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Seismic Performance of Tall Buildings with and Without Outrigger and Belt Truss Systems

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Abstract

The construction of tall buildings today is increasing all over the world to meet the needs and challenges of the construction industry. The intention to build tall buildings is due to population growth and insufficient horizontal space. The increase in height of tall buildings requires special attention to the lateral stiffness of the structure, where the introduction of outrigger sections and belt trusses plays an essential role. In this paper, an investigation has been performed to study the behavior of outrigger and belt trusses in different locations of the building using response spectrum analysis. For this analysis, a three-dimensional building model is developed for G + 16, G + 20, and G + 24 RC buildings with and without outrigger and belt truss systems to find out the performance of outrigger and belt trusses subjected to earthquake loading conditions. The analysis is done by dynamic analysis (Response spectrum method) in the zone (IV) as per IS code, using ETABS software, and the analysis results were compared among lateral displacements, story drift, and story stiffness to find out the optimal position of outriggers and an efficient reduction of story displacement and story drift in a tall building. It was observed that the introduction of outrigger and belt trusses at the middle stories reduces considerable story displacement and drift and enhances the stiffness of the structure. By providing outriggers and belt truss systems in middle stories, story displacement is reduced up to 60%, story drift is reduced by up to 50%, and story stiffness is increased by up to 10%.

Keywords: Outrigger and belt trusses, Response spectrum, Story displacement, Story drift, Story stiffness

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1. Introduction

Recent technological developments in several aspects related to building materials, construction methods and equipment, analysis, and structural design have allowed tall buildings to spread all over the world, especially in emerging economies. Tall buildings play a major role as important structures in urban and developed cities. High-rise buildings represent a potential solution from an economic, ecological, and social point of view [1], [6]. In addition, the lack of land in some cities has led to increasing demand for tall buildings in that cities [3], [9]. The race to the sky to build the tallest building is primarily associated with the development of innovative and innovative lateral load resistance systems. Over the past five decades, engineers have been able to develop several new framing options as structural systems (e.g. diagonal system, outrigger system, attached duct system) in many tall buildings to meet the criteria of aesthetics, ease of maintenance, and safety in addition to minimizing materials consumption [7],[13]. The outrigger and belt truss systems are one of the most effective structural systems for resisting lateral loads. The outrigger and belt truss systems consist of the central core of the brace or shear wall and the horizontal supports or deep beams connecting the central core to the perimeter columns. The loads are transferred from the core to the outer columns by two technical methods or in the other sense, there are two types of stable systems depending on the transmission, namely the conventional system and the virtual system [5],[15]. The conventional type of system means that the earthquake moment is transmitted directly from the inner core walls to the outer columns of the building through rigid supports. But this type of virtual system relies on inflexible dual-floor diaphragms to transmit seismic moments from the core to the building's outer columns. [11].

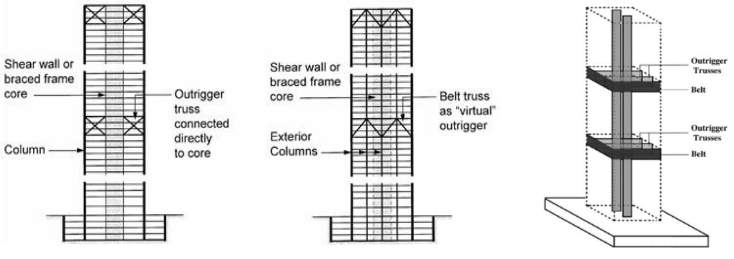


Figure 1. Conventional and virtual outrigger and belt truss system [11],[7].

As per (IS 16700-2017), A building of height greater than 50m, but less than or equal to 250m is called a tall building. In 1965, Fazlur Khan classified structural systems according to their ability to withstand lateral loads. This classification divides structural systems into four categories as shown in Figure 2.

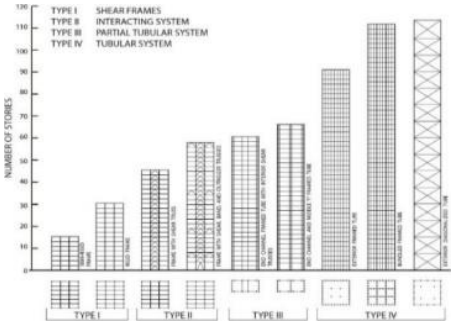


Figure 2. A structural system of tall buildings [5].

