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An Analytical study on Application of Virtual Outrigger in Tall Buildings to Reduce Disproportionate Collapse and Increase Efficiency

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Abstract - *Virtual outriggers are an up gradation of conventional outrigger and belt truss system. Outriggers are systems which resist lateral load. It consist of stiff arms connecting core and outer columns, when engaged in tall slender buildings resist bending of the core and hence reduce overturning moment and maximum lateral deflection of free core. Virtual outriggers are advantageous compared to conventional outriggers because they save space and prevent complicated connections.*
In this paper an 80-storey RCC building frame is studied and conventional outriggers are first modeled and the optimum positions are fixed based on least lateral deflection of the building model. The study is carried out in ETABS 2016. From the gap identified in literature review, a four outrigger system was modeled. Virtual outriggers are then employed in the model building. Response spectrum analysis was done and maximum lateral displacement, storey drifts of model were compared for distinct variations of virtual outrigger systems. The effect of various configurations of belt truss is studied. Effect of virtual outriggers on progressive collapse is also done. For the 3-D model about 31% reduction in maximum displacement and 34% reduction in storey drifts are achieved with optimum location of the virtual outrigger and x bracing are found to be most effective configuration for belt truss. Virtual outriggers act as an effective method in controlling progressive collapse by distributing the extra gravity loads equally.
Key Words: Bracings, Outrigger and belt truss, progressive collapse, Response spectrum analysis, Virtual outrigger

1. INTRODUCTION

Outrigger and belt system is a productive and economical system which resists lateral load that is administered on tall slender buildings. Outrigger member is a stiff beam or truss tying core to outrigger columns which refrains the core from rotation under effects of lateral loading and the belt member connects all the outer columns together to distribute the load equally and lessen the differential lengthening and shrinking of perimeter columns. Belt can be a truss or beam. This system reduces parameters like maximum lateral deflection, storey drifts and core moment and improves the strength and overturning stiffness of buildings. Outrigger and belt truss/wall extends to a minimal depth of one storey and this result in uninhabitable floors which poses as a hindrance to efficiency of conventional outrigger. Virtual outrigger is an upgraded version of conventional outrigger. It consists of only a belt member. All the functions done by outrigger member in conventional outrigger systems are done by tough and firm floor members or slabs at the level of outrigger. The moment in the core gets conveyed to the belt truss as plain couples and is transmitted to foundation as vertical forces through belt member. The slab gets stressed severely and hence slabs thicker than normal are required and should be gauged and reinforced accordingly. Even though the efficiency of the virtual outrigger is lesser compared to conventional outrigger it is negligible due to the advantages of virtual outrigger system in building. Several other improvisations were made to conventional outrigger before virtual outrigger like offset outriggers and diagonal outriggers. In offset outriggers the outrigger member are kept at a distance away from core and hence direct connection to core is not required. In diagonal outriggers the outrigger trusses are diagonally connected. The factors affecting the efficacy of outrigger system are the stiffness and location of the outrigger and belt truss system, the size and shape of building, floor-to- floor height of the building, and the core etc.

2. METHODOLOGY AND MODELLING

2.1 Software Study

ETABS is an engineering software product that is commonly used to analyze and design multi-story building. This paper focuses on analyzing an 80 storey R.C.C building model for outcome of lateral loads -wind and earthquake loads. Loads considered are taken with reference to IS-875(Part 3), IS 1893(2002) code. The steps involved are;

1. Set stories and grid system
2. Define material properties
3. Define section properties like frame and slab sections
4. Draw beam, column, slab and wall sections
5. Define load cases and load combinations
6. Assign all loads- dead and live loads on structural members
7. Model and draw outrigger and belt truss

8. Define response spectrum and time history functions
9. Define mass source and assign diaphragms
10. Define load cases and model cases
11. Run analysis for load cases and combinations
12. Obtain displacement and drift from storey response plots
13. Model virtual outrigger and run the analysis
14. Obtain results for distinct variations of virtual outrigger
15. Model varying belt truss configurations and compare the results
16. Study the effect on progressive collpse

2.2 Details of model

The details of the model used for study are shown in table 1. Table gives structural details as well as details for seismic and wind analysis. In this study, an 80-storey structure of a commercial building has been analyzed by using ETABS software. The plan selected is rectangular in shape. It is an architectural plan and not an existing or proposed building. The structure is analyzed for static and dynamic wind and earthquake force.

