Computational Engineering and Physical Modeling 1-3 (2018) 67-78

Contents lists available at CEPM

Computational Engineering and Physical Modeling

Journal homepage: www.jcepm.com

The Effects of Outrigger Type and Distribution on Seismic Behavior of Super-Tall Building

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https://doi.org/10.22115/CEPM.2018.125321.1016

ARTICLE INFO

Article history:
Received: 17 March 2018
Revised: 18 September 2018
Accepted: 18 February 2019

Keywords:
Super-tall building;
Outrigger system;
Seismic behavior;
Numerical modeling.

ABSTRACT

Seismic performance and behavior of super-tall building is one of significant place of doubt while using energy dissipated outriggers. To enhance the seismic performance of super-tall building structures using outrigger is one common method; however, the performance and behavior of the outrigger varies based on the outrigger section and more importantly the elevation and multitude of outrigger in structure, that could cause great differences in seismic behavior of outrigger and the compressive force that is going to apply to mega columns. To evaluate the seismic performance of the building, a case study was carried out. The models was provided with two different outrigger and two different outrigger distribution and results was find out for each model to compare and present the best model that has the higher performance in whole building. The numerical models for the structures in different condition were established with the aid of ETABS software. The responses of the modeled buildings were obtained for TSC 2007 and TSC 2017 and compared. The results show that using outrigger at roof level could significantly affect the story displacement; however, it increases the periods at both X and Y directions.

How to cite this article: Ahani A, Ahani E, Abbaszadeh H. The Effects of Outrigger Type and Distribution on Seismic Behavior of Super-Tall Building. Comput Eng Phys Model 2018;1(3):67–78. https://doi.org/10.22115/cepm.2018.125321.1016

2588-6959/

1. Introduction

One of the best ways to withstand and bear lateral loads in super tall buildings are use and implementation of outrigger system. Outrigger system is consist of shear walls which acts as a central core and outrigger trusses or deep girders which connecting the central core to the mega columns. The efficiency of a structural system in withstanding lateral is evaluated in terms of its ability to resist great lateral loads, which increases as the height of the building increase. In design of super-tall buildings, stability and stiffness are more significant than strength to resist greater lateral and gravity loads [1].

For example, with the economic amendment and rapid urbanization in China, many skyscrapers have been constructed or are under construction. A large part of these high-rise buildings utilize hybrid steel-concrete structure systems such as Steel Frame-Reinforced Concrete (RC) core tubes, due to their unique advantage in reducing construction costs and time. To reduce the inter-story drift of super-tall buildings under earthquakes and winds, the outer frame and the core tube are usually linked together by outriggers to reinforce a story. However, in presence of the outriggers, the lateral stiffness is much larger at the strengthened story than that of the adjacent stories, which has led to a sudden change in the internal forces in the structural members of such stories and the possible configuration of weak stories under serious earthquakes [2].

Most usual systems which are used for withstanding lateral loads in tall steel buildings are moment resisting frames and braced frames. In moment resisting frames yielding causes ductility, but due to their flexibility fails to provide enough stiffness; however, braced frames provide required stiffness. The various concentric bracing forms are efficient in seismic performance. Patil et al. studied Seismic performance of different braced 2-D high rise buildings for different story height [3]. Eccentric bracing and knee bracing are bracing systems which are dissipating energy by yielding of the shear walls and knee elements, these bracing systems are also very effective in seismic performance (Roeder and Popov) [4], Hjelmstad and Popov [5] and Balendra et al. [6–8]). However, outrigger systems increases the stiffness of super-tall buildings by the introduction of stiff outriggers at different locations (Patil and Sangle [9]).

Taranath [10] has examined the theoretical approach to outrigger braced frames by assuming a tall building as a cantilever beam with rotational springs at various story heights on the lateral load resisting system. The equations which were optimizing the location of the springs were used as simple as possible [11]. In addition, an investigation with a uniform and non-uniform truss belt under inverted triangular and uniform lateral loadings. A graphical approach is also provided for the analysis of braced frames with horizontal load-bearing outrigger trusses. This procedure follows a simple approach to find the optimal location for the outrigger through the height of the structure and a quick assessment of the behavior of the outrigger braced super-tall structure. A graphical analysis method is also proposed to optimize the position of outriggers on shear walls [12]. Hoenderkamp and Sniedder [13] provided a simple method for analyzing the face of the outriggers with solid frames in high-rise buildings subjected to horizontal loading. Previously, a simple graphical method for analysis was given to provide the desired outrigger location in a super-tall shear wall structures and reinforced concrete shear wall-steel truss with a perimeter belt structure [14,15]. A manual calculation model for a graphical technique is provided to estimate the overall performance of a steel outrigger structure with a concrete shear walls under wind load. An approximate analysis method is presented to calculate the natural vibrational periods for super-tall steel buildings included braced frames with outrigger trusses. This method is proposed for the relationship between the natural frequencies of the structure and the top deflection and rotation [16].