2. Literature Review

Amoussou et al. (2021) did an investigation on simplified modeling and analysis methods for skyscrapers with outrigger systems. The results of the simplified approach were verified with the analysis results of the detailed ETABS model, where static, modal, and dynamic analyses were performed. The applicability of the proposed method to different configurations of high-rise buildings with outrigger systems was also verified by a parametric study. A comparative study with several previous studies was performed to demonstrate the effectiveness of the proposed method. It was found that the applied simple modeling method has good accuracy in predicting the horizontal displacement and interstate deviation in linear and nonlinear analysis. As a result, the simplified modeling approach gives a deep understanding of the outrigger system behavior and its parameters. Wael Al Haddad et al. (2020) did a comprehensive research on the introduction of outrigger and belt truss systems in skyscrapers. The actual definition of outrigger and belt truss systems, different configurations and structural materials of the outrigger and belt truss system, the operation of the outrigger and belt truss system, and the advantages and disadvantages of the outrigger and belt systems were discussed. Ho, G. W. (2016) has evaluated the performance of the outrigger system in tall buildings. The concept of the outrigger system, optimum topology, design, and construction consideration was studied and presented. Lee, S., & Tovar, A. (2014) have done an investigation of the location of outriggers in high-rise buildings using topology optimization. The results showed that the outrigger placement problem was solved using topology optimization. The further method was used for the material penalty parameter to obtain the plane "0–1". The versatility of the proposed design method has been demonstrated using a realistic FEM model of a three-dimensional 201 m tall building. Kiran et al. (2012) have studied the static and dynamic behavior of outrigger systems for tall buildings. various alternative 3D models have been made using ETABS software for reinforced concrete structures with a central core with an outrigger and without an outrigger by varying the relative flexural stiffness from 0.25 to 2.0 with step 0.25. In addition, the position of the outriggers was modified along the height of the building by considering the relative height parameter of the outriggers

from 0.975 to 0.4. The results show that the performance of the outrigger is most effective for the relative height of the outrigger equal to 0.5.

This research focused on performing a comparison between RC framed irregular buildings with and without concrete outrigger and belt trusses structural systems as diagonal elements in different locations along the height of the buildings to find the suitable location which reduces the story displacement, story drift and increases the stiffness of the building under actual strong earthquakes by using ETABS software.

3. Objective of Study

In the present paper, the seismic performance of tall buildings with and without outrigger and belt truss systems are carried out in zone IV using Response spectrum analysis. Outrigger and belt trusses in two different locations are studied. Different characteristics like story displacements, the story drifts, and story stiffness of tall buildings with and without outrigger and belt trusses along X&Y directions are studied.

4. Methodology

In this research work modeling and analysis of the G+16, G+20, and G+24 buildings have been done in ETABS. The height of buildings (G+16=51m, G+20=63m, and G+24=75m) are greater than 15 m and are located in zone IV, a static analysis method is not applicable. Hence analysis of structures is carried out by linear dynamic analysis (Response spectrum method).

5. Modeling and Analysis

In this research, three buildings with different heights (G+16, G+20, and G+24), with and without outrigger and belt truss systems are considered. Outrigger and belt truss systems are introduced as RC diagonal members in ETABS. The exact dimension of the outrigger and belt trusses found after the design check-in ETABS. The necessary data for analyzing the buildings are given in Tables [1], [2], and [3] as follows:

Table 1: Geotechnical and Geological Data

S.No	*Variable*	*Type*	*Reference*
1	Type of soil	Medium soil	IS 1893(part 1):2016 [18]
2	Type of foundation	Raft footing	IS 2950(part1):1981 [19]
3	seismic zone	IV	IS 1893(part 1):2016 [18]
4	seismic zone factor	0.24	IS 1893(part 1):2016 [18]

Table 2: General data collection and condition assessment of the building

S.No	*Description*	*Information*	*Remarks*
1	Type of building usage	Residential	
2	Plan Size	30m×40m	
3	Building height	G+16=51m	
		G+20=63m	
		G+24=75m	
4	Building structure	Special moment frame with structural wall	IS 1893(part 1):2016 [18]
5	Open ground story	yes	
6	Horizontal floor system	Beams and slabs	IS 456: (2000) [22]
7	Grade of concrete	M30, M40	IS 10262: 2009 [20],[22]
8	Grade of steel	Fe 500	IS 431(part 1): 1982 [21]
9	Used software	ETABS 19.1.0	

Table 3: Dimension of the structural members

G+16		
S.No	*Member*	*Dimension (mm)*
1	Column	400×700
2	Beam	300×500
3	Central core shear wall	300
4	Exterior and Interior masonry walls	250&150
5	Slab thickness	150
G+20		
6	Column	400×900
7	Beam	300×500
8	Central core shear wall	300
9	Exterior and Interior masonry walls	250&150
10	Slab thickness	150
G+24		
11	Column	500×1000
12	Beam	300×500
13	Central core shear wall	400
14	Exterior and Interior masonry walls	250&150
15	Slab thickness	150

All the structural members which are shown In Table 3 are defined according to the design check of ETABS software, in which the column size, beams, and so on are taken differently by the change of the number of stories.

