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Economically Prudent Design (EPC) of Outrigger-Based Structural Systems

Sachin Kuckian and Hussin Yahia
Department of Civil Engineering, Middle East College of Engineering, Muscat, Oman
E-mail: skuckian@mec.edu.om, hyahia@mec.edu.om

Abstract - **As the construction of mega-tall buildings in all major cities around the world accelerates, the seismic risk associated with them also rises. Hence study on the response of tall buildings to earthquake loads is gaining significant importance. Outrigger tall buildings are one of the most common structural structures because they are simple to construct, cost-effective, and have significant lateral stiffness. Therefore, this research explores a structural outrigger system for high-rise buildings to analyze the output of a system by changing the place of outrigger positions. Dynamic research was performed in accordance with IS 1893, the response spectrum and time of California's most recent earthquakes. The parameters discussed are lateral displacements, inter-storey drifts for static analysis, and base force, displacement, and spectral acceleration for dynamic analysis. From the analyzed results, it was found that an outrigger when located at H0/H=0.6 causes a maximum reduction in the lateral displacement. Hence outrigger located at H0/H=0.6 is the desired location to provide an outrigger in a structural system and could act as an initial economical prudent design solution in the construction of tall buildings with outriggers. Time history analysis shows that the reduction is maximum when the outrigger is located at H0/H=0.9 for LA03, H0/H=0.85 for LA06 H0/H=1.0 for LA14.**

Keywords: **Outrigger, Time History, Response Spectrum, Tall Buildings, Seismic Load**

I. INTRODUCTION

Urbanization has captivated humanity since the 1880s. With the spread of cities, the difficulty of finding ground and the need to prevent more urban sprawl have contributed to the advancement of construction growth in structural structures and associated technical issues [1]. From a structural engineering standpoint, tall buildings are characterized as a risky factor, because their height plays an important structural function in response to lateral and horizontal forces. Tall buildings also have thousands of inhabitants at risk of a natural catastrophe, so worldwide ground motion must be considered during construction because a partial or complete collapse of buildings may result in disasters of unpredictable magnitude [2]. When designing tall buildings that are vulnerable to dynamic excitations such as earthquakes and winds, it can be beneficial to factor in maintenance costs as well as initial investment and performance [3]. Numerous studies and investigations have been done to determine how much motion is generated in a building to ensure that the inhabitants are not disturbed. Several design standards and consensus documents have been released during the past few years, demonstrating the growing importance of performance-based seismic design in the field of tall building design. An important shift from a linear strength-based approach to a nonlinear deformation-based design practice has resulted from the additional dimensions introduced to tall building design by performance-based earthquake engineering. As a result, traditional prescriptive seismic design rules' stipulations regarding the structural requirements of tall structures might be relaxed. However, design principles have yet to fully mature, and there are several areas on which consensus has not yet been established. However, it must be noted that the design profession is not yet ready to completely execute the needs of performance-based design [4].

Additional structural architecture features are often pursued to decrease building reaction to lateral loads. The two general structural shapes are structural types of general structures into the interior and exterior categories an internal load-bearing framework were the bulk of the lateral mechanism is present inside the house [5]. To minimize the drift in tall buildings, typical interior systems are stiff or brace, shear wall, shear frame, shear contact, and outrigger design. Since outrigger-based forms have been constructed in several or the entire world's tallest buildings in the past decades. To this configuration, a reinforced concrete or steel braced center is joined by two flexural walls to two reinforced concrete or steel members at appropriate locations [6]. Al-Azri (2019) studied the best possible shape to reduce the sway just like the outrigger functions. Usually, these outriggers are positioned around the height of the building [7]. As stated by Fawzia *et al.,* (2010) the deflection of the tall building can be controlled by use of belt truss and outriggers systems [8].

As earthquakes are unpredictable and unpreventable natural phenomena, taking suitable precautions in the design of tall buildings is only option to designers [9]. A braced construction is the better choice for tall buildings, as it is both less expensive and rigid, with a side-bracing benefit [10]. Importantly, a damped or horizontal structure along the vertical height /- can increase the overall structural strength of a framework without altering the appearance of the structure itself, which is a major improvement over lateral resisting system [11]. Lateral earthquake tolerance can be measured by analyzing the post and the role of the outrigger mechanism as well as how it stands up to lateral loads [12]. Therefore, this project focuses on studying the behavior of structural system based on location of outriggers and the performance of the system in terms of reducing lateral displacement at the top of the building maintaining the integrity of the specifications.

II. METHODOLOGY

Lee *et al.,* (2010) studied the nonlinear geometric behavior of tall wall-frame buildings in which the wall-frame systems with outrigger trusses are modeled as a shear-flexural cantilever with rotational springs [13]. An out-out-rigger beam structure is formed by linking the lateral and resistive cores, with each other in an extremely stiff manner, and is used to restrain lateral movement [14]. A response spectrum and time history analysis was conducted on structural models to analyses the structural structure performance for tall buildings subjected to lateral loads. The variables listed in this analysis are lateral movement, inter-storey drift and shear moment.

A. Model Description: The model considered is a three dimensional 40 storey building, (see, fig. 1 and ST1 (a-c) for description). The average storey height is 3.5 m, with a cumulative height of 140 m. The beams, frames, shear walls, and outriggers are believed to be made of concrete (M 40 grade). The column and beam sizes taken into account in the study are 0.45 m X 0.50 m and 0.23 m X 0.45 m, respectively. Moreover, outrigger locations in building are described in ST2.