The conventional continuum method is represented to obtaining the effect of the location of the outrigger by Zeidabadi et al. [17]. The governing equations of wall-frame structures with outriggers formulated through the continuum approach idealizing the whole structure as a shear–flexural cantilever with rotational springs. Combined systems of the shear core, framed tube, and outrigger-belt truss which are implemented in Super-tall building structures are modelled using continuum approach. The optimized location of concentrated, uniform and triangular load was extracted for outrigger truss belt system [18]. Belt trusses and basements acts as virtual outriggers for super-tall buildings. However, virtual outriggers has less effect than conventional direct outriggers due to the decrease in stiffness of the indirect force transfer method [19]. The basic design optimization procedure of super-tall buildings performed mainly for lateral wind loads to find the optimum locations and a number of outriggers in super-tall buildings [20]. Other significant parameters such as drift and moments on the shear walls monitored for different outrigger locations in super-tall buildings.

Existence of outriggers at various levels of the building increase stiffness of the building in lateral direction. An approximate analysis of the complex multi-outrigger braced structure is presented based on a continuous method using a set of outriggers. By increase in outrigger numbers, the provided results become more reliable and accurate [21]. Furthermore, Wu and Li [22] evaluated the optimum design of outriggers in tall buildings. The effects of the outriggers locations on drift, core reaction force and the period of the high-rise structures are presented. Bayati et al. [23] demonstrated drift reduction in uniform belted structures with rigid outriggers. In this study by using optimized multi-outriggers system dimensions of elements and foundation were decreased. Fawzia and Fatima [24] by provision of truss belt and outrigger system adjust the deflection of composite building subjected to wind loads. The corresponding reductions in lateral deflection for one, two and three outrigger systems are 34%, 42% and 51% respectively. Fawzia et al. [25] Examines the effects of a cyclic wind on buildings in which outrigger systems implemented. Increase in height of the building and keeping the dimensions of the building plan reduces the lateral rigidity. Therefore, it was necessary to obtain stiffness by increase on bracing size and provision of additional lateral resisting system such as truss belt and outriggers.

Furthermore, the super-tall buildings which are composed of different combined lateral load systems studied by some researchers. Brunesi et al. [26] investigated super-tall buildings with outriggers and belt trusses using fiber based finite element model archetype. Seismic performance is evaluated based on effects of bracing and outrigger belted truss. In addition, Fan et al. [27] studied the Taipei financial center which is composed of concrete filled steel tube columns, steel brace core and belt. The computational results shows that the super-tall building with the mega-frame system have very great ability to reserve strength, and the super-tall building would satisfy the design needs under different seismic events. In addition, Lu et al. [28] studied the collapse behavior of a super-tall mega-braced frame core tube building which is 550 meters high in the high risk seismic zone. A finite element model is created based on the fiber-beam and multi-layer shell models. The failure mode and mechanism of earthquake-induced collapse are studied. It is obtained from previous studies that the optimum location of outrigger in super-tall buildings is mainly evaluate on wind loadings. Therefore investigating the behavior of outrigger braced systems in high-rise buildings is essential.

This paper aims to provide some significant information on seismic behavior of super-tall building models, as the goal of this study is to represent the effect of outrigger type and location the multitude of outriggers keeps constant (3 outrigger) in each model. In addition, effect of outrigger type and location for two types of outrigger and two different distribution (location) was obtained and seismic behavior of them assessed based on TSC 2007 and TSC 2017.

2. Case study and modeling

International Finance Centre building plan and elevation in Hong Kong was chosen for this research as case study that consist of 89 floor (415 meters). Fig. 1a shows the structural plan that was used in modeling. Material properties and concrete that was used in structure was shown in Table 1 while Table 2 depicts material strength, elastic modulus and density in more detail. In addition, Table 3 represents the mega column, secondary columns, outriggers, and belt trusses details.