In this research paper, all frames are modeled as a special moment-resisting frame having central core shear walls. Columns and beams are modeled as frame elements and shear walls are modeled as shell elements. The test models are including two different types of models:

1. Conventional building.
2. Building with two different numbers and locations of outrigger and belt trusses systems.

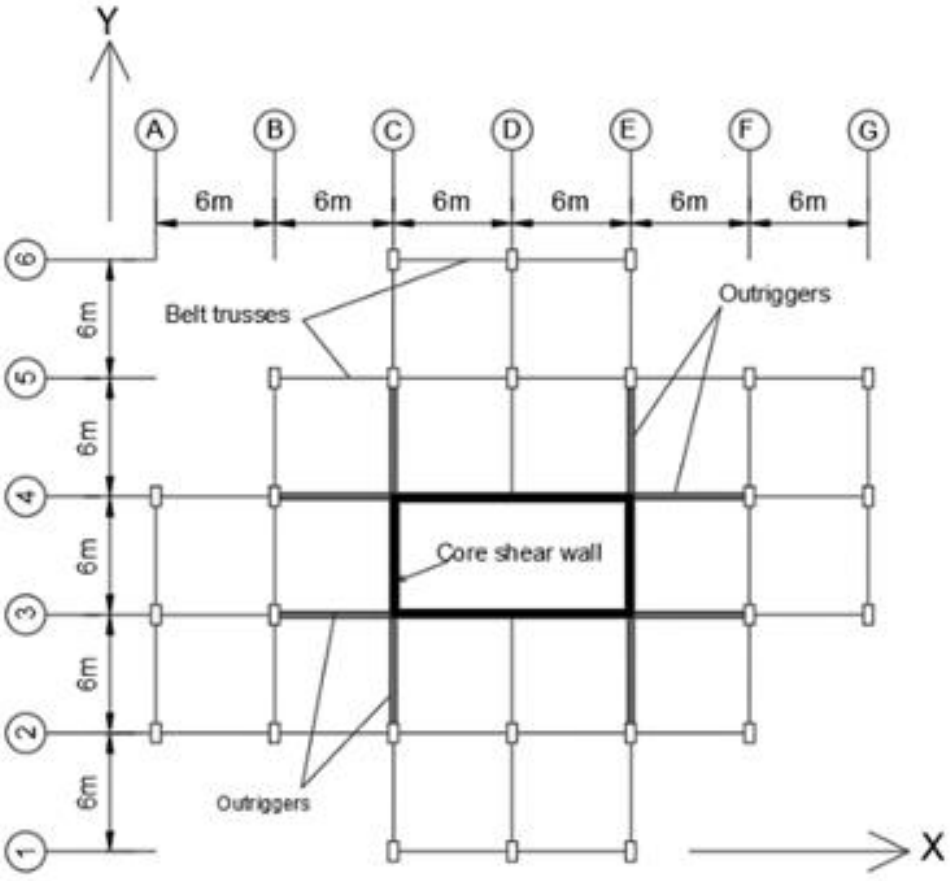


Figure 3. Plan of the building.

The designation of the test models is as follows:

1. MOB1-G+16 without outrigger and belt truss systems as presented in Figure 4a.
2. MOB2-G+16 with outrigger and belt truss systems in the 9th and 16th stories as presented in Figure 4b.
3. MOB3-G+16 with outrigger and belt truss systems in the 6th and 13th stories as presented in Figure 4c.
4. MOB4-G+20 without outrigger and belt truss systems as presented in Figure 4d.
5. MOB5-G+20 with outrigger and belt truss systems in the 10th and 20th stories as presented in Figure 4e.
6. MOB6-G+20 with outrigger and belt truss systems in 7th and 15th as presented in Figure 4f.
7. MOB7-G+24 without outrigger and belt truss systems as presented in Figure 4g.
8. MOB8-G+24 with outrigger and belt truss systems in the 14th and 24th stories as presented in Figure 4h.
9. MOB9-G+24 with outrigger and belt truss systems in 9th and 18th as presented in Figure 4i.