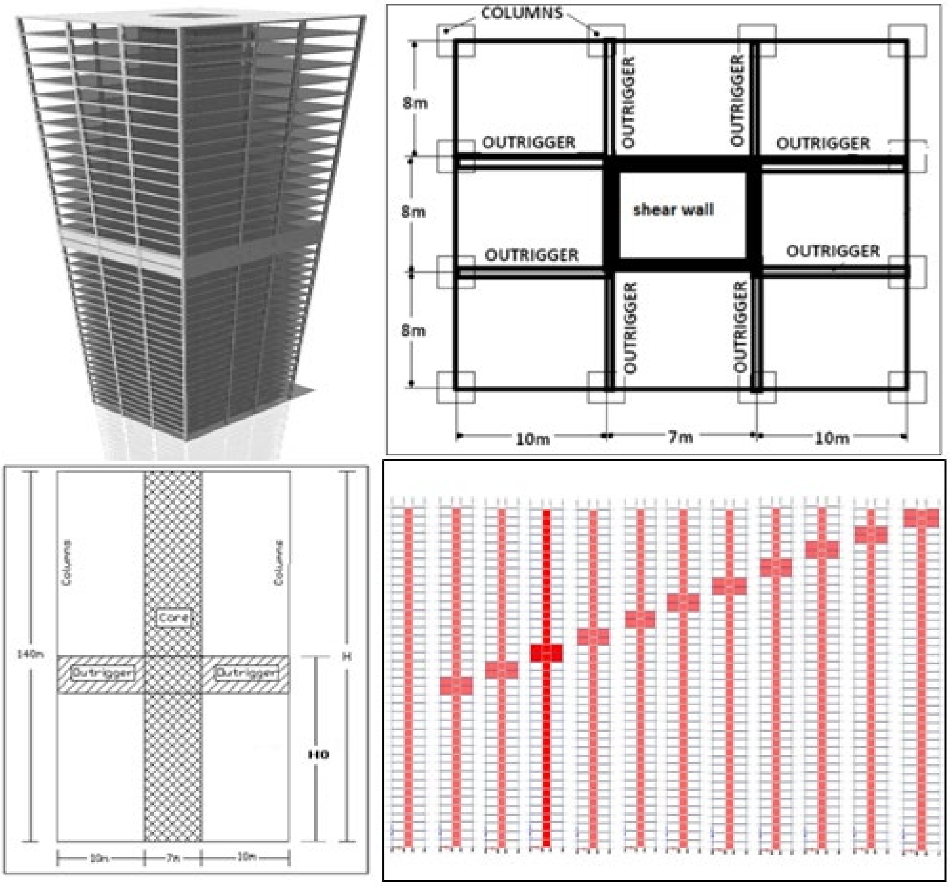

Fig. 1 Plan, isomaetric view, elevation and location of the outrigger details for different models

III. LOADINGS

Seismic loading is one of the fundamental concepts of earthquake engineering, which involves using an excitement caused by an earthquake into a structure [15]. This can be done by testing the structures by applying the earthquake loads from past historical earthquakes. In this research seismic load static and response spectrum analysis has been carried out for zone II as per IS 1893 (Part I): 2002 [16], see Table I. The accelerograms details were taken from the study conducted by [17, 18]. The acceleration time histories used in dynamic analysis are focused on historical earthquake data from the California zone. The first two accelerograms were Los Angeles (LA) 03 and 06 from El Centro Array 5, James Road and El Centro Array 6 earthquakes reported in 1940 as El Centro earthquake and have PGA values of 0.386 g and 0.23 g respectively. While the third accelerograms is LA 14 from Northridge, LA Country Fire Stations earthquake in 1994 (Fig. 2). To get a stronger historical hazard model, the ground motion between the M6-M7.3 ranges are expanded to provide a ten percent threat to surpass California's long-established model and consistent hazard thresholds. The reaction spectrum method was used to conduct the hierarchical structure analysis whereas 5% inherent damping was taken. The accelerograms are converted into response spectra curves and used for the analysis. Acceleration response spectra are plotted by using output values from Seismo Signal software as shown in S1. Peak values of accelerations from response spectrum curves are 13.728g, 8.892g and 22.876g for LA03, LA06 and LA14 respectively.

TABLE I DETAIL OF LOADING

(a) Gravity Load	
Live load	3 kN/m^2
Dead load (Floor finish)	1 kN/m^2
(b) Lateral Load (Earthquake Loads)	
(I) Static Analysis	
Earthquake Zone	Zone V
Zone factor	0.36
Soil type	medium (II)
Damping	5%
Importance factor	1.0
Response reduction factor	3.0
(II) Dynamic Analysis	
Earthquake Zone	Zone II
Soil type	medium (II)
Accelerograms	-LA03 (El Centro Array 5, James Road) -LA06 (El Centro Array 6) -LA14 (Northridge, LA)

