Egyptian Knowledge Bank

ASGE Vol. 03 (01), pp. 1-16, 2022

International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/
Print ISSN 2785-9509 *Online ISSN 2812-5142*

Seismic Behavior of Virtual Outrigger System

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ABSTRACT

The outrigger system is an economical and effective solution to improve the seismic performance of high-rise buildings. Numerous studies have been carried out on the optimum position of the outrigger system. However, space availability is the main factor as potential locations of outriggers are typically limited to refuge and mechanical floors. This paper proposes some methods to reduce obstructed space at the outrigger level. Comparative studies were performed on A 40-story core-wall building with conventional and proposed virtual outrigger in terms of lateral displacement, drift, base shear, base moment, core moment and fundamental natural period for different positions of the outrigger system. The building was subjected to eleven ground motions scaled to meet the expected peak ground acceleration in Cairo zone. This study concludes recommendations for proposed outrigger configurations which can give higher performance than conventional outrigger and extra free area can be obtained.

Keywords: Outrigger System, Virtual Outrigger, Tall Building, Nonlinear time history analysis, optimum location.

1. INTRODUCTION

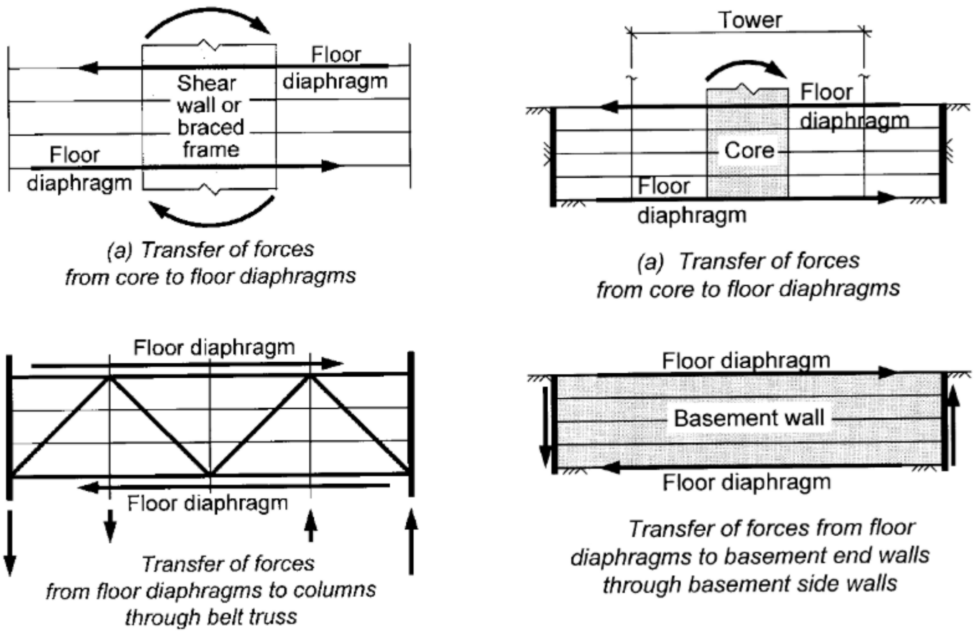
In recent years, the development of tall buildings has progressed quickly. The progress of concrete technology, structural systems and construction techniques made it possible to build tall building. The outrigger system is an efficient and cost-effective method in minimizing seismic response of tall buildings and has been used widely as a seismic resistance system. This system basically consists of an inner core and external columns, connected via one or two stories deep with concrete wall or truss members called outriggers. When lateral loads are applied to the building such as seismic or wind loads, the outrigger system applies a moment of resistance on the core Structure by the mobilization of the perimeter columns' axial stiffness.
Taranath [1],[2],[3] studied the optimum location of outrigger for a simplified method to determine the optimum location of outriggers based on compatibility method by matching the rotation of core and outrigger's showed that the optimum location is at 0.455L measured from the top assumed that the lateral load is uniform and the structure is linearly elastic. Smith et al. [4],[5] found that outrigger effectively decrease the displacement of the roof, inter-story drift and core moment by increasing the System stiffness and proposed analytical equations for determining the optimum location of outriggers considering the flexibility of outrigger, core, and axial area of columns they provided 2 charts giving efficiency of providing 1 to 4 outriggers, with certain non-dimensional factor-ω as mentioned previously. The efficiency is measured in terms of reducing lateral drift and reduction in core's moment. Wu and Li [6] discussed that when the structures are subjected to

Article history: Received January 2022 & Accepted February 2022
DOI: 10.21608/asge.2022.152692.1002

uniformly distributed and triangularly distributed loads over the building height there was difference 4–5% in results.

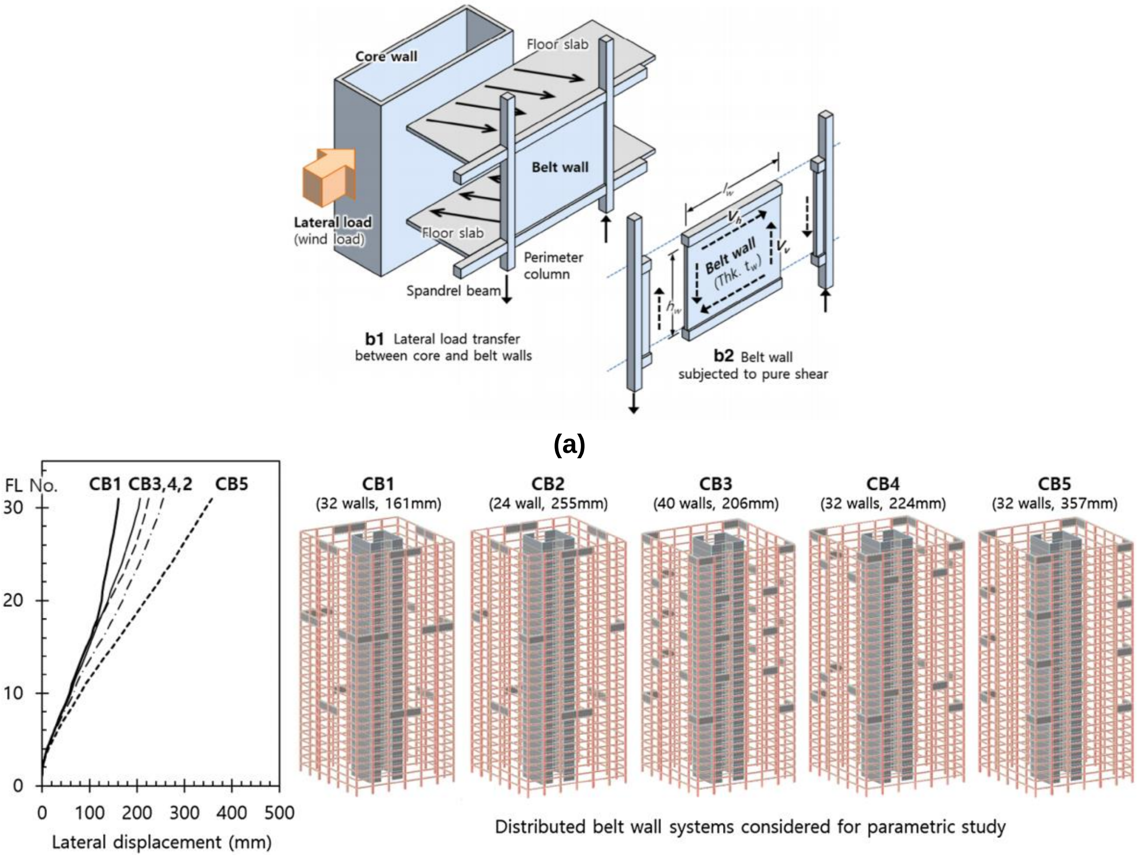
R. J. Smith and Willford [7] proposed the concept of the damped-outrigger by inserting dampers between the outrigger truss end and the perimeter column to increase the damping, instead of increasing the stiffness. [8], [9],[10], [11], [12] investigated The efficiency of damped outrigger systems,[13],[14], [15] investigated damped-outrigger system incorporating buckling restrained braces. Virtual outriggers was proposed by R. Shankar Nair [16] and also called belt-truss system. It provides effectively reduce the lateral displacement. In this type, the diaphragm stiffness is a critical factor in the load paths. If the diaphragm is not stiff enough, then the outrigger system will be less efficient. The way in which overturning moment in the core is converted into a vertical couple at the exterior columns is shown in Figure1.a part of the moment in the core is converted into a horizontal couple in the floors. The horizontal couple, transferred through the two floors to the truss chords, is converted by the truss into vertical forces at the exterior columns. The basement of a tall building can serve as a virtual outrigger. Some fraction of the moment in the core is converted into a horizontal couple in the floors at the top and the bottom of the basement. This horizontal couple is transmitted through the floor diaphragms to the side walls of the basement, which convert the horizontal couple into a vertical couple at the ends as shown in Figure1.b. Distributed belt wall system can be used as virtual outriggers and the performance of the system depends on the number and arrangement of belt walls [17] as shown in Fig.2 a, b.

