Performance of Multi-Outrigger Structural System in Geometrically Irregular Shaped High-Rise Building

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Abstract

The evolution of tall building has been enlarging worldwide and brings up various challenges. When building height increases, the stiffness of the structure largely reduces. For lateral load resisting outrigger system is very much effective to control the lateral Drift. Thus, to boost the performance of the structure under various lateral loading such as in wind or earthquake outrigger structural system plays very efficient.

In present paper an investigation has been focused on performance of multi outrigger structural system in geometrically irregular shaped building. Static and dynamic behavior of 50 storey irregular shaped building with different outrigger configurations was analyzed by using ETABS Software. Time history analysis for ground motion data of El Centro was carried out. The Parameters discussed in this paper include Storey Displacement, Storey Drift, Base shear, Base moment, Time period and Torsion for static and dynamic behaviour of different outrigger configurations

Key Words: *Outrigger, Belt truss, Time history Analysis, Geometry irregularity, High-Rise Building.*

1. Introduction

Nowadays tall buildings become taller and higher due to less availability of space in metro cities due to increasing population. Due to lesser space and higher land rates high rise building is the only feasible solution to accommodate the demands of developing cities.

But in India various developed cities lie in seismically active regions. Effect of lateral forces such as wind and earthquake become more crucial in design of high rise frames due to its higher heights. Hence special systems shall be developed for resisting such lateral forces in addition to gravity loads in tall buildings. After study it is observed that there are various lateral load resisting structural systems are employed for designing the high rise building projects.

1.1. Outrigger Structural System

In lateral load resisting structural system outrigger system works efficiently for lateral forces. Basically, in outrigger structural system, central core wall of structure and peripheral columns are connected with a rigid beam which is either in form of deep RCC beam or steel truss. Often in a building there could be some architectural constraints and it is difficult to provide outrigger beam which might obstruct the planning at that time it will be suitable to provide belt truss instead of conventional outriggers.

Belt truss is basically a rigid RCC beam or Steel truss which connects all the peripheral columns so as to engage them in unison to resist lateral movements.

This lateral load resisting system is used to control excessive story drift due to lateral loads generated either by wind or earthquake.

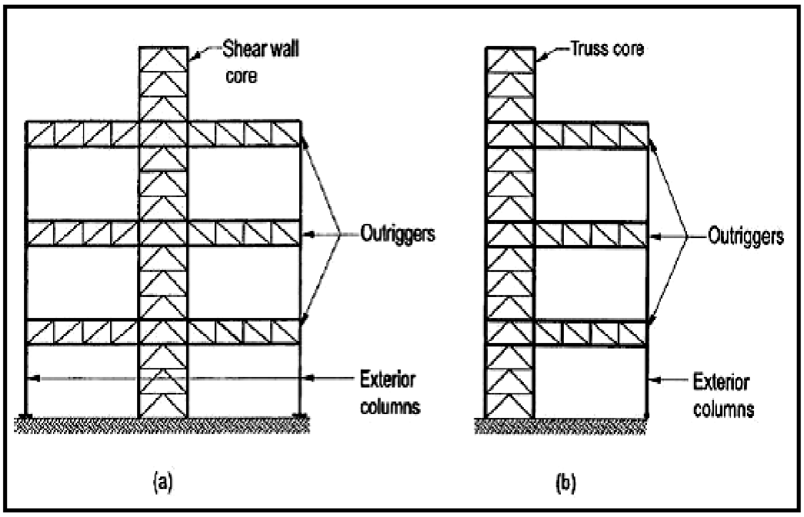

Figure 1. Outrigger Structural System

1.2. Concept of Outrigger

The outrigger concept was originally derived from sailing canoe which runs on wind pressure during its journey in sea. Sometimes even in the high storm these sailing ship withstand to its position. Similarly, tall building can withstand to high lateral load by introducing outrigger in structure.

If we compare the element of sailing ship and building then Central core wall of building behave like a vertical mast of the sailing ship. And outrigger beam or truss is act like a spreader. Similarly, peripheral columns are representing the shrouds of sailing ship. This phenomenon has a great potential to be employed in tall buildings.

Figure 2. Concept of Outrigger

1.3 Behaviour of Outrigger

The provision of outrigger structural system comprises of central core wall (i.e. lift shear wall) connected to the peripheral columns by single or double storey deep beam in case of RCC structure or sometime steel truss of that particular storey height is provided. This deep beam or steel truss is commonly referred as outrigger.

The working principle of outrigger structural system is very simple. When lateral loading either wind or earthquake load applied on the structure the rotation of central core wall is reduced due to the originating of axial forces in peripheral columns. Specifically, Tensile force is developed in windward columns and similarly compressive force will develop in leeward columns.

The result is the bending moment at a specific location where outrigger beam is provided is drastically reduced. As shown in figure 3. For restraining the rotation of outriggers peripheral columns are also connected.

This can be possible by connecting the all peripheral columns with steel truss which is generally referred as belt truss or sometime single or double storey deep wall around the structure. Sometime it referred as "belt wall".

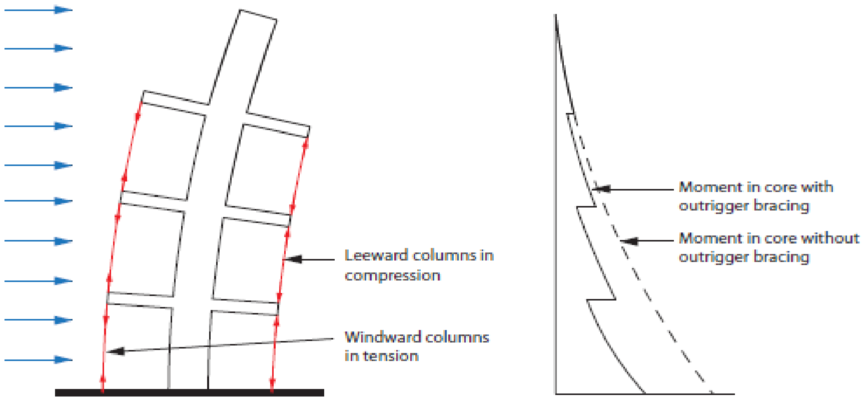

Figure 3. Behaviour of Outrigger

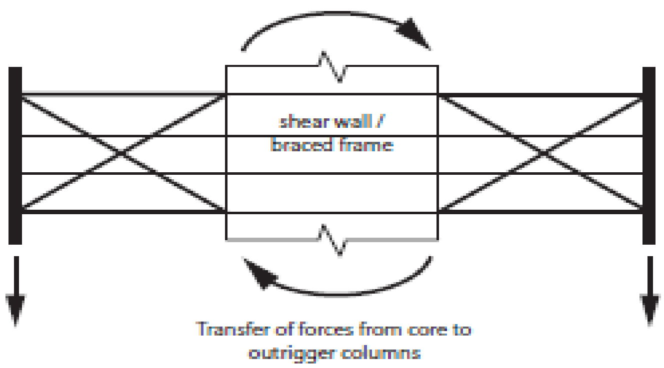

Figure 4. Behaviour of Outrigger

2. Objectives of Research

1. To develop Finite Element model of reinforced concrete multi-storeyed building prototypes with geometrically irregular and unsymmetrical L shaped plan layouts with different outrigger configurations.
2. To perform Static analysis of Geometrically irregular L shaped building models for earthquake analysis as per IS 1893 (Part 1) 2002
3. To perform Dynamic analysis of geometrically irregular L shaped building models by response spectrum method using software ETABS. Furthermore, Dynamic analysis for earthquake assessment shall be performed by time history method in which structure will be subjected to Time history load functions.
4. To determine the best possible location of possible belt-truss and outriggers arrangement by comparison of results for static and dynamic actions.
5. To perform a parametric study which include Storey Displacement, Storey Drift, Base Shear, Base Moment, Time Period and Torsion.