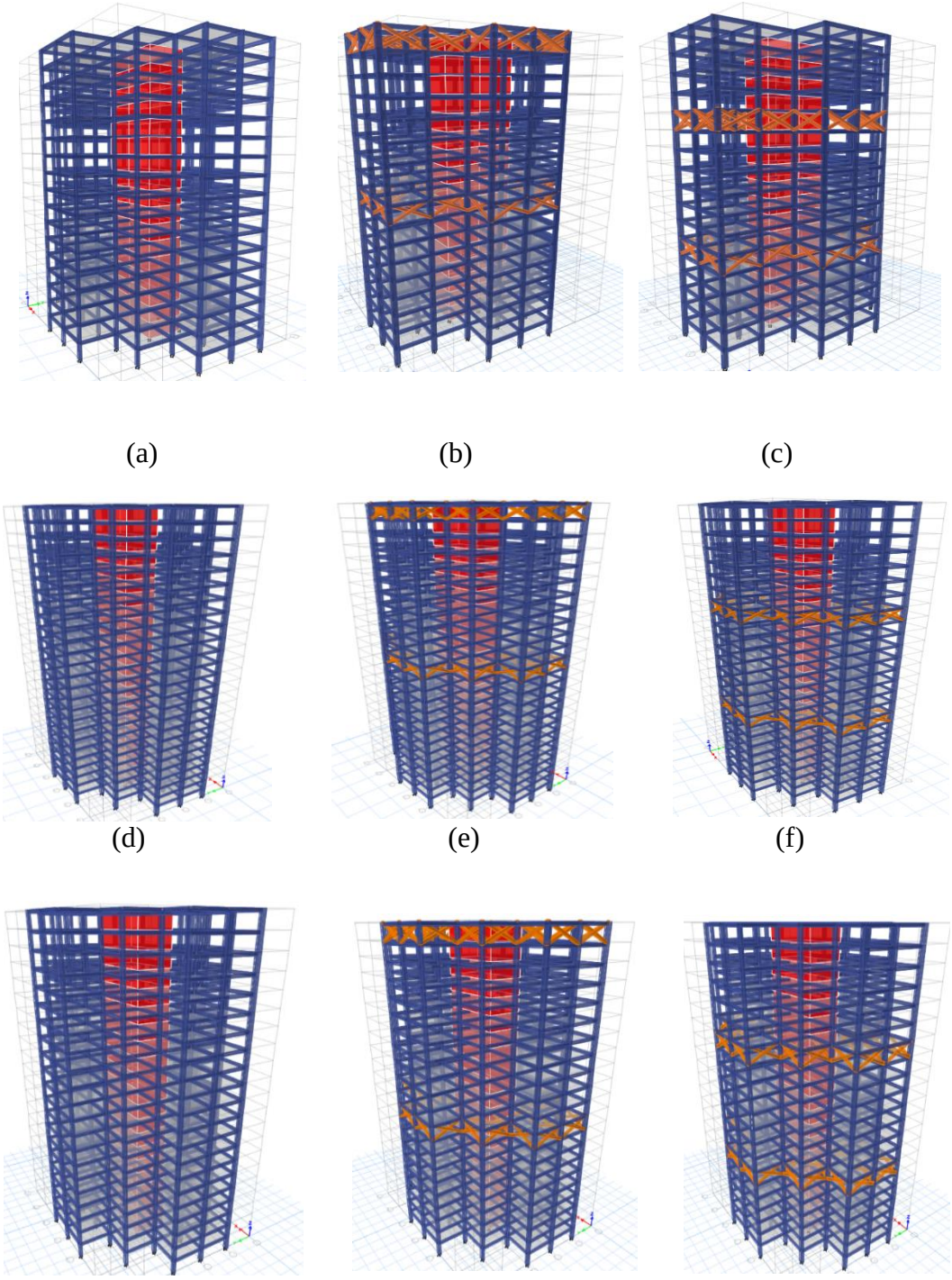
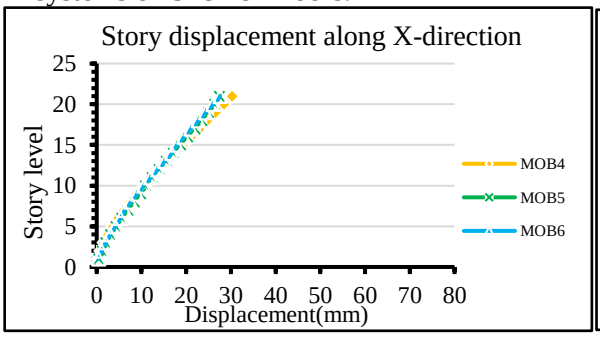


Figure 4. Buildings with and without outrigger and belt truss systems.