Table -1: Details of Model

Floor dimensions	56mx54m
Height of building	280m
Storey height	3.5m
Depth of slab	160mm
Beam sizes	800x900mm (1-20th storey) 750x900mm(21st-40th storey) 400x700mm(41st-60th storey) 250x600 (61st -80th storey)
Column sizes	1000X1000mm(1-40th storey) 900x900mm(41-80th storey)
Size of core wall	800mm
Size of outrigger and belt truss	ISA 200X200X25mm
Live load-floor; terrace	3kN/m^2,1.5kN/m^2
Seismic zone/zone factor	III/0.16
Response reduction factor	5
Importance factor	1
Soil type	I -hard rock
Terrain category	IV
Wind speed	50m/s

The plan of the model is shown in figure 1. The building has two lifts at the centre. There are four ducts provided nearby the lifts.

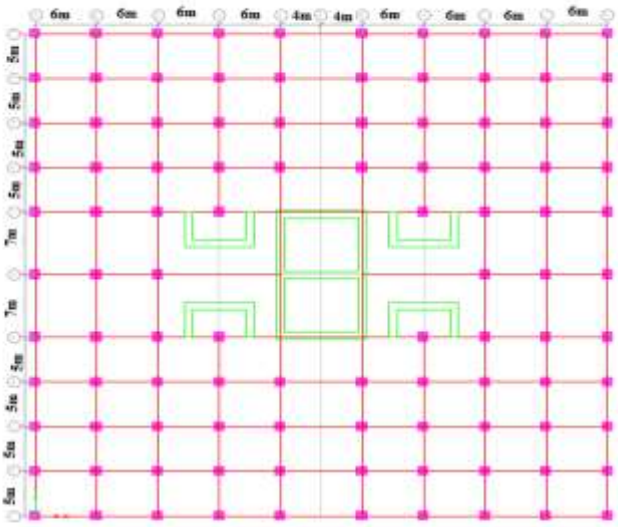

Fig -1: Plan of model

Bare frame is analyzed first. The optimum position of four outrigger system is found by placing outrigger and belt truss system at each floor and running analysis to obtain the least lateral displacement under seismic loads. A total number of 34 models are analyzed under 4 cases. After analyzing each case one model gives the optimum position.

The models analyzed are;

- Bare frame

Case 1; Analysis of Bare Frame with single outrigger for first optimum location.

- Model M1-Outrigger with Belt truss at 0.1H Position
- Model M2-Outrigger with Belt truss at 0.2H Position
- Model M3-Outrigger with Belt truss at 0.3H Position
- Model M4-Outrigger with Belt truss at 0.4H Position
- Model M5-Outrigger with Belt truss at 0.5H Position
- Model M6-Outrigger with Belt truss at 0.6H Position
- Model M7-Outrigger with Belt truss at 0.7H Position
- Model M8-Outrigger with Belt truss at 0.8H Position
- Model M9-Outrigger with Belt truss at 0.9H Position

- Model M10-Outrigger with Belt truss at 1.0H Position

Case 2: Analysis of Bare Frame with double outrigger system for Second position keeping first position common at 0.6H

- Model M11-Outrigger with Belt truss at 0.1H Position
- Model M12-Outrigger with Belt truss at 0.2H Position
- Model M13-Outrigger with Belt truss at 0.3H Position
- Model M14-Outrigger with Belt truss at 0.4H Position
- Model M15-Outrigger with Belt truss at 0.5H Position
- Model M16-Outrigger with Belt truss at 0.7H Position
- Model M17-Outrigger with Belt truss at 0.8H Position
- Model M18-Outrigger with Belt truss at 0.9H Position
- Model M19-Outrigger with Belt truss at 1.0H Position

Case 3: Analysis of Bare Frame with three outrigger system for third position keeping first position common at 0.6H and second at 0.2H