3. Models Considered for Analysis

In Present study, three-dimensional 50 storied building with plan dimension 53 m x56 m are modelled (Fig 5). The typical floor height is 3.5m giving a total height of 182m. The beams, columns and shear walls are modelled as RC elements and outrigger is modelled as structural steel truss. Column and beam sizes considered in the analysis are 750mmx750mm and 300x650mm respectively.

A total 10 Different outrigger configurations by varying the position and number of outrigger beam and belt truss has been modelled and analyzed.

1. M7 50-1 Without outrigger
2. M8 50-2 Outrigger at top
3. M9 50-3 Outrigger at 2/3 height
4. M10 50-4 Outrigger at mid-height
5. M11 50-5 Outrigger at top and mid-height
6. M12 50-6 Outrigger at top, mid-height and 2/3rd height
7. M13 50-7 Double outrigger at top
8. M14 50-8 Double outrigger at mid-height
9. M15 50-9 Double outrigger at 2/3 third height
10. M16 50-10 Double outrigger at top and mid-height

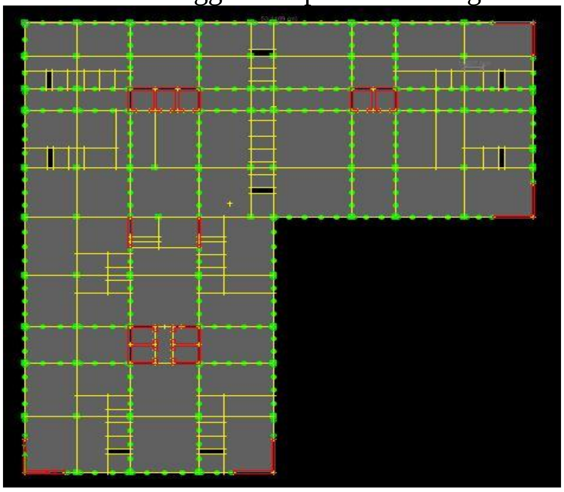

Figure 5. Typical Plan of Building

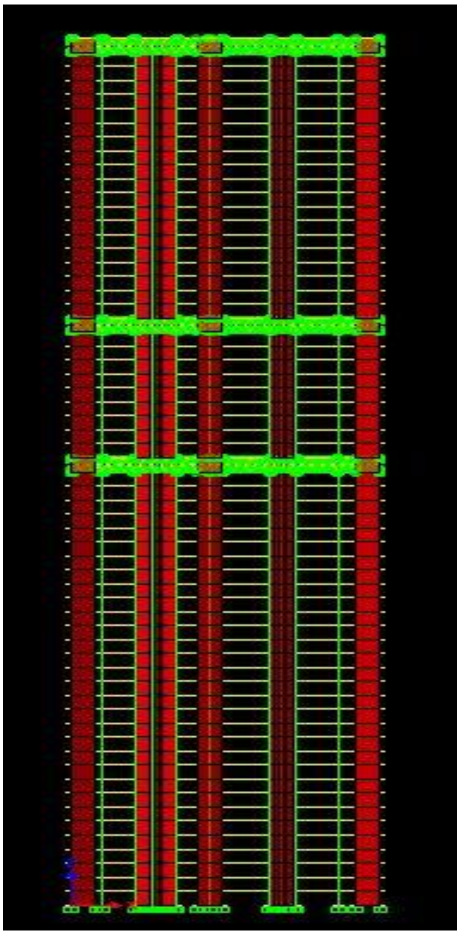

Figure 6. Elevation (Model No 6- OUTRIGGER AT Top, Mid & Two third Height)

The assumptions behind modelling this system are that the connection between shear wall core and foundation is rigid. The outrigger truss is rigidly connected to the stiff core on one side and simply supported on the peripheral column other side. Simple support condition is achieved through releasing major and minor moments (M33 & M22) of truss element at the peripheral column junction such that bending moments are not transferred and only axial thrust is exerted to the columns. The columns are sized and shall be designed such that it can safely carry the extra axial force (weather compression or tension) caused due to outriggers. The material behavior for analysis is considered to be linearly elastic. The outrigger trusses are kept very stiff so as to act as a rigid arm to transfer moments of core to the external column with minimum loss of forces due to distortion and flexure of outrigger itself.

4. LOAD CONSIDERATION & ANALYSIS OF THE FRAME

Equivalent static analysis method as per IS code is employed for assessing the static behavior of the models. Response spectrum and Time History analysis methods are employed to assess the linear dynamic behavior of the models.
Ground acceleration data in time domain is selected from historical data of California region.

Finite element software ETABS is used to carry out the above-mentioned analysis. In ETABS, shear walls and slabs are modelled as four nodded thin shell elements with default auto meshing. Beams, columns and truss elements are modelled as two nodded line elements. In addition, the truss members are released for moments on both of its ends to get exclusive axial brace behavior. Semi rigid diaphragm is assigned to all the floor elements to engage all columns in resisting lateral forces.

Loading:
For slabs, UDL of 1.5kN/m2 floor finish load and 4kN/ m2 of live load is considered as per IS-875 part 2 for commercial buildings.
For beams, uniform line load of 6kN/ m2 load is considered for partition walls made up of light weight blocks.
Seismic load is considered confirming IS 1893 (PART-1) 2002. The following parameters have been considered for seismic analysis-
Seismic Zone = Zone IV (Z= 0.24)
Importance Factor = 1
Type of Soil = Medium Soil (Soil Type II)
Response Reduction Factor = IV
Damping Ratio = 5%
Time Period (Tx and Ty) = 4.24 Sec
Diaphragm = Semi Rigid

The structure is analyzed as per the loading combinations providing in IS: 875 (part 5).
1.5(DL + LL)
1.2(DL + LL + EQX)
1.2(DL + LL - EQX)
1.2(DL + LL + EQY)
1.2(DL + LL - EQY)
1.5(DL+ EQX)
1.5(DL - EQX)
1.5(DL+ EQY)
1.5(DL - EQY)
0.9DL + 1.5EQX
0.9DL - 1.5EQX
0.9DL + 1.5EQY
0.9DL - 1.5EQY

5. Results and Discussions

The following results of 50 storey building are studied, the Parameters discussed include variation of Storey Displacement, Storey Drift, Base shear, Base moment, Time period and Torsion for static and dynamic behaviour of different outrigger configurations.

5.1 Storey Displacement

Chart 1 and 2 shows profile for variation of storey displacement in equivalent static analysis. As well as well as Chart 3, 4, 5 and 6 shows the variation of top storey displacement in different outrigger configurations for equivalent static analysis and response spectrum analysis. It is observed that top displacement in model 9 (OUTRIGGER AT Mid Height) is reduced up to 16%. And if we consider the multi outrigger system i.e. two or more outrigger storey then in model 16(Double outrigger at top and mid) it observed that top storey displacement reduced up to 29%.

