STUDY ON RESPONSE OF OUTRIGGER STRUCTURE TO NON LINEAR DYNAMIC ANALYSIS

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ABSTRACT

A nonlinear analysis is an analysis where a nonlinear relation holds between applied forces and displacements. These analyses are generally done for High Rise Buildings. One such structure which is used for analysis in this project is Outrigger structural system. Outriggers are interior lateral structural systems provided to improve the overturning stiffness and strength of high-rise buildings. The main aim of this project is to optimize the position and number of outriggers and compare the time history results to check the feasibility. After Optimization it was found that the optimum position was approximately at the center for all models and optimum number of outriggers for 25, 50, 75 and 100 story buildings were 5, 5, 7 and 10 respectively. The P-Δ effect also played its role considerably in higher story buildings and it had no role in 25 story building. The reduction in displacement was 50 % in 25 story building and it has increased to 62 % in 100 story building which tells that outriggers are more efficient in high rise structures. Also, shorter buildings have undergone periodicvibration with respect to the acceleration during time history analysis but taller buildings due to longer time period, it took time to transfer the acceleration to top story and they undergo damped oscillation after the end of ground motion which concludes that taller buildings are effective against seismic forces compared to shorter buildings which is why short buildings are designed with much care against seismic forces.

KEYWORDS: *Outrigger Structure, Nonlinear Dynamic analysis, Inter Story Drift, Optimum Position.*

1. INTRODUCTION

Population growth causes a land shortage, and high-rise structures are chosen as a solution. The natural disasters have an impact on these high-rise structures. Natural disasters like earthquakes are the most destructive because they cannot be controlled and cause structural components to be damaged and disrupted (Brunesi et al., 2016). Outriggers are which attached to canoes as extended floats to offer stability and prevent overturning when cruising. The similar idea has been applied in construction since the 1950s to give tall, narrow buildings lateral stability (Amoussou et al., 2021). The assessment of existing buildings that have not been designed according to modern design codes is one of the major challenges of earthquake risk mitigation, as well as the development of effective strengthening techniques (Shi et al., 2021). To the understand the behavior of existing buildings, accurate modelling strategies and appropriate seismic assessment methodologies are important (Chiu et al., 2022). The focus of this issue is on recent advances in analytical methods and modelling approaches for the seismic assessment of RC buildings (Ghobarah, 2000).

1.1 Outriggers

The outrigger systems are broadly used structural systems. It could be constructed from steel or concrete brace and shear wall connected with core and periphery columns or rigid deep beam or brace that attaches the periphery column of the frame to the central core (Kavyashree et al., 2021). When lateral loads act on the structure, the outrigger restrained column resists the core rotation and decrease the displacement by bending of core and perimeter columns (Xing et al., 2022). This in turn making the building lateral deflection smaller than when the freestanding core withstand the loading alone (Rassati et al., 2011). The system has the advantage of avoiding core rotation along with significant reduction of the lateral deflection. The outrigger system effectively accounts for flexural rigidity of the structure and core accounts for the shear resistance (Habrah et al., 2022).

1.2 Literature Review

Based on previous researches, it is noted that the most of the authors have studied behavior of the outriggers by finite element analyses using softwares like SAP2000, MIDAS and other programs like draindx (Yun & Han, 2021). The concept of FEA is that is generates the mesh for structures and performs several iterations until the desired result is acquired (Sofi et al., 2018). Several finite element software programmes were also used to create 3D models and advance the effectiveness of structural design (Amoussou et al., 2021). A series of numerical examples were used to investigate the accuracy of the different methods of analysis for structures (Kamgar & Saadatpour, 2012). Response spectrum or the static equivalent method were frequently used to examine building structures with severe characteristics like horizontal and vertical irregularity since these methods cannot precisely reproduce the non-linear behavior of actual ground motions (Xiao & Wang, 2022). When estimating a structure's reaction to dynamically linear and non-linear seismic loadings, the time history method is typically the most suitable and accurate method (Gao et al., 2021). The height and slenderness of the structure are critical aspects in structural displacement as they make the structure more flexible and susceptible to the effects of lateral stresses (Laccone et al., 2021).