- Model M20-Outrigger with Belt truss at 0.1H Position
- Model M21-Outrigger with Belt truss at 0.3H Position
- Model M22-Outrigger with Belt truss at 0.4H Position
- Model M23-Outrigger with Belt truss at 0.5H Position
- Model M24-Outrigger with Belt truss at 0.7H Position
- Model M25-Outrigger with Belt truss at 0.8H Position
- Model M26-Outrigger with Belt truss at 0.9H Position
- Model M27-Outrigger with Belt truss at 1.0H Position

Case 3: Analysis of Bare Frame with four outrigger system for fourth position keeping first position common at 0.6H , second at 0.2H and third at 0.8H

- Model M28-Outrigger with Belt truss at 0.1H Position
- Model M29-Outrigger with Belt truss at 0.3H Position
- Model M30-Outrigger with Belt truss at 0.4H Position
- Model M31-Outrigger with Belt truss at 0.5H Position
- Model M32-Outrigger with Belt truss at 0.7H Position
- Model M33-Outrigger with Belt truss at 0.9H Position
- Model M34-Outrigger with Belt truss at 1.0H Position

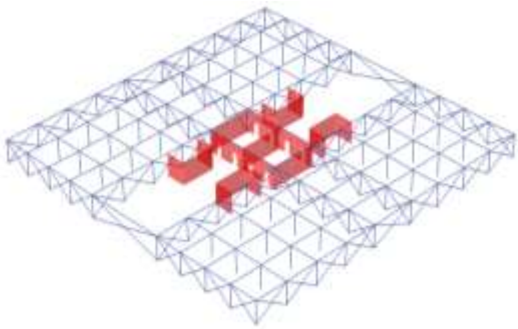

Fig -2: Structural model with outrigger and belt truss

3. VIRTUAL OUTRIGGER

Virtual outriggers are modified conventional outriggers. The advantages of virtual outriggers are vast that they are widely deployed. Floor space is saved in virtual outrigger which is occupied by outrigger member in conventional system. The complicated connection between outrigger and core is avoided and outrigger columns can be placed as per architectural and functional requirements. The conventional outrigger is modified to virtual outrigger by taking out the outrigger members and leaving only belt member. The virtual outrigger model is shown in figure 3. The core is not directly connected to the outrigger columns instead the floor members are used to transfer the moment from the core to the outer columns.

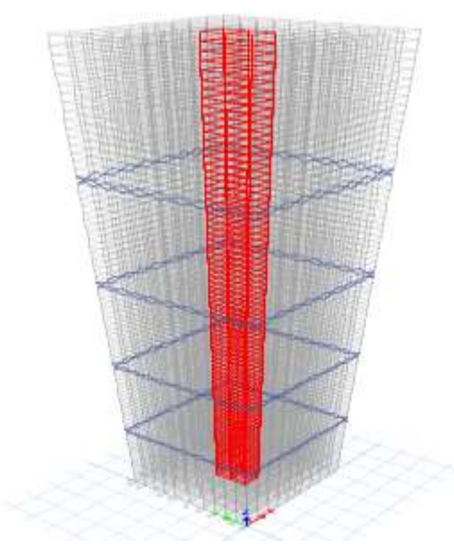

Fig -3: Elevation of virtual outrigger model

3.1 Determination of Optimum Position

The analysis results of models are shown in table 2 to table 5. The optimum position of single outrigger system is obtained from analysis of case 1. The results from table 2 show that M6 which is model with outrigger and belt truss system at 48th storey gives the least displacement. The lateral displacement reduces by 20% with single outrigger system. Hence 48th storey is the optimum position of single outrigger system. In table 3 results of case 2 models are shown and model M12 gives the least displacement. Lateral displacement reduced by 31% with double outrigger system. Hence optimum position of second outrigger is at 16th storey with first outrigger at 48th storey.

Table -2: Displacement of Models in Case 1

Model	Displacement (mm)
BARE FRAME	219
M1- 8th storey	192
M2-16th storey	191
M3-24th storey	189
M4-32nd storey	187
M5-40th storey	184
M6-48th storey	175
M7-54nd storey	179
M8-64th storey	181
M9-72nd storey	191
M10-80th storey	192

Table 4 shows the case 3 models and model M25 gives the least displacement. The lateral displacement reduces by 36% with three outrigger system. Hence optimum position of third outrigger is 64thstorey.