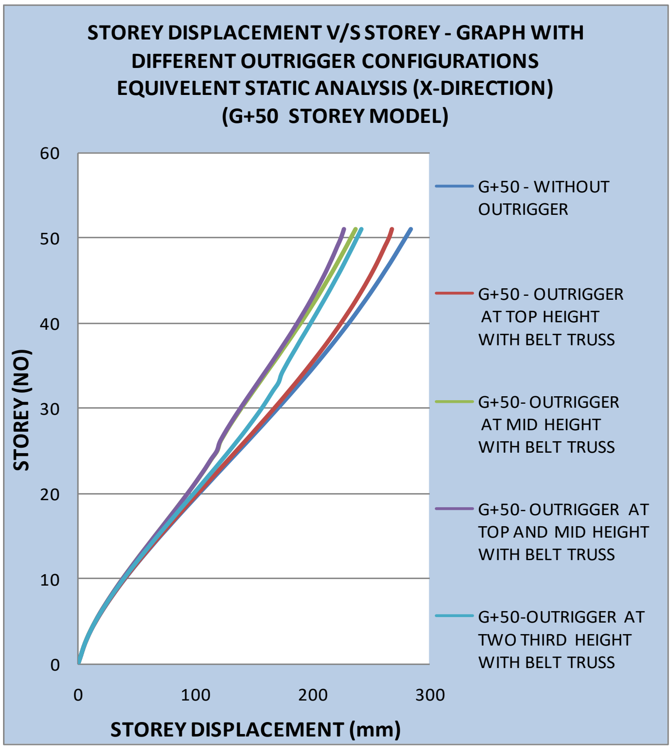

Chart 1. Equivalent Static Analysis (X Direction)

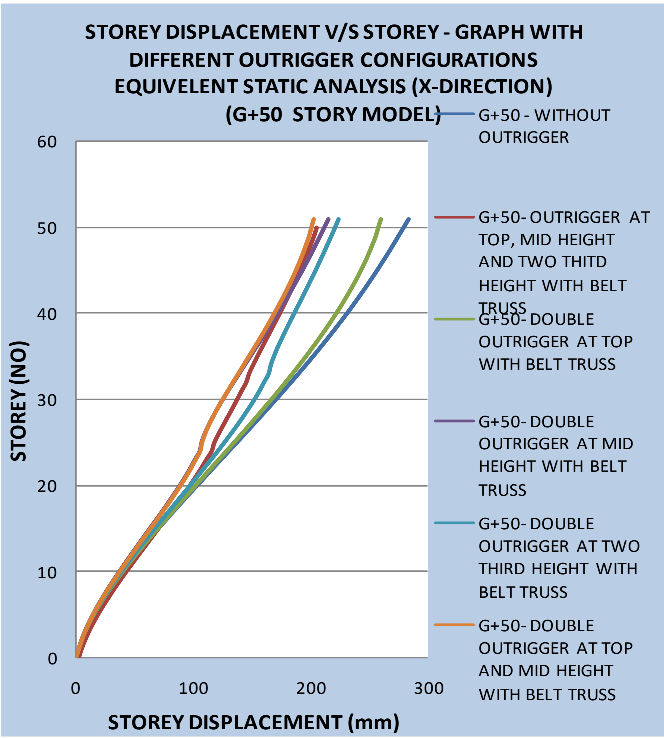

Chart 2. Equivalent Static Analysis (X Direction)

Table -1: Percentage Reduction in Top Displacement with Different Outrigger Configuration (Equivalent Static and Response Spectrum Analysis- X & Y Direction)

		M7 (50-1)	M8 (50-2)	M9 (50-3)	M10 (50-4)	M11 (50-5)	M12 (50-6)	M13 (50-7)	M14 (50-8)	M15 (50-9)	M16 (50-10)
EQXD		284	268	237	227	242	205	260	216	223	202
SPECX		193	180	160	152	164	138	172	143	149	131
TH-X		110	106	95	93	103	90	103	94	97	86
EQYD		257	247	218	211	223	191	241	200	208	192
SPECY		154	149	132	128	136	119	149	123	131	120
TH-Y		90	87	86	83	83	76	87	84	83	80
% Redu In Storey Disp	EQXD	5%	16%	20%	15%	28%	8%	24%	21%	29%	
	SPECX	6%	17%	21%	15%	28%	11%	26%	23%	32%	
	TH-X	4%	13%	16%	7%	19%	7%	14%	12%	22%	
	EQYD	4%	16%	21%	16%	30%	8%	24%	25%	31%	
	SPECY	3%	14%	17%	12%	23%	3%	20%	15%	22%	
	TH-Y	3%	4%	8%	7%	15%	3%	7%	7%	11%	

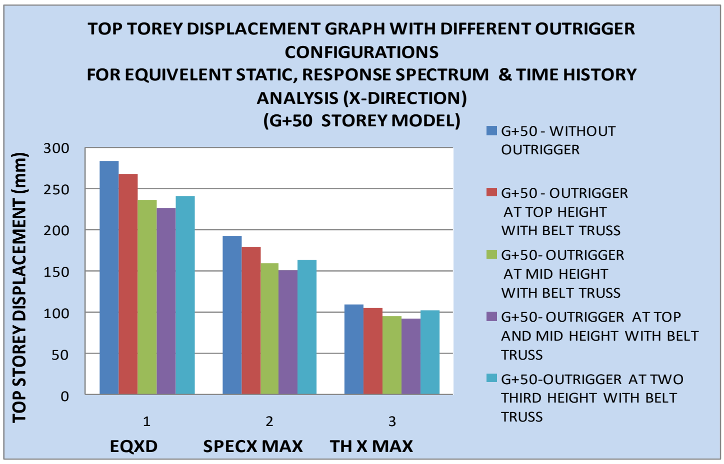

Chart 3. Top Displacement (X Direction)

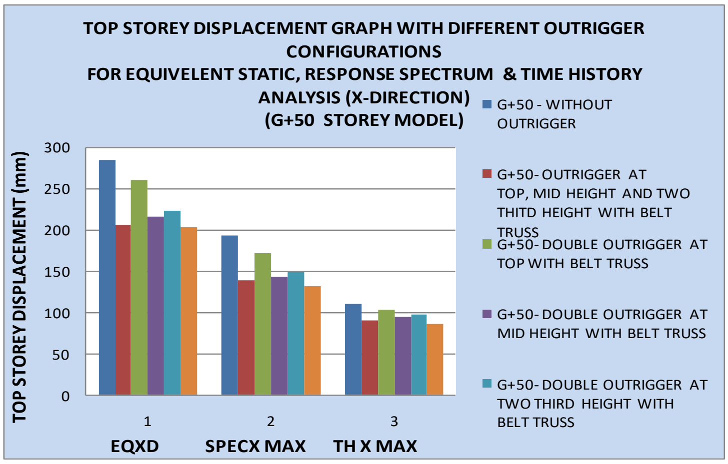

Chart 4. Top Displacement (X Direction)

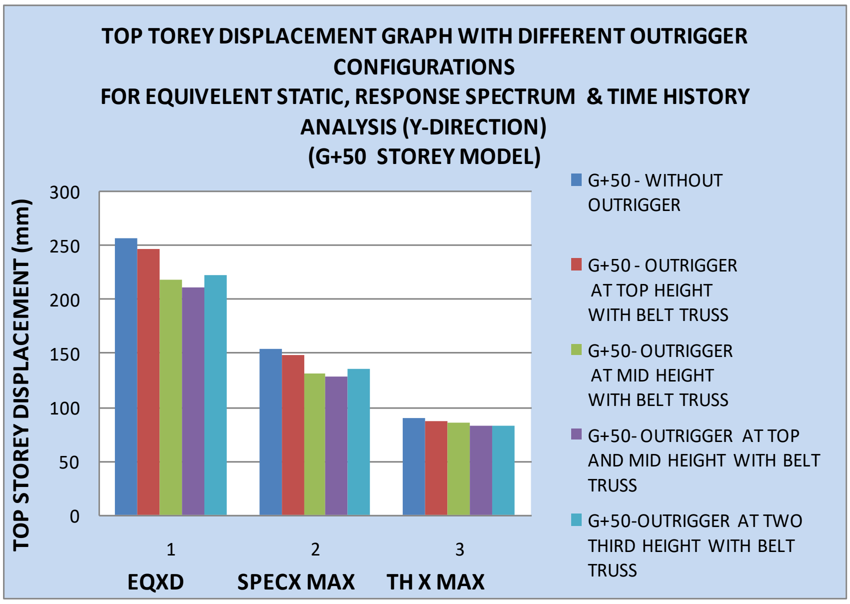

Chart -5: Top Displacement (Y Direction)