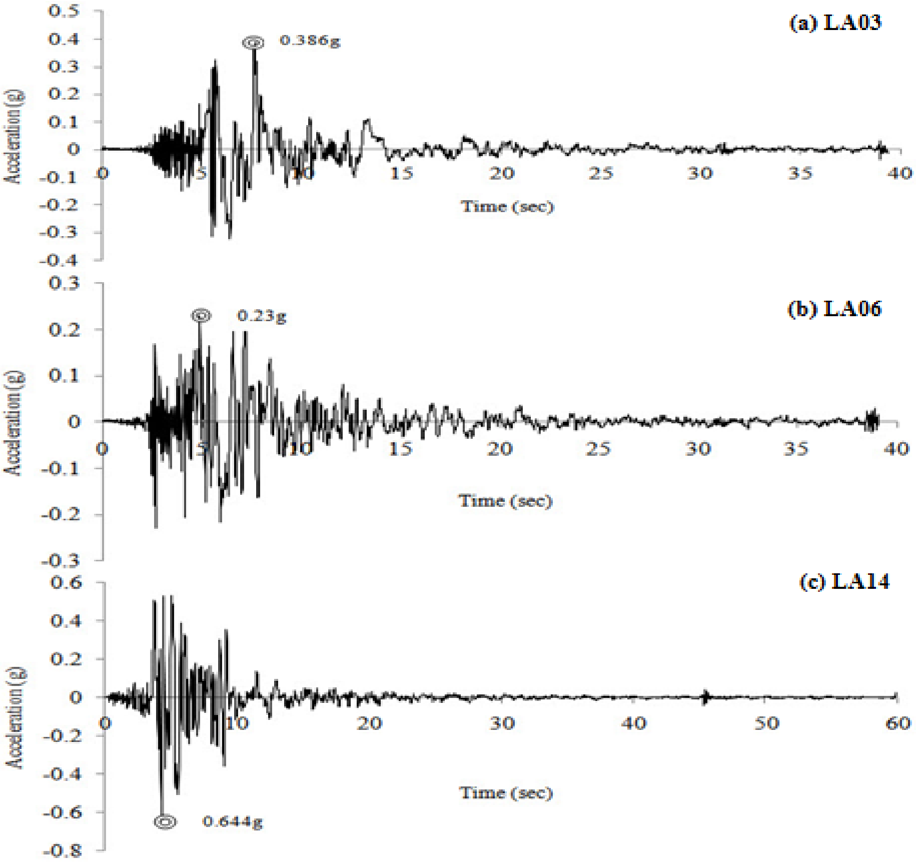

Fig. 2 Accelerograms of different earthquakes

IV. RESULTS OF THE STUDY

A. Static Analysis on Damper Location

Fig. 3 and ST3-4 depict the variation in lateral displacement and inter-storey drift for various outrigger locations in X direction. For lateral displacement, the outrigger location H_0/H was varied between 0.5-1.0. For $H_0/H=0.6$ there is 52.14 % reduction in response, as the H_0/H ratio increases beyond 0.6 there is gradual reduction in response for outrigger which is clearly indicated in the graphs. The variation of inter-storey drift in the top storey for different location of the outrigger varied between 0.5-1.0 (H_0/H). For H_0/H =0.6 there is 51.29% reduction in response at the 40th floor when outriggers are located at 23th & 24th floors, as the ratio increases, the reduction in response at the top floor also increase. Moreover, the regression analysis of displacement along X direction showed that R^2 range or the statistical correlation data lie between 0.982 - 0.9972 for the displacement to correlate the stiffness of the buildings considering the dimensions, loadings. The R^2 value for the inter-storey drift is quite changing for different models as it stiffness values keeps varying based on the position of the outriggers, Table II.

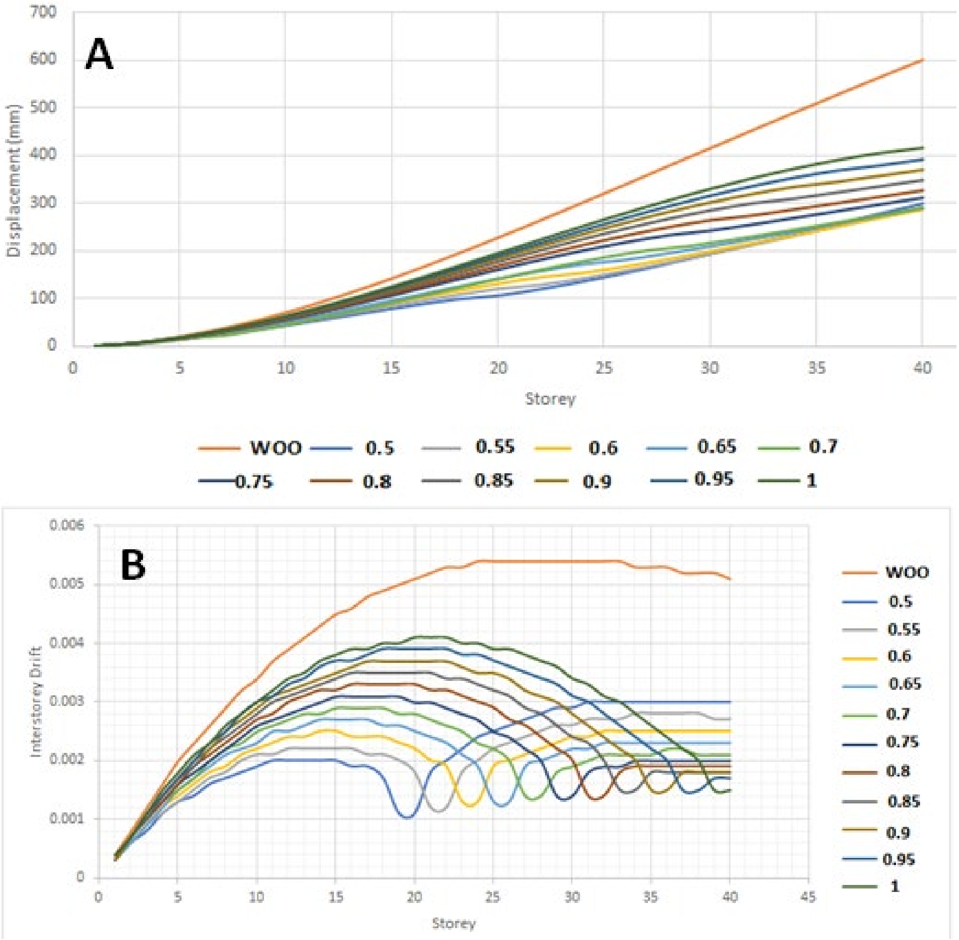

Fig. 3 (A) Variation of lateral displacements and (B) Inter-storey drift with different location of outrigger when earthquake is in X-direction. Where WOO is without outrigger