Table 1
Material Properties.

	Outrigger	Column	Belt truss	Shear walls (core)	Beam
Concrete	-	C28	-	C28	-
Steel	ST37	-	ST37	-	ST37
Reinforcement	-	-	-	AII	-

Table 2
Material Characteristics.

	f'_c (Mpa)		E (Mpa)	Density (kN/m^3)	Density (kg/m^3)
Concrete	28		25000	23.561	2402
	f_y (Mpa)	f_u (Mpa)	E (Gpa)	Density (kN/m^3)	Density (kg/m^3)
Steel	400	600	200	76.929	7849.097
Reinforcement	240	360	200	76.929	7849.097

Distribution 1 is consist of three outrigger that was set on between floors number 21-23, 45-47, and 67-69; and Distribution 2 is consist of three outrigger like previous distribution that was applied between floors number 28-30, 58-60, and 87-89. There are four different case that was investigated in this study case (1) using outrigger I and distribution 1, case (2) using outrigger I and distribution 2, case (3) using outrigger II and distribution 1, and case (4) using outrigger II and distribution 2. Fig. 4c shows the belt truss that was used in this research the belt truss consider to be constant to have better comparison of seismic performance due to change in either outrigger type or outrigger location.

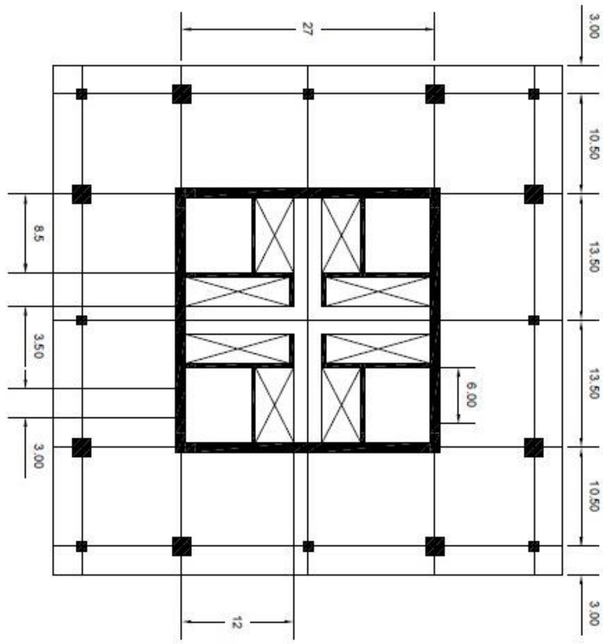


Fig. 1. Typical Plan of case study.

The seismic analysis of current study was response spectrum analysis based on the envelope curve of standard spectrum in TSC 2007 and TSC 2017. According to TSC 2007 building importance factor (I) should be got 1 for the intensive short-term buildings. Ground acceleration (A_0) considered 0.4g in which g is Gravitational acceleration. The local site class of the studied model is Z2 which is used for dense sand, gravel, stiff and very stiff clay and silty clay. Parameters that have been extracted form TSC 2017 was partially different from TSC 2007 but building importance factor and ground acceleration was same as TSC 2007. While building distance from fault parameter was introduced, local site according to TSC 2017 was appointed ZC. Response spectrum for both codes is illustrated in Fig. 2. Envelope of the response spectrums for analyzing of the building used. While the spectrum curve of TSC 2017 is rigorous in lower periods the curve is more conservative for tall building in TSC 2007.

Fig. 3 shows elevation by considering outrigger, and shows elevation consist of belt trusses. As it is illustrated in figure, distribution of outrigger and belt truss was changed; however, type of belt trusses keep constant.