The lack of research at this point made main objective of this study is providing design recommendations for outrigger configuration to avoid architectural limitations by getting extra free area. Firstly various models of conventional outrigger are run in order to get the optimum location of 2nd outrigger by fixing the position of 1st outrigger location at top and changing the position of the 2nd outrigger from.1h to .9h.Then after getting the control model of conventional outrigger with the best reduction ratio of displacement and drift. This paper suggests some outrigger configurations to avoid architectural limitations by comparing the effect of proposed systems with the performance of Optimum conventional outrigger model.



(a) (b)

Fig.1. (a) Force transfer using belt truss as virtual outrigger (b) Force transfer using basement as virtual outrigger. [16]



(a)

(b)

Fig.2.(a) Distributed belt wall systems. (b) Force transfer mechanism of distributed belt walls. [17]

2. FINITE ELEMENT MODELS

The 40-story RC core-wall model, including one ground, and 39 residential stories, had a height of 144.5 m. Three dimensional view and typical plan layouts are given in Fig. 3.a, b. All slab thicknesses were 0.2 m .All coupling beams were 2.5 m in length, and the other model properties are given in Table 1. The finishing load (which is the mass source) is 0.15 ton/m2 and live load for first floor and residual stories are 0.3 ton/m^2 and 0.45 ton/m^2, respectively. The modulus of elasticity can be calculated in terms of the characteristic compressive strength fc as $4700\sqrt{fc}$. Different stiffness modifiers were assumed according to UBC97. The analysis was carried out using Etabs software. Dynamic time history, using eleven ground motion records near-fault regions to perform the seismic analysis of the considered model as shown in Table 2 and Fig. 5. The P-Δ effect was considered during the analysis of the building model.

2.1 Outrigger Systems Description

- Model of outrigger are conventional outrigger with belt truss, as shown in Fig. 3.c. As outrigger sectional area of the diagonal members is 0.18 m2.
- Model of the building with belt truss only by removing internal members of the outrigger as shown in Fig. 3.d

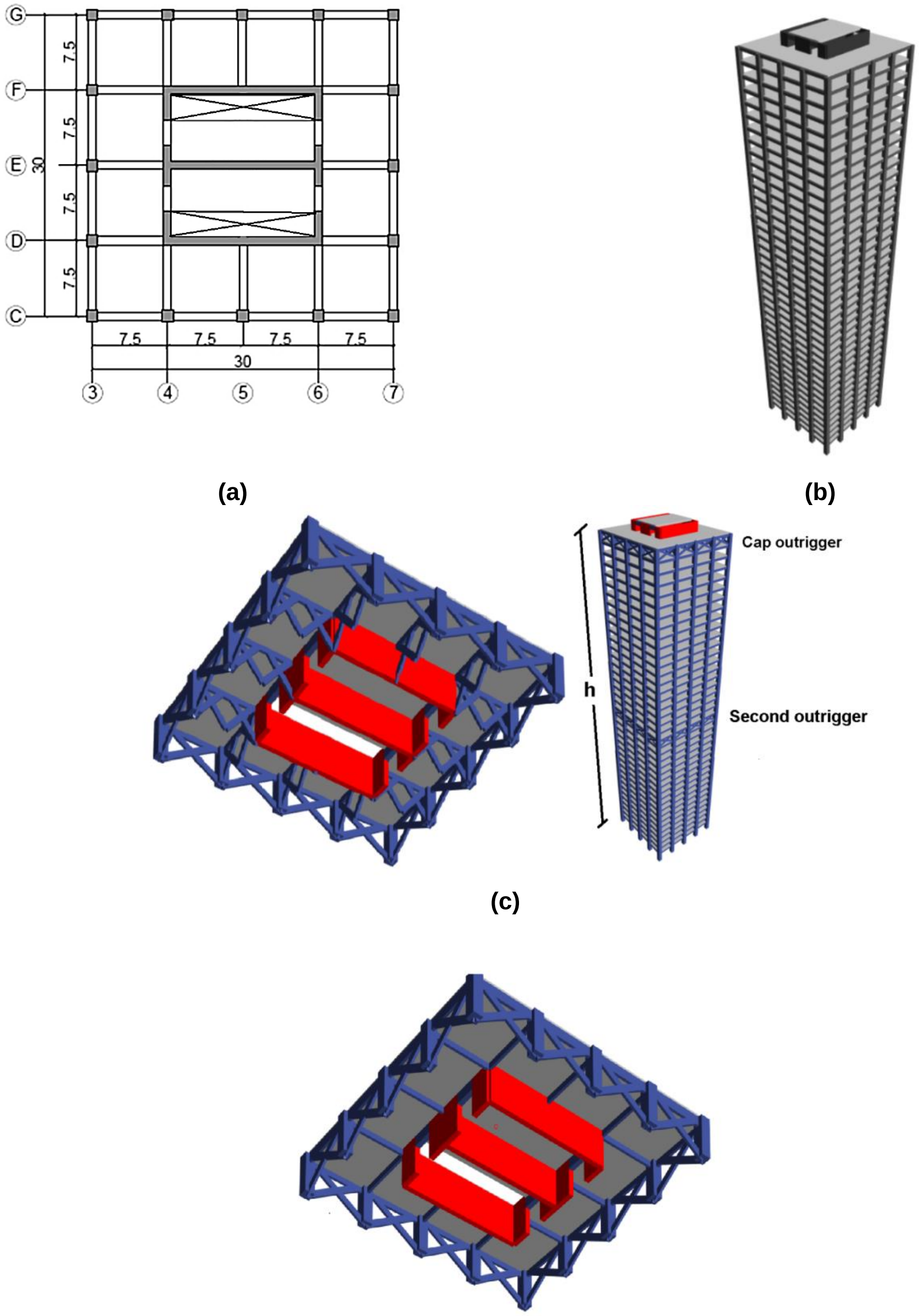
2.1.1 Proposed outrigger systems

All proposed outrigger systems are shown in Fig. 4.