1.2.1 Concept of outrigger structural system

The idea is based on the bamboo plant, and the structural organization adheres to biomimetic design principles. Performance-based criteria are also used to optimize lateral stiffness and shape the cross section. In comparison to an evenly spaced setup, the bamboo-based outrigger system offers considerable advantages in terms of lateral rigidity. The structure's lateral stiffness shows shear and only to a lesser level bending sensitivity. Fig 1 depicts the working of an outrigger in a bamboo and how it is used in a structural system.

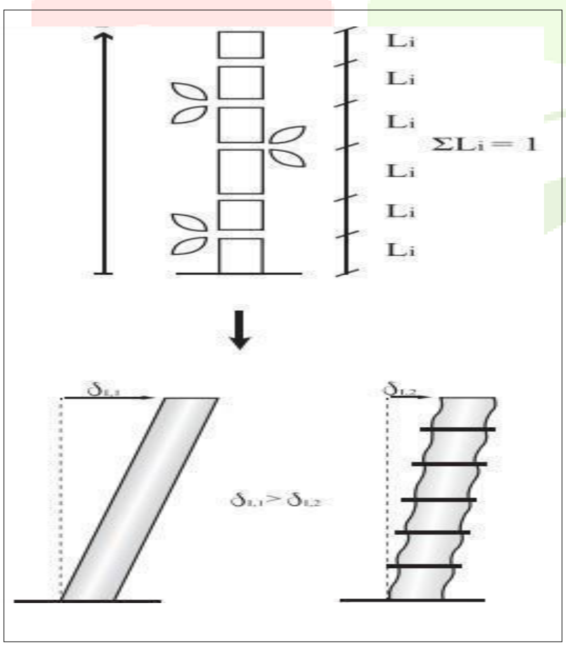

Fig 1 - Mechanics of bamboo transferred into the design of a tall building for outrigger placement.

A lateral load-resisting system known as an "outrigger system" is one in which the external columns are connected to the central core wall at one or more levels using belt trusses and highly rigid outriggers. In order to limit the danger of structural and non-structural damage during small or medium lateral loads caused by either wind or seismic stress, the outrigger system is frequently employed to efficiently manage the excessive drift due to lateral load. A central core made of braced frames or shear walls, known as an outrigger structural form, connects the core to the outside via horizontal cantilever trusses or girders.

2. METHODOLOGY

A floor plan of 32 m × 32 m size as shown in Fig 2 with story height 3.5 mand slab thickness of 175 mm is considered. Modelling and analysis of structure are carried out using ETABS software. Bearing in mind the previously worked journals, we have considered an RCC outrigger for the model as shown in Fig 2. The thickness of outrigger was assumed to be 250 mm at the beginning. Later, the thickness was changed to find out the optimum thickness which gives the minimum story displacement and drift ratio. Before that, the optimum position is determined by varying the position of outrigger for every 5 stories and the optimum number of outriggers is determined by using this data. The same plan was adopted for modelling of 25, 50, 75 and 100 story buildings and time history analysis are carried out by taking the ground motion data of Bhuj and El Centro to compare results.