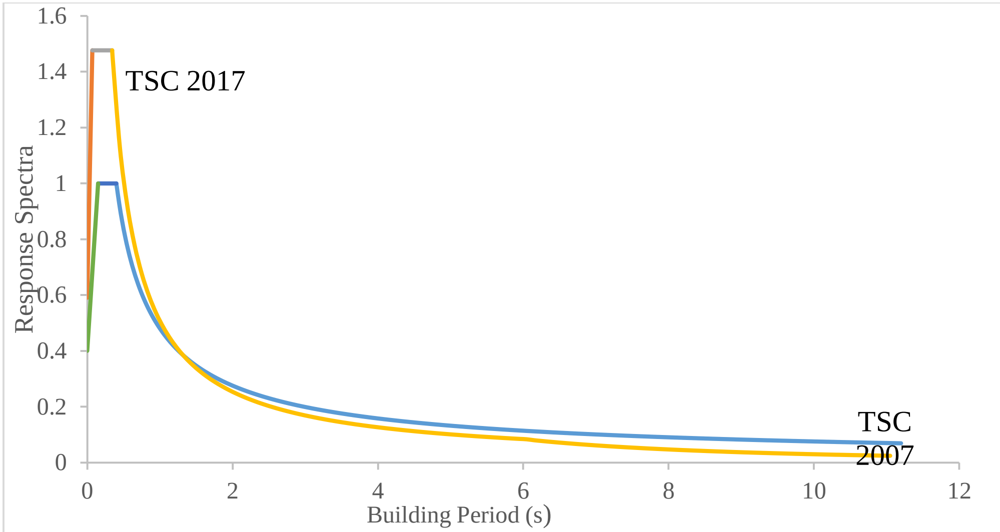


Fig. 2. Standard response spectrum of TSC 2007 and TSC 2017.

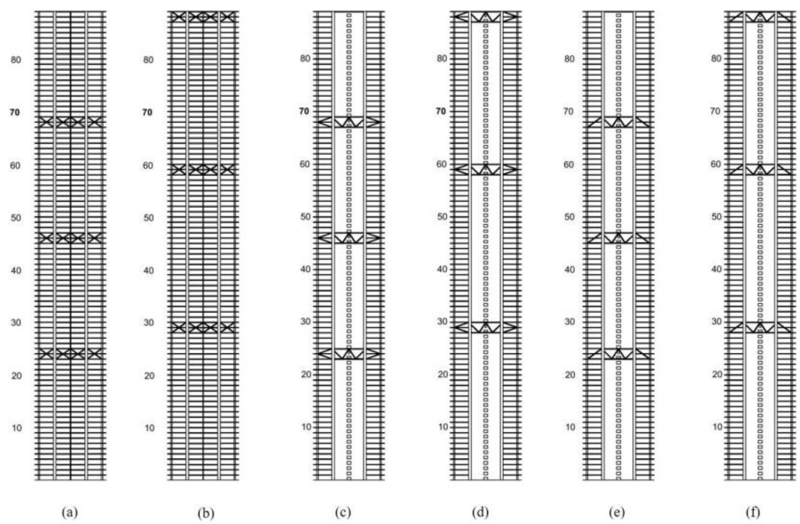
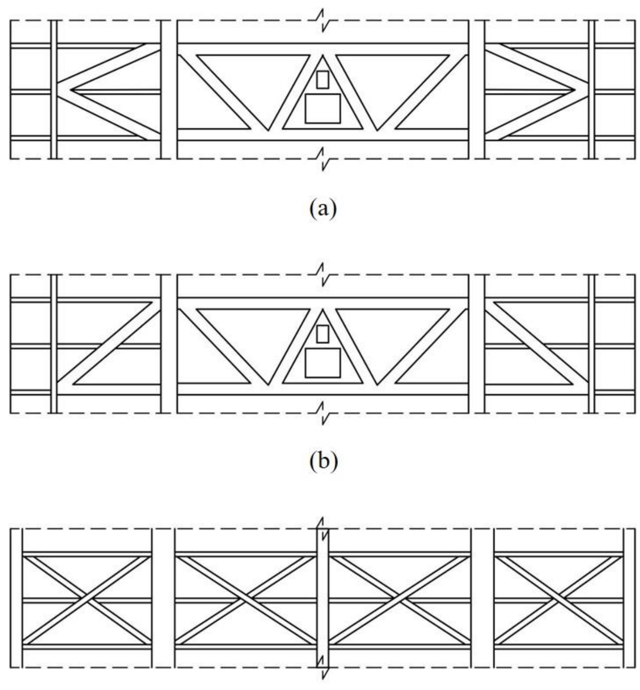


Fig. 3. Elevation with a) belt truss distribution 1, b) belt truss distribution 2, c) outrigger type I, distribution 1, d) outrigger type I, distribution 2, e) outrigger type II, distribution 1, and f) outrigger type II, distribution 2.

Table 3
Elements Details.