Figure 4 and ST5-6 show the variation of lateral displacement and inter-storey for different location of the outrigger due to the earthquake in Y direction. For lateral displacement the outrigger location H0/H was varied between 0.5-1.0. For $H_0/H=0.6$ there is 52 % reduction in response at the top storey. However, when H0/H ratio increases beyond 0.6 there is gradual reduction in response for outrigger which is clearly indicated in the graphs.

The variation of inter-storey drift at different levels of the structure for different location of the outriggers H_0/H is varied between 0.5 -1.0. For $H_0/H=0.6$ there is 42.87 % reduction in response at the 40th floor when outriggers are located at 23 & 24th floors, S. Table III shows the regression analysis of displacement and inter-storey drift along Y direction. The R^2 range or the statistical correlation data lie between 0.9973 - 0. 983. There is no variation has been noticed between the H0/H and inter-storey correlation value as the outrigger was placed along the X direction.

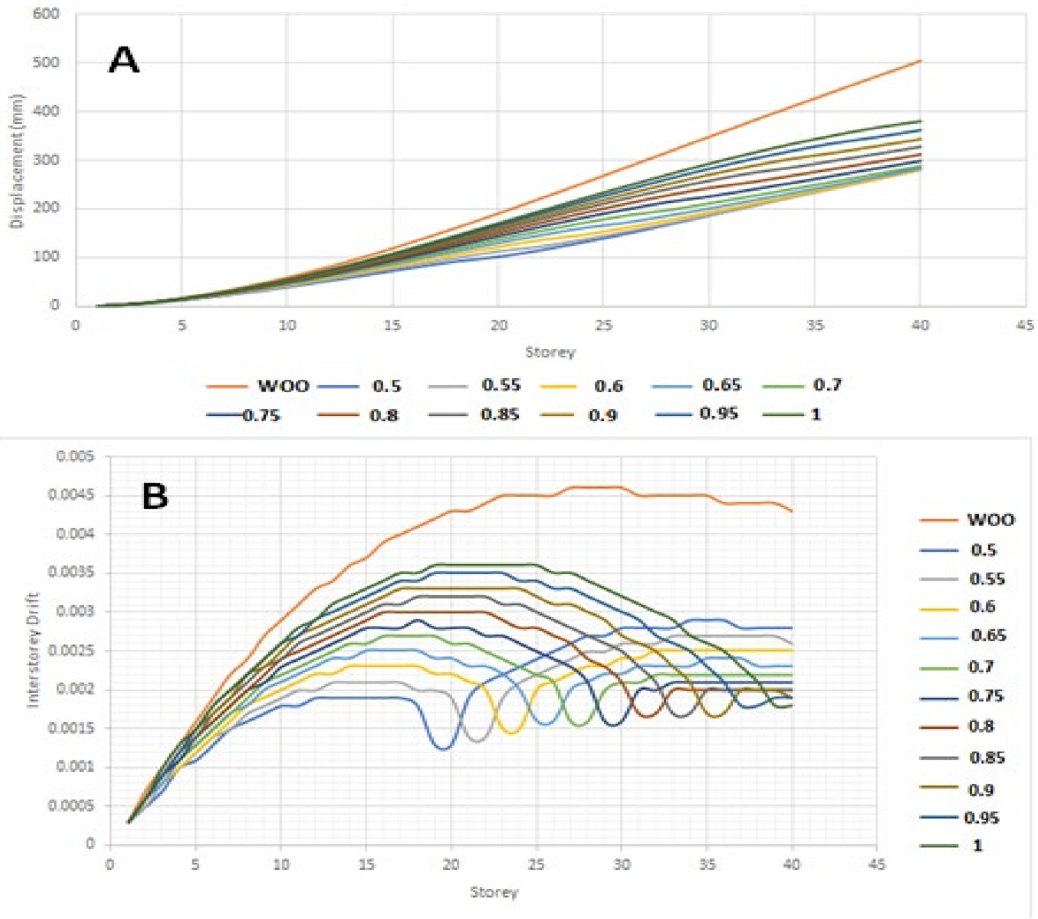

Fig. 4 (A) Variation of lateral displacements and (B) Inter-storey drifts with different location of outriggers when earthquake is in in Y-direction. whereas WOO is without outrigger

