger system in M1, M2, and M3 is 11.97%, 13.48%, and 15.2%, respectively.
3. The optimum location of the outrigger system with respect to top story deflection varies with the *H/B* ratio, whereas the optimum location of the outrigger system with respect to story drift, despite varying *H/B* ratio, gives a similar optimum position nearly at the middle height of the buildings.
4. The required level of reduction in story drift and top story deflection depends on the stiffness of the outrigger system and the damping of the system. It also depends on the shape of the building, slenderness ratio, and stiffness of the outrigger truss system.

The following studies could be relevant and continue this research:

1. The plot for the *L/B* ratio and optimum location of the outrigger.
2. Consideration of soil structure interaction can be carried out, and a comparison for the fixed base and spring-dashpot analysis can be done.
3. Outriggers with damping elements can be introduced to get more efficient results.

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Declarations

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