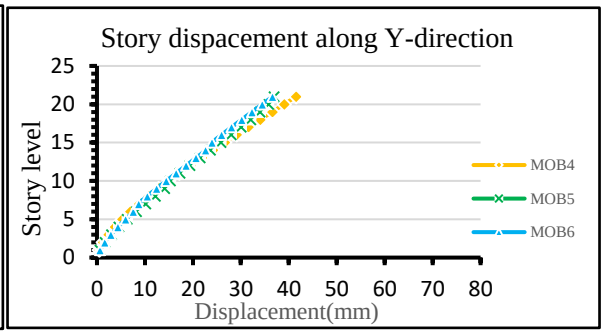
6. Results and Discussions

The results obtained from the analysis of models are compared and discussed as follows.

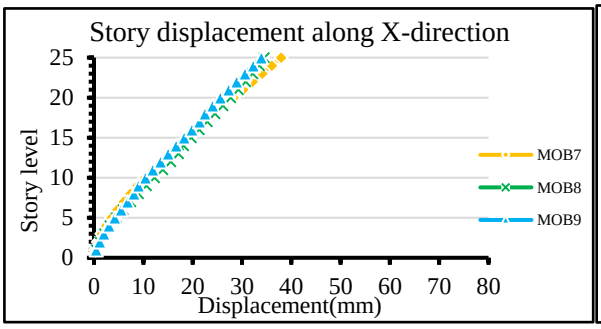
The variation of story displacements in tall buildings with and without outrigger and belt truss systems under seismic loads as indicated in Figure 5, is observed that in G+16 buildings the story displacement was reduced by 16.29% along the X-direction and 12.7% along the Y-direction by providing outriggers and built truss systems on 9th&last floors and reduced by 16.7% along X-direction and 13.8% along Y-direction by providing outriggers in 6th&13th floors. In G+20 buildings, the story displacement was reduced by 10.45% along the X-direction, and 12.4% along the Y-direction by providing outriggers and built truss systems on the 10th&last floors and reduced by 9.7% along the X-direction and 13.4% along Y-direction by providing outriggers and built truss systems on 7th&15th floors. In G+24 buildings, the story displacement was reduced by 10.14% along the X-direction, and 58.6% along the Y-direction by providing outriggers and built truss systems on the 14th& 24th floors and reduced by 11.4% along the X-direction and 58.5% along Y-direction by providing outriggers and built truss systems on 9th&18th floors.