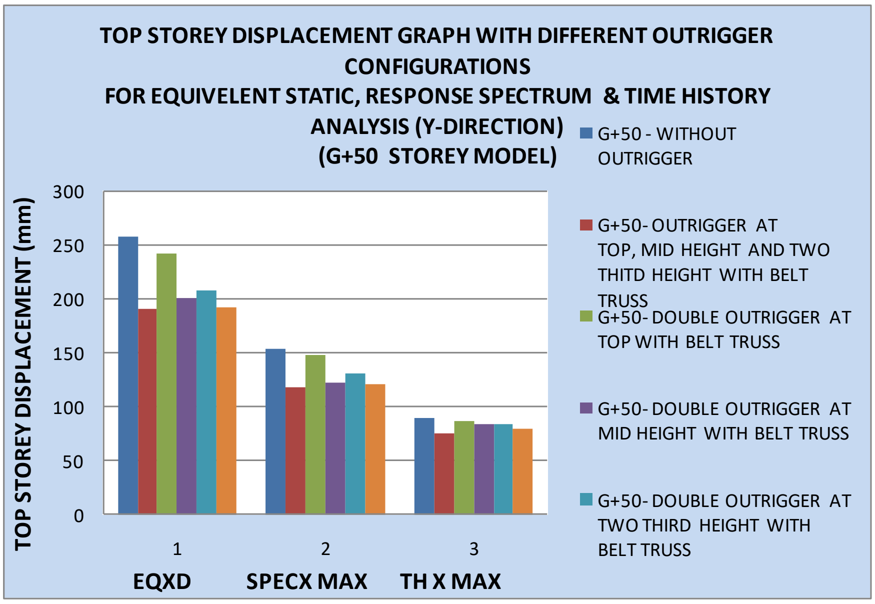

Chart -6: Top Displacement (Y Direction)

5.2. Storey Drift

Chart 7, 8 and table 2 shows profile for variation of storey drift in equivalent static analysis, response spectrum analysis and time history analysis in X and Y direction

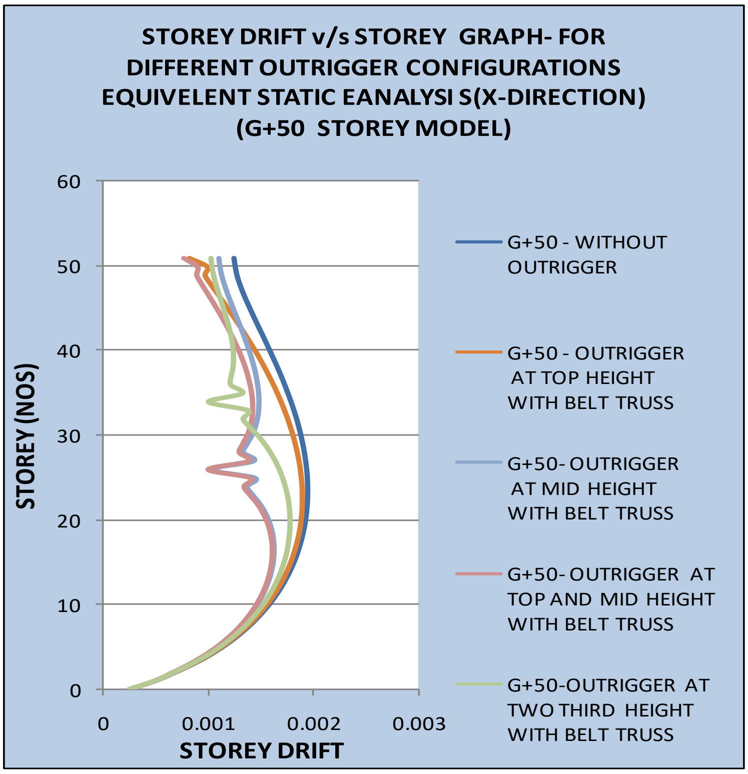

Chart 7. Equivalent Static Analysis (X Direction)

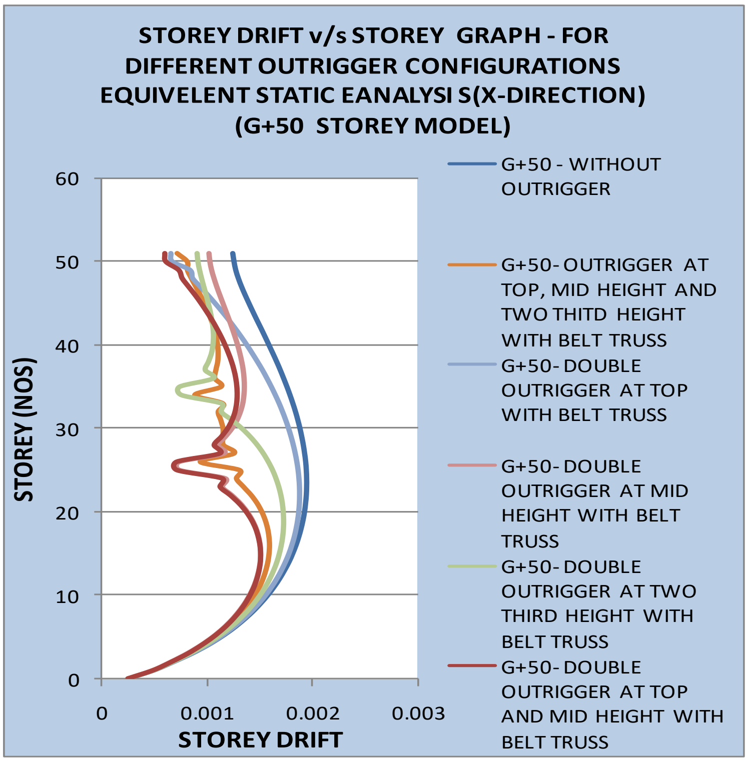

Chart 8. Equivalent Static Analysis (X Direction)

Table -2: Percentage Reduction in Storey Drift With Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis in X and Y Direction)

	M8 (50-2) %		M9 (50-3) %		M10 (50-4) %		M11 (50-5) %		M12 (50-6) %		M13 (50-7) %		M14 (50-8) %		M15 (50-9) %		M16 (50-10) %	
					TOP	38			TOP	42							TOP	51
EQXD	TOP	34	MID HT	47			2/3 HT	44	2/3	50	TOP	47	MID HT	62	2/3 HT	58		
					MID	48			MID	52							MID	63
					TOP	40			TOP	44							TOP	55
SPECX	TOP	35	MID HT	48			2/3 HT	45	2/3	52	TOP	50	MID HT	62	2/3 HT	60		
					MID	48			MID	53							MID	66
					TOP	42			TOP	47							TOP	51
TH-X	TOP	36	MID HT	47			2/3 HT	42	2/3	51	TOP	50	MID HT	59	2/3 HT	58		
					MID	49			MID	47							MID	61
					TOP	32			TOP	39							TOP	47
EQYD	TOP	24	MID HT	47			2/3 HT	43	2/3	52	TOP	38	MID HT	61	2/3 HT	57		
					MID	48			MID	52							MID	63
					TOP	32			TOP	39							TOP	48
SPECY	TOP	25	MID HT	47			2/3 HT	43	2/3	52	TOP	39	MID HT	62	2/3 HT	58		
					MID	47			MID	53							MID	64
					TOP	26			TOP	44							TOP	40
TH-Y	TOP	28	MID HT	40			2/3 HT	41	2/3	53	TOP	43	MID HT	55	2/3 HT	57		
					MID	42			MID	49							MID	57

The variation of storey drift as indicated in table 2, it is observed that the storey drift is reduced by 34% by providing outrigger at top (Model 8) and it is reduced up to 47% by providing outrigger at Mid height (Model 9). Further it can be observed that in multi outrigger structural system storey drift is reduced up to 63% by providing double storey outrigger at top and mid height.