- (FEM0) Virtual Outrigger by Increase the thickness of the slab to 1 m below and above the level of the outrigger and detach the beams from that slab.
- (FEM1) Virtual Outrigger by using skew paneled beams with section (0.30*1.00) m below and above the level of the outrigger.
- (FEM2) Using vierendeel outrigger with sections (.8*1.40)m at story 24 level and (.6*1.40)m at 40 story level
- (FEM3) Adding bracing with sectional area of the diagonal members is 0.09 m2 to model (FEM2) at banal beside the core.
- (FEM4) Adding bracing with sectional area of the diagonal members is 0.18 m2 to model (FEM0) at banal beside the core.
- (FEM5) Adding bracing with sectional area of the diagonal members is 0.18 m2 and vertical members is 0.09 m2 to model (FEM2) at mid banal between the core and outer column.
- (FEM6) Adding bracing with sectional area of the diagonal members is 0.18 m2 and vertical members is 0.09 m2 to model (FEM0) at mid banal between the core and outer column.
- (FEM7) Adding side bracing with sectional area of the diagonal members is 0.09 m2 and vertical members is 0.09 m2 to model (FEM0).
- (FEM8) Adding side bracing with sectional area of the diagonal members is 0.09 m2 and vertical members is 0.09 m2 to model (FEM2).
- (FEM9) Two stories Vierendeel outrigger with sections (.8*1.40)m at story 24,25 level and (.6*1.40)m at 40,39 story level
- (FEM10) Two story conventional outrigger with belt truss. Outrigger sectional area of the diagonal members is 0.18 m2

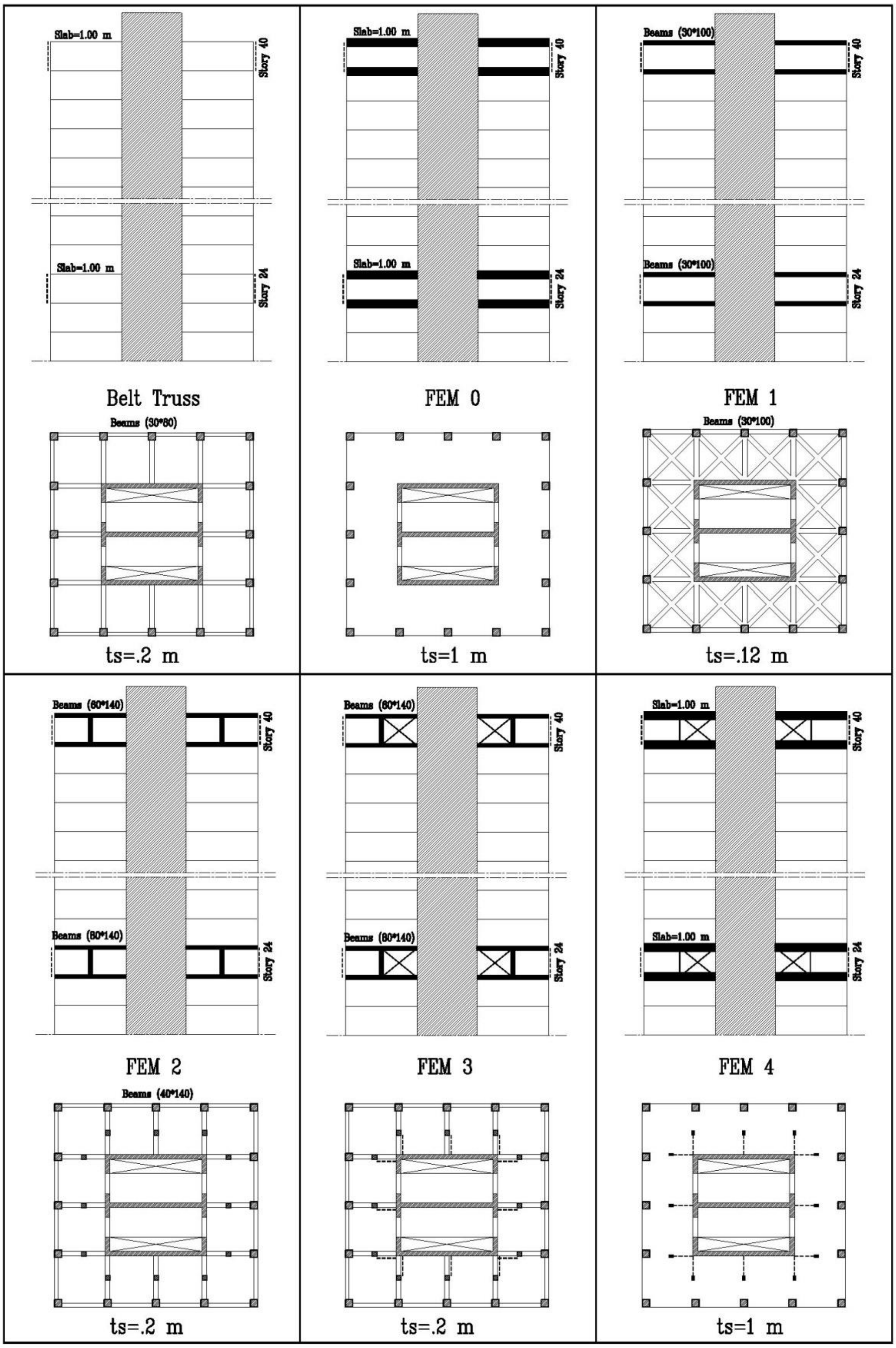
Table 1 General model properties

Table 1General model properties					
Story heights	4.5m	ground foor			
	3.5m	above ground floor			
Column dimensions	1.6 ×1.6m	from	1st	to	13th
	1.4 ×1.4m	from	14th	to	26th
	1.2 ×1.2m	from	27th	to	40th
Beam dimensions	0.3 ×0.80m	from	1st	to	40th
Coupling beams dimention	1.00 ×1.20m	from	1st	to	13th
	0.80 ×1.20m	from	14th	to	26th
	0.6 ×1.20m	from	27th	to	40th
	.3 m	Ground	slab		
Slab thickness	.2 m	other	slabs		
core wall thicknesses	1.00 m	from	1st	to	13th
	.80 m	from	14th	to	26th
	.60 m	from	27th	to	40th
Specified concrete strength	60 Mpa	from	1st	to	13th
	50 Mpa	from	14th	to	26th
	40 Mpa	from	27th	to	40th
outrigger	Steel 52	Fy	=	3.6	t/cm2
		Fu	=	5.2	t/cm2



(a) (b) (c) (d)

Fig. 3 (a) Typical plan. (b) Three-dimensional view of model (c) conventional outrigger (d) Belt truss.


Slab=1.00 m
Story 40
Slab=1.00 m
Story 24
Belt Truss
Beams (30*80)
ts=.2 m
Slab=1.00 m
Story 40
Slab=1.00 m
Story 24
FEM 0
ts=1 m
Beams (30*100)
Story 40
Beams (30*100)
Story 24
FEM 1
Beams (30*100)
ts=.12 m
Beams (60*140)
Story 40
Beams (60*140)
Story 24
FEM 2
Beams (40*140)
ts=.2 m
Beams (60*140)
Story 40
Beams (60*140)
Story 24
FEM 3
ts=.2 m
Slab=1.00 m
Story 40
Slab=1.00 m
Story 24
FEM 4
ts=1 m