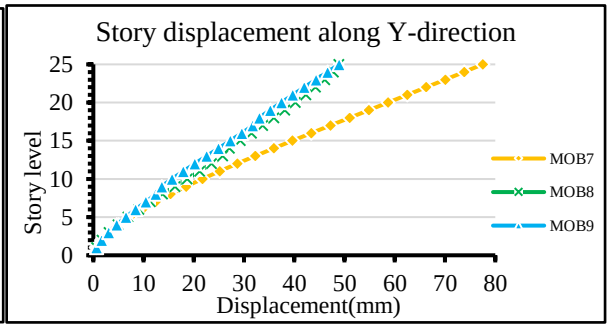
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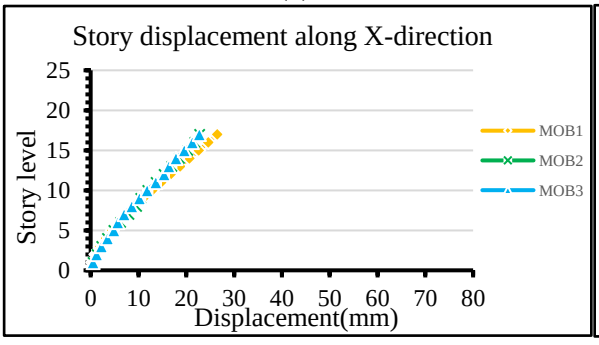
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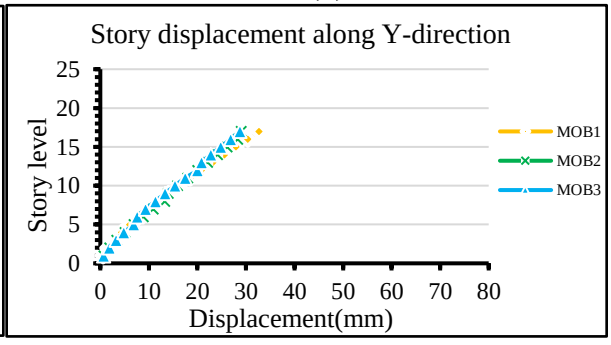
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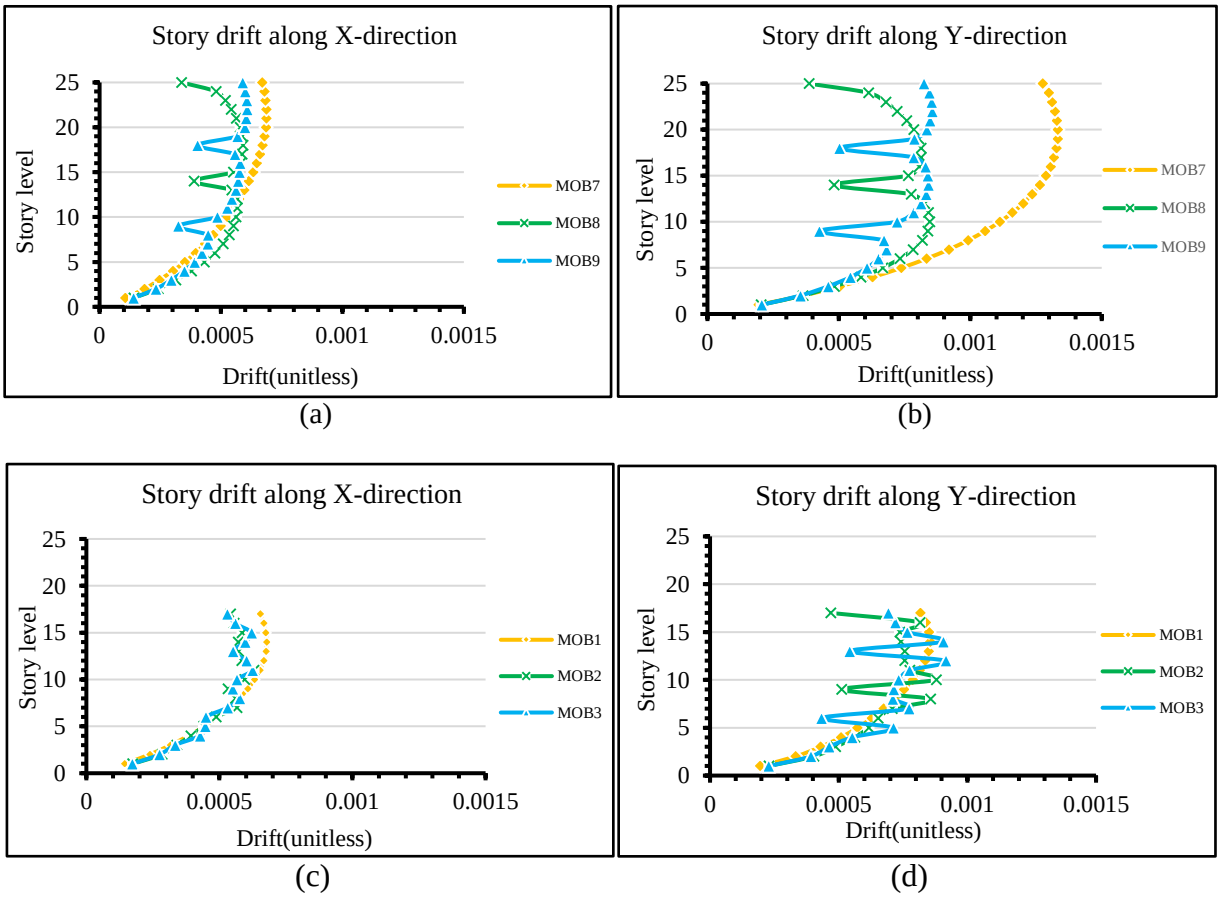
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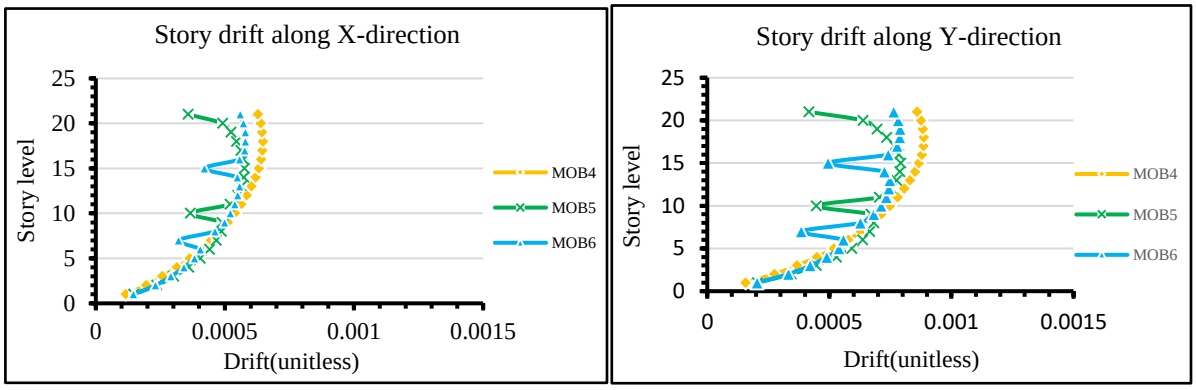