It can be observed from graphs in chart 7 and 8, the sudden change or drop in story drift is due to high stiffness in wall at those outrigger stories due to presence of stiff trussed which restricts rotation of walls.

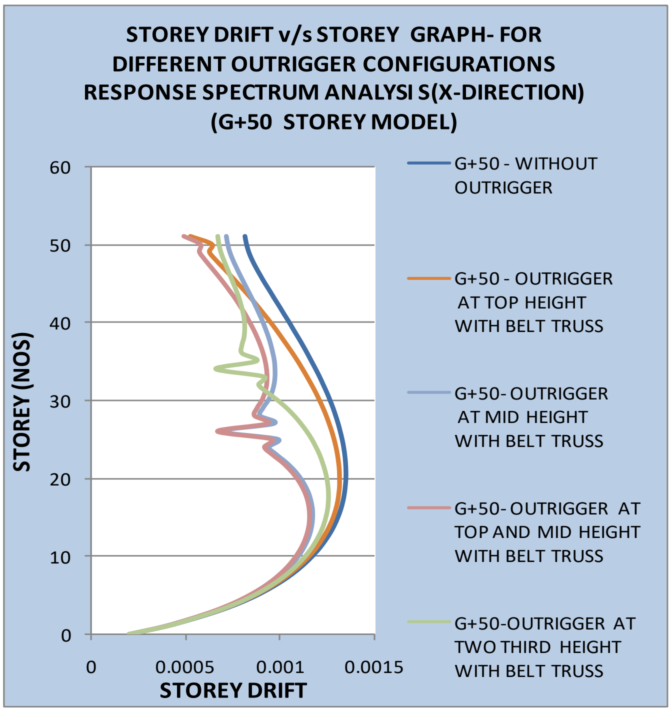

Chart 9. Response Spectrum Analysis (X Direction)

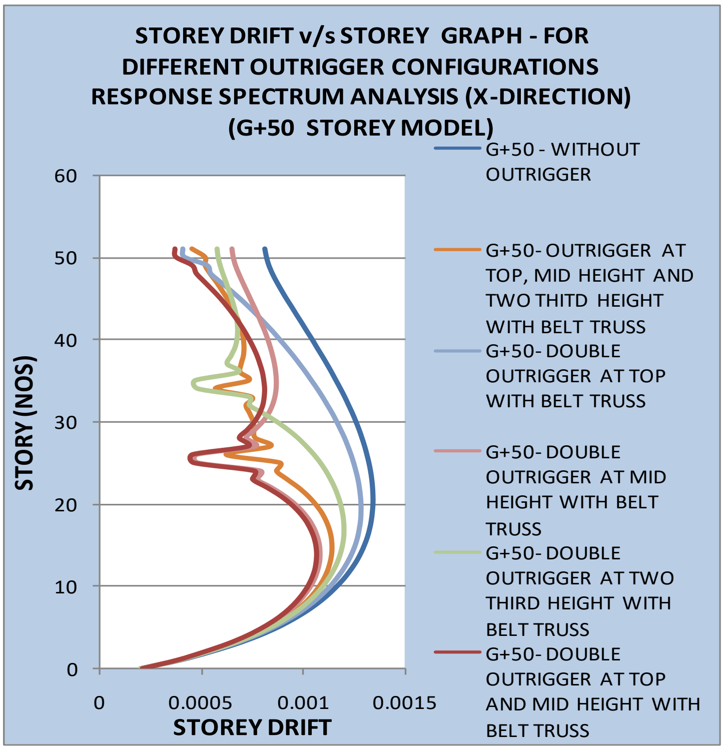

Chart 10. Response Spectrum Analysis (X Direction)

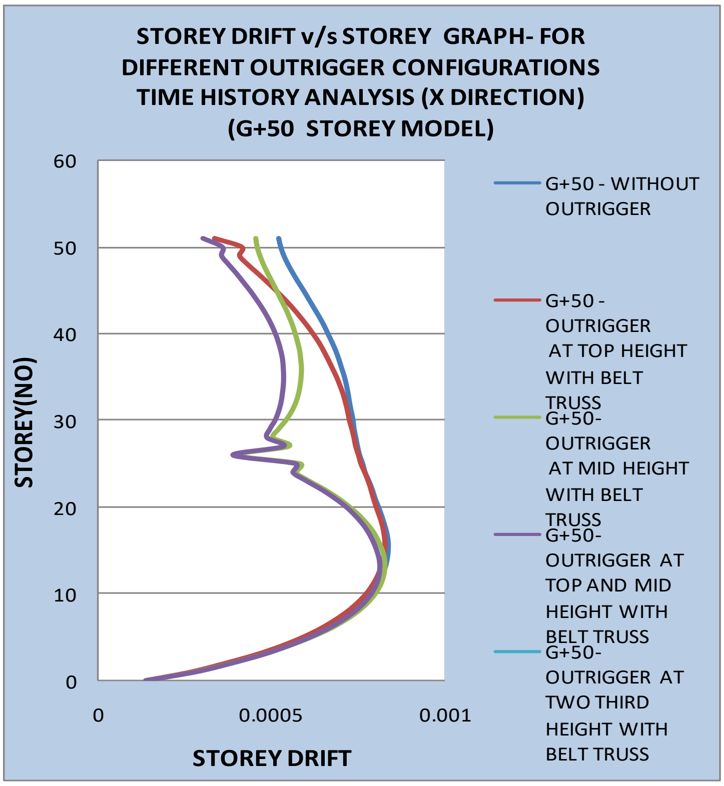

Chart -10: Time History Analysis (X Direction)

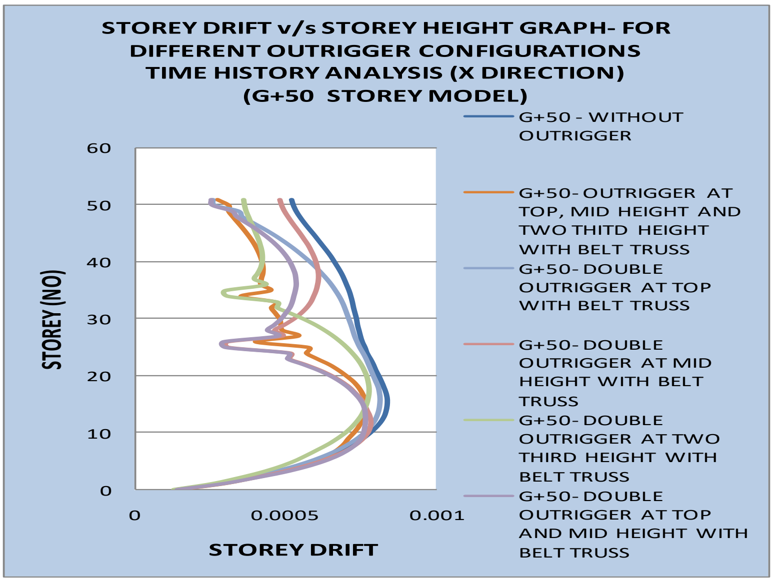

Chart -11: Time History Analysis (X Direction)

6.3 Base Reactions

Chart 12; table 3 shows graphs for variation of base reaction in different outrigger configurations for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in (X Direction).

And similarly Chart 13, table 3 shows graphs for variation of base reaction in in different outrigger configurations for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in (Y Direction).

And from Chart 12 and 13 it observed that there is no significant variation of base reaction values with provision of different outrigger configurations.