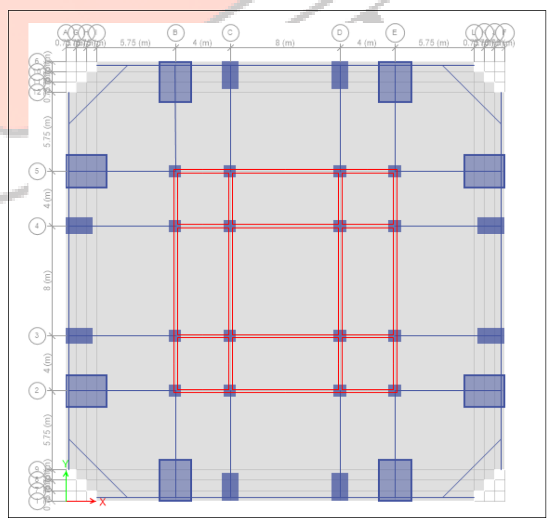

Fig. 2 - Floor Plan for Project without Outrigger

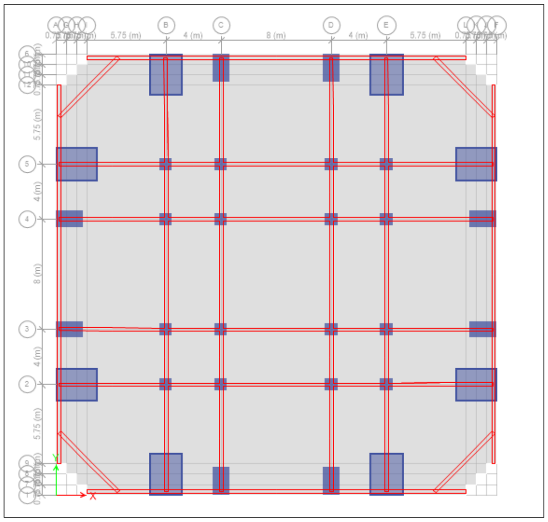

Fig. 3 - Floor Plan for Project with Outrigger

The data required for the section of structural members was partly considered from some of the members of Taipei 101 which is a belt outrigger system with 10 outriggers along the building height. The 3-D view of the model is shown in Fig 4. The dimensions shown in Tables 1 and 2 has arrived from the trial-and-error basis until all the members pass the design criteria as per IS 456:2000 and the model until it was within the permissible limits of maximum story drift ratio and displacement as per IS 1893:2016. The Steel Box section is used for exterior super columns which are 8 in number. They are Composite columns embedded with RCC.

Fig. 4 - 3-D Plan of Model

Table 1- Dimensions and details of the Outrigger structural member

Outrigger Section Type	RCC
Strength of Concrete	M60
Thickness of the Section	250 mm

Table 2- Dimensions of the Structural members of Model

Super Columns	1200x3000 mm
Thickness of Box Section	65 mm
Columns of Core	900x900 mm
Remaining Columns	1200x2000 mm
Beam Section	500x500mm

2.1 P-Delta Analysis

When axial and lateral forces are simultaneously applied to framed and wall elements, it accounts for geometric non-linearity resulting in secondary structural behavior. This is known as P-Delta effect and it is more profound in tall structures where high vertical axial loads act upon the laterally displaced structures which is caused by high lateral forces, either it may be due to wind or earthquake. A non-iterative P-Delta analysis is performed for the models based on the mass since these are tall structures.

2.2 Time History Analysis

Time History analysis was performed as an additional step to compare the models when located in two different areas. It gives the response of the building behavior with respect to the time. One of the locations was taken as Bhuj in Gujarat which has recorded a magnitude of 7.7 on January 26th 2001. The ground motion data was taken from CESMD (Center for Engineering Strong Ground Motion Data). The other location was El Centro in California which has recorded a magnitude of 6.9 on March 19th 1940. The ground motion data was taken from PEER (Pacific Earthquake Engineering Research). The Ground motion records of the two incidents are depicted graphically in Figs 5 and 6 respectively.

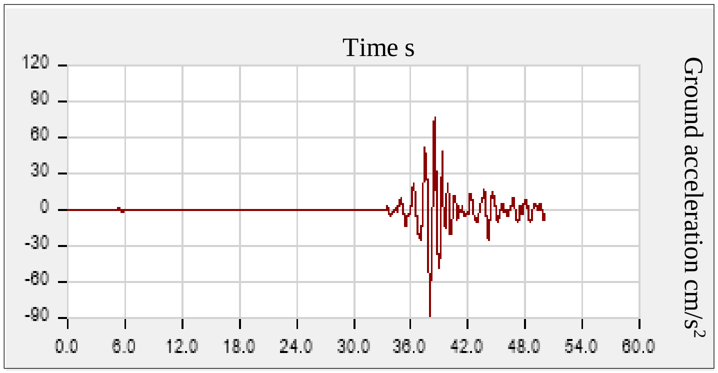

Fig 5 – Ground motion records of Bhuj in X-Direction (ground acceleration vs time)

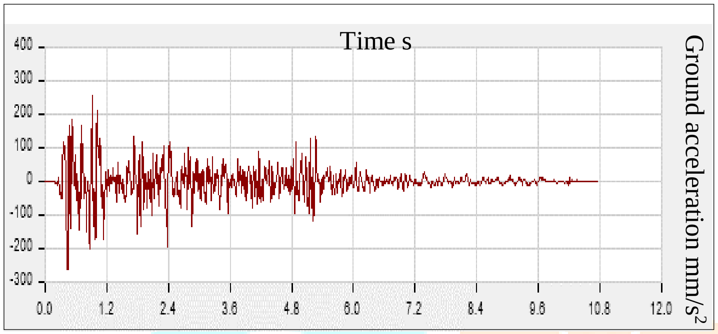

Fig 6 – Ground motion records of El Centro in X-Direction
(ground acceleration vs time)

3. RESULTS AND DISCUSSION

Tall structures are the most critical against the lateral loads, thus the parameters like maximum top story displacement, maximum inter-story drift ratio become significant in determining the optimum position of outriggers. Therefore, these parameters are compared in all the cases to determine the position of outrigger, number of outriggers and the thickness of outriggers effectively and stability against the lateral loads and the results are shown and discussed.