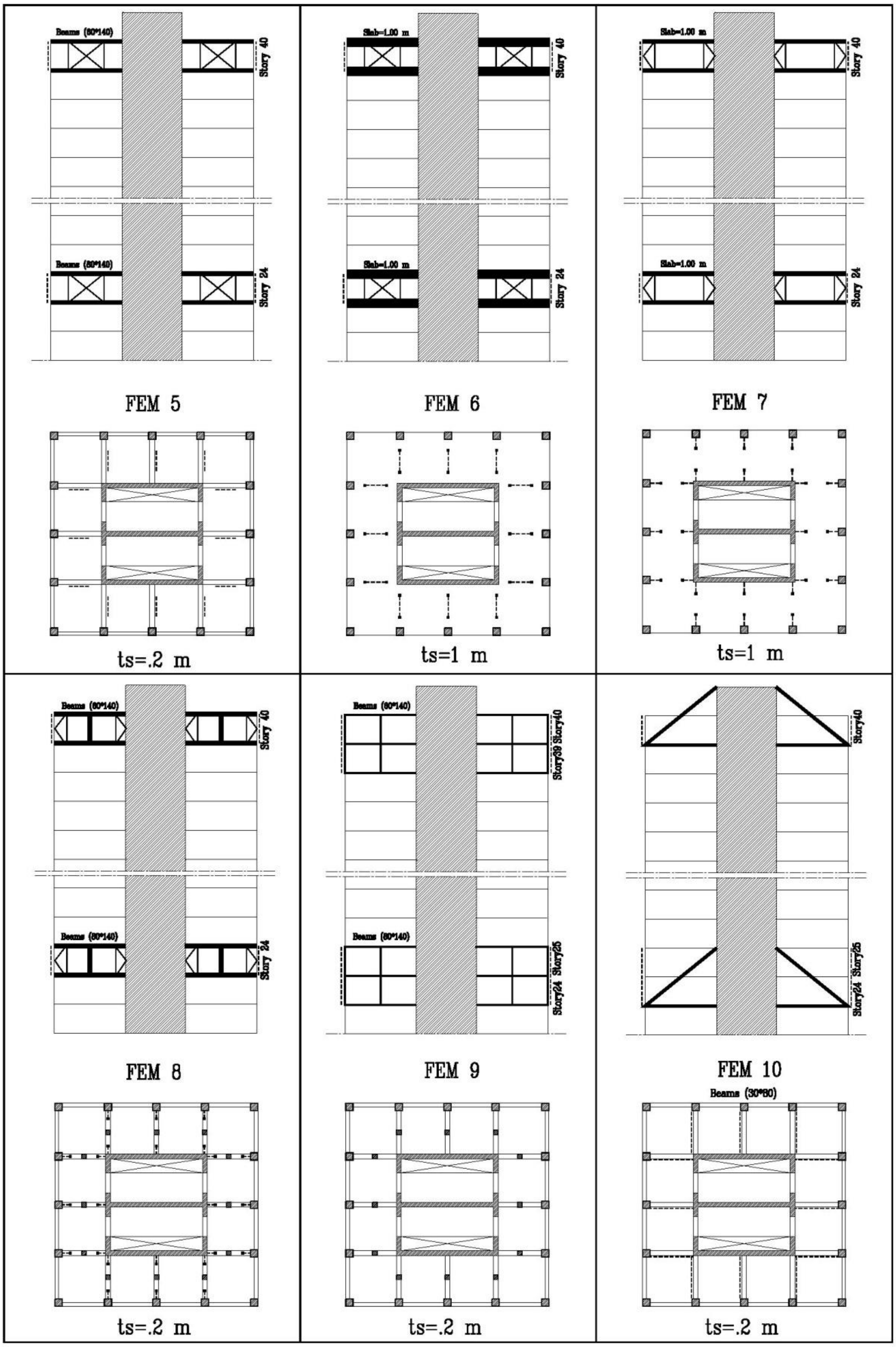


Fig. 4 proposed outrigger systems

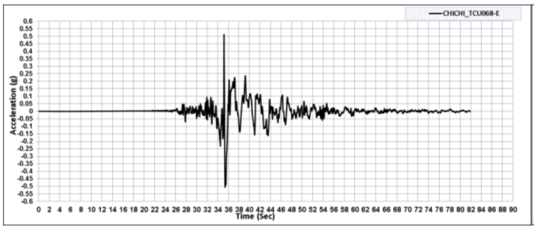
3. Time-History Analysis

Eleven different ground-motion with low frequency rang PGA/PGV < 0.8 g/m/s [9]. The ground motion records are obtained from the PEER Strong Motion Database and there PGAs were scaled to 0.15 g (Zone 3). Table 2 and Fig. 5,6 provide the characteristics of the selected records. The results were calculated as mean values of the structural responses.

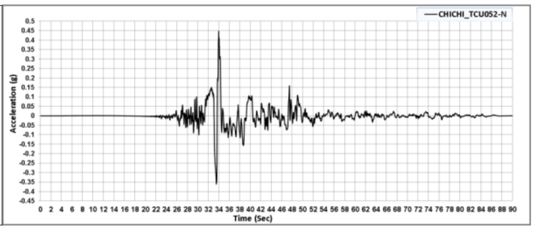
Table 2 Ground motions database

	Year	Earthquake	Station	Magnitude	Rrup	PGA	PGV	PGD	PGV/ PGA
					(km)	(g)	(cm/sec)	(cm)	
1	1999	"Chi-Chi_ Taiwan"	"TCU052"(N)	7.62	0.66	0.447	172.3	226.5	0.393
2	1999	"Chi-Chi_ Taiwan"	"TCU068"(E)	7.62	0.32	0.512	249.518	297.063	0.497
3	1999	"Chi-Chi_ Taiwan"	"TCU074(N)"	7.62	13.46	0.38	44.934	15.28	0.121
4	1995	"Kobe_ Japan"	"KJMA 00"	6.9	0.96	0.834	91.078	21.077	0.111
5	1999	"Kocaeli_ Turkey"	"Izmit 90 "	7.51	7.21	0.23	38.279	24.283	0.17
6	1999	"Kocaeli_ Turkey"	"Yarimca 060"	7.51	4.83	0.227	69.696	62.308	0.313
7	1989	"Loma Prieta"	"Gilroy - Gavilan Coll."	6.93	9.96	0.354	36.05	14.688	0.104
8	1992	"Landers"	"Yermo Fire Station"	7.28	23.62	0.245	51.109	41.698	0.213
9	1994	"Northridge-01"	"Arleta - Nordhoff Fire Sta"	6.69	8.66	0.3451	41.1	10.2	0.122
10	1979	"Imperial Valley-06"	"Brawley Airport"	6.53	10.42	0.163	36.596	25.67	0.229
11	1979	"Imperial Valley-06"	"El Centro Array #10"	6.53	8.6	0.173	50.675	35.382	0.299

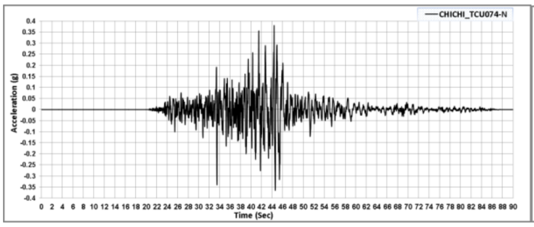
PGA, peak ground acceleration; **PGV**, peak ground velocity; **PGD**, peak ground displacement; $\mathbf{M_w}$, magnitude, **Rrup**: Closest distance to the fault plane.