(f)

Figure 5. Story displacement (a) Story displacement along X-direction in G+16, (b) Story displacement along Y-direction in G+16, (c) Story displacement along X-direction in G+20, (d) Story displacement along Y-direction in G+20, (e) Story displacement along X-direction in G+24 and (f) Story displacement along Y-direction in G+24.

The variation of story drifts in tall buildings with and without outrigger and belt truss systems under seismic loads as indicated in Figure 6, clearly indicates the reduction of story drift in buildings with outrigger and belt truss systems. In G+16 buildings the story drift was reduced by 7.6% along the X-direction and 2.6% along the Y-direction by providing outriggers and built truss systems on the 9th&last floors and reduced by 8.5% along the X-direction and 6.6% along Y-direction by providing outriggers in 6th&13th floors. In G+20 buildings, the story drifts were reduced by 12.3% along the X-direction, and 11.9% along the Y-direction by providing outriggers and built truss systems on the 10th&last floors and reduced by 11.7% along the X-direction and 12.3% along Y-direction by providing outriggers and built truss systems on 7th&15th floors. In G+24 buildings, the story drifts were reduced by 16.5% along the X-direction, and 57.6% along the Y-direction by providing outriggers and built truss systems on the 14th& 24th floors and reduced by 12.9% along the X-direction and 55.8% along Y-direction by providing outriggers and built truss systems on 9th&18th floors.

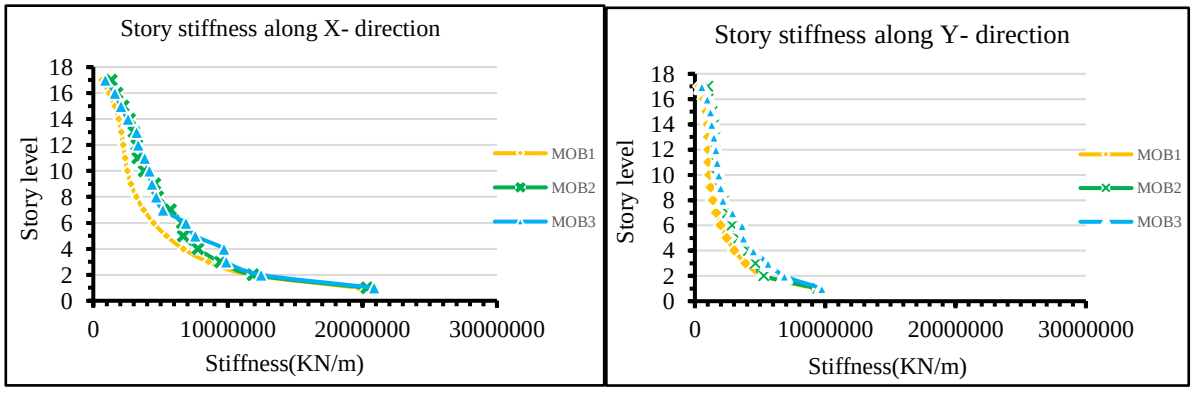




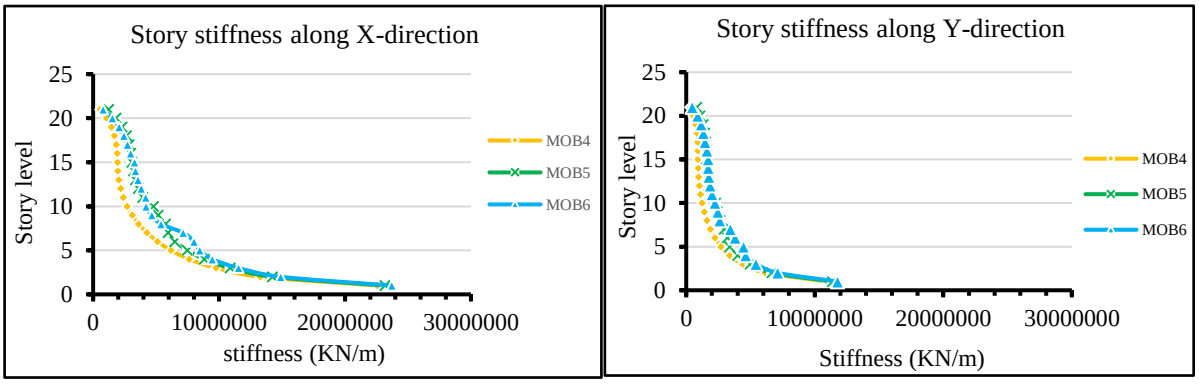
(e) (f)