Table -3: Displacement of Models in Case 2

Model	Displacement (mm)
M11- 8th storey	173
M12-16th storey	151
M13-24th storey	152
M14-32nd storey	154
M15-40th storey	159
M16-54nd storey	164
M17-64th storey	166
M18-72nd storey	167
M19-80th storey	168

Table -4: Displacement of Models in Case 3

Model	Displacement (mm)
M20- 8th storey	154
M21-24th storey	153
M22-32nd storey	152
M23-40th storey	150
M24-54nd storey	149
M25-64th storey	140
M26-72nd storey	152
M27-80th storey	153

Table 5 shows the case 4 models and model M30 gives the least displacement. Hence the optimum position of fourth outrigger is 32nd storey. The lateral displacement reduces by 41% with four conventional outrigger systems.

Table -5: Displacement of Models in Case 4

Model	Displacement (mm)
CASE 4	
M28- 8th storey	148
M29-24th storey	141
M30-32nd storey	130
M31-40th storey	139
M32-54nd storey	145
M33-72nd storey	147
M34-80th storey	149

The optimum position of four outrigger and belt truss system are obtained at 48th, 16th , 64th , 32nd storey respectively. The displacement of model is seen to reduce from 219mm to 130mm in model with four outrigger systems.

4. RESULTS AND DISCUSSIONS

4.1 Lateral Displacement

Lateral displacement can be defined as the total displacement of ith storey with respect to ground level and there is maximum permissible limit prescribed in IS codes. Lateral loads have a greater effect on taller buildings and hence should be studied thoroughly.

The virtual outrigger model is analyzed and the results are compared in chart 1. Model with belt truss member only shows higher lateral displacement of 175mm compared to conventional outrigger. But the displacement is lower when compared to bare frame. There is 20% reduction in lateral displacement of virtual outrigger and conventional outrigger system even though there is no change in slab thickness in the virtual outrigger model.

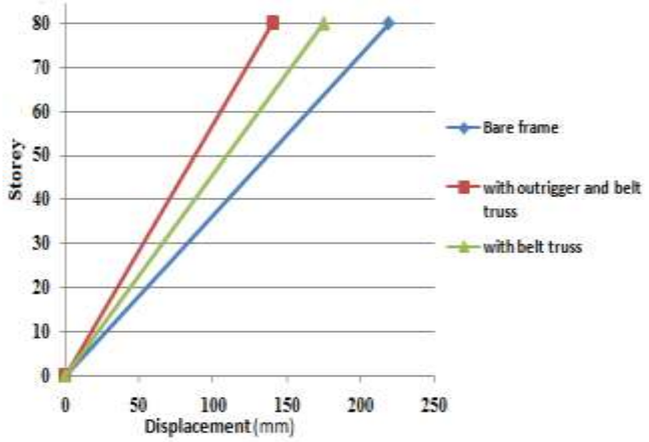

Chart -1: Comparison of lateral displacement

In chart 2 the graph shows virtual outrigger models with varying depth of slab at the level of outrigger.

When the thickness of slab increases the lateral displacement decreases. When slab thickness is increased from 160mm to 200mm the result obtained is comparable with conventional outrigger system. At 200mm deep slab the lateral displacement reduces to 154mm. Increasing slab depth can further reduce the displacement but may pose economical issues. The variation in the lateral displacement is neglected considering the advantages of virtual outrigger.

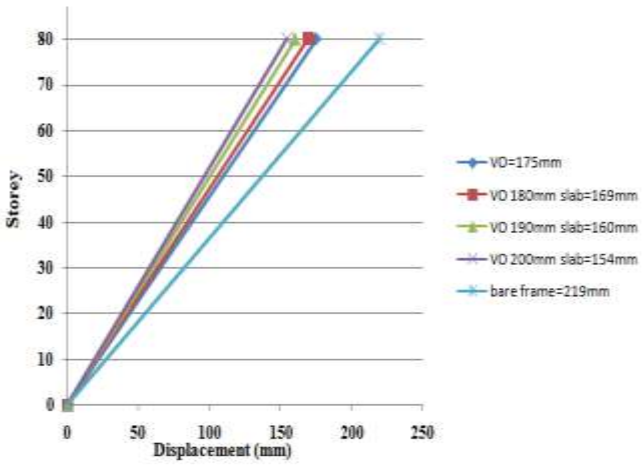

Chart -2: Lateral displacement of virtual models with varying slab thickness

Chart 3 shows the virtual outrigger model with varying depth. Depth is increased from one storey to three storeys deep. The graph shows that as depth of belt truss increase the displacement reduces and is almost comparable with conventional outrigger system. Since the outrigger members are absent the system stays economical even for increased depths. Sometimes the slab thickness are increased by 10 folds.