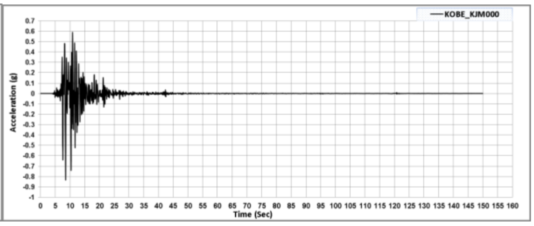
1-Chi-Chi_ Taiwan TCU052 (N)



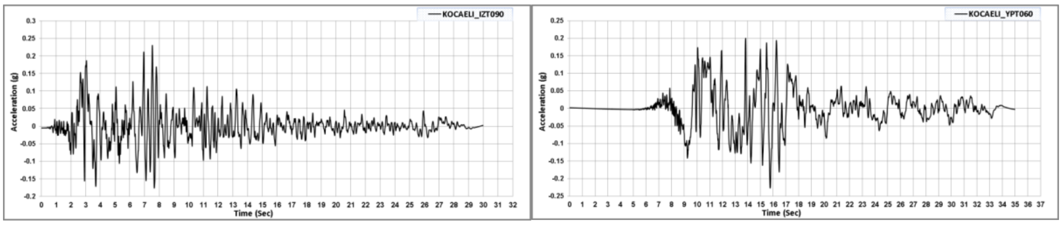
2-Chi-Chi_ Taiwan TCU068 (E)



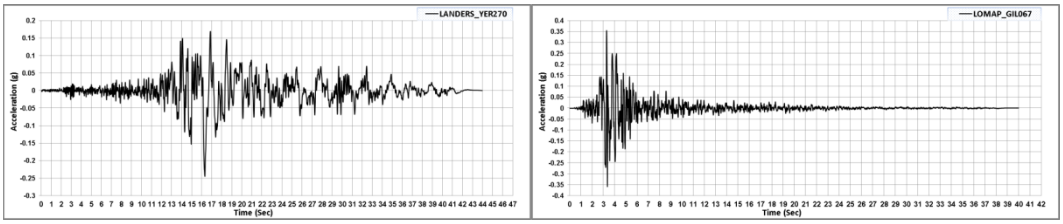
3-Chi-Chi_ Taiwan TCU074 (N)



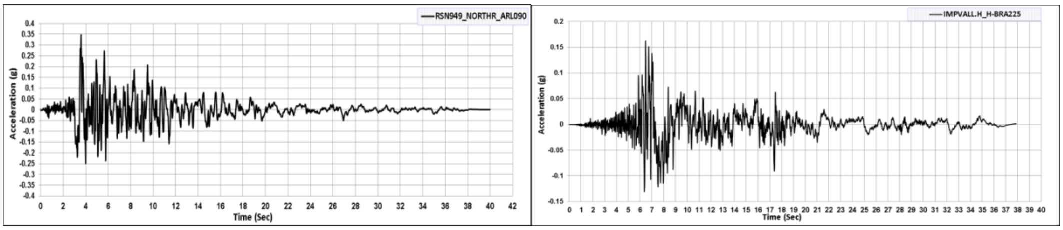
4-Kobe_ Japan KJMA 00



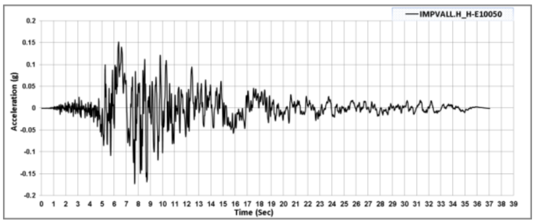
5-Kocaeli_ Turkey Izmit 90 6-Kocaeli_ Turkey Yarimca 060



7-Loma PrietaGilroy - Gavilan Coll **8-Landers Yermo Fire Station**



9-Northridge-01-Arleta-Nordhoff Fire Station **10-Imperial Valley-06 Brawley Airport**



11-Imperial Valley-06 El Centro Array #10

Figure 5. Time-history accelerations of eleven earthquake records

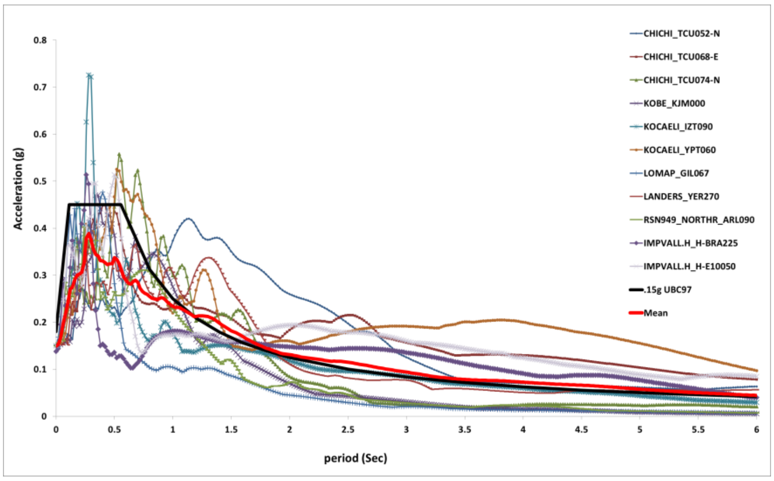


Figure 6. Elastic and average spectrum for the selected earthquake records against the demand spectrum curve provided by UBC97

4. PARAMETRIC STUDY

The main objective of this study is providing design recommendations for outrigger configuration to avoid architectural limitations by getting extra free area obtained from removing outrigger members. The Comparative studies have been carried out based on the lateral story displacements, story drifts and time period.

5. Results and Discussion

5.1 optimum location of 2nd conventional outrigger

Various models are run in order to get the optimum location of 2nd outrigger when 1st outrigger location is fixed at top. Results are based on the mean of lateral story displacements, story drifts. Nine options of location of 2nd outrigger from.1h to .9h are compared in Fig.5, including the structure without any outriggers. The results show that optimum position of second outrigger at .6 times the height of the structure from the bottom of the building with (39.867%) & (38.611%) max and min displacement reduction see Fig.7& 8. And (46.292% & 44.161%) max and min drift reduction see Fig.9& 10. For first four modes of vibration periods see Fig.11. The allowable maximum lateral displacement at the top of the building of H/500 and the allowable drift ratio is assumed to be equal to 0.02 according to UBC97.