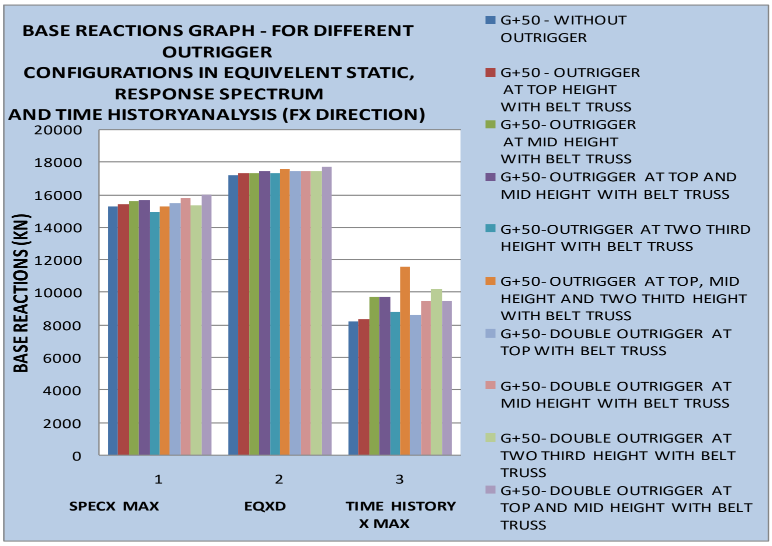

Chart 12. Base Reactions graph With Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- X Direction)

Table 3. Base Reactions (in kN) for Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- X &Y Direction)

		M7 (50-1)	M8 (50-2)	M9 (50-3)	M10 (50-4)	M11 (50-5)	M12 (50-6)	M13 (50-7)	M14 (50-8)	M15 (50-9)	M16 (50-10)
		kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
FX	SPECX	15278	15399	15605	15703	14946	15295	15501	15808	15336	16003
	EQXD	17249	17376	17375	17508	17376	17640	17508	17508	17508	17773
	TH-X	8213	8366	9731	9716	8818	11604	8576	9488	10225	9478
FY	SPECY	15598	15631	15933	15956	15076	15443	15662	16061	15127	16146
	EQYD	17249	17376	17375	17508	17375	17641	17508	17508	17508	17772
	TH-Y	8923	9678	9047	9026	9520	10495	9660	9057	9888	9940

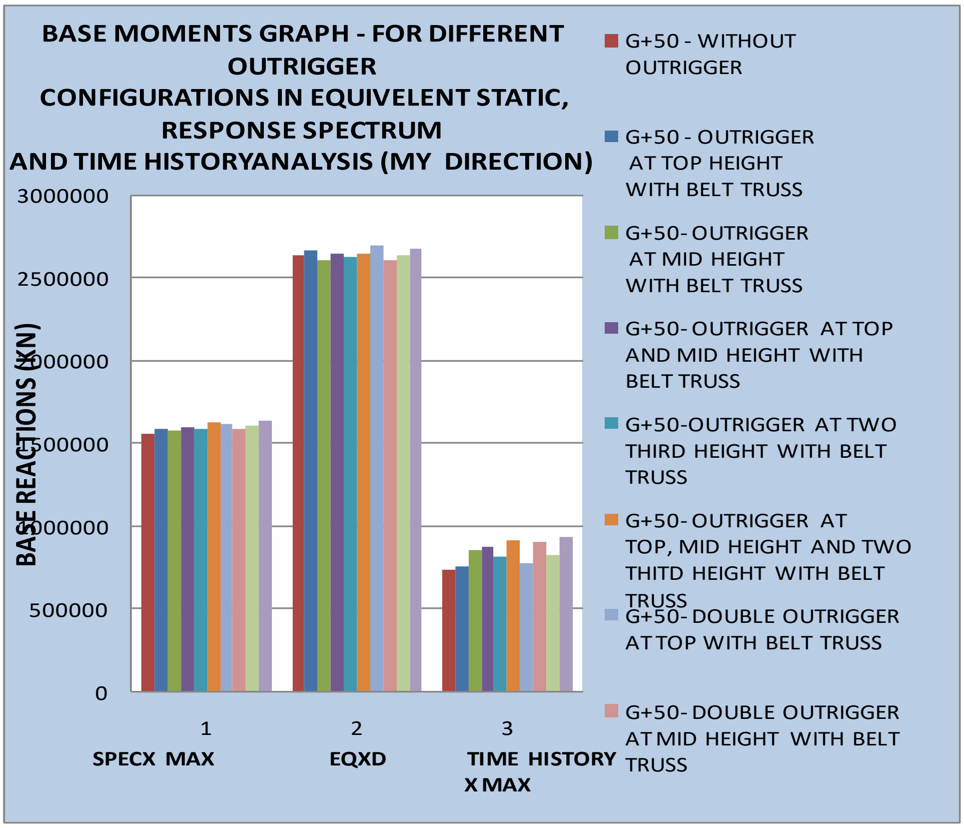

Chart 13. Base Reactions graph With Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- Y Direction)

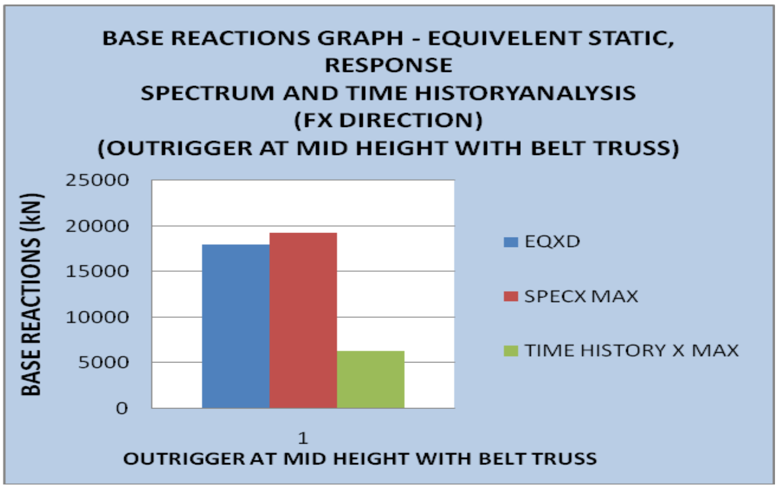

Chart 14. Base Reaction graph With Different methods of analysis (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- FX Direction) (Outrigger at Mid Height with Belt Truss)

Chart 14 and Chart 15 shows graphs for variation of base reaction for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in X Direction and Y direction respectively for (Modal- 3 - Outrigger at Mid Height with Belt Truss)

Above graphs indicate that, there is no significant difference in base shear values among different models due to addition of outriggers. Reason behind that is, the outrigger doesn't significantly increase the seismic weight of the building and as per the codal philosophies the seismic inertial forces are directly proportional to the weight of the building. So, no increase in weight results in no increase in base shears.

However, in case of time history results few variations could be observed but they are due to the random nature of ground motions and its variable effect on various frames and floor stiffness.

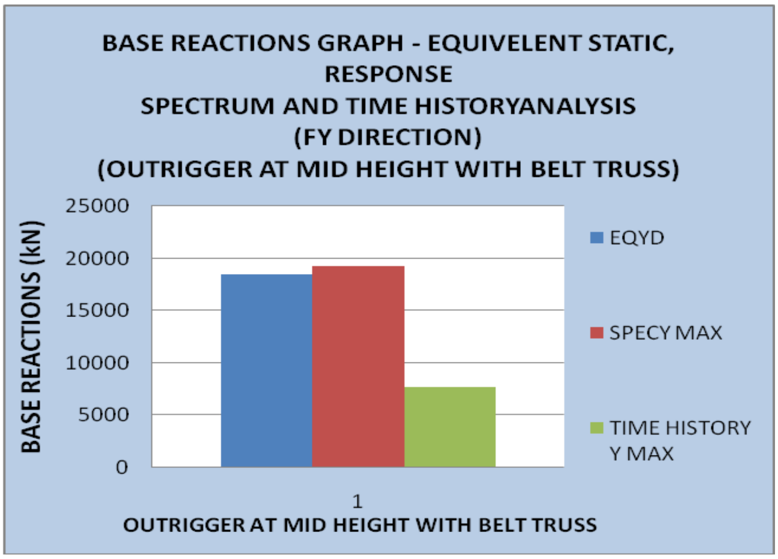

Chart 15. Base Reaction graph With Different methods of analysis (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis-FY Direction) (Outrigger at Mid Height with Belt Truss)

5.4 Base Moments

Chart 16; table 4 shows graphs for variation of base Moments in different outrigger configurations for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in (X Direction)

And similarly Chart 17, table 4 shows graphs for variation of base moments in different outrigger configurations for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in (Y Direction)

And from Chart 16 and 17 it observed that there is no significant variation of base moment values with provision of different outrigger configurations.

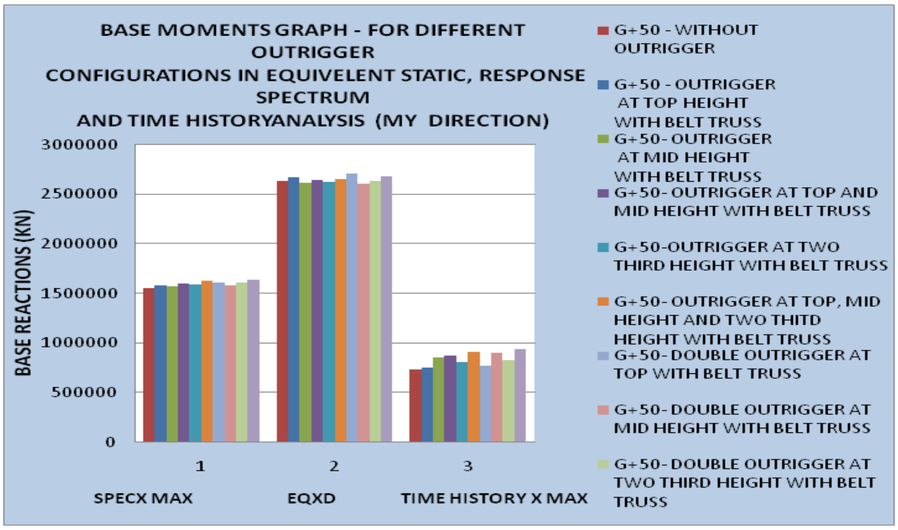

Chart 16. Base Moments graph With Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- My Direction)

Table -4: Base Moments (in kN-m) for Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- My Direction)

I		M7 (50-1)	M8 (50-2)	M9 (50-3)	M10 (50-4)	M11 (50-5)
		kN-m	kN-m	kN-m	kN-m	kN-m
MY	SPECX	1559309	1588505	1574726	1602972	1590473
	EQXD	2640245	2672500	2614176	2650011	2630570
	TH-X	732582	756987	859010	874918	811594
MX	SPECY	1630553	1647264	1634775	1653361	1644421
	EQYD	2651691	2684851	2625770	2662070	2642525
	TH-Y	997197	1014708	1067578	1080555	1029913
		M12 (50-6)	M13 (50-7)	M14 (50-8)	M15 (50-9)	M16 (50-10)
		kN-m	kN-m	kN-m	kN-m	kN-m
MY	SPECX	1627115	1614981	1587657	1613360	1637523
	EQXD	2653997	2706712	2612443	2639673	2683962
	TH-X	917430	771266	905391	827415	936892
MX	SPECY	1669576	1662182	1631991	1650367	1667710
	EQYD	2665205	2719371	2624497	2652219	2696415
	TH-Y	997197	1014708	1067578	1080555	1029913

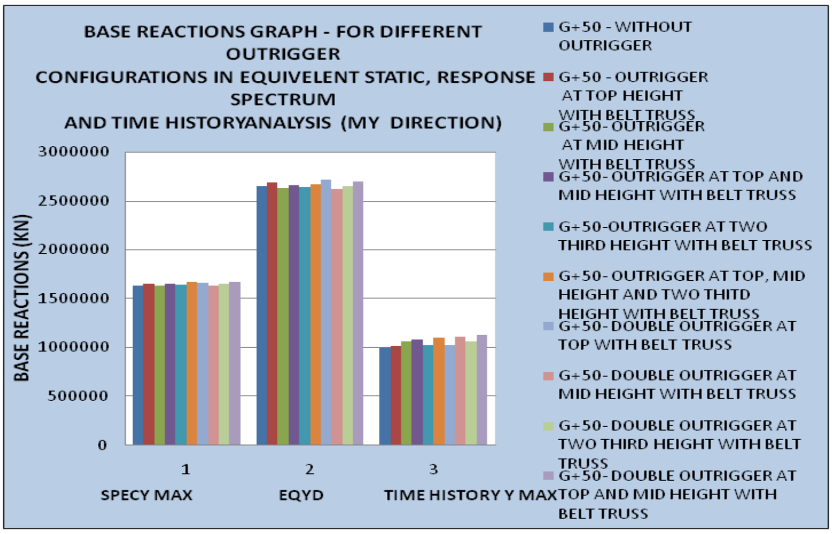

Chart 17. Base Moments graph With Different Outrigger Configuration (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- Mx Direction)

Chart 18 and Chart 19 shows graphs for variation of base Moments for Equivalent static analysis, Response Spectrum analysis and Time History Analysis in X Direction and Y direction respectively for (Modal- 3 - Outrigger at Mid Height with Belt Truss)

The above graphs are clearly indicating that there is no significant difference in base shear values for equivalent static analysis and response spectrum analysis. But for Time history analysis base reaction value considerably decrease up to 60 % in X direction and 58% in Y direction. The main reason for this change being due to variable mass at different floors and Equivalent static analysis and response spectrum methods fails to catch the same.

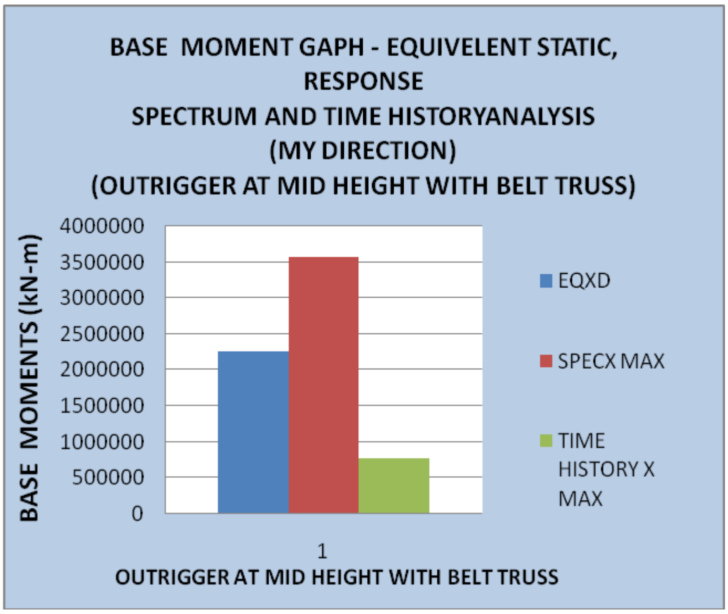

Chart -18: Base Moments graph With Different methods of analysis (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- MY Direction) (Outrigger at Mid Height with Belt Truss)