3.1 Analytical Study and Validation for Fundamental Frequencies

The results of a model (Alhaddad et al., 2021) in ETABS is compared with the same model in SAP2000 to check the validity and accuracy of software. This validation helps in moving forward to the next step in the project and run analysis to the primary model accordingly. The software results are validated with each other, which are shown in Table 3.

Table 3 - Base reactions of 9 joints of the model

Name of Base Joint	Fz in ETABS (KN)	Fz in SAP2000 (KN)	% Difference
(1, A)	282.55	326.62	15.59
(2, A)	496.28	502.75	1.30
(3, A)	282.55	326.62	15.59
(1, B)	529.69	533.71	0.75
(2, B)	1258.25	1061.03	-15.67
(3, B)	529.69	533.71	0.75
(1, C)	282.55	326.62	15.59
(2, C)	496.28	502.75	1.30
(3, C)	282.55	326.62	15.59

SAP2000 is a general Structural Analysis Program. ETABS is specialist in Design of Vertical elements like Columns and Shear walls and is mostly used for Multi Story buildings. High end analysis applications for such structures like Time dependent material definitions like creep and shrinkage, Column shortening Analysis can be proceeded. All these factors will be considered while modelling in ETABS. It performs analysis based on each story. Hence, there is a percentage difference observed between the two softwares. However, SAP2000 can be used for general structural constructions like water retaining tanks, stadiums, airport hangers, chimneys and so on. Therefore, the analysis can be proceeded in ETABS.

3.1 Optimum Position of Outrigger

It is the first step to find the optimum position of the outrigger and the above-mentioned parameters i.e., maximum top story displacement and inter-story drift are considered to find the optimum position. To do this, the outrigger position is varied for and the results are noted by positioning it at every 5 stories in each result. The worst possible Load Combinations are taken while studying these parameters i.e., 1.2DL + 1.2LL + 1.2EQ **(LC1)** for limit state of collapse and DL + 0.8LL + 0.8EQ **(LC2)** for limit state of serviceability from table 18 of IS 456: 2000. The maximum lateral displacement and Inter-Story Drift ratios of 100 story building for Load Combination LC1 are shown in Figs 7 and 8 respectively which show that a single outrigger system has its optimal location when placed approximately at the center of the building.

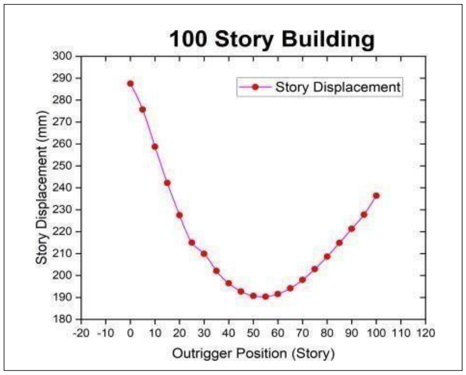

Fig 7 – Maximum Displacement versus Outrigger Position for 100 Story Building for LC1

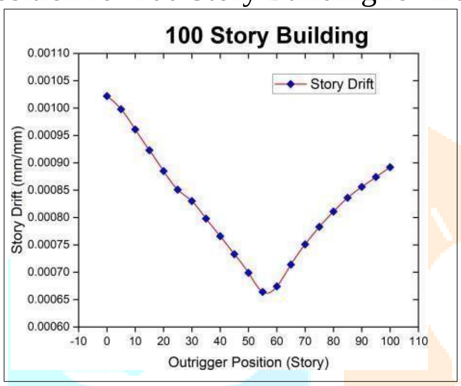

Fig 8 – Inter-Story Drift Ratio versus Outrigger Position for 100 Story Building for LC1

3.1 Optimum Numbers of Outriggers

Since the maximum top story displacement and story drift ratio are minimum when the outrigger is positioned approximately at the center of the building, to find the optimum number of outriggers, the model can be divided into equal number of parts corresponding to the number of outriggers and the same properties i.e., inter-story drift ratio and maximum lateral displacement can be studied and they are illustrated in Figs 9 and 10 for 100 Story Building.