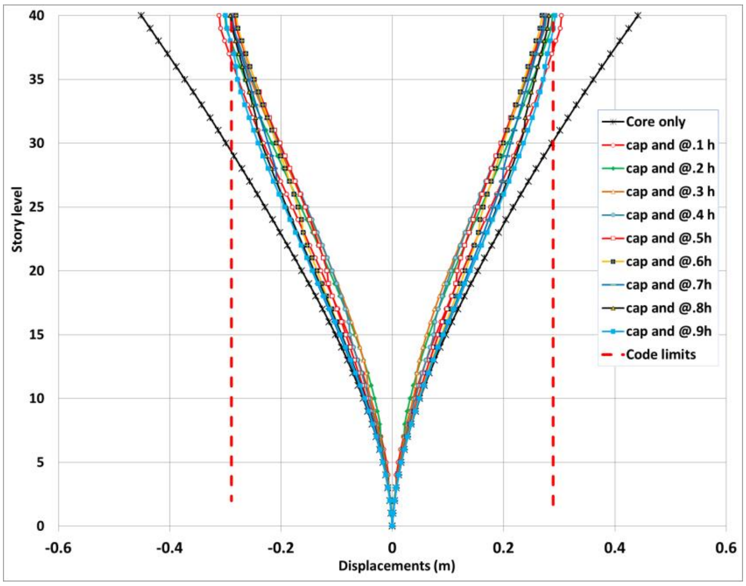


Figure 7. Story displacements under earthquake records

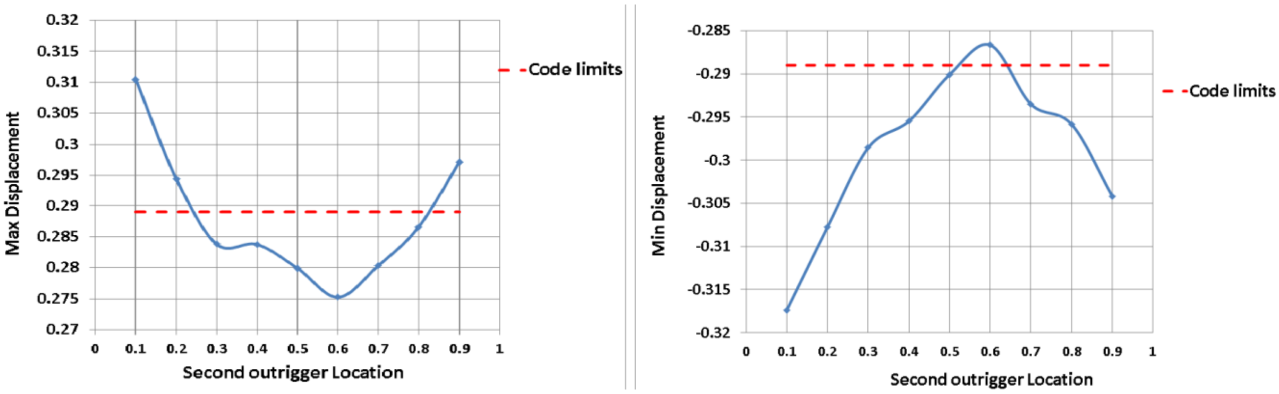


Figure 8. Story max and min top disp. for different positions of 2nd outrigger

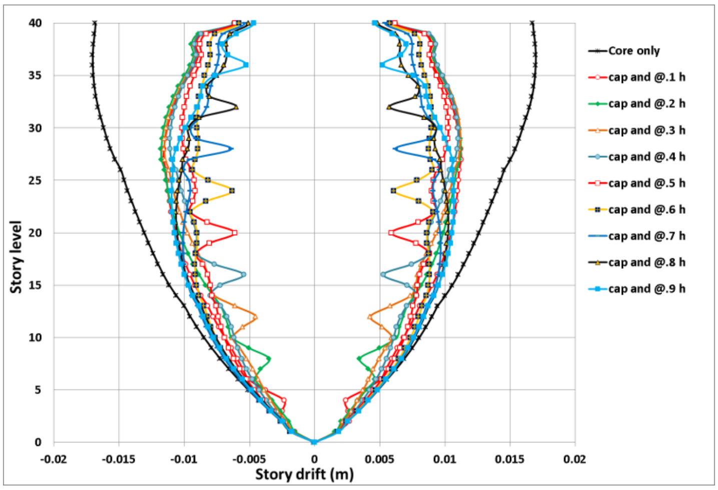


Figure 9. Story drift under earthquake records

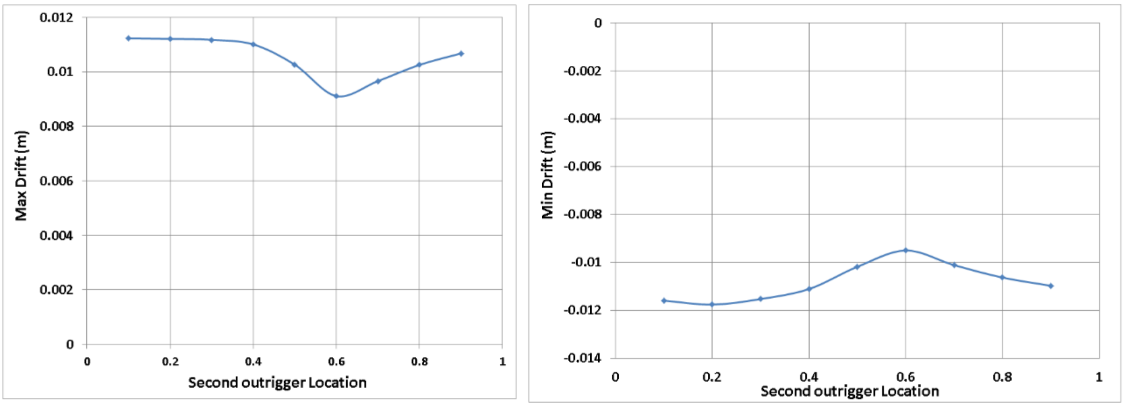


Figure 10. Story max and min drift for different positions of 2nd outrigger

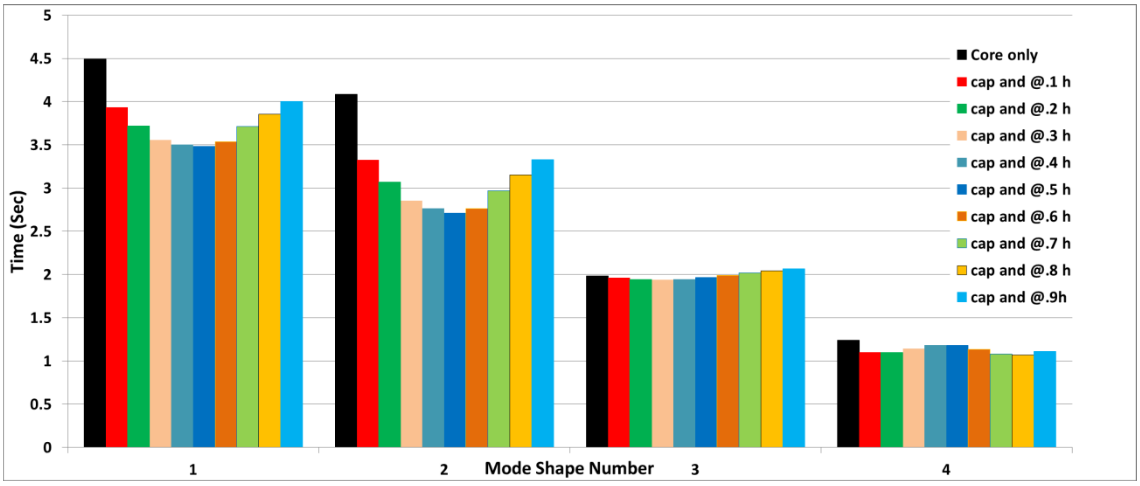


Figure 11. Modal Periods of first four modes

5.2 Results of proposed Outrigger systems.

After getting the optimum location of 2nd outrigger causing max reduction of displacement and drift. this paper suggest some outrigger configuration to avoid architectural limitations by comparing the effect of proposed systems with the effect of Optimum location of conventional outrigger as given in Table 3. For displacement, drift and modes of vibration periods of proposed systems see Fig.12& 13&14.The reduction percentages of the proposed methods of displacement and drift as ratio of core only model are shown in Fig.15

Table 3 Propose outrigger systems ratio of conventional outrigger

Proposed systems	Max Disp.Ratio %	Min Dis.Ratio %	Max Drift.Ratio %	Min Drift.Ratio %
Belt.	43.39228	36.55879	13.16862	12.98909
FEM0	76.89641	76.15255	72.00713	71.83924
FEM1	72.43592	73.66776	53.99898	51.31755
FEM2	91.81988	91.13182	91.69638	92.28109
FEM3	97.3544	96.02043	98.65002	99.26804
FEM4	88.67616	91.24717	89.17474	91.62898
FEM5	99.65094	99.35828	101.1717	101.9697
FEM6	94.87646	95.40811	96.29394	99.70723
FEM7	84.24908	87.38076	83.34183	84.17621
FEM8	95.83815	94.55563	97.07081	97.13868
FEM9	101.7382	102.5026	98.62455	98.76233
FEM10	103.1306	103.9652	88.35967	88.56802