Figure 6. The story drifts (a) Story drift along the X-direction in G+16, (b) Story drift along the Y-direction in G+16, (c) Story drift along the X-direction in G+20, (d) Story drift along the Y-direction in G+20, (e) Story drift along X-direction in G+24 and (f) Story drift along Y-direction in G+24.

The variation of story stiffness in tall buildings with and without outrigger and belt truss systems under seismic loads as indicated in Figure 7, clearly indicates the increase of story stiffness in buildings with outrigger and belt truss systems. In G+16 buildings the story stiffness increases by 3.1% along the X-direction and 2.7% along the Y-direction by providing outriggers and built truss systems on the 9th&last floors and increases by 5.6% along the X-direction and 5.8% along Y-direction by providing outriggers in 6th&13th floors. In G+20 buildings, the story stiffness increased by 27.9% along the X-direction, and 30.2% along the Y-direction by providing outriggers and built truss systems on the 10th&last floors and increase by 22.8% along the X-direction and 26.4% along Y-direction by providing outriggers and built truss systems on 7th&15th floors. In G+24 buildings, the story stiffness increases by 31.4% along the X-direction, and 16.9% along the Y-direction by providing outriggers and built truss systems on the 14th&24th floors and increases by 27.9% along the X-direction and 14.8% along Y-direction by providing outriggers and built truss systems on 9th&18th floors.

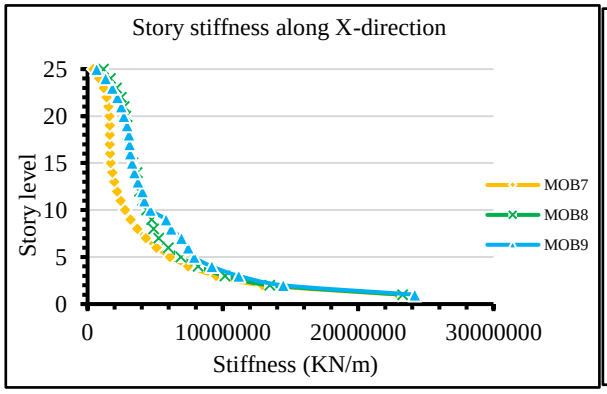


(a) (b)

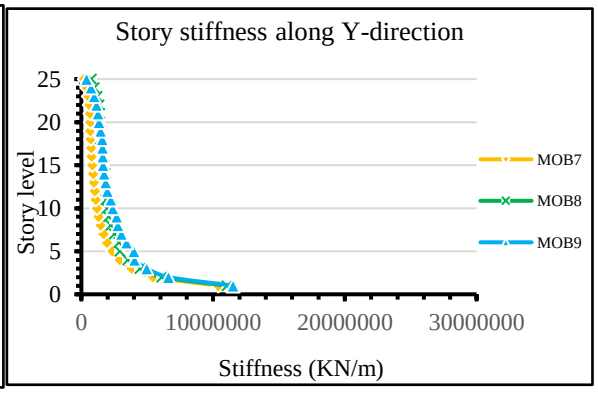


(c)

(d)



(e)



(f)

Figure 7. Story stiffness (a) Story stiffness along X-direction in G+16, (b) Story stiffness along Y-direction in G+16, (c) Story stiffness along X-direction in G+20, (d) Story stiffness along Y-direction in G+20, (e) Story stiffness along X-direction in G+24 and (f) Story stiffness along Y-direction in G+24.

7. Conclusion

The utilization of outriggers and belt trusses in tall buildings increases stiffness and reduces story displacement and story drift under lateral loads. Based on the results obtained from the analysis, the following conclusion was made:

- Outrigger and belt truss systems increase the performance of the building while subjected to earthquake loads by increasing the story stiffness and reducing the story displacement and story drift.
- The outrigger and belt truss systems at the top of the building are less efficient, the outrigger and belt truss systems are better to provide at mid-height, the benefits of placing at the middle stories resulting up to 50% reduction in story drift, and up to 60% reduction in story displacement.
- Providing the outrigger and belt truss systems increases the stiffness of the building under earthquake loads by up to 10%.

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