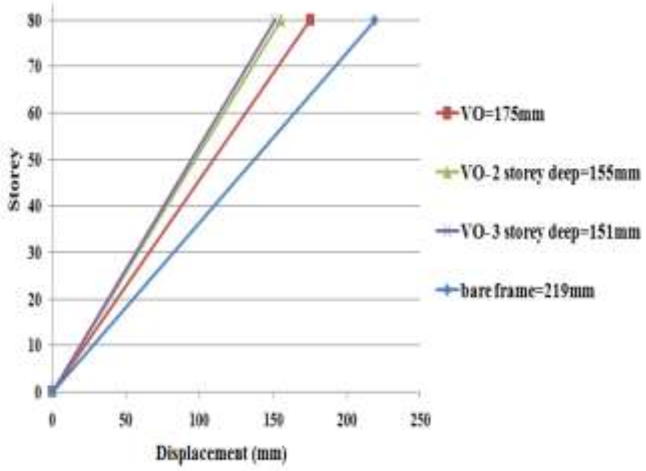

Chart -2: Lateral displacement of virtual models with varying storey deep

The displacement reduces from 175mm to 151mm for three storey deep belt trusses. Even if the values of lateral displacement of conventional and virtual vary it is neglected because of its advantages over conventional system.

4.2 Storey Drifts

Storey drift is the drift of one level of a multistory building relative to the level below. Interstorey drift is the difference between the roof and floor displacements of any given storey as the building sways during the earthquake.

Storey drifts of bare frame, conventional outrigger and virtual outrigger with varying depth and slab thickness is compared in table 6.

Table -6: Storey Drift of Types of Outrigger System

Models	Max. Storey drifts	% reduction
Bare Frame	0.001361	--
Conventional outrigger	0.000849	37%
Virtual outrigger	0.001105	18%
Virtual with 200mm deep slab	0.000945	31%
Virtual with 3-storey deep	0.000901	34%

The comparison of storey drifts shows that employing outrigger in tall buildings reduces storey drifts. In model with conventional outrigger system the drift gets reduced by 37%. As virtual outrigger with no change is used the reduction is only 18% but still gives lesser value than bare frame.

When virtual outrigger is with 200mm deep slab and is 3-storey deep, the reduction in storey drift is by 31% and 34% and is comparable with conventional system. Hence in summary outrigger reduces the storey drift.

5. STUDY ON VARYING CONFIGURATIONS OF BELT TRUSS

Different configurations are used for belt truss member. The type of configurations affects the efficiency of the building which is represented by lateral displacement and the storey drifts. The type of configurations include diagonal bracing, double diagonal or x bracing, k or v bracing, inverted v bracing. Figure 4 shows the various configurations.

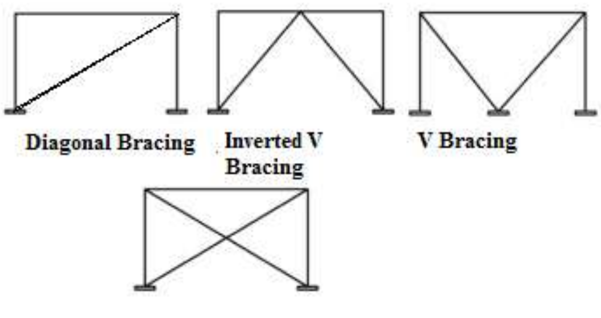

Fig -4: Various configurations of belt truss used in the study

Conclusions are made based on lateral displacement and storey drifts. Table 7 shows that lateral displacement and storey drift is least for x bracing. Hence it can be suggested to use double bracing system in tall buildings to improve the lateral stiffness against lateral loads. This validates use of X bracing in the project model.