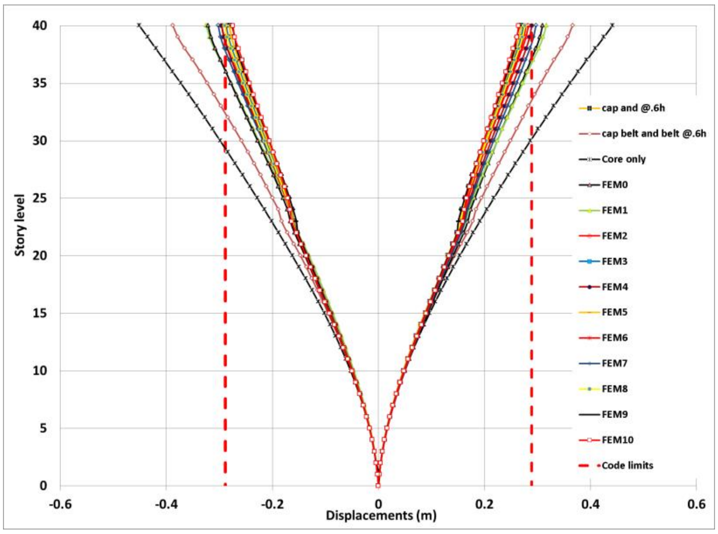


Figure 12. Story displacements under earthquake records for propose outrigger systems

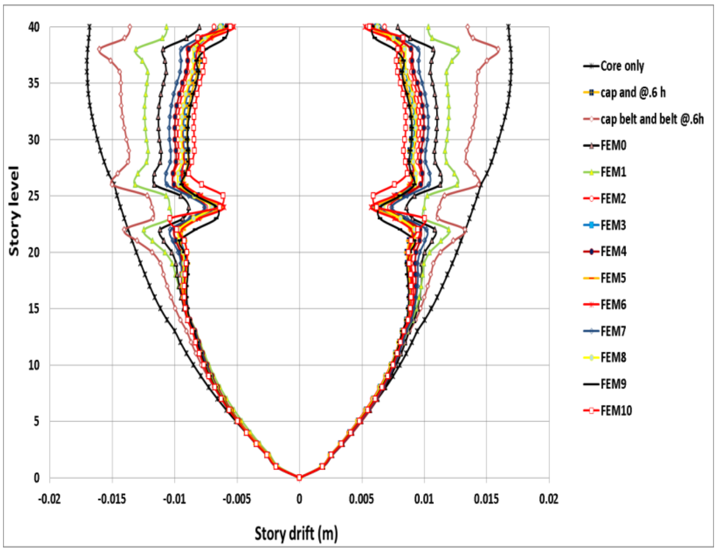


Figure 13. Story drift under earthquake records for propose outrigger systems

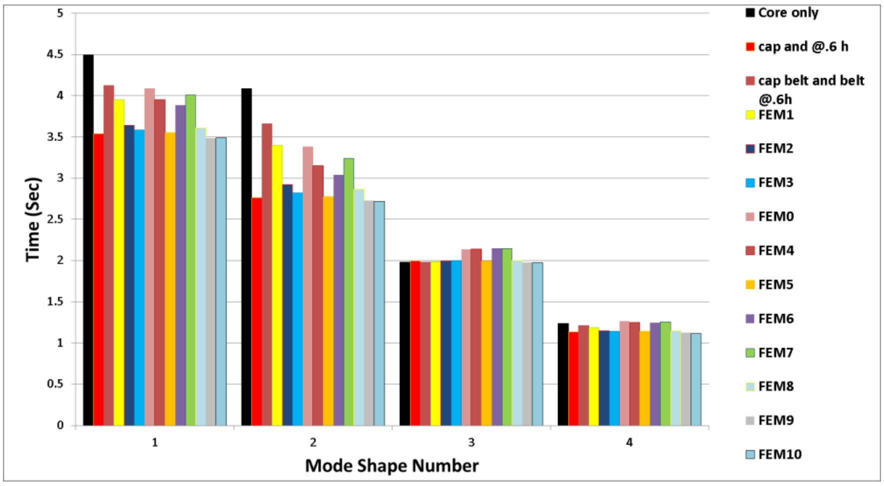


Figure 14. Modal Periods of first four modes for propose outrigger systems

The drift curve of core only model in Fig. 9,13 show cusps on the 13 and 26 floors because the model has abrupt changes in member properties at those floors. Fundamental period of first and second modes could possibly signify the change in stiffness of the structure. Proposed systems give high and effective performance as we can get the same efficiency in reducing lateral displacement and inter story drift as the conventional outrigger.

FEM10, FEM9 can give higher disp. reduction than conventional outrigger.

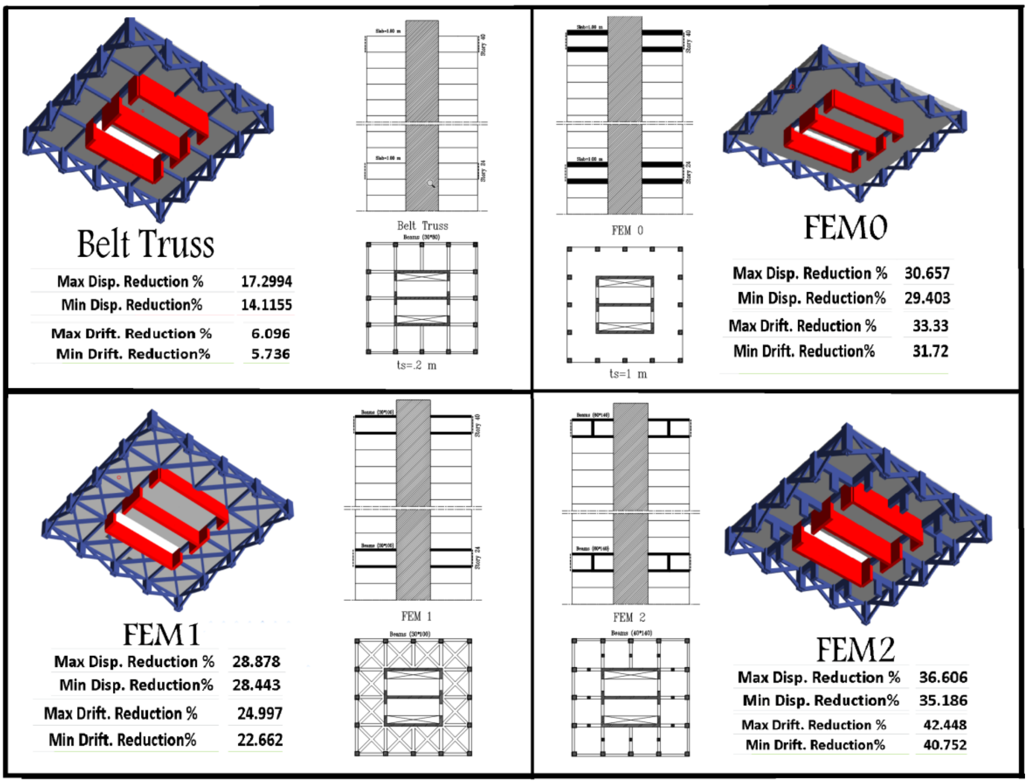
FEM5 can give the same disp. and higher drift reduction than conventional outrigger.

FEM3, FEM8 and FEM6 can give almost same disp. and higher drift reduction of conventional outrigger.

FEM2 and FEM4 can give the almost same performance.