	Type (section)	Largest length (m)	Width (m)	Thickness (mm)	Area (cm^2)
Outrigger I	Tube	12.04	0.9	90	2916
Outrigger II	Tube	13.02	0.9	90	2916
Mega columns	Filled Tube	4	2	80	40000
Secondary columns	Filled Tube	4	0.8	30	1600
Shear Walls (core)	Reinforced Concrete	4	-	2000	20000
Slab	Reinforced Concrete	10.5	9	200	-
Beam	IPE 270	10.5	0.135	0.01-0.006	45.9

In models designing at ETABS software outrigger sections was continued in two upper and lower stories inside the core (shear walls) to reach the higher stiffness in whole mode and this is performed at all cases.



(a)

(b)

(c)

Fig. 4. Sections of a) Outrigger type I, b) Outrigger type II, and c) Belt truss.

In addition, Fig. 4a shows the outrigger type 1 and its detail properties were shown in Table 3. Fig. 4b shows the outrigger type II for this study and detailed information was given in Table 3. Fig. 5 shows the mega columns section, detailed information about sections could be find in Table 3. It should be noted due to overlap of shear walls and floor slabs, in ETABS modification factor, 0.95 value assigned to weight and mass. Beams connections are pinned-pinned at models.

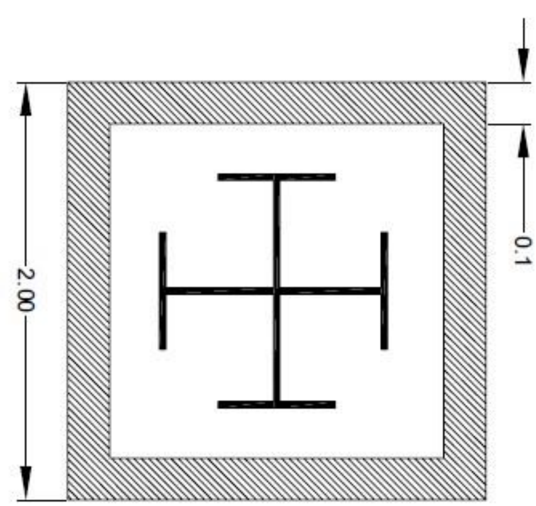


Fig. 5. Mega column type section (2 (m) – 0.1 (m)).

3. Results and discussion

For better comparison results was obtained for 2 different values of modification factor (R), First seismic behavior related parameters were find out using R=1, then the other set of results obtained for R=6. The R values is between 1-1/2 and 8, which former is for unreinforced concrete and masonry shear walls and the latter for properly detailed shear walls, braced frames and moment frames. To ensure ductile behavior of the building, the code has very specific detailing requirements (based on lab testing) for the structural members involved in the lateral force resisting system. This ensures the members don't fail prior to reaching the required ductility. For analyzing seismic behavior of tall building, response spectrum method had been used, since tall buildings period are fluctuating in large interval. Response spectrum has been obtained from TSC 2017 in which

Table 4
Base shear, Periods, and Displacement.

	direction	Base Shear (kN)	Period (s)	Displacement (cm)			
				1st outrigger level	***2nd outrigger level***	***3rd outrigger level***	***roof***
Case 1	X	260389	6.957	21.54	74.51	135.98	197.58
(R=1)	Y	254572	7.169	21.65	76.08	139.31	203.24
Case 2	X	265919	6.862	34.42	108.93	186.94	189.3
(R=1)	Y	259750	7.069	34.71	111.01	192.22	194.69
Case 3	X	254283	7.115	21.77	75.97	139.61	203.51
(R=1)	Y	247515	7.376	21.91	77.82	143.72	210.43
Case 4	X	259710	7.025	34.92	111.36	193.81	196.37
(R=1)	Y	254400	7.241	35.32	113.82	198.63	201.28
Case 1	X	43398	6.957	3.59	12.42	22.67	32.93
(R=6)	Y	42428	7.169	3.61	12.68	23.22	33.87
Case 2	X	44319	6.862	5.74	18.16	31.16	31.55
(R=6)	Y	43291	7.069	5.78	18.5	32.03	32.45
Case 3	X	42380	7.115	3.63	12.66	23.27	33.92
(R=6)	Y	41252	7.376	3.65	12.98	23.95	35.07
Case 4	X	43285	7.025	5.82	18.56	32.3	32.73
(R=6)	Y	42400	7.241	5.89	18.97	33.11	33.55

Table 4 shows the base shear, periods, displacement at outrigger location, and roof displacement for four cases with two different modification factor values R=1 and R=6, as it is presented periods are constant in two different modification factor because modification factor dose not effected the periods; however, Table 4 illustrated that values for R=6 are logical based on previous studies.

The story displacements of four different cases with two various outriggers of super-tall buildings corresponding to different directions for both modification factor R=1 and R=6 are illustrated in Fig. 6-7, It is apparent from figures that the case 3 has the best performance based on story displacements. Story displacement also shows that the results for R=1 are not logical as the unit value for modification factor is too low. However, results show a logical values for R=6 of roof displacement 300-350 (mm) that is acceptable for this structures. Story drifts of four cases for X and Y direction is depicted in Fig. 8.

Base shear amount is greater in X-direction compared with Y-direction either in R=1 or in R=6 condition. Fig. 9a illustrate the base shears for all four cases with two different R, as it is shown there is a great differences between R=1 and R=6 base shears. Base shear values in all four cases are so close and there is no great difference among cases.

In addition, periods for all cases in both X and Y direction was shown at Fig. 9b. Periods in X-direction in all cases are lower than Y-direction periods. Fig.9b shows that case 2 has the lowest period; however, case 3 has the greatest period among cases.

Fig. 10 shows the deformations of all cases in both X and Y directions, as it is illustrated case 1 and case 4 has the lowest deformation compared others. In case 2 outrigger type I used that has greater stiffness than outrigger type 2 that was used in case 3; however, their deformation obtained approximately equal that is effected from distribution of outrigger. Thus, using outrigger at roof level (outrigger distribution) could change the behavior of structure significantly.

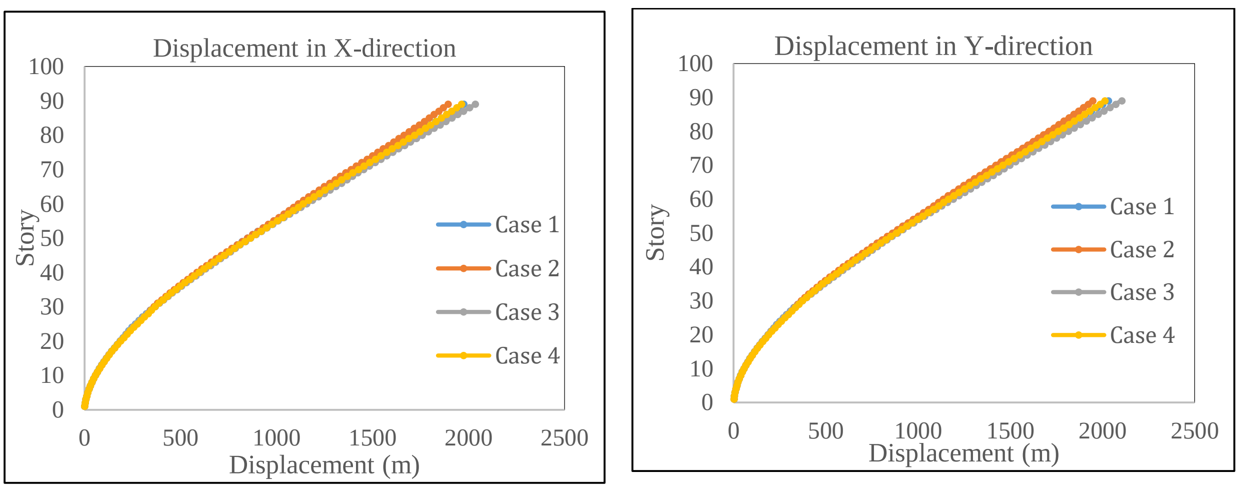


Fig. 6. Story-Displacement curves in X and Y directions for R=1.