TABLE II REGRESSION ANALYSIS FOR THE DISPLACEMENT AND INTERSTOREY DRIFT TO EARTHQUAKE IN X-DIRECTION

Model	**H_0/H**	**Regression Analysis for Displacement along X direction**	**Regression Analysis for Inter storey drift along X direction**
1	Without Outrigger	$y = 16.382x - 77.766$ $R^2 = 0.9874$	$y = 0.0001x + 0.0021$ $R^2 = 0.7239$
2	0.5	$y = 11.966x - 41.795$ $R^2 = 0.993$	$y = 2E-05x + 0.0026$ $R^2 = 0.0498$
3	0.55	$y = 11.309x - 36.738$ $R^2 = 0.9921$	$y = 6E-05x + 0.0009$ $R^2 = 0.8079$
4	0.6	$y = 10.62x - 31.718$ $R^2 = 0.9912$	$y = 1E-05x + 0.0026$ $R^2 = 0.018$
5	0.65	$y = 9.9241x - 27.019$ $R^2 = 0.9905$	$y = 4E-05x + 0.0011$ $R^2 = 0.6678$
6	0.7	$y = 9.2467x - 22.997$ $R^2 = 0.9907$	$y = 7E-06x + 0.0025$ $R^2 = 0.007$
7	0.75	$y = 8.6329x - 20.127$ $R^2 = 0.9923$	$y = 3E-06x + 0.0024$ $R^2 = 0.002$
8	0.8	$y = 8.0158x - 23.64$ $R^2 = 0.9937$	$y = 3E-05x + 0.0014$ $R^2 = 0.4104$
9	0.85	$y = 7.7346x - 19.114$ $R^2 = 0.9972$	$y = 3E-06x + 0.0023$ $R^2 = 0.0026$
10	0.9	$y = 7.5145x - 21.395$ $R^2 = 0.9969$	$y = 6E-06x + 0.0021$ $R^2 = 0.0102$
11	0.95	$y = 7.4813x - 25.627$ $R^2 = 0.992$	$y = 1E-05x + 0.0019$ $R^2 = 0.0438$
12	1	$y = 7.6486x - 31.688$ $R^2 = 0.9822$	$y = 2E-05x + 0.0017$ $R^2 = 0.1689$

TABLE III REGRESSION ANALYSIS FOR THE DISPLACEMENT AND INTER STOREY DRIFT TO EARTHQUAKE IN Y-DIRECTION

Model	H_0/H	Regression Analysis for Displacement along Y direction	Regression Analysis for Interstorey drift along Y direction
1	Without Outrigger	y = 13.748x - 65.342 R² = 0.9872	y = 9E-05x + 0.0017 R² = 0.7305
2	0.5	y = 10.8x - 40.761 R² = 0.9933	y = 3E-05x + 0.0021 R² = 0.1512
3	0.55	y = 10.301x - 36.908 R² = 0.9933	y = 2E-05x + 0.0021 R² = 0.1002
4	0.6	y = 9.7744x - 33.007 R² = 0.9933	y = 6E-05x + 0.0009 R² = 0.8492
5	0.65	y = 9.2386x - 29.377 R² = 0.9935	y = 2E-05x + 0.0021 R² = 0.0768
6	0.7	y = 8.7234x - 26.267 R² = 0.9941	y = 5E-05x + 0.0011 R² = 0.7557
7	0.75	y = 8.2503x - 23.988 R² = 0.9953	y = 4E-05x + 0.0013 R² = 0.585
8	0.8	y = 7.8503x - 22.834 R² = 0.9967	y = 2E-05x + 0.002 R² = 0.0684
9	0.85	y = 7.5504x - 23.023 R² = 0.9973	y = 2E-05x + 0.0019 R² = 0.0708
10	0.9	y = 7.3706x - 24.649 R² = 0.9957	y = 2E-05x + 0.0018 R² = 0.1082
11	0.95	y = 7.3286x - 27.718 R² = 0.9909	y = 2E-05x + 0.0016 R² = 0.1992
12	1	y = 7.4351x - 32.167 R² = 0.983	y = 3E-05x + 0.0014 R² = 0.3721

A. Dynamic Analyses

1. Time History Analysis

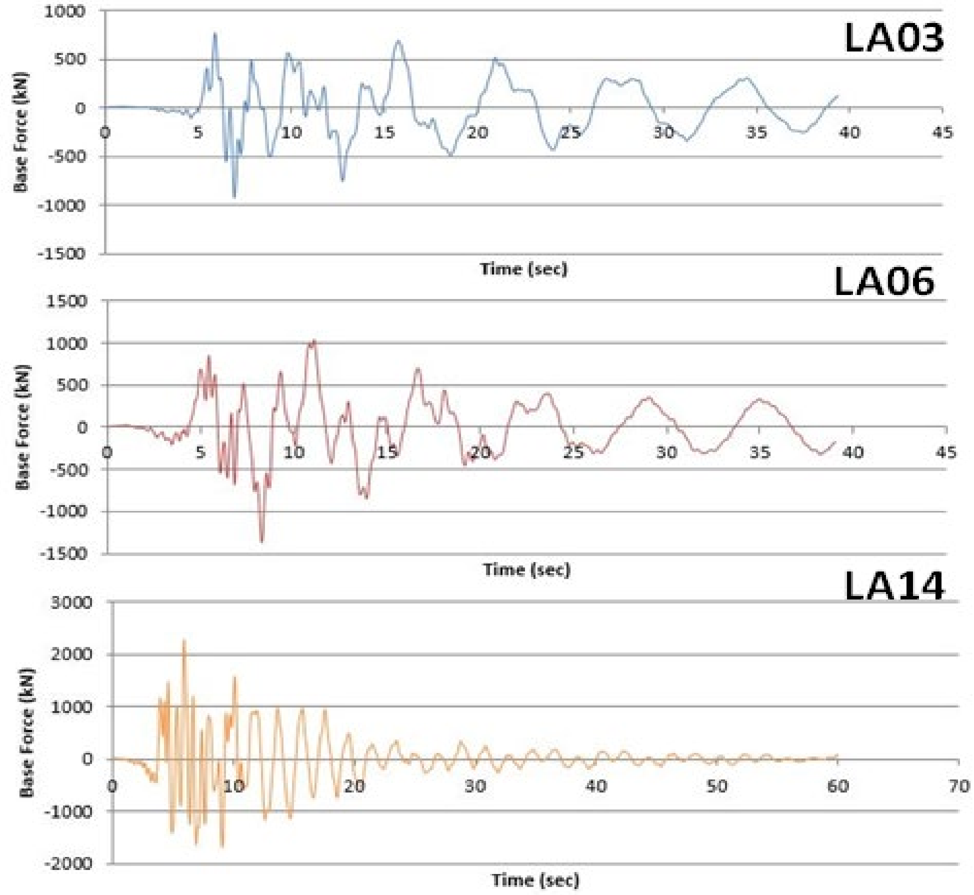

Fig. 5 Variation of base force against time for, LA03, LA06 and LA14 earthquakes ($H_0/H=0.5$)

