

Effectiveness of Various Outrigger Systems of Different Structural Materials for Lateral Load Resistance in Reinforced Concrete High-Rise Buildings



N. A. A. C. Nissanka, A. M. Fernando, and J. C. P. H. Gamage

Abstract With the rapid urbanization and fast pace of development in high-strength materials, construction of tall structures has become a go-to option. It is concerned with considerably reducing the weight of buildings while enhancing the slenderness and flexibility of structures. However, as the height increases the structures become more critical under wind and earthquake-induced lateral loads, as it reduces lateral stiffness which is pivotal in maintaining a building's structural efficiency. In such instances, outrigger and belt truss structural systems are often introduced in high-rise structures to provide adequate lateral stiffness to maintain the wind deflection and drift criteria within acceptable limits. According to the Author's knowledge, extensive studies have been done up to date, which only consist of investigations with outrigger systems of a single material, consisting of simple square and rectangular shaped building plan layouts having no consideration for vertical irregularity of the building. Hence, this study aims to bring a broader understanding of both conventional outrigger and virtual outrigger systems by identifying the most efficient lateral load resisting outrigger system for a reinforced concrete high-rise building by analyzing a range of structural materials and alternative arrangements with vertical irregularity. A three-dimensional (3D) numerical model of a high-rise building with lateral load resisting systems was developed and validated theoretically. A parametric study was conducted to determine the applicability of selected alternative outrigger systems. Results indicate that the combination of the outrigger and belt truss structural system in concrete indicated maximum performance while attaining the maximum reduction of 29.7% and 28.5% in lateral displacement and inter-storey drift, respectively. These values tend to vary with each outrigger structural arrangement and the structural material, while all systems seem to significantly enhance the structural performance of the building against wind action, hence resulting in more resilient and sustainable buildings.

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1 Introduction

Recent advances in the creative design approaches of architects, rapid urbanization and lack of urban lands, excessive cost, and the necessity to prevent disorder in urban expansion have resulted in the growth of high-rise constructions. In the early days, very few structural forms were used in the design of tall buildings. However, due to the rapid technological advancements in modern science along with innovations in material technology, developments in construction techniques and operating systems at present, enables various structural configurations and profiles to be used for tall buildings [1]. In doing so, the buildings become more critical under wind and earthquake-induced lateral loads, as it reduces the structural stiffness of the building. By accommodating a very effective and efficient core wall structural system into a tall building, drift, and displacement parameters due to lateral loads can be reduced remarkably [2]. Nevertheless, in tall buildings, as the structure height increases, the standalone core wall structural system can barely provide sufficient structural stiffness to control the drift and displacement criteria within the acceptable limits. Therefore, in such cases, outrigger structural systems are introduced into tall buildings where deep and stiff elements are connected through the central core wall system and most exterior columns of the building, reducing the sway of the building [3, 4].

The structural performance and efficiency of outrigger systems used in tall buildings to resist lateral loadings depend on several factors such as different forms of structural outrigger configurations, the number of outrigger levels provided in the building, relative locations of outrigger/outriggers along its height of the building, outrigger plan layout, outrigger truss depths, primary structural materials used, etc. [4]. When considering the outrigger plan layout, both conventional outriggers and virtual outriggers are currently used as efficient lateral load resisting mechanisms in tall buildings. The comparison of structural performance of both conventional and virtual outrigger systems to resist lateral loads in tall buildings has been widely investigated and these studies have extensively used various outrigger typologies to determine the optimum number and positions of outriggers to be used at different heights of the building [5]. However, those studies are mostly limited only to concrete outriggers [6–8]. Further, much of the previous work is based on square and rectangular shaped buildings considering simple grids and plans with minor consideration for vertical irregularity in the building structure (Prasad et al. 2016) [9, 10]. Hence, the present study uses both a circular and a rectangular topology having vertical irregularity along its height which represents the actual building topology in modern structures. Moreover, not many studies are based on a single model with distinct forms of outrigger arrangements to identify the most efficient outrigger structural system. Therefore, this study is extended towards analyzing the behaviour of a reinforced concrete high-rise building, for different types of outrigger arrangements

under different structural materials to identify the most efficient outrigger structural system and the optimum primary structural materials to be used in each system when subjected to wind loading.