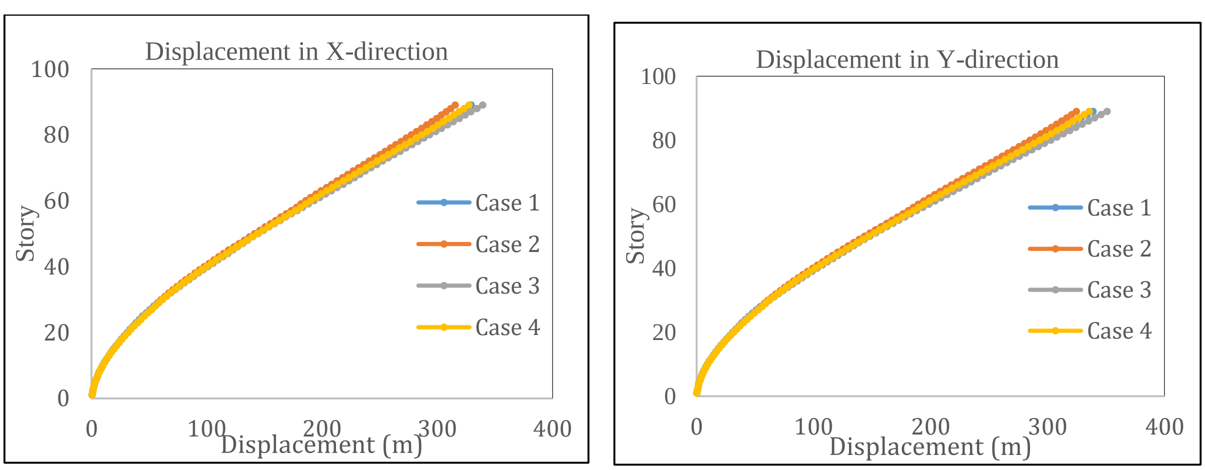


Fig. 7. Story-Displacement curves in X and Y directions for R=6.

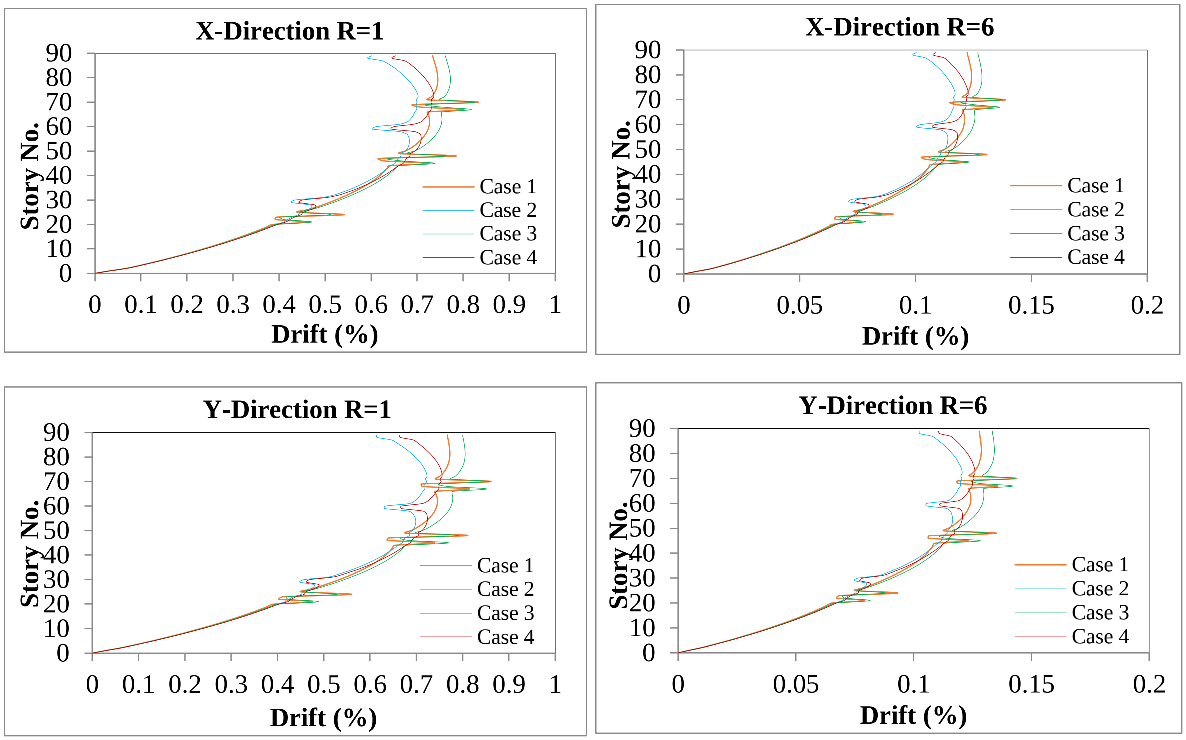


Fig. 8. Story Drift of Studied systems on X and Y direction.