2. Response Spectrum Analysis

Response spectrum analysis was carried on the model which showed maximum response to the lateral displacement during static analysis i.e., model with $H_0/H=0.6$ having outrigger at 23rd & 24th floors, Fig. 6.

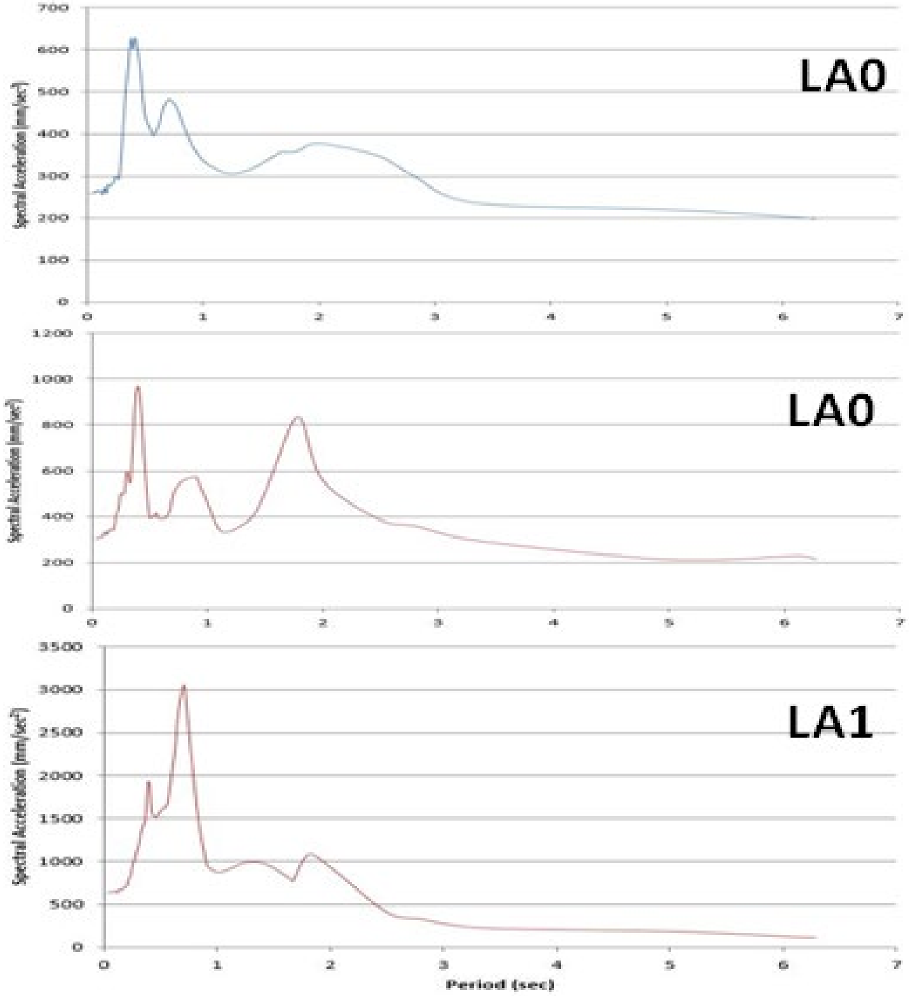

Fig. 6 Variation of Spectral acceleration for H_0/H =0.6 (LA03, LA06 and LA14).

While Fig. 7-8 summarize the maximum reduction in the lateral displacements and inter-storey drift due to static earthquake analysis in X and Y direction respectively. For the economical design of the outrigger based tall buildings, the optimum location of the outrigger is very important [9]. Hence the maximum reduction for the sway was observed at H0/H = 0.6. both for the earthquake load in X and Y direction. As the outrigger behaves like a vertical cantilever beam [6], the maximum lateral displacment would take at the free end as as reuslt the maximum displacment is observed to be at the top.

The optimal position of the outrigger for both static and dynamic behavior for the structure considered is at mid height when the criterion is lateral displacement. As the height of the building increases there is reduction in lateral rigidity [19]; the centroid of the building along 3 axis places an important role in terms of positioning of the outriggers. Although, this method gives an initial understanding to the designers on the location based on the size and the height of the building. This method is not a substitute for the finite element analysis method.

The maximum inter-storey drift reduction was observed to be 51.29% in the X direction. Since the forces in the inter-storey viscous dampers directly depend on the inter-storey velocities, in addition to the peak inter-storey drifts, the peak inter-storey velocities also play a significant role in the evaluation of the structural response in structures with added inter-storey viscous dampers [20]. Using the inter-storey drift spectrum over the standard displacement response spectrum is that it takes into account the higher modes [21]. Since the buildings is subjected to 3 earthquake data for the dynamic analysis, maximum inter-storey drift ratio shifts from upper half to lower half of the tall buildings as the lateral stiffness ratio increases [22]. The inter-storey drifts are observed to be more in tall buildings without the outrigger. The dynamic performance of a building can be enhanced by increasing its damping rather than its stiffness, mass, or strength to reduce vibration. Tuned Mass Dampers (TMDs) have been used on tall buildings for some time, but often engineers design the structure to satisfy the strength requirements and then fix the acceleration difficulties, rather than the other way around [23]. As result, inclusion of stiff horizontal beam (outrigger) at the mid for H0/H = 0.6, adds an additional coherent damping and also balances out in terms more reduction which leads to economical design.