2 Literature Review

2.1 Structural Systems for Tall Buildings

From a structural engineer's perspective, the selection of the best and the most appropriate structural form for a high-rise building mainly depends on the efficient arrangement of major structural elements to resist the different gravity and horizontal loading combinations. Several other factors such as internal planning, structural material and method of construction, external architectural appearance and perspectives, operation of services, nature and extent of horizontal loading applied on structure, and the height and aspect ratio of the building are also considered crucial [11, 12]. When the structure is taller and slender, it is necessary to select the most appropriate structural form with the required structural stability. Sitapara and Gore [13] have discussed various types of lateral load resisting structural systems including Rigid frame structural systems, Wall-frame structural systems, Braced frame structural systems, Outrigger structural systems, and Tubular structural systems which are employed in high-rise structures to resist lateral forces. Out of those, the outrigger structural system is scientifically proven to be the most effective method to be used for high-rises [14].

2.2 Outrigger Structural System

These systems consist of deep and stiff elements that connect the central core wall system and the most exterior columns of the building, helping in reducing the sway of the building as presented in Fig. 1 [15]. It is recommended that at least one storey deep outriggers are to be accommodated in tall buildings in order to make them sufficiently effective and to increase the flexural and shear rigidity of buildings [9]. This mechanism greatly assists in reducing the moment in the core system of the buildings when compared to a free-standing core wall system without outriggers [14]. As depicted in Fig. 2, the restraint induced by the use of outriggers notably reduces the top storey drift and lateral displacement while improving the structural stiffness of the building by 20–30% [13]. Generally, the insertion of outriggers greatly reduces the available interior space of a building. Therefore, in general, they are placed at mechanical equipment floor levels not to hinder the floor function in the normal floor levels.

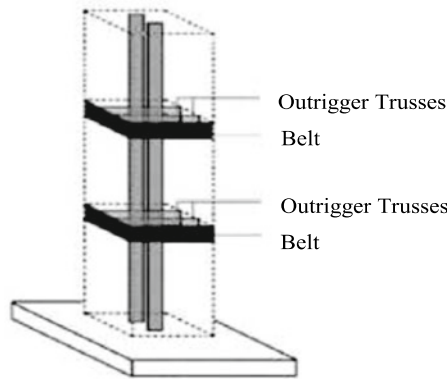


Fig. 1 Multi-level outrigger and belt truss system

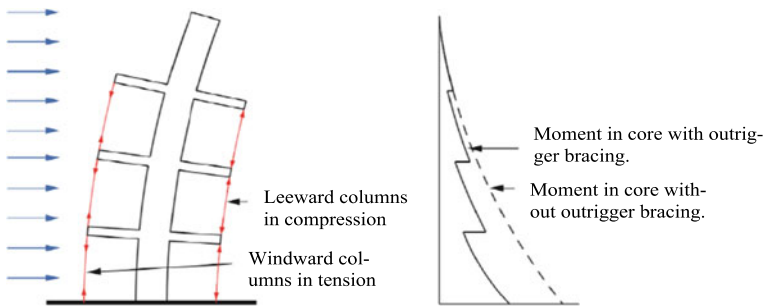


Fig. 2 Outrigger structure displaced under lateral loading and resultant core moments

2.3 *Types of Outrigger Systems and Research Trends*

Over the past years, outriggers have been extensively utilized in tall building structures [1, 16, 17]. The comparative study by Thejaswini and Rashmi [18] outlines that when accommodating an outrigger at the optimum location of the building, a drift can be fully controlled. Similarly, [14] has studied the progression of the outrigger structural system with time in tall buildings and different applications in terms of optimum topology, design, and construction considerations. Due to the rapid enhancements in technology and science, the choices have widened accordingly with time for the options of structural materials to be used in outriggers as well as for structural forms to be used. Two major forms of outrigger systems can be recognized based on the structural mechanism of connectivity between the outriggers and the core wall system. They are conventional outrigger system and virtual outrigger system. In the conventional outrigger system, outrigger girders are directly tied in between the core walls and exterior columns of the building. In the virtual outrigger concept, the overturning moment is transmitted from the core to the perimeter columns in a

similar pattern, with no direct connection between the outrigger trusses and the core. Due to the curtailment of this direct connection, it mitigates most of the drawbacks which are associated with the conventional outrigger system. However, the study by [6] has resulted in a maximum lateral displacement in virtual outrigger systems. It has also showcased that multi-outrigger systems can reduce structural elements and foundation sizes as well.

The location of the outrigger across the building plan layout is more important for the lateral behaviour of the structure. Several studies have investigated the optimum outrigger locations to be selected during the design stage [19–21, 10]. As per the findings, a general guideline for the location of a single outrigger is to place it at halfway of the building height. For two outriggers, $1/3$ and $2/3$ height would be the optimum locations. If three outriggers are to be used, $1/4$, $1/2$, and $3/4$ heights are ideal to be used. In case of a three-outrigger system, if one outrigger is to be placed at the top storey, the remaining two outriggers should be located at $1/3$ and $2/3$ height of the building.

Even though extensive studies have been conducted, several research gaps can be identified after a thorough review of the literature. Primarily, there is a lack of research work on actual architectural plans where the outrigger structural system has been used in the irregular shape of buildings having vertical irregularity since most of the studies are based on square and rectangular shaped buildings having simple layouts. Almost all researchers have investigated the static and dynamic behaviour of structures under elastic limits. Only some have used the non-linear time history analysis method. Moreover, researchers have studied the optimum outrigger position for conventional outrigger systems, but there is a lack of data on the optimum location for the virtual outrigger systems. Hence, a necessity arose to study the multi-outrigger level approach and effects of the two storeys deep and three storeys deep outrigger by adopting two or three numbers of outrigger levels in a tall structure. There exist only a few studies on single models with different outrigger types. Therefore, extensions in identifying the optimum usage of outrigger systems along with different types of truss outriggers are required.

3 Methodology

3.1 Structural Model

The proposed structure is a 55 storey, 197.5 m high RC high-rise building which is assumed to function as an area for retail, offices, and residential space. Single storey deep two outrigger levels have been provided at two mechanical floor levels in fixed positions, to minimize the reduction of usable floor area and any disturbance to aesthetic appearance. Pertaining to the findings of Shivacharan K (2015), the first outrigger is placed on the 18th level ($1/3$ of the building height) and the second outrigger is placed on the 36th level ($2/3$ of the building height). Table 1 denotes the

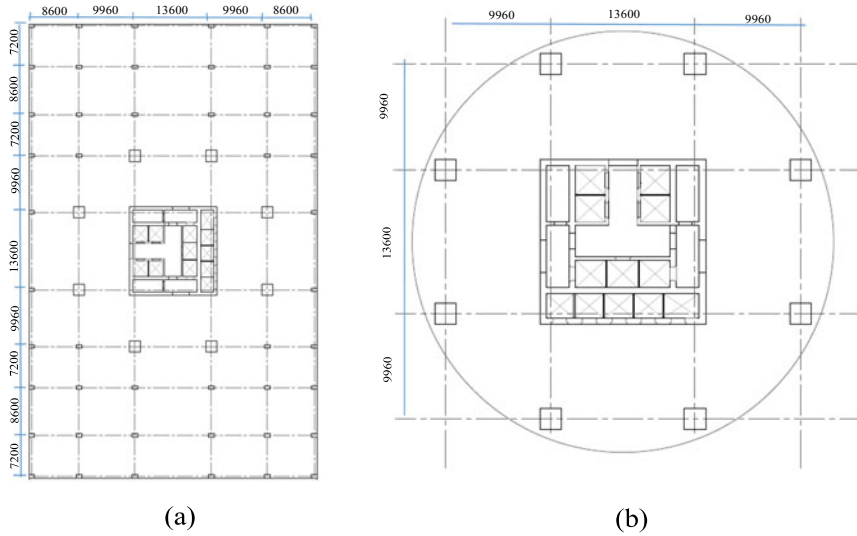


Fig. 3 a Layout of the structural floor plan from Level 1–Level 8, b Layout of structural floor plan from Level 9–Level 55 (dimensions in mm)

information related to this section. To account for vertical irregularity, the geometry of the building is changed from a rectangular shape to a circular shape beyond level 8 onwards. The bottom floors represent podium floors and the upper floors represent a standalone single tower as in a real structure as presented in Fig. 3. The section properties and material properties of each structural element including outriggers are presented in Table 1.

The primary idea of this study is to identify the effectiveness of conventional and virtual outrigger systems on the structural performance of a RC high-rise building through several combinations of belt truss and outrigger arrangements under each category of different structural materials. Therefore, a total of 10 model types, (as in Table 2) with different outrigger types; only outrigger, only belt truss, and a combination of both belt truss and outrigger under different structural materials; concrete, steel, and composite were modelled.

3.2 Design Loads

Dead loads, super imposed dead loads, live loads, and wind loads are the primary loads considered in structural modelling. The dead load is considered the self-weight of the structure. The self-weight of structural elements is automatically generated by the software based on assigned material properties. Unit weight of concrete and steel was taken as 25 kN/m^3 and 78 kN/m^3 , respectively. Superimposed dead loads and live loads were considered as per BS EN 1991–1.1–2001 [22]. The static wind

Table 1 Section properties and material properties

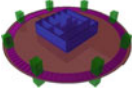
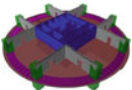
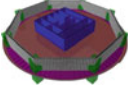
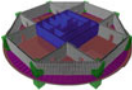

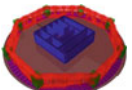

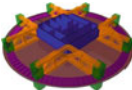
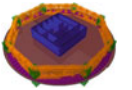
Element		Size (m)		Material properties
Column	Mega columns	1.2 × 1.2		M50
	Podium columns	0.6 × 0.6		
		Width (W)	Depth (D)	
Beam	Perimeter Beams	0.6 × 0.6		M30
		1.2 × 0.6		
	Internal Primary Beams	0.6 × 0.6		
	Internal Secondary Beams	0.6 × 0.4		
Beams at outrigger levels	Perimeter Beams	0.6 × 2		
	Internal Primary Beams	0.6 × 0.6		
	Internal Secondary Beams	0.4 × 0.6		
Slab	At top & bottom of outrigger floors	0.2		M30
	Other levels	0.15		
RC core walls		0.4,0.3		M50
Reinforced concrete wall outriggers		0.4		M50
Steel outriggers	H Iron	1 × 1 × 0.1 × 0.1		S355
Composite outrigger	Concrete Beam	1 × 1		M50
	H Iron	0.6 × 0.6 × 0.06 × 0.06		S355

loads were calculated as per BS EN 1991-1.4-2005 [23], where the wind loads were applied as diaphragm forces for each floor in the building. Basic load combinations were established in accordance with BS EN 1990:2002 [24].

3.3 Method of Analysis


The structure was analysed as a three-dimensional elastic structure, in the CSIETABS structural analysis software. When modelling, columns and beams were modelled as frame elements and shear walls and slabs were modelled as shell elements. Foundation deformations were neglected in the structural analysis and pin supports were assigned to columns at the base. Auto meshing is done for slab elements while manual meshing was used for wall elements.

Table 2 Model arrangements

Model ID	Model description	Model arrangement
NO	Structural model without outrigger	
Concrete material		
O-CONCTERE	Structural model of concrete outrigger only	
B-CONCRETE	Structural model of concrete belt truss only	
OB-CONCRETE	Structural model of concrete outrigger with belt truss	
Steel material		
O-STEEL	Structural model of steel outrigger only	
B-STEEL	Structural model of steel belt truss only	
OB-STEEL	Structural model of steel outrigger with belt truss	
Composite material		
O-COMPOSITE	Structural model of composite outrigger only	
B-COMPOSITE	Structural model of composite belt truss only	

(continued)

Table 2 (continued)

Model ID	Model description	Model arrangement
OB-COMPOSITE	Structural model of composite outrigger with belt truss	

4 Results and Discussion

4.1 Natural Period and Corresponding Frequencies

The results of the natural period and corresponding frequencies for the first two modes of each outrigger structural model of concrete, steel, and composite and for the structural model without outriggers are presented in Table 3.

The frequency of a structure is a characteristic of stiffness. It directly affects the structural performance of a building. The structural model without outriggers has the highest building period for both Mode 1 (Y direction) and Mode 2 (X Direction) when compared with other outrigger structural models. The combination of both outrigger and the belt truss structural system (OB) has the lowest building period for both Mode 1 and Mode 2. The belt truss only (B) outrigger structural system has the highest building period under each material category of concrete, steel, and composite.

Table 3 Natural period and corresponding frequencies for structural models

Model name	Period		Frequency		% Frequency increase	
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
	Y direction	X direction	Y direction	X direction	Y direction	X direction
	s	s	Hz	Hz	%	%
NO	7.613	6.989	0.131	0.143	–	–
O-CONCRETE	6.466	5.903	0.155	0.169	18	18
B-CONCRETE	6.576	6.043	0.152	0.165	16	16
OB-CONCRETE	6.425	5.843	0.156	0.171	18	20
O-STEEL	6.614	6.059	0.151	0.165	15	15
B-STEEL	6.749	6.223	0.148	0.161	13	12
OB-STEEL	6.503	5.944	0.154	0.168	17	18
O-COMPOSITE	6.684	6.128	0.150	0.163	14	14
B-COMPOSITE	6.823	6.296	0.147	0.159	12	11
OB-COMPOSITE	6.561	6.003	0.152	0.167	16	16

When comparing different materials, concrete type outrigger systems tend to perform relatively well. The frequency in the structure was increased by a maximum of 18% in the most critical direction of Y for the outrigger systems O and OB compared to the one without outriggers. For outrigger system B, the frequency was increased by a maximum of 16%. For the outrigger types of steel material, a significant difference was observed where the frequency for OB system is increased by 17%, while for systems O and B 15% and 13% increments were obtained. The same pattern of structural performance was observed in different outrigger types of composite material, where the structure frequency was increased by 16%, 14%, and 12% for OB, O, and B systems, respectively.

4.2 Maximum Wind-Induced Lateral Displacement.

The structural model without outriggers has the maximum wind-induced lateral deflection on the top storey in both X and Y directions and those results exceeded the maximum allowable lateral displacement value of H/500. Maximum wind-induced lateral deflection on the top storey values has been reduced in all other outrigger structure models of concrete, steel, and composite in both directions. The values are less than the maximum allowable lateral displacement. Summarized results for the maximum wind-induced lateral deflection in both X and Y directions for each structural model of no outriggers and with outriggers under different structure materials of concrete, steel, and composite are illustrated in Table 4.

When comparing the performance of outrigger structure models of different outrigger arrangements, the pattern of varying the top storey lateral displacement

Table 4 Maximum wind-induced lateral displacement for structural models

Modal name	Displacement at top			% Reduction in displacement	
	X direction	Y direction	Allowable limit	Δx	Δy
	mm	Mm	mm	%	%
NO	397.52	430.562	395		
O-CONCRETE	276.919	309.734	395	30.3	28.1
B-CONCRETE	293.138	321.134		26.3	25.4
OB-CONCRETE	272.072	302.709		31.6	29.7
O-STEEL	292.896	325.108	395	26.3	24.5
B-STEEL	312.624	340.454		21.4	20.9
OB-STEEL	284.691	314.316		28.4	27.0
O-COMPOSITE	299.497	331.555	395	24.7	23.0
B-COMPOSITE	319.377	347.417		19.7	19.3
OB-COMPOSITE	289.792	319.202		27.1	25.9

values is almost unchanged under each material category of concrete, steel, and composite. The minimum deflection in both axes is achieved by the OB outrigger system and the outrigger system B has achieved the maximum deflection in both axes. For different outrigger types of concrete material, the maximum reduction of 29.7%, in the top storey lateral displacement was achieved for OB, O, and B outrigger systems, respectively. Similarly, steel and composite material structures exhibited the same trend, where OB, O, and B outrigger systems in steel have reductions of 27.0%, 24.5%, and 20.9%, with 25.9%, 23.0%, and 19.3% reductions for the composite structure material. The profile of lateral displacement at the top storey for each outrigger building model with varying material options for the most critical direction (Y direction) is presented in Fig. 4.

4.3 Maximum Inter-Storey Drift

The Maximum inter-storey drift values in both X and Y directions for each structural model without outriggers and with outriggers under different structure materials were compared with the maximum allowable inter-storey drift value of 0.25% as demonstrated in Table 5. The structural model without outriggers has the maximum inter-storey drift in both X and Y directions. Those results exceed the maximum allowable inter-storey drift value of 0.25%. Figure 5 illustrates the inter-storey drift of the structure without outriggers in the most critical direction. In contrast, all the other models with different combinations of outrigger structures exhibit values less than the maximum allowable limit. Figure 6 depicts the inter-storey drift for each structural material having different outrigger arrangements [6].

For OB outrigger systems, the maximum reduction in the inter-storey drift of 28.5% was achieved by the concrete type of outrigger with 26.6% and 25.7% for steel and composite types, respectively. The same trend was observed for the other two outrigger systems, where in O type 27.3%, 24.7%, and 23.4%, in B type 25.3%, 21.1%, and 19.6% reductions were obtained for material of concrete, steel, and composite type, respectively.

5 Conclusion and Recommendations

The current study investigated the behaviour and effectiveness of various outrigger systems under different structural materials for a multi-storey reinforced concrete high-rise building when subjected to wind loads. A parametric study was conducted on a numerical model. Different outrigger structure types: only outriggers (O), only belt truss (B), and a combination of both outriggers and belt truss (OB) with varying material categories of concrete, steel, and composite were compared with the structural model without outriggers based on the parameters such as natural frequency,

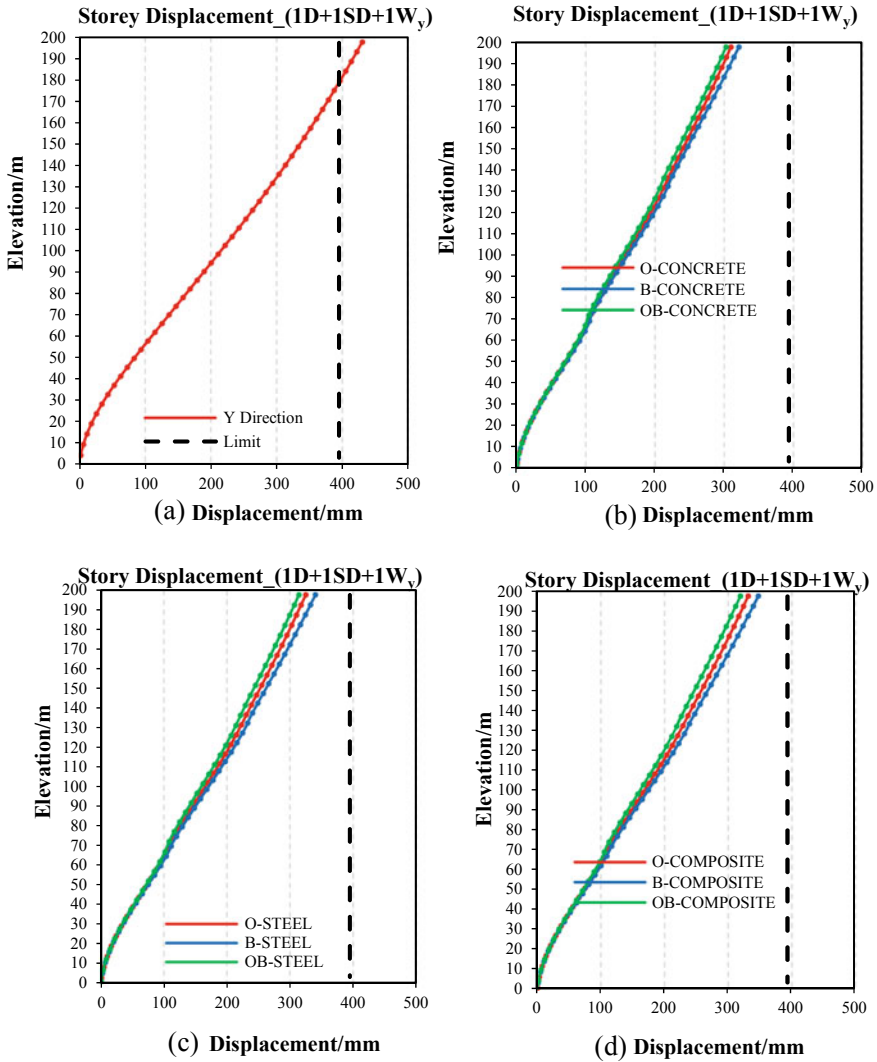


Fig. 4 Maximum storey displacement for structural models, **a** without outriggers, **b** concrete outriggers, **c** steel outriggers, **d** composite outriggers in Y-Direction

maximum lateral displacement of top storey and inter-storey drift. The findings of the investigation can be summarized as follows:

1. The insertion of conventional and virtual outrigger systems has effectively contributed to reduce the natural period of a building by increasing the structural stiffness. It has achieved a decrease in the maximum wind-induced lateral deflection at the top storey and maximum inter-storey drift of the structure by increasing the resistance against the lateral loads.

Table 5 Maximum inter-storey drift for structural models

Modal name	Maximum storey drift			% Reduction in storey drift	
	X direction	Y direction	Allowable limit	Δx	Δy
	%	%	%	%	%
NO	0.2495	0.2648	0.25	-	-
O-CONCRETE	0.1814	0.1925	0.25	27.3	27.3
B-CONCRETE	0.1896	0.1978		24.0	25.3
OB-CONCRETE	0.1778	0.1894		28.7	28.5
O-STEEL	0.1911	0.1993	0.25	23.4	24.7
B-STEEL	0.2013	0.209		19.3	21.1
OB-STEEL	0.1852	0.1943		25.8	26.6
O-COMPOSITE	0.1951	0.2029	0.25	21.8	23.4
B-COMPOSITE	0.2053	0.2129		17.7	19.6
OB-COMPOSITE	0.1882	0.1967		24.6	25.7

2. Concrete-type outriggers exhibit the best structural performance in reducing the building period, top storey lateral displacement, and inter-storey drift. Both OB and O-type concrete outrigger systems have almost similar reduction percentages.
3. For steel outrigger structure types, OB outrigger system is proven to be the best outrigger structure type in reducing all the three parameters of the building compared to the other two outrigger systems. A similar trend was observed for composite material models.

As per the findings, it is clearly depicted how outrigger systems are utilized to obtain a resilient infrastructure. Further, it is seen how different materials and arrangements can result in enhanced structural performance. Following are several recommendations for future studies:

- Outrigger and belt trusses can be placed at different locations of a building along its height and can identify the most optimum location for each outrigger structure type under each category of different structural materials, concrete, steel, and composite.
- The study can be used for different types of truss outriggers and belt trusses under different structural materials of concrete, steel, and composite.
- A similar study can be carried out by increasing the depth of the outriggers into two or three storeys

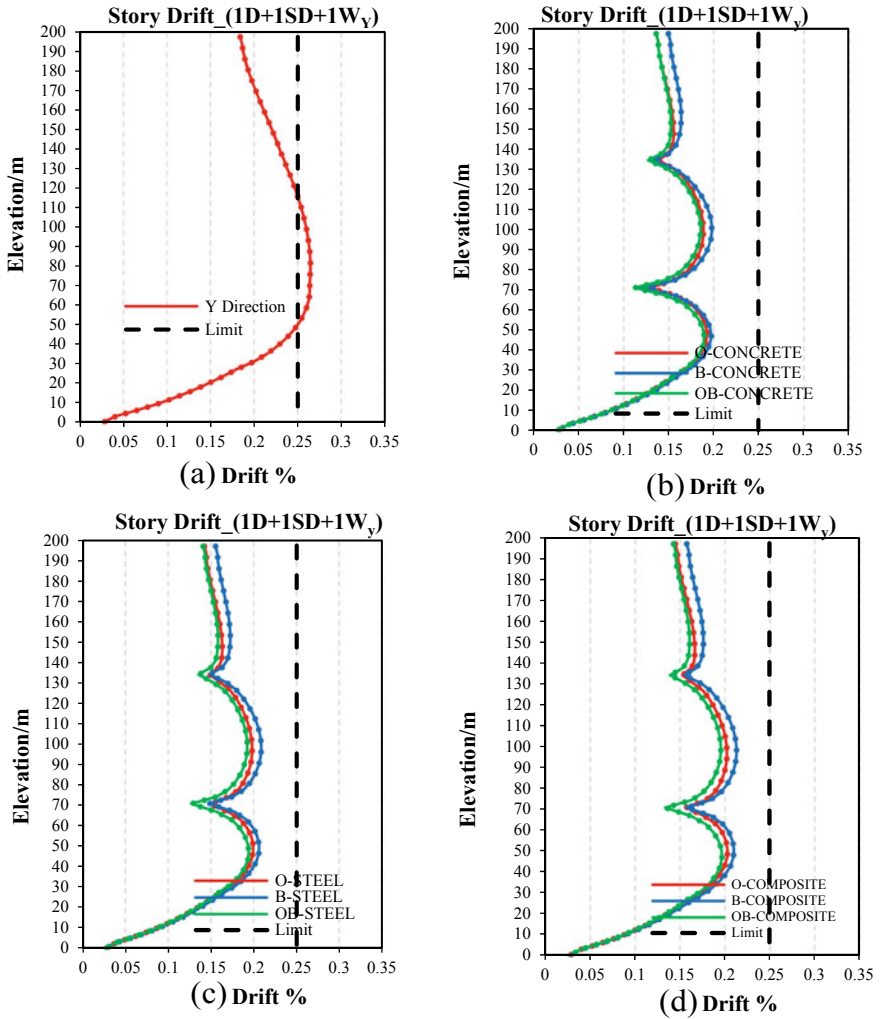


Fig. 5 Maximum inter-storey drift for structural models **a** without outriggers, **b** concrete outriggers, **c** steel outriggers, **d** composite outriggers in Y-Direction

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