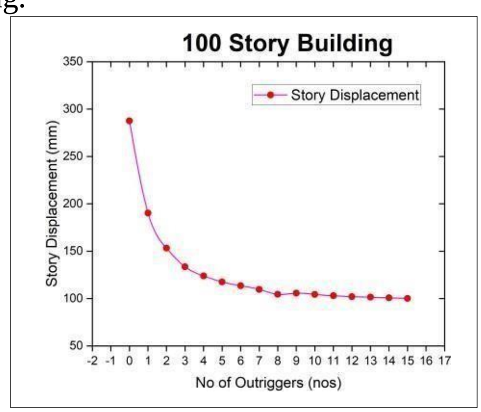

Fig 9 – Maximum Displacement versus no of Outriggers for 100 Story Building for LC1

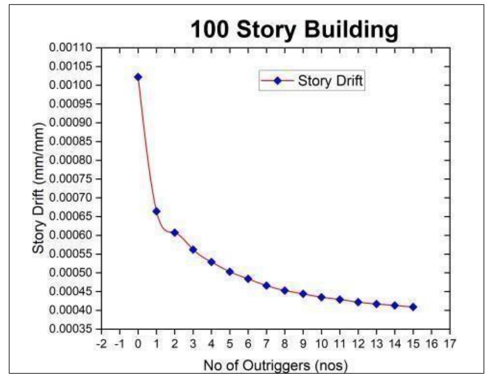

Fig 10 – Inter-Story Drift Ratio versus no of Outriggers for 100 Story Building for LC1

The models of number of outriggers for which the reduction in magnitude is in between 3 – 4 % has been selected as optimum number of outriggers and shown in table 4.

Table 4 - Different Story Buildings and the derived optimum number of Outriggers

No of Storys	Optimum Number of Outriggers
25	5
50	5
75	7
100	10

3.3 Optimum Thickness of Outrigger

This is the last step involved in the optimization of the outriggers. The initial thickness assumed for the outrigger was 250 mm. Now, this thickness will be both increased and decreased to find the Optimum thickness of Outrigger. This step is conducted to the optimum number of outriggers found before and the thickness of the core of the building remains the same. The change in displacement for 100 story model are shown in Fig 11 with optimum thickness in table 3.3.

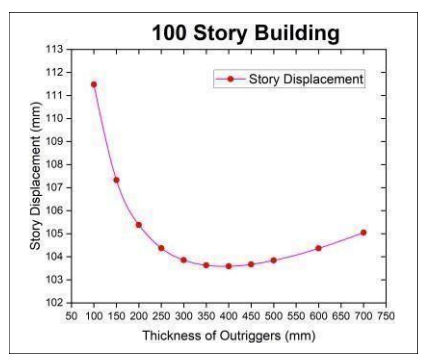

Fig 11 – Maximum Displacement versus Outrigger Thickness for 100 Story Building for LC1

Inter-story drift in the same way is studied by changing the thickness of outriggers. There was little to no change in the inter-story drift ratio compared to varying the number of outriggers. The optimum thickness of outriggers is shown in Table 5.

Table 5 - Different Story Buildings and the derived optimum Thickness of Outriggers

No of Storys	Optimum Thickness of Outriggers (mm)
25	500
50	500
75	500
100	400

3.1 P-Delta Effect

As discussed earlier, P-Δ effect is a reference to abrupt changes in ground shear and overturning moments and it is sufficiently observed in tall structures. After optimizing the structure in terms of position, number and thickness, P-Δ check is applied on the 4 models if there are any abrupt changes in the behavior of the model. The maximum lateral displacement values before and after P-Δ effect are tabulated in table 6 and plotted in Fig 12.

Table 6 - Different Story Buildings and Maximum Lateral Displacement before and after P-Δ effect for the LC1

No of Storys	Before P-Δ Check (mm)	After P-Δ Check (mm)
25	12.7835	12.7954
50	21.0781	21.7573
75	43.0738	44.5857
100	103.5874	107.3614

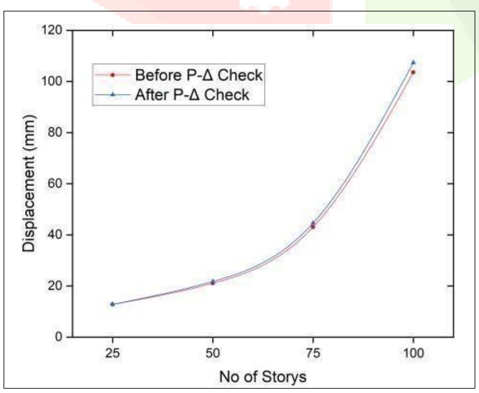

Fig 12 – Maximum Displacement versus number of Storys for LC1 for P-Δ check

It can be observed from Fig 12 that the effect of P- Δ was not significant in 25 Story model and thus it is to the fact that P-Δ effect can be observed in high-rise buildings. Since the model is symmetrical and hence the earthquake parameters, the magnitude of inter-story drift is same in both the directions. The decrease in Maximum Story displacement after

Table 7 - Different Story Buildings and Maximum Lateral Displacement before and after placing outriggers for LC1

Max Displacement (mm)		Permissible Displacement (mm)
Before Outrigger (mm)	After Optimization (mm)	
24.2172	12.7954	176
41.6045	21.7573	351
136.4131	44.5857	526
287.5131	107.3614	701

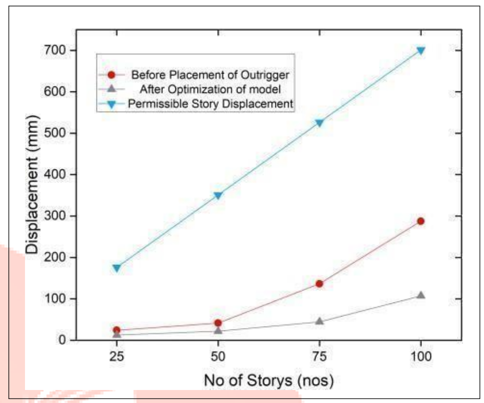

Fig 13 - Different Story Buildings and Maximum Lateral Displacement before and after placing outriggers for LC1

optimizing the outrigger structure has been tabulated in table 7 illustrated in Fig 13.

The Maximum permissible story displacement is limited to L/500 i.e., where L is the building height in mm. The values obtained are well within the limit for 25, 50, 75 and 100 story models are as shown in table 7.

3.4 Time History Analysis

After Optimizing all the models, they are subject to earthquake effects occurred in Bhuj and El Centro by taking the time history parameters i.e., time vs acceleration plots. Response Spectrum analysis assumes the entire building as an SDOF structure and performs analysis for the maximum magnitude. Whereas time history analysis in the software simulates the real time ground acceleration on the building. This helps in getting a better correlation between acceleration and displacement magnitudes. The correlated corresponding values after comparison verify the method of analysis. The relation between acceleration and displacement characteristics for a 25 and 100 story building for El Centro Earthquake are shown in Fig 14 and Fig 15 respectively and for Bhuj

Earthquake in Fig 16 and Fig 17.

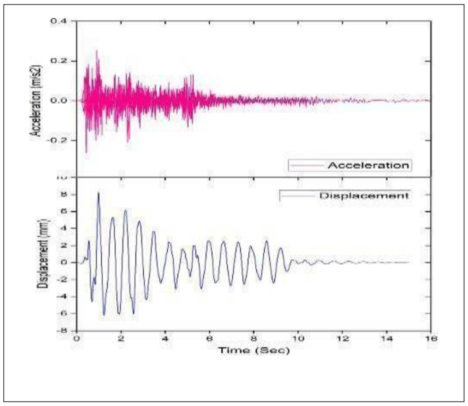

Fig 14 – Relation between Acceleration and Displacement characteristics with respect to time in response to El Centro earthquake for 25 Story Building in X direction

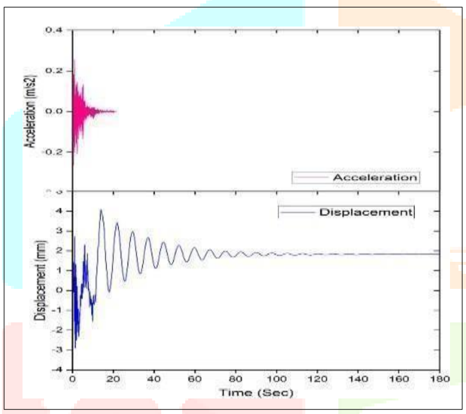

Fig 15 – Relation between Acceleration and Displacement characteristics with respect to time in response to El Centro earthquake for 100 Story Building in X direction

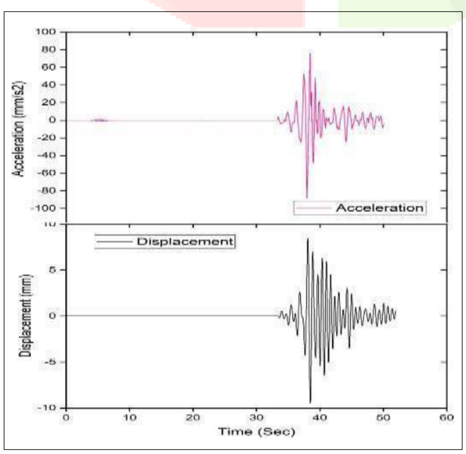

Fig 16 – Relation between Acceleration and Displacement characteristics with respect to time in response to Bhuj earthquake for 25 Story Building in X direction

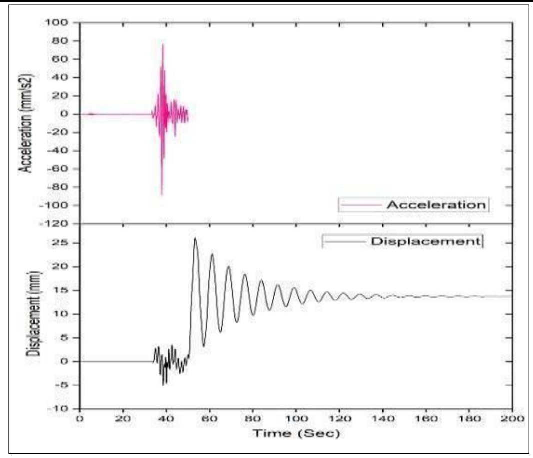

Fig 17 – Relation between Acceleration and Displacement characteristics with respect to time in response to Bhuj earthquake for 100 Story Building in X direction

We can conclude from the results that the magnitude of displacement is synchronized with acceleration in 25 story building. But in case of higher story buildings, the presence of displacement was observed but not synchronized completely and the building tended to vibrate even after the end of ground acceleration and a natural damped oscillation was observed in these buildings. Also, the displacement response was for a longer period of time as the height of the building increased which was to the fact that as the height of the buildings increase, the time period increases and the frequency decreases. Another observation was that the shorter buildings vibrated with higher maximum displacement for a shorter period of time. This also verifies that, the taller the buildings are, the more is the flexibility and the longer it takes for the force resulting from the acceleration to get transferred from ground to top story. Whereas the shorter buildings are stiffer and vibrate more vigorously subject to earthquake forces and the support elements must be designed more carefully so that they can withstand greater forces than those of taller buildings.

4. CONCLUSION

The objective of the study is to check the feasibility of an outrigger after optimizing the model with respect to position, number of outriggers and thickness of outriggers and verifying the response of structure to dynamic analysis. The concluding remarks are as follows:

1 A minimum magnitude of maximum lateral displacement and inter-story drift were observed when the outrigger was placed at approximately the center of the building and the decrease in displacement in all the 4 models was around 30-40 % due to placement of outrigger.

2 The optimum number of outriggers in 25, 50, 75 and 100 story buildings were 5, 5, 7 and 10 respectively. Outriggers are generally not preferred in a 25-story building unless it is an unsymmetrical structure. As the height of building has increased, a nearly rationale formula has been deduced i.e., the optimum number of outriggers can be around 10 % of the number of storys.

3 The reduction in displacement after optimizing the model was 50 % in 25 story building and it has increased to 62 % in 100 story building concluding that outriggers are more efficient when they are used in high rise structures which reduce the excess overturning moments at the base of the structure by increasing the stiffness.

4 The Dynamic analysis when conducted to compare the acceleration and displacement properties, the shorter structures due to lesser time period are undergoing displacement corresponding to the acceleration and shake vigorously. Taller buildings on the other hand due to their longer time period, it takes time to transfer the ground acceleration to the top story with greater energy dissipation causing sway movement and they undergo damped oscillation naturally until they come to rest. This concludes that taller buildings are more effective against seismic forces compared to shorter buildings.

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