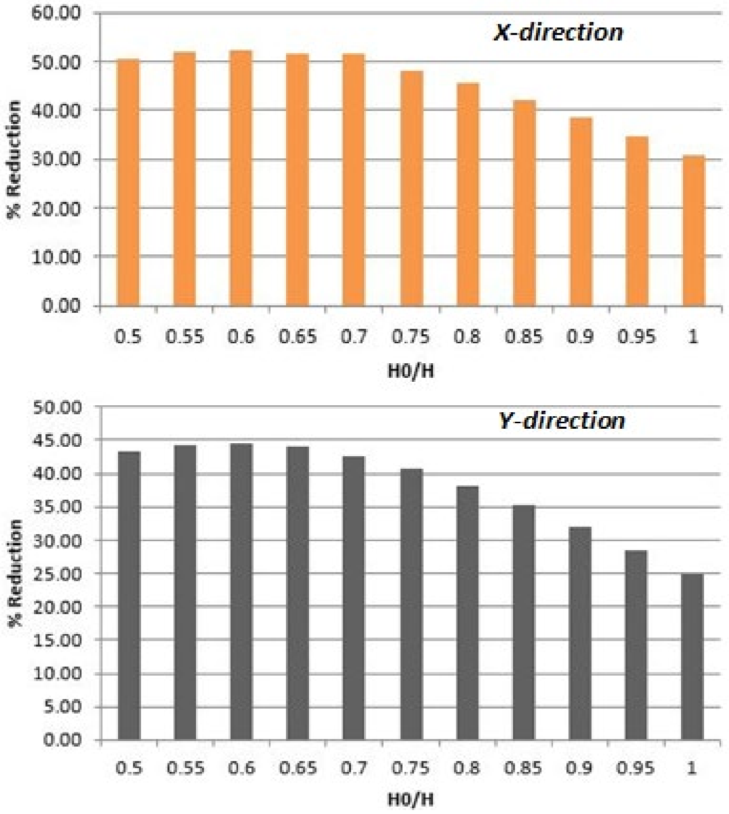

Fig. 7 Percentage reduction in lateral displacement for various models considered.

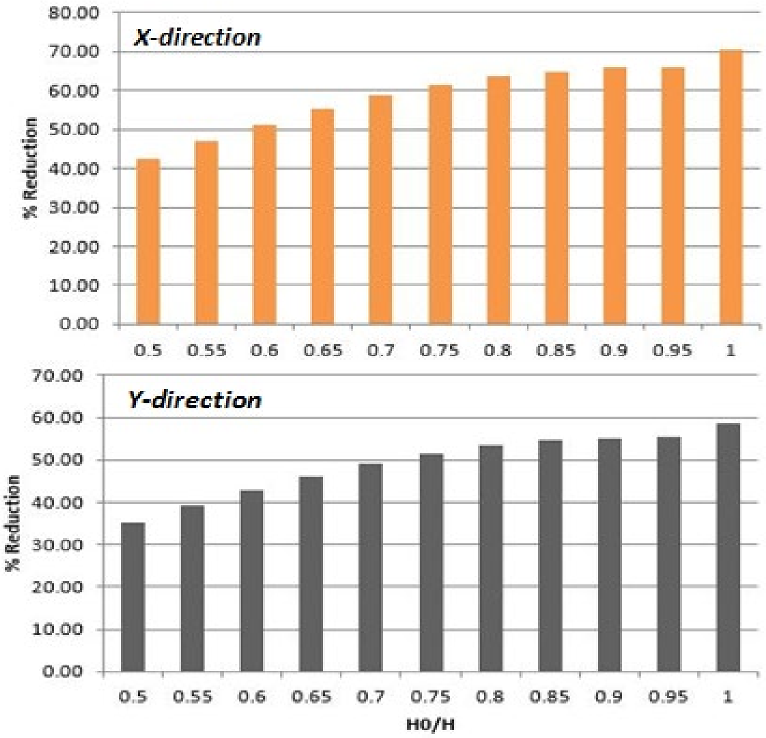

Fig. 8 Percentage reduction in storey drift for various models considered

V. CONCLUSION

Following conclusions are drawn from the result analysis based on outrigger location and performance of the structural system with varying outrigger location.

1. Outrigger when located at H0/H=0.6 causes maximum reduction in the lateral displacement, hence it is the desired location to provide outrigger in a structural system and could act as an initial economical design solution in construction of tall buildings with outriggers.
2. The analysis show that the performance of outrigger is efficient in reducing lateral displacement to a maximum of 52.14% and inter storey drift to a maximum of 51.29% in X-direction when compared to structure without outrigger.
3. Time history analysis show that the reduction in base shear is up to a maximum of 29.26% when outrigger is located at H0/H=0.9 for LA03, 37.9% when outrigger is located at H0/H=0.85 for LA06 and 17.49% at H0/H=1.0 for LA14.
4. The reduction in displacement is up to a maximum of 40.92% when outrigger is located at H0/H=0.95 for LA03, 40.03% when outrigger is located at H0/H=1 for LA06 and 54.27% at H0/H=0.95 for LA14.