FEM7 can give higher performance than FEM0

FEM1 the lest performance of the proposed models



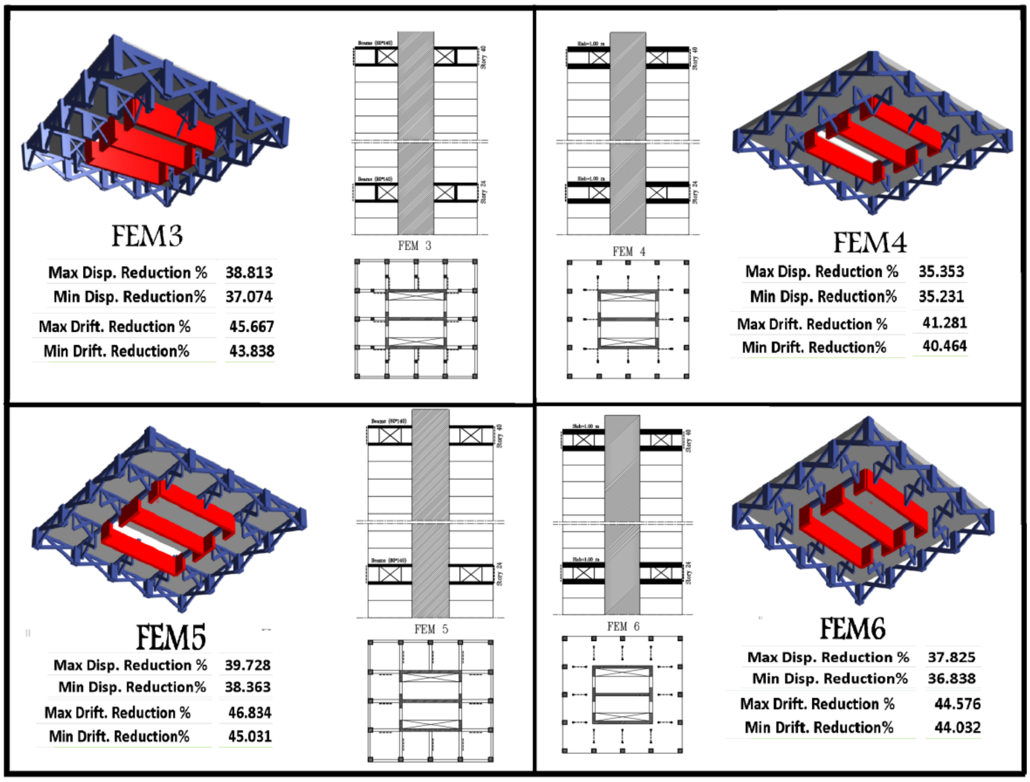
Belt Truss	
Max Disp. Reduction %	17.2994
Min Disp. Reduction%	14.1155
Max Drift. Reduction %	6.096
Min Drift. Reduction%	5.736

FEM0	
Max Disp. Reduction %	30.657
Min Disp. Reduction%	29.403
Max Drift. Reduction %	33.33
Min Drift. Reduction%	31.72

FEM1	
Max Disp. Reduction %	28.878
Min Disp. Reduction%	28.443
Max Drift. Reduction %	24.997
Min Drift. Reduction%	22.662

FEM2	
Max Disp. Reduction %	36.606
Min Disp. Reduction%	35.186
Max Drift. Reduction %	42.448
Min Drift. Reduction%	40.752

Conv .Max Disp. Reduction %	39.867	Conv .Max Drift. Reduction %	46.292
Conv .Min Disp. Reduction%	38.611	Conv .Min Drift. Reduction%	44.161



FEM3	
Max Disp. Reduction %	38.813
Min Disp. Reduction%	37.074
Max Drift. Reduction %	45.667
Min Drift. Reduction%	43.838

FEM4	
Max Disp. Reduction %	35.353
Min Disp. Reduction%	35.231
Max Drift. Reduction %	41.281
Min Drift. Reduction%	40.464

FEM5	
Max Disp. Reduction %	39.728
Min Disp. Reduction%	38.363
Max Drift. Reduction %	46.834
Min Drift. Reduction%	45.031

FEM6	
Max Disp. Reduction %	37.825
Min Disp. Reduction%	36.838
Max Drift. Reduction %	44.576
Min Drift. Reduction%	44.032

Conv .Max Disp. Reduction %	39.867	Conv .Max Drift. Reduction %	46.292
Conv .Min Disp. Reduction%	38.611	Conv .Min Drift. Reduction%	44.161

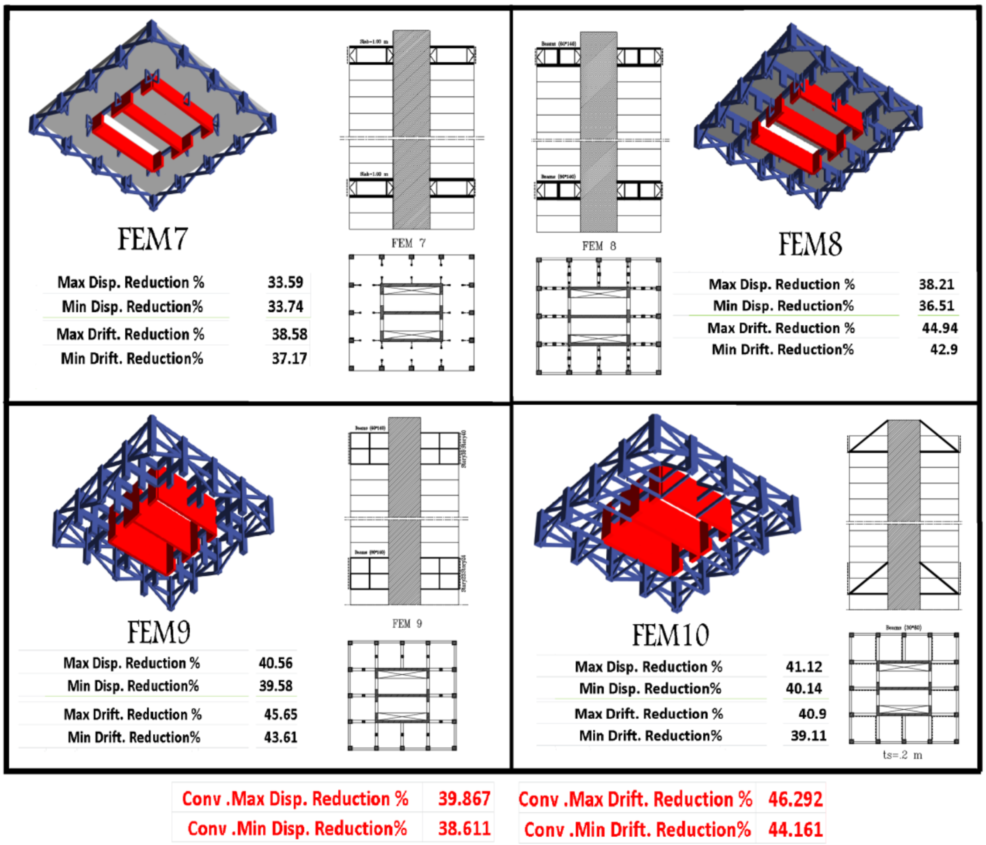


Figure15. Reduction ratios of proposed outrigger systems

6. CONCLUSIONS

This paper proposed outrigger configurations which can reduce obstructed space and make it possible to locate the outrigger in optimum location with reduction of architectural limitations. The main conclusions of this study are presented as follows:

1- Fundamental period of first and second modes could possibly signify the change in stiffness of the structure.
2- Using two stories Vierendeel outrigger with belt truss can achieve high performance as the conventional belt and outrigger do.
3- Adding one or half bracing banal to the floor of virtual outrigger increase the seismic performance of building we can call it "semi virtual outrigger".
4- Variety of proposed systems gives the designers flexibility to choose the suitable for architectural requirements.
5- The diaphragm stiffness is a critical factor of the performance of virtual outrigger.

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