Table -7: Lateral displacement of model with varying belt truss configurations

Bracing type	Lateral displacement (mm)	Storey Drifts
Bare frame	219	0.001361
X bracing	175	0.001073
V bracing	192	0.001342
Inverted V bracing	193	0.001242
Diagonal bracing	202	0.001211

6. PROGRESSIVE COLLAPSE

Progressive collapse can be simply described as the partial or whole collapse of an entire building due to loss of a load carrying member, the column, due to natural or manmade hazards. Buildings that are tall are susceptible to progressive collapse. Buildings with lateral load resisting systems are found to resist or prevent progressive collapse. The load from the effect of removing a column is distributed among all other columns equally by the help of belt truss and hence helps in providing an alternate load path for the gravity load developed. Linear static analysis is done in ETABS software and at the bay where column is removed the structure is subjected to a load combination of 2(DL +0.25LL). Demand-Capacity ratio or DCR of columns is calculated from the software and is checked with acceptance criteria for progressive collapse. If DCR>1.5 (for atypical configurations) then column fails and progressive collapse is initiated.

Table -8: DCR values of columns affected due to column removal in bare frame

Building Conditions	**Case No**	**Column Removed**	**Columns affected**	**DCR values**
Bareframe	Case 1	C1(first floor)	C2(first floor)	1.817
			C2(ground)	1.848
			C3 (second floor)	1.804
	Case 2	C101(First floor)	C51 (Ground)	1.089
			C5(Ground)	1.017
	Case3	C7(First floor)	C1(Ground)	1.821
			C6 (Ground)	1.8
			C8 (Ground)	1.836

Table -9: DCR values of columns affected due to column removal in model with virtual outrigger

Building Conditions	Case No	Column Removed	Columns affected	DCR values
With virtual outrigger				
	Case 1	C1 (first floor)	C2(first floor)	1.053
			C2(ground)	1.036
			C3 (second floor)	1.056
	Case 2	C101(First floor)	C51 (Ground)	1.05
			C5(Ground)	1.02
	Case 3	C7(First floor)	C1(Ground)	1.013
			C6 (Ground)	1.001
			C8 (Ground)	1.026

Bare frame and model with virtual outrigger is analyzed for three cases of column removal. In case 1 a corner column on floor above ground is removed. In case 2 a column at middle along shorter direction is removed and in case 3 an inner column is removed. All three cases are analyzed and the table 8 and table 9 give the results.

The table shows that building without virtual outrigger system undergoes progressive collapse since DCR ratio exceeds 1.5 while the model with virtual outrigger remains intact even after removal of columns with DCR ratio less than 1.5.

7. CONCLUSIONS

The conventional outrigger system reduced to virtual outrigger system with only belt truss around the building and no outrigger truss connecting core and perimeter columns is analyzed in this study. The study can be concluded as below.

- The virtual outrigger system is analyzed for response spectrum. The virtual outrigger with no changes showed 25% higher displacement than conventional outrigger system but showed 10% lesser displacement than bare frame.
- Virtual outrigger was also modified by increasing the depth of the belt truss from single storey deep to two storeys deep and to three storeys deep and the variation in displacement was determined to vary from 175 to 151 mm.
- Virtual outrigger was then modified by increasing the slab thickness of the floor at the outrigger level from 160mm to 200mm and the displacement for each was determined to vary from 175 to 154 mm.
- Storey drifts for the building model was also determined from storey response curve. Storey drifts reduced from 0.001361 for bare frame to 0.000814 for model with four outriggers and increased to 0.001105 when outrigger arms were removed.
- Storey drift reduced to 0.000945 and to 0.000901 for virtual outrigger model with 200mm deep slab and 3 storey deep belt truss.
- Storey drift reduced by 37% when conventional outrigger system was introduced in the model.
- When virtual outrigger with 200mm deep slab was employed, the drift reduced by 31% when compared with bare frame
- When virtual outrigger belt truss 3-storey deep was employed, the drift reduced by 34% when compared with bare frame
- Study on configuration of belt truss gives following results
- X bracing is more economical since it has less structural weight
- X bracing is more efficient since it gives least displacement and least storey drift.

Progressive collapse study shows that buildings with buildings with virtual outrigger helps in maintain the DCR ratio below 1.5 and hence the structure withstands progressive collapse. The building remains safe even after the removal of columns. The building is most affected with removal of corner column and interior column.

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