VI. FUTURE SCOPE OF WORK

1. Multi outrigger systems with 2 or 3 outriggers can be analyzed and the optimum location of outriggers can be found out.
2. Dampers can be used along with outriggers and similar analysis can be carried out to check the performance of outrigger with dampers.
3. The derived curve between (H0/H) and storey and good R square values may be used in extrapolating with different storeys and change in the dimensions of the outriggers.

REFERENCES

[1] M. J. Park, and Y. K. Ju, “Disaster Assessment of Tall Buildings in Korea by K-Rapid Visual Screening System Focusing on Structural Safety,” *Buildings,* Vol. 12, No. 4, pp. 442, 2022.

[2] C. Fang, “Applicability of Damped Outrigger Systems Using Timoshenko Beam Theory,” *International Journal of Structural Stability and Dynamics*, pp. 2250076, 2022.

[3] I. Venanzi, *et al.,* “Multi-hazard loss analysis of tall buildings under wind and seismic loads,” *Structure and Infrastructure Engineering*, Vol. 14, No. 10, pp. 1295-1311, 2018.

[4] M. N. Aydınoğlu, “Challenges and problems in performance-based design of tall buildings, in Performance-Based Seismic Engineering: Vision for an Earthquake Resilient Society,” *Springer*, pp. 279-300, 2014.

[5] M. M. Ali, and K. S. Moon, “Structural developments in tall buildings: current trends and future prospects,” *Architectural science review*, Vol. 50, No. 3, pp. 205-223, 2007.

[6] A. Dangi, and S. Jamle, “Determination of Seismic parameters of RCC Building Using Shear Core Outrigger, Wall Belt and Truss Belt Systems,” *International Journal of Advanced Engineering Research and Science*, Vol. 5, No. 9, pp. 305-309, 2018.

[7] N. M. N. Al-Azri, S. Kuckian, and H. Gaur, “Reducing the Impact of Wind Load with Shape of High Rise Buildings,” *Journal of Student Research*, 2019.

[8] S. Fawzia, and T. Fatima, “Deflection control in composite building by using belt truss and outriggers systems,” *Proceedings of the World Academy of Science, Engineering and Technology*, pp. 800-805, 2010.

[9] N. Herath, *et al.,* “Behaviour of outrigger beams in high rise buildings under earthquake loads in Australian Earthquake Engineering Society” *Conference*, 2009.

[10] N. Priyanka, , *et al.,* “Comprehensive Analysis of Outrigger System for High Rise Structures Subjected to Wind and Earthquake Loadings, in Sustainability Trends and Challenges in Civil Engineering,” *Springer*, pp. 601-618, 2022.

[11] T. Wang, S. Yang, and X. Wang. “Analysis of construction parameters of outriggers in the mega column-core tube-outrigger structure based on seismic reliability. in Structures,” *Elsevier*, 2022.

[12] A. Habrah, M. Batikha, and G. Vasdravellis, “An analytical optimization study on the core-outrigger system for efficient design of tall buildings under static lateral loads,” *Journal of Building Engineering*, Vol. 46, pp. 103762, 2022.

[13] J. Lee, *et al.,* “Geometric nonlinear analysis of tall building structures with outriggers,” *The Structural Design of Tall and Special Buildings*, Vol. 22, No. 5, pp. 454-470, 2013.

[14] K. Kamath, N. Divya, and A. U. Rao, “A study on static and dynamic behavior of outrigger structural system for tall buildings,” *Bonfring international journal of industrial Engineering and Management Science*, Vol. 2, No. 4, pp. 15-20, 2012.

[15] S. M. Walls, “FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings”, *ASCE for the Federal Emergency Management Agency*, Washington, DC, November 2000. R. Forghani, Totoev Y. Z. S. Kanjanabootra, “Experimental investigation of the water penetration through semi interlocking masonry (SIM) walls”, Proc. Annual Meeting of Architectural Institute of Japan, Kobe, Japan, September 2014, pp. 889-890. *Masonry Society Journal*, Vol. 25, No. 1, pp. 41-52, 2004.

[16] S. K. Jain, “Review of Indian seismic code, IS 1893 (Part 1): 2002,” *Indian concrete journal*. Vol. 77, No. 11, pp. 1414-1422, 2003.

[17] S. Kuckian, *et al.,* “A study on seismic response of reinforced structures retrofitted with fluid viscous dampers in shear walls,” *GRIN Verlag,* 2019.

[18] A. AR, *et al.,* “Seismic response of a structure retrofitted with fluid viscous dampers in core wall–an analytical study,”.

[19] A. Gupta and D. Podder, “Optimum position of outrigger-belt system in a high-rise RCC building through pushover analysis,” *Asian Journal of Civil Engineering*. Vol. 22, No. 2, pp. 277-296, 2021.

[20] F. Adachi, *et al.,* “Importance of interstory velocity on optimal along-height allocation of viscous oil dampers in super high-rise buildings,” *Engineering structures*. Vol. 56, pp. 489-500, 2013.

[21] G. Guo, *et al.,* “Self-similar inter story drift spectrum and response distribution of flexural-shear beam with non-uniform lateral stiffness,” *Bulletin of Earthquake Engineering*. Vol. 17, No. 7, pp. 4115-4139, 2019.

[22] D. Yang, J. Pan, and G. Li, “Interstory drift ratio of building structures subjected to near-fault ground motions based on generalized drift spectral analysis,” *Soil Dynamics and Earthquake Engineering*. Vol.30, No.11, pp. 1182-1197, 2010.

[23] M. Jackson, and D. M. Scott. “Increasing efficiency in tall buildings by damping. in Structures Congress,” 2010.