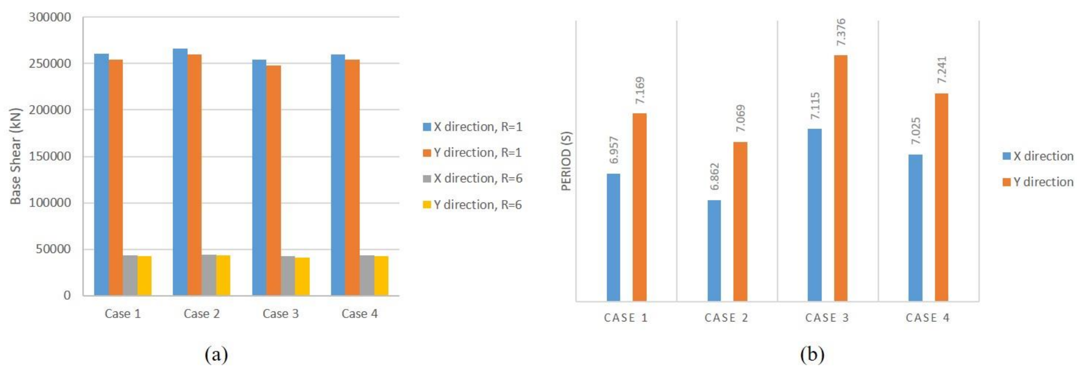


Fig. 9. a) Base shears, and b) Periods.

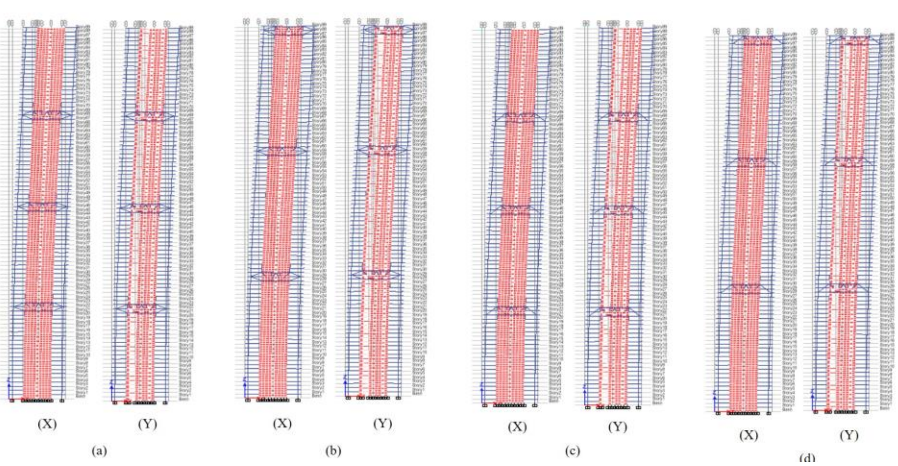


Fig. 10. Deformations for TSC 2017 (R=1) a) case 1, b) case 2, c) case 3, and d) case 4.

4. Conclusion

In this work an attempt is made to evaluate the seismic performance of four different super-tall outrigger braced building to determine the seismic behavior of each model with different outrigger type and different outrigger distribution. For this purpose, the models were analyzed using ETABS software and results for base shear, period, story displacement was find out for all cases and comparison was made based on them.

- Results for base shears in Table 3 showed that there is not such great different in base shear amount among cases and it is approximately equal to 250000 (kN) for R=1, and 4300 (kN) for R=6 either at X or at Y direction.
- Periods are lower at X-direction compared to Y-direction. Case 2 has the lowest period (T=6.862 (s)), and case 3 reaches the greatest period (T=7.376 (s)).
- Story displacement at Y-direction are greater than displacement at X-direction in all cases and different R values. In either R=1 or R=6 and in both directions case 3 has the greatest and case 2 has the lowest displacement (see Fig. 5-6).
- Further addition of second and third outrigger in the outrigger braced buildings increases the base shear with decreasing the story displacement.
- By considering that stiffness of outrigger type I is greater than outrigger type 2, case 2 with outrigger type 2 and distribution 2 gives the lowest story displacement. Thus, it is found that distribution is significantly influenced the story displacement and using outrigger at roof level could affect the result.

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