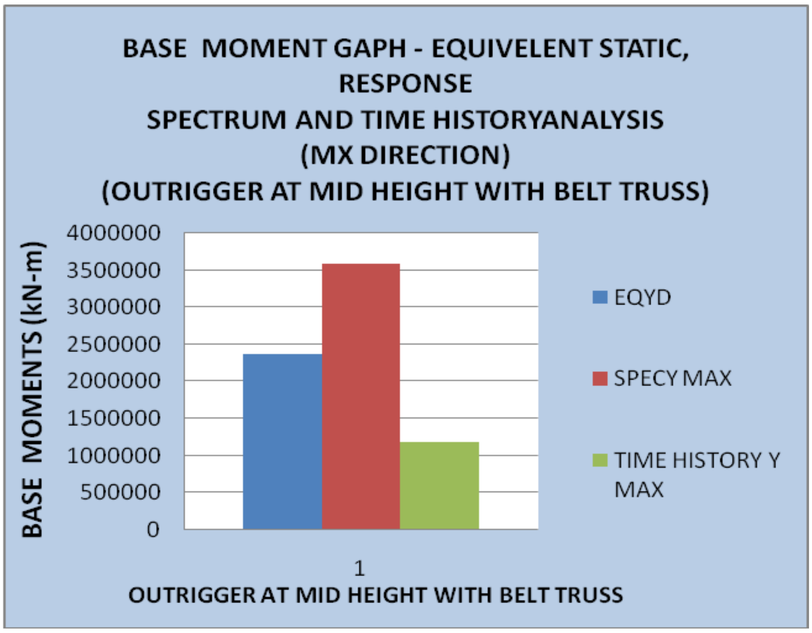

Chart 19. Base Moments graph With Different methods of analysis (Equivalent Static Analysis, Response Spectrum Analysis and Time History Analysis- MX Direction) (Outrigger at Mid Height with Belt Truss)

5.4 Time Period

Chart 20 and table 5 shows graphs for variation of time period in different outrigger configuration for modal analysis and it is found that there is maximum reduction in time period when outriggers are placed at mid height of the structure.

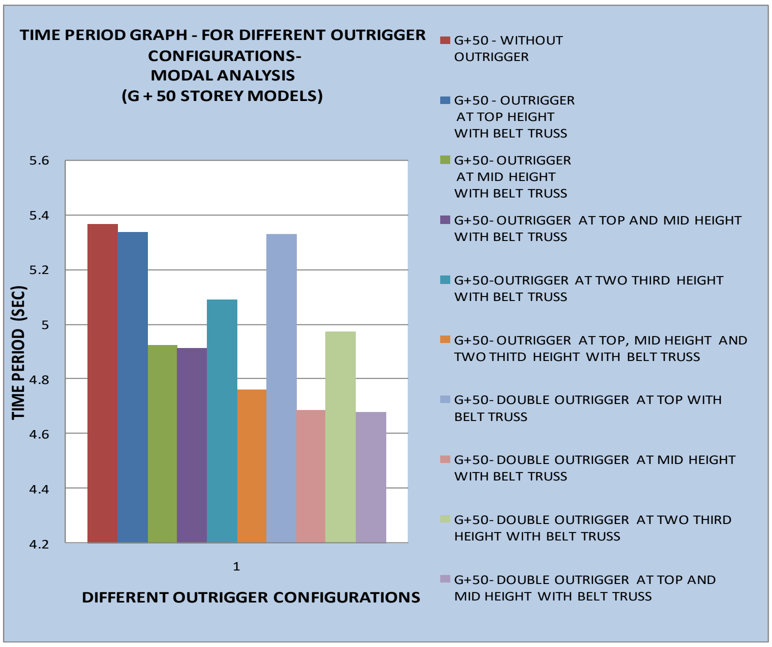

Chart -20: Time Period with Different Outrigger Configuration (Modal Analysis)

Table 5: Percentage Reduction in Time Period with Different Outrigger Configurations (Modal Analysis)

PERCENTAGE REDUCTION IN TIME PERIOD FOR DIFFERENT OUTRIGGER CONFIGURATIONS									
	M8	M9	M10	M11	M12	M13	M14	M15	M16
% Reduction in Time Period	0.4	8.2	8.4	5	11.1	0.6	12.6	7.2	12.7

6.5 TORSION

Chart 21 and Table 6 shows profile for variation of torsion in modal analysis for different outrigger configurations. It is observed that torsion in model 10 (OUTRIGGER AT Mid Height) is reduced up to 38%. And if we consider the multi outrigger system i.e. two or more outrigger storey then in model 16(Double outrigger at top and mid) then it observed that torsion reduced up to 46 %.

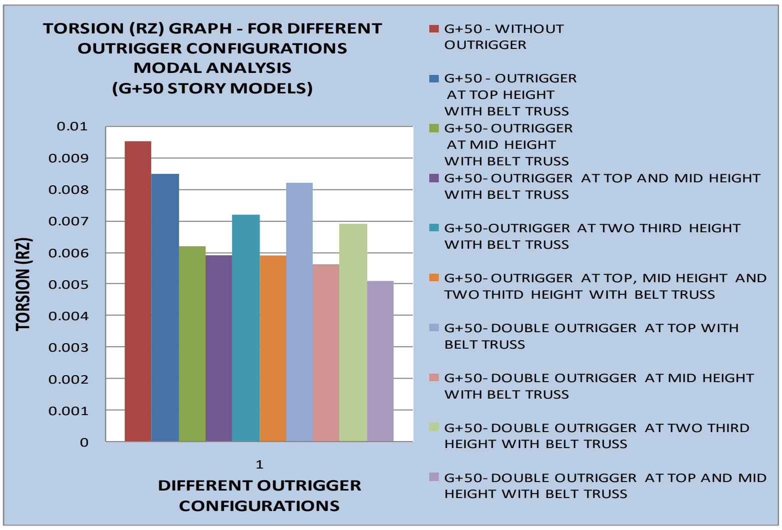

Chart -21: Torsion with Different Outrigger Configurations (Modal Analysis)

Table 6: Percentage Reduction in Torsion with Different Outrigger Configurations (Modal Analysis)

PERCENTAGE REDUCTION IN TORSION (RZ) FOR DIFFERENT OUTRIGGER CONFIGURATIONS									
	M8	M9	M10	M11	M12	M13	M14	M15	M16
% Red in Torsion (RZ)	11	35	38	24	38	14	41	27	46

6. CONCLUSIONS

The present work is clearly focused on the study of seismic response of geometrically irregular shaped (in plan) structures and study of various parameters which include Storey displacement, Storey drift, Base reactions, Base moments, Time Period and Torsion by introducing outrigger structural system. For irregular shaped buildings which are vulnerable to twisting, the use of outrigger at proper location minimizes twisting effect and the use of outrigger structural system in high rise building increases stiffness and makes the structural form efficient under lateral load.

Based on the analysis results obtained following conclusions are made:

1. In static and dynamic behaviour when we consider the storey displacement and storey drift parameters then the optimum location of outrigger is at mid height.
2. In parameter study of Storey Drift it is reduced by 16% by providing outrigger at top (Model 9) and it is reduced up to 24% by providing outrigger at mid height (Model 14). Further it can be observed that in multi outrigger structural system storey drift is reduced up to 30% by providing double storey outrigger at top and mid height.
3. In parametric study of base shear there is no significant difference in base shear values for equivalent static analysis and response spectrum analysis. But for Time history analysis base reaction value considerably decrease up to 60 % in X direction and 58% in Y direction. The main reason for this change being due to variable mass at different floors and Equivalent static analysis and response spectrum methods fails to catch the same.
4. By introducing outrigger structural system the time period can be controlled considerably. In parametric study there is maximum reduction in time period when outriggers are placed at mid height of the building.
5. In geometrically irregular structure it is very challenging task to control the torsion. Therefore As per parametric study of different outrigger configurations it is observed that torsion in model 10 (OUTRIGGER AT Mid Height) is reduced up to 38%. And if we consider the multi outrigger system i.e. two or more outrigger storey then in model 16(Double outrigger at top and Mid) then it reduced up to 46%.
6. For different outrigger configurations, base shear does not alter to great extent.
7. From the graphs of storey displacement it is observed that the displacement obtained by Equivalent static analysis is higher than Dynamic analysis such as Response spectrum and Time history analysis.
8. Equivalent static analysis is not sufficient when buildings are in geometrically irregular shape and it is essential to perform dynamic analysis due to non linear distribution of forces.
9. It can be concluded that optimum location of outrigger is at mid height of the building.

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