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Optimizing Lateral Stiffness in High-Rise Structures: Investigating the Optimal Outrigger Location under Wind Load

[1]Ranjitsinh M. Gaikwad, [2]Dr. C. P. Pise
[1]Student, [2]Professor
[1]Department Of Civil Engineering
, [1]SKN Sinhgad College Of Engineering
Korti, Pandharpur, India
[1]ranjeet.gaikwad9519@gmail.com, [2]chetan.pise@sknscoe.ac.in

Abstract— With the proliferation of high-rise structures worldwide, meeting the stiffness demands imposed by earthquake and wind-induced lateral loads has become a crucial aspect of their design. While traditional solutions like shear walls and bracing systems effectively address stiffness requirements, their cost-effectiveness diminishes as the height of the structure increases. To overcome this challenge, this research proposes the implementation of an outrigger system, offering enhanced lateral stiffness while minimizing costs. The objective of this study is to identify the optimal location for the outrigger system in high-rise structures under wind load conditions. A comprehensive investigation of 100-story high-rise structures was conducted using the outrigger system, with the outrigger location varied along the height of the structure. The performance evaluation of each structure was carried out using various response parameters, including top-storey displacement and storey drift ratio. The ETABS software was employed for structural analysis, considering wind load as the primary lateral load scenario.The results of the analysis demonstrated the significant influence of outrigger placement on reducing lateral displacement and improving overall structural stiffness. Structures equipped with four outriggers exhibited an approximate 19% reduction in lateral displacement compared to those without outriggers. These findings highlight the efficacy of the outrigger system in mitigating the adverse effects of lateral loads and enhancing the structural performance of high-rise buildings.In addition to the performance evaluation, a thorough cost analysis was conducted to assess the economic viability of the outrigger system. Factors such as construction, material, and maintenance costs were considered to compare the cost-effectiveness of the outrigger system with traditional solutions like shear walls and bracing systems.This research contributes to the optimization of high-rise structure design by providing valuable insights into the effectiveness and cost-efficiency of outrigger systems. The identification of the optimal outrigger location enables designers and engineers to achieve improved structural performance while reducing reliance on more expensive solutions. The outcomes of this study serve as a valuable reference for future high-rise construction projects, facilitating informed decision-making in the pursuit of safe, cost-effective, and resilient structures.

Index Terms - Wind load, Optimal location, Structural performance, Cost analysis, Cost-effectiveness, Earthquake loads, Shear walls, Bracing systems, Structural optimization, Tall buildings, Building design, Wind engineering

Introduction

The rapid development of tall buildings in recent years has been driven by the increasing urbanization and migration of populations from rural areas to metropolitan cities in search of employment opportunities. As a result, these cities are becoming denser, and the availability of land is diminishing. This scarcity of land, coupled with rising land costs, has made high-rise structures an efficient and cost-effective solution for accommodating the growing population in these urban centers. Countries like India, with their large and increasing population, have witnessed a surge in the construction of multi-story buildings to meet the rising demand for housing and commercial spaces. The structural systems employed in tall buildings can be broadly classified into two categories: interior structures and exterior structures. This classification is based on the distribution of the components of the primary lateral load-resisting system within the building. An interior structure refers to a system where the major portion of the lateral load-resisting components is located within the building's interior. Conversely, an exterior structure places the primary lateral load-resisting components predominantly at the building perimeter. It should be noted that minor components of the lateral load-resisting system can be present in the opposite category.

The need for this study arises from the prevalence of lateral loads, such as wind and earthquake forces, in modern tall buildings. These loads are typically counteracted using bracing systems or shear walls. However, as the height of the building increases, the stiffness of the structure becomes increasingly critical. To address this, outrigger systems are often incorporated into the building design to provide additional lateral stiffness.In the design of buildings with outrigger systems, determining the optimum location for the outrigger beams is essential to achieve an economical design. Surprisingly, there is a lack of scientific research or case studies focused on identifying the optimal outrigger location specifically under wind loads. This research aims to fill this knowledge gap by investigating the most efficient outrigger location for high-rise structures subjected to wind loads. Furthermore, the design of tall and slender structures is heavily influenced by lateral loads, which dictate the governing factors of strength, stiffness, and serviceability. As buildings become taller and more slender, considerations such as top-storey displacement and inter-storey drift ratio gain significance in addition to the overall structural efficiency. Designing structural members based on maximum lateral displacement and drift requirements supersedes traditional design approaches solely based on allowable stress criteria.

In light of these challenges, various lateral schemes have been proposed and implemented worldwide to address the structural demands of tall and slender buildings. These schemes aim to optimize structural performance while minimizing architectural impacts. The selection and design of an appropriate lateral load-resisting system are vital to ensure the safety, stability, and serviceability of high-rise structures. In this study, we aim to contribute to the understanding of high-rise structure design by investigating the optimal outrigger location for enhancing lateral stiffness in the presence of wind loads. The findings of this research will provide valuable insights for structural engineers and designers, enabling them to optimize the performance and cost-effectiveness of high-rise structures while meeting the imposed drift requirements and ensuring occupant comfort and safety.

Literature Review

The behavior and optimization of outrigger systems in tall building design have been the focus of several researchers. Smith and Salim [1] investigated the flexibility of outriggers in braced tall building structures and developed an expression for top drift. They also determined the optimum location of outriggers to minimize top drift, considering the flexural rigidity ratios between the core, columns, and outriggers. Ali and Moon[2]proposed a new classification of high-rise structures, distinguishing between interior and exterior structures. They discussed current trends such as outrigger systems and diagrid structures, as well as the use of aerodynamic and twisted forms in high-rise buildings.

Optimizing the use of multi-outrigger systems in tall buildings was studied by Bayati et al[3] Their research focused on parameters such as lateral displacement and storey drift, demonstrating that multi-outrigger systems can reduce the dimensions of structural elements and foundations. Herath et al. [4]aimed to identify the optimum outrigger location in tall buildings under earthquake loads. They conducted response spectrum analysis of a 50-storey building and found that the structure performed optimally when the outrigger was placed between the 22nd and 24th levels, corresponding to approximately 0.44-0.48 times the building's height.

Moon [5]) investigated the structural efficiency of outrigger structures by studying different lateral bending stiffness distribution cases between the braced core and perimeter mega columns. Their findings showed that the optimal stiffness distribution ratio depends on the height-to-width aspect ratio of the building. Balling and Lee [6]developed a simplified skyscraper model for the preliminary design of tall buildings with outrigger and belt truss systems. Their model accurately predicted displacement and stress responses compared to a detailed finite element model. The review conducted by Khanorkar et al[7] encompassed various techniques and methods used to investigate outrigger and belt truss systems in tall buildings. Parameters such as lateral displacement, storey drift, core moment, and optimal positioning of outriggers and belt trusses were reviewed. The study concluded that these systems hold potential for the design and development of tall buildings. Choi et al. [8] gives an overview of outrigger system including historical background pertinent design considerations and design recommendations for outrigger systems in a high rise structures. Considering various dimesnsions.Chen and Zhang [9] Deals with an existing mathematical model of the outrigger braced structures; the MGA was utilized to achieve Pareto optimal solutions, which have two tradeoff objective functions: top drift and core base moment. Then, MATLAB was employed to explore the multi-objective automatic optimization procedure for the optimal design of outrigger numbers and locations under wind excitation. Chuangjie Fang et al .[10]This paper present promising solutions that has been proposed in the damped outrigger system, where dampers are vertically installed between outriggers attached to the core and perimeter columns, leading to a significant increment of structural damping. To gain insight into the design of damped outrigger systems subject to seismic excitation, a stochastic optimization procedure is proposed.Pao-Chun Lin et al.[11]Deals with study and investigates the seismic behavior of a damped-outrigger system incorporating buckling-restrained brace (BRB-outrigger). The outrigger effect combined with the energy dissipation mechanism of the buckling-restrained brace (BRB) effectively reduce the seismic response of the building. This study proposes the methods to evaluate the inelastic seismic response of structures with multiple damped-outriggers based on a spectral analysis (SA) procedure.Safwan Al-Subaihawi et al. [12]This paper examines the ability of damping devices placed between outrigger trusses and perimeter columns to mitigate dynamic vibrations in a tall building structure. The implementation of this approach to mitigate windinduced vibrations for a 40-story building is assessed via a series of real-time hybrid simulations (RTHS), in which a numerical model of the complete building actively interfaces with physical dampers in the laboratory via actuators.Han-Soo Kim et al. [13] This paper deals with Optimum location of outrigger in tall buildings using finite element analysis and gradient-based optimization method. In this study, the optimum locations of outriggers minimizing the top drift of tall buildings are identified using a gradient-based nonlinear programming approach

Overall, these studies contribute to the understanding of outrigger systems, their optimal design, and their impact on the behavior of tall buildings. They provide valuable insights into the efficiency, stiffness enhancement, and seismic performance of outrigger structures, offering guidance for the design and optimization of tall building systems. From the review of literature, it is observed that several researchers have studied and done their work on the optimal design of outriggers in terms its location(s). There is not much information available on how many number of outrigger(s) required in high- rise structure. Further studies are needed in the direction of efficacy of the outrigger(s) in terms of structural performance.

Outrigger system

In modern tall buildings, lateral loads induced by wind or earthquake are often resisted by a system of coupled with bracing system or shear walls. But when the building increases in height, the stiffness of the structure becomes more important and introduction of outrigger system is often used to provide sufficient lateral stiffness to the structure. Outrigger(s) are rigid horizontal structural element connected between building central core and mega column/ perimeter column to improve overall lateral stiffness and strength of structure. So, outrigger system is formed by tying two structural system, one is a core system and other one is perimeter system. Performance of outriggers system more significance than rigid system with shear wall as well as bracing truss system due to the positive interaction between the two tied systems.

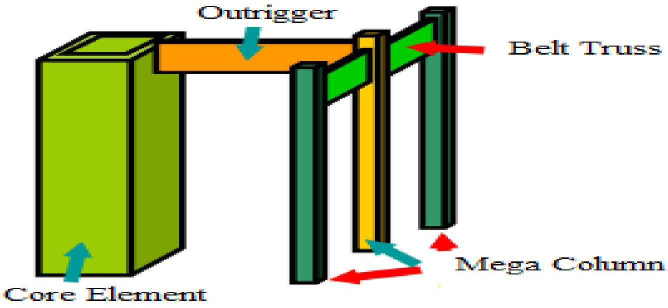


Figure 1 Core element with outrigger and belt truss system (Shivacharan et al.[14]

Types Of Outrigger System

There are two types of outrigger systems: conventional (direct) outrigger system and virtual (belt truss) outrigger system. The conventional outrigger system, also known as the core and outrigger structural system, involves connecting the core element of the building to select perimeter columns using outriggers. This extension of the core structure enhances the lateral stiffness for taller buildings and mobilizes the perimeter columns to resist lateral loads. The outriggers help reduce the internal overturning moment of the core but do not affect shear forces.

The virtual outrigger system, also known as the core, outrigger, and belt wall system, further enhances lateral stiffness by connecting outrigger columns to adjacent columns using deep beam elements called belt trusses. This system shares loads between multiple columns, increasing axial stiffness and utilizing more gravity columns to counteract tension loads generated by lateral loads. The movements of floor diaphragms are transferred to columns through the belt trusses, stabilizing the core. In the virtual outrigger system, belt trusses can also provide higher torsional stiffness and may be used in a direct outrigger system as well.

Modelling and analysis

A. Assumptions

Following assumptions should be made before analysis of structure in ETABs:

1) The stiffness of bare frame is uniform throughout height of a structure.
2) The outriggers are rigidly attached to the core.
3) The core is rigidly attached to the foundation.
4) Axial strain in the mega columns must be the same as the axial strain in the core under gravity loads.
5) Tensional effects are not considered.

B.Geometrical Configurations

Details of the Model

The 100 stories high rise structure is considered for the dissertation study. The total height of a structure is 400m which is shown in Fig 2. There are 20 mega columns on the periphery of structure. The following information gives the detail geometric configuration of the structure:

No of Stories : 100
Plan Dimension of Structure : 50m X 50m
Central Core : 30m X 30m
Bay Length : 5.00m
Thickness of Slab : 250mm
Beam Size : 300mm X 1000mm
Column Size : 2100mm X 2100mm
Mega Column Size : 2500mm X 2500mm
Wall Size : 800mm
Area of Outrigger Section : 0.15m^2
Area of Belt Truss : 0.15m^2
Depth of Outrigger Section : 8.00m (Two Story's)

The grade of concrete and grade of steel for given structure is M60 and HYSD500 respectively. The grade of steel for outrigger section is Fe345. Live Load (LL) is 4.00kN/m^2 and Floor Finish (FF) is 1.50kN/m^2 on structure. Table 1 gives the brief information about the wind as per IS 875: (Part 3) – 2015.

Table 1 Input data for wind analysis

Contents	Descriptions
Basic Wind Speed	44m/s
Risk Coefficient (*k*1)	1.07
Terrain Category	IV
Topography Factor (*k*3)	1.00
Importance Factor for Cyclonic Region (*k*4)	1.00
Internal Pressure Coefficient (*C*pi)	+/- 0.50
Windward Pressure Coefficient (*C*pw)	1.45
Leeward Pressure Coefficient (*C*pl)	1.75

The following Figure 2. gives information about elevation of structural model. there is possibility of outrigger(s) at every 20th storey (i.e. 80m). So, total 31models may exist with varying the outrigger positions as wll as number of outriggers.

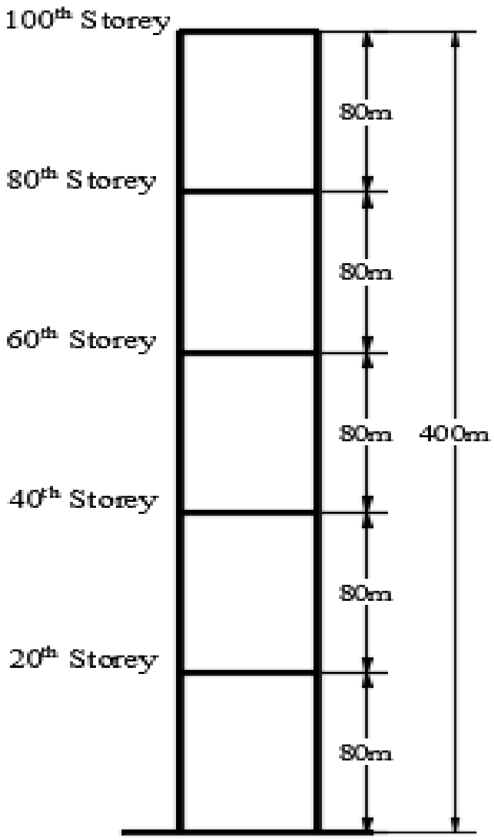


Figure 2. Elevation of structural model

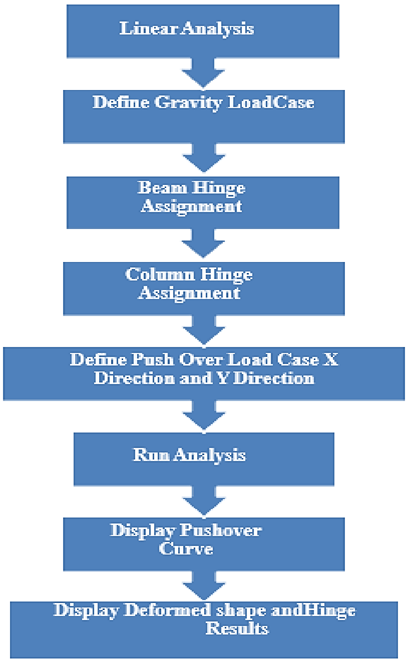


Figure 3. Flowchart for Nonlinear Static (Pushover) Analysis using ETABS

Results And Discussions

C. Lateral Displacement of Top Storey

Structure experience lateral loads (earthquake load and wind load), as results structure deflected in lateral direction. If the height of structure is increases, structure experiences more lateral load on it. So, lateral displacement of the structure is also increases.

Following figures show lateral displacement of top storeys. In that on X-axis location of outrigger(s) are shown. The roman number before 'O' indicates the number of outrigger(s) and number after 'O' indicates the position details of outrigger(s) in structure. Here 'O' stands for outriggers and belt trusses.

Table 2 Location of outriggers

ID No.	Descriptions
1	Outrigger at 20th Storey
2	Outrigger at 40th Storey
3	Outrigger at 60th Storey
4	Outrigger at 80th Storey
5	Outrigger at 100th Storey

For example ID number 'IO1' represents the structure with one outrigger which is located at 20th storey (i.e. 80m from bottom of the structure). Whereas ID number 'IIO12' reflects that structure with two outriggers which are located at 20th storey and 40th storey (i.e. one outrigger at 80m and other at 160m from bottom) respectively.

Figure 3 gives the brief information about top storey lateral displacement of structure with one outrigger for different location of outrigger. Lateral displacement for top storey of structure with outrigger located at 20th storey is 734.364mm. 727.464mm, 741.707mm, 757.358 and 771.553 are top storey lateral displacement for structure with outrigger located at 40th, 60th, 80th and 100th respectively.

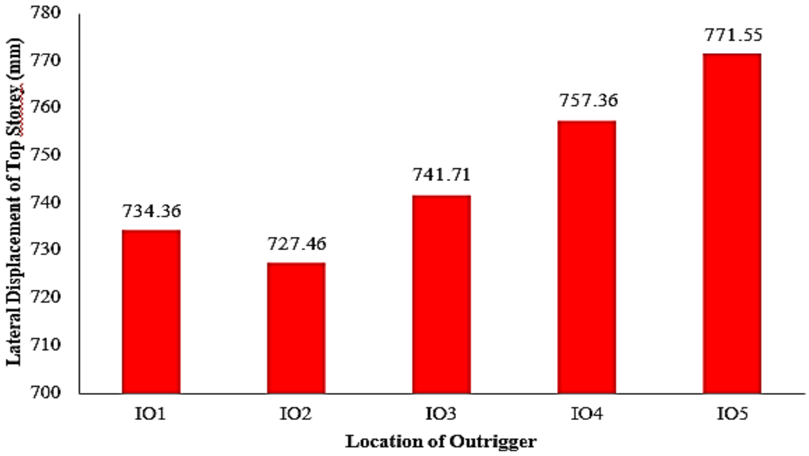


Figure 3 Lateral displacement of top storey for structure with one outrigger

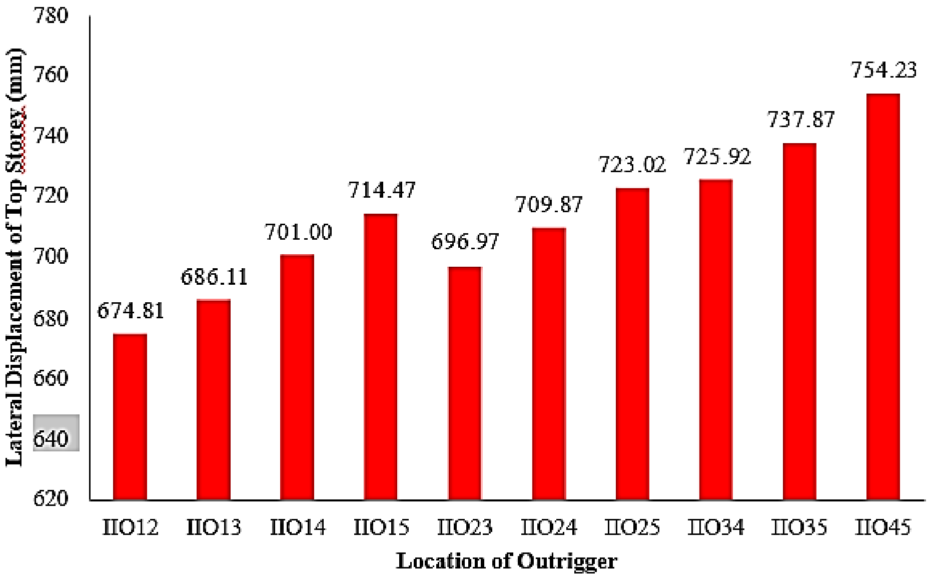


Figure 4 Lateral displacement of top storey for structure with two outriggers

Figure 4 and Figure 5 gives the lateral displacement of top storey for structure with two outriggers and three outriggers with different locations of outriggers. There are total 10 models in structure with two outriggers and 10 models in structure with three outriggers each.

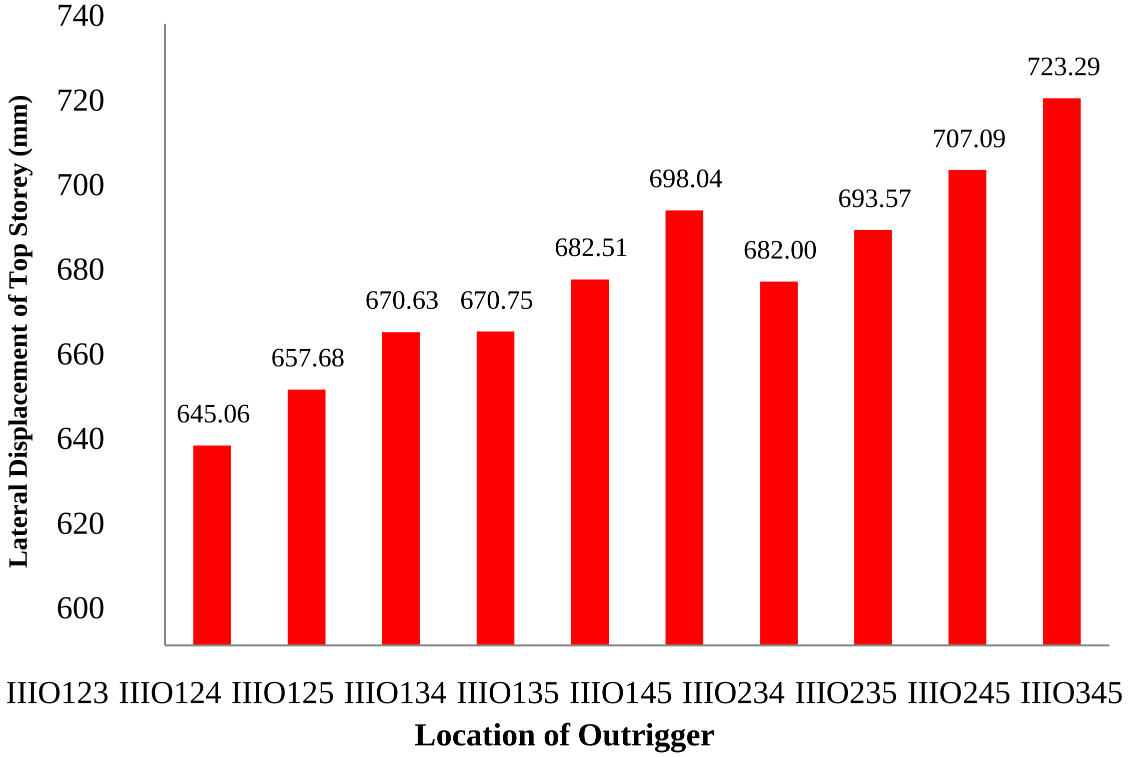


Figure 5 Lateral displacement of top storey for structure with three outriggers

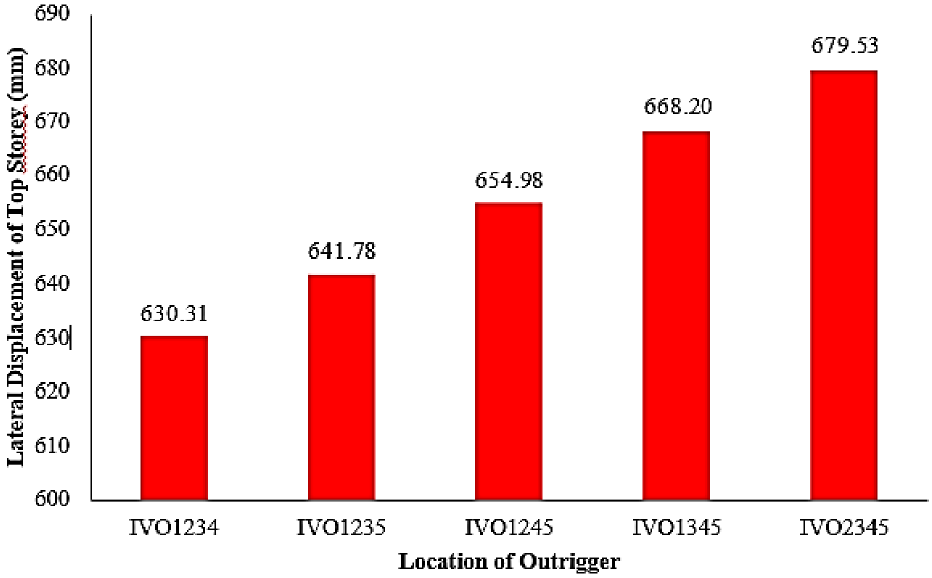


Figure 6 Lateral displacement of top storey for structure with four outriggers

Figure 6 gives the information about lateral displacement of top storey for structure with four outriggers with five different possible locations and Figure 7 gives the lateral displacement of top storey for structure with outriggers at each 20th storey.

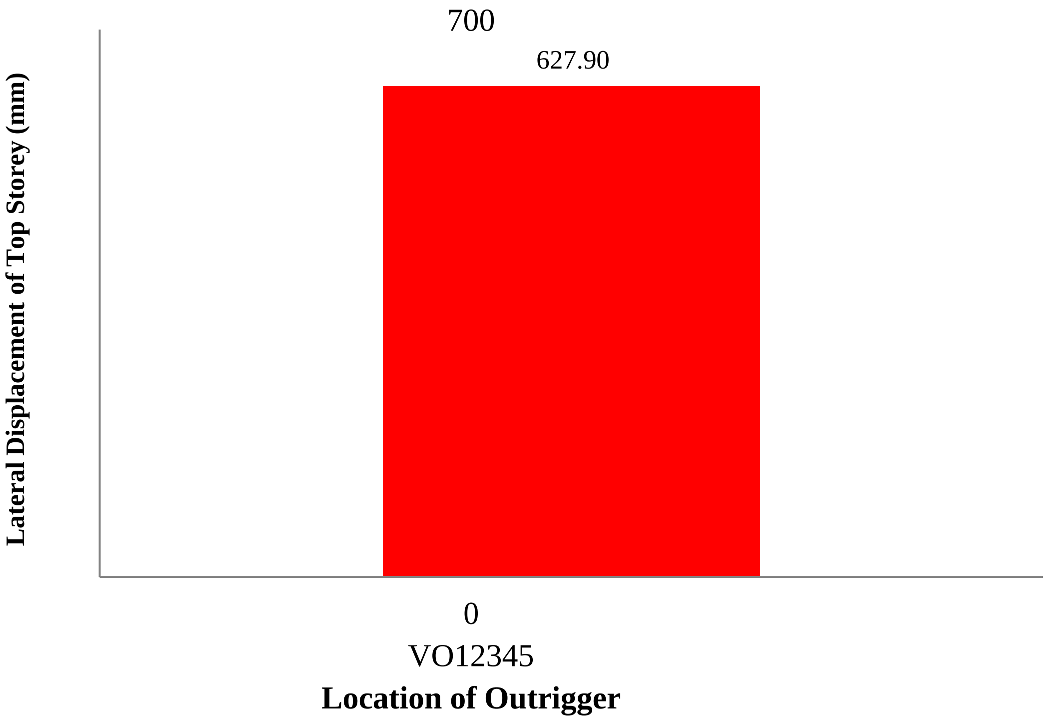


Figure 7 Lateral displacement of top storey for structure with five outriggersFigure 8 Top storey lateral displacement against number of outrigger(s)

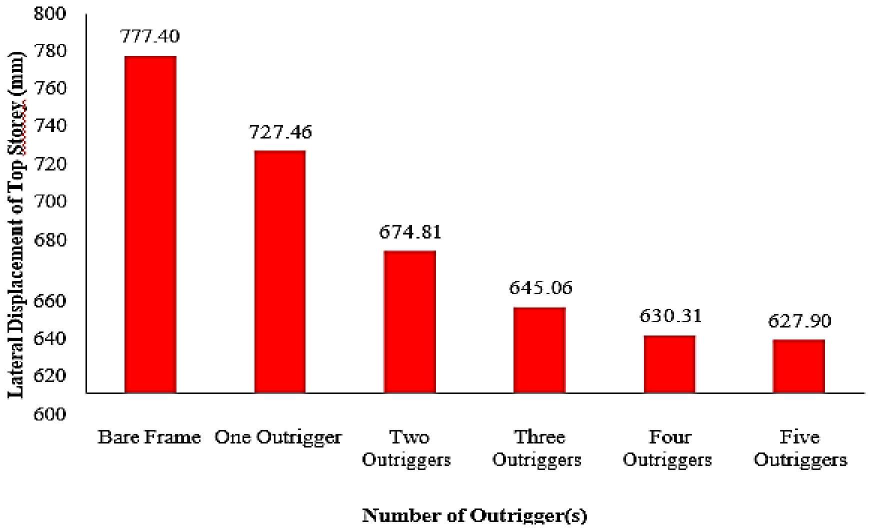


Figure 8 gives the brief idea about lateral displacement of top storey against number of outrigger(s) for optimal locations of outrigger(s).

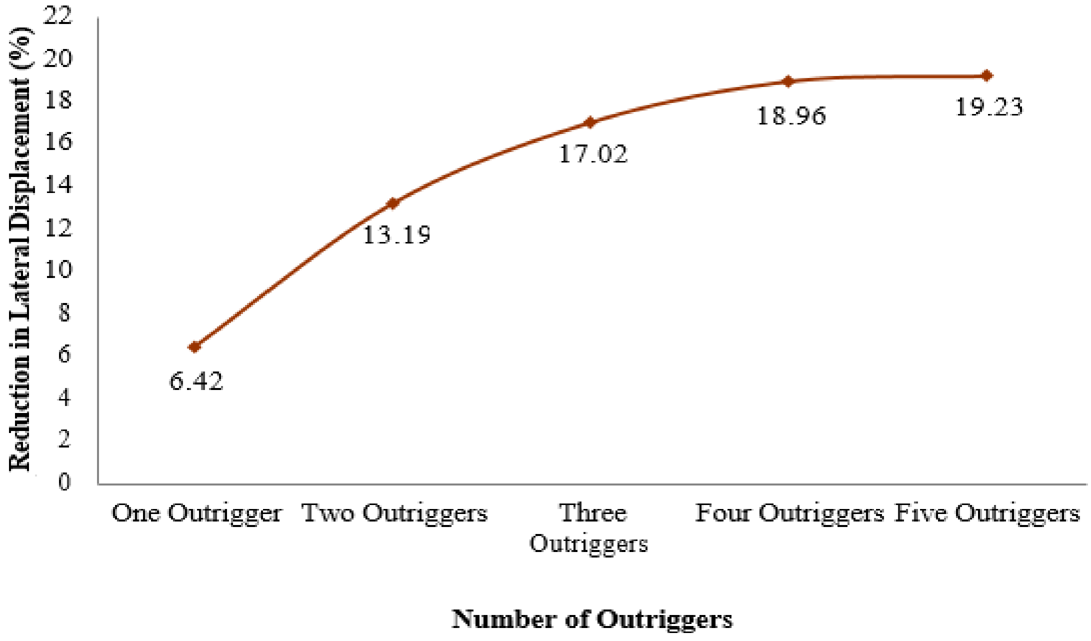


Figure 9 Percentage reduction in lateral displacement against number of outrigger(s)

Figure 9 gives the brief idea about reduction percentage in lateral displacement oftop storey structure for optimal position of outrigger(s).

1) Lateral Displacement

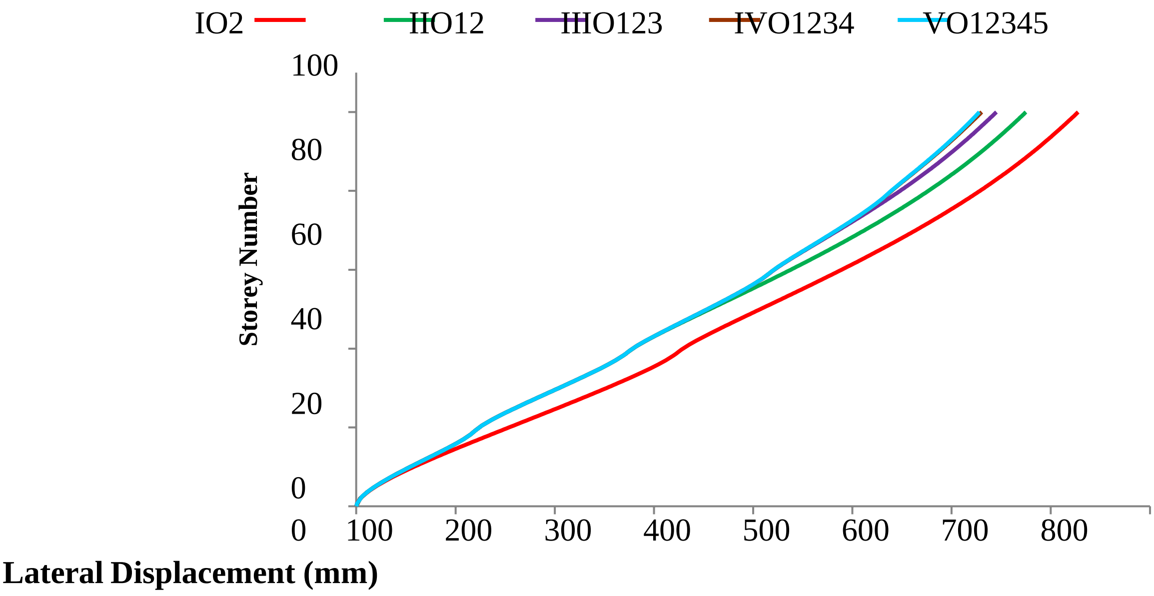


Figure 10 Lateral displacement due to wind loading against storey number

Figure 10 shows the lateral displacement against the storey number. It is observed that, as height of structure increases, lateral displacement also increases. But, there is sudden drop in lateral displacement at the level of outrigger(s) due to enhancement in lateral stiffness at that level. Also, there is overall reduction in lateral displacement as number of outrigger(s) increases in structure.

2) Storey Drift Ratio

Storey drift ratio is the ratio of lateral displacement of two consecutive stories. In other word it is ratio of lateral displacement of upper storey to the lateral displacementof lower storey.

$$Storey\ Drift\ Ratio = \frac{u(i+1)}{u_i} \qquad (6.1)$$

Where,

$u(i+1)$ = lateral displacement for $(i+1)^{th}$ floor,

ui = lateral displacement for i^{th} floor.

Figure 11 shows the Storey drift ratio for structural model with one outrigger whichis located at five different positioned (i.e. 20th, 40th, 60th, 80th and 100th storey). For structure with one outrigger which is located at 40th storey gives storey drift ratio low as compared to remaining four configurations.

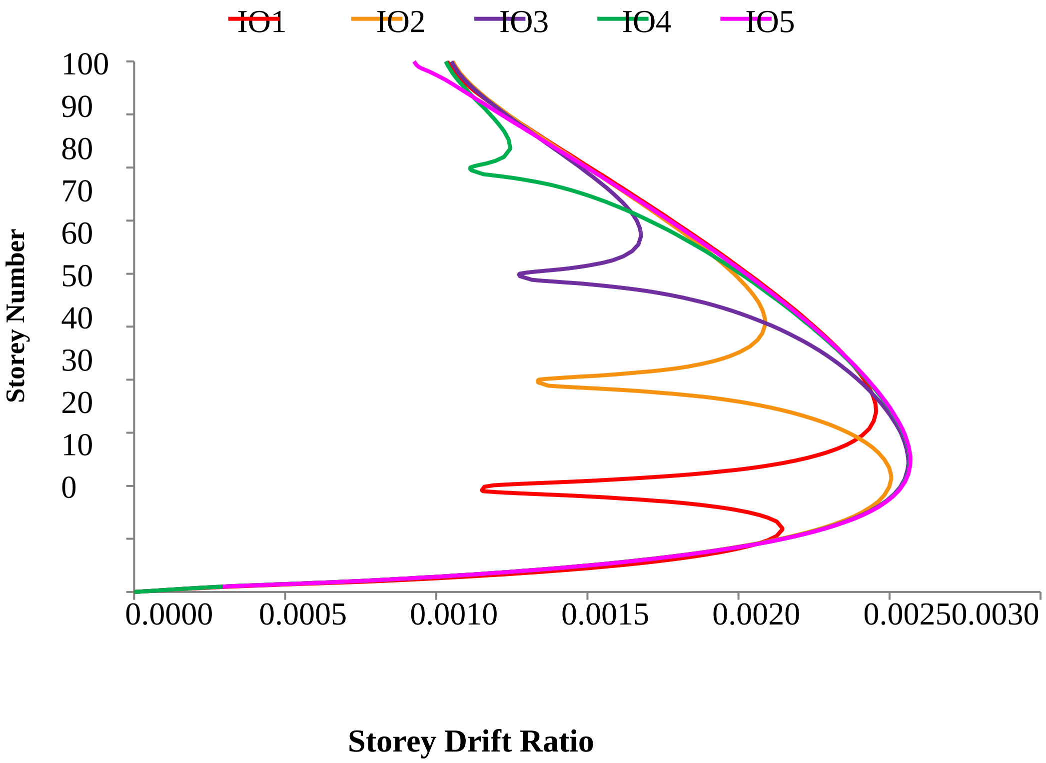


Figure 11 Storey drift ratio for structure with one outrigger

Figure 11, Figure 12, Figure 13 and Figure 14 gives information about storey drift ratio structure with two outriggers, structure with three outriggers, structure with four outriggers and structure with five outriggers respectively.

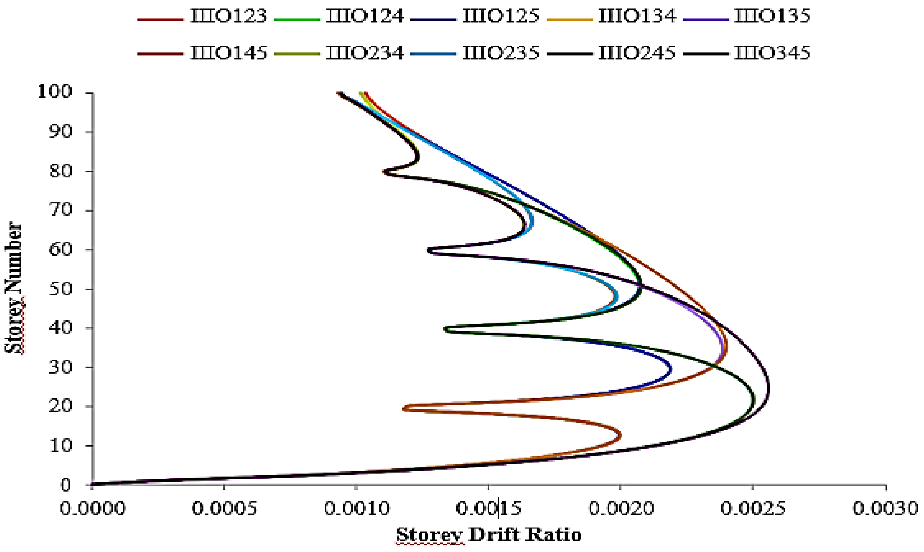
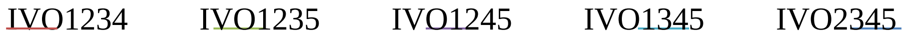


Figure 12 Storey drift ratio for structure with three outriggers



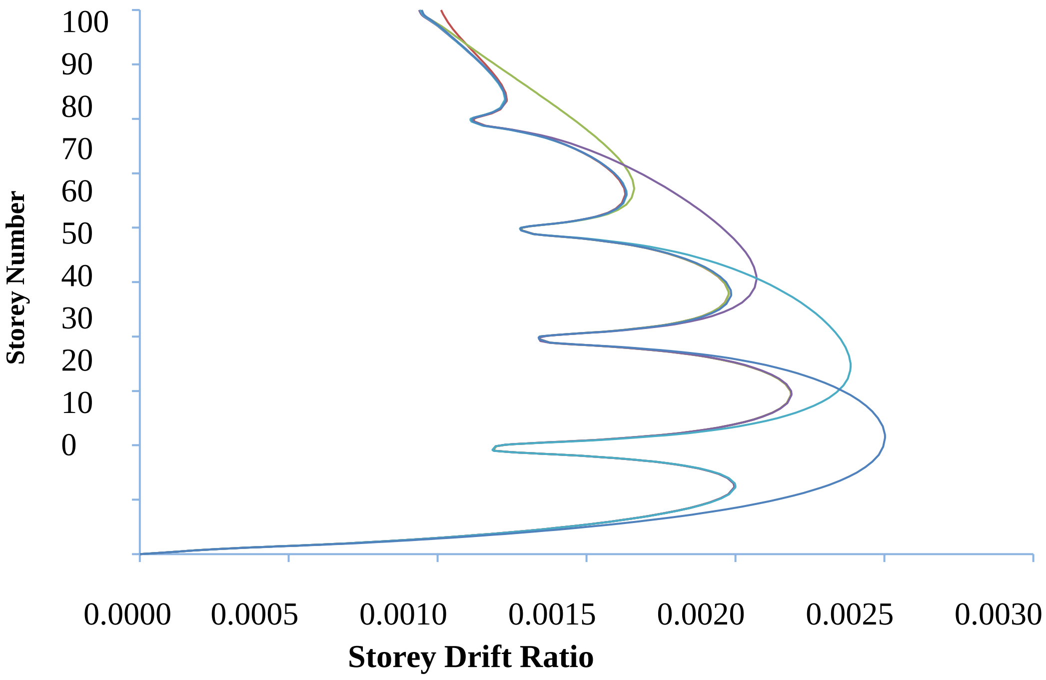


Figure 13 Storey drift ratio for structure with four outriggers

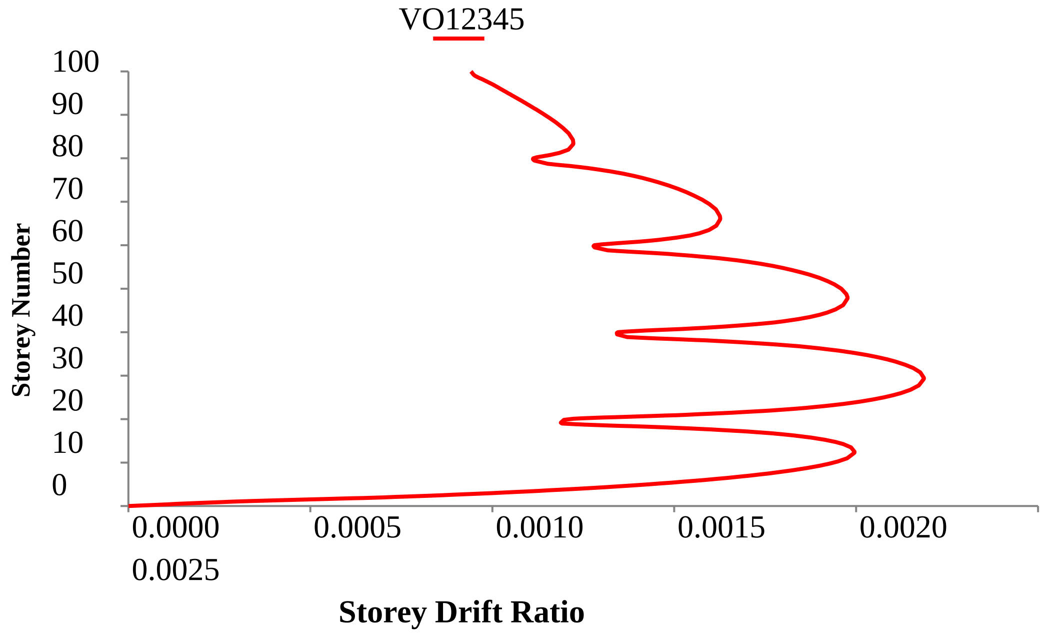


Figure 14 Storey drift ratio for structure with five outriggers

Figure 15 gives the storey drift ratio for optimal location of outrigger system. For bare frame structure, storey drift ratio is high in between 20th storey to 40th storey. At the level of outrigger(s), storey drift ratio is low due to there is reduction in lateral Displacement at that level where as some amount of reduction in storey drift ratio atthe each level of outrigger location(s).

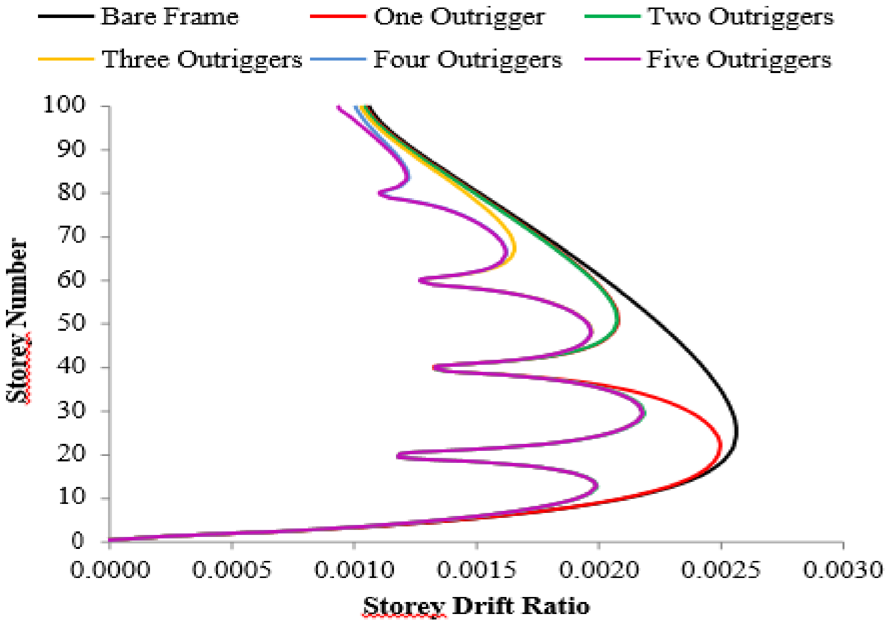


Figure 15 Storey drift ratio against optimal position of outrigger(s)

6.1.1 Storey Shear

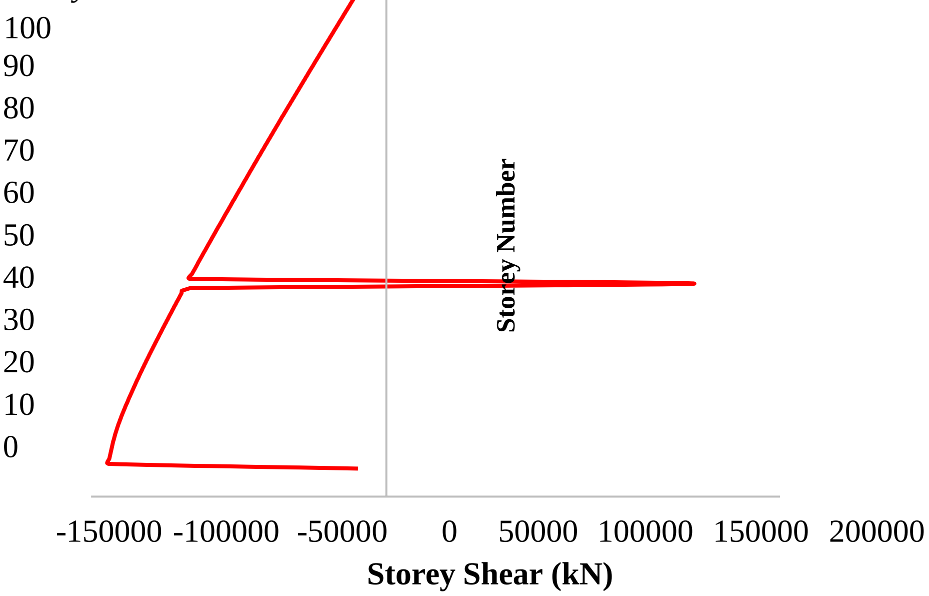


Figure 16 Storey shear due to wind loading for IO2 configuration

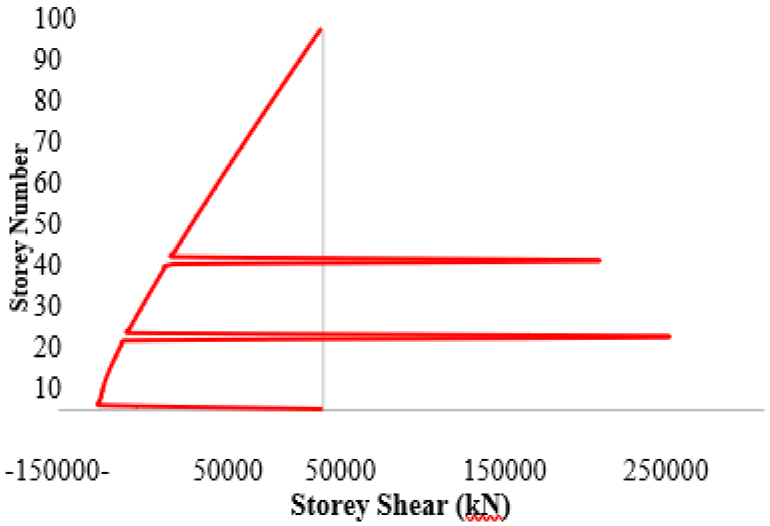


Figure 17 Storey shear due to wind loading for IIO12 configuration

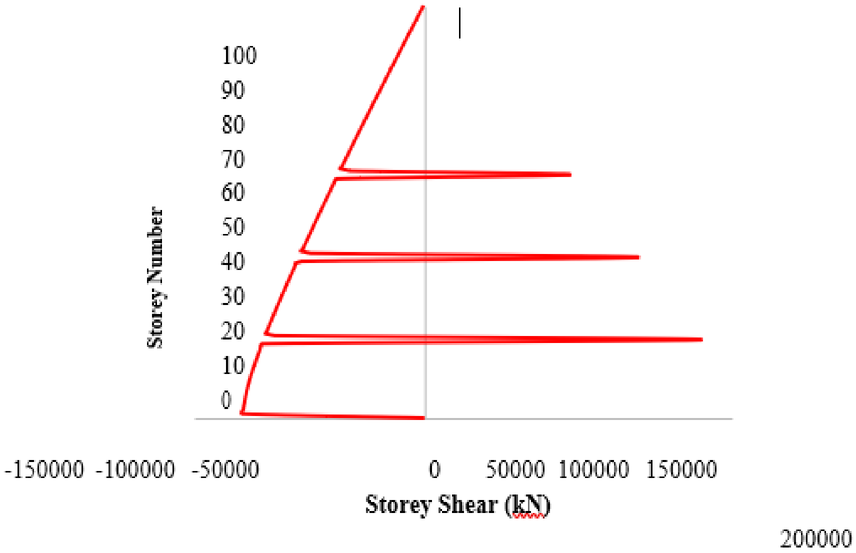


Figure 18 Storey shear due to wind loading for IIIO123 configuration

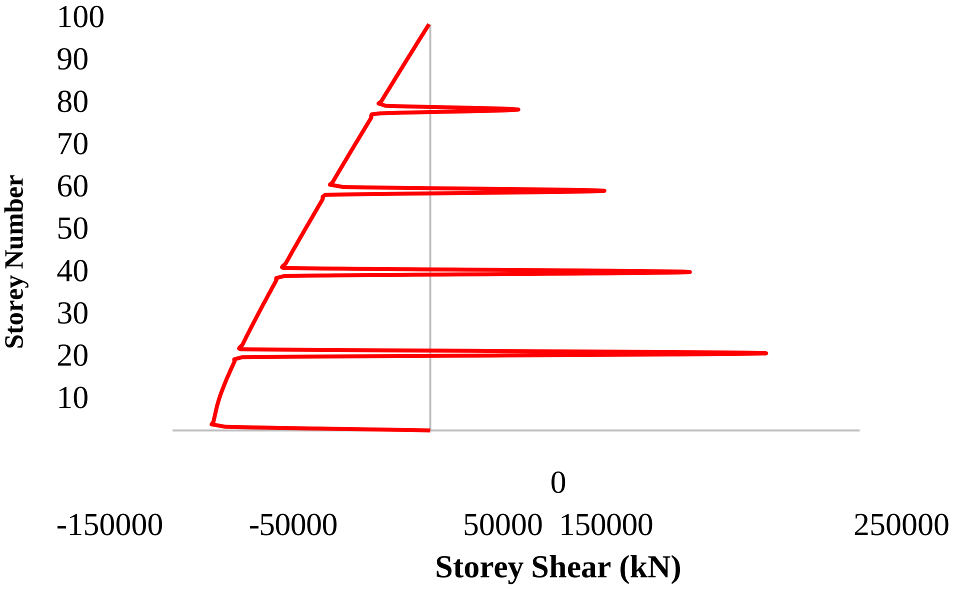


Figure 19 Storey shear due to wind loading for IVO1234 configuration

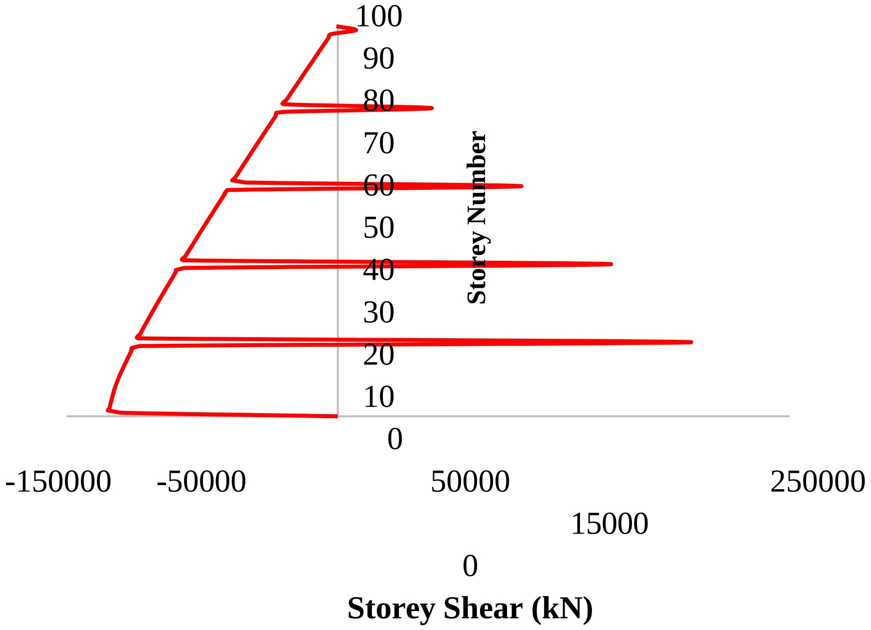


Figure 20 Storey shear due wind loading for VO12345 configuration

Due to gravity load and lateral loads, storey shear increases as we move vertically downward. From above figures it is observed that, at the level of outrigger and belt truss system, there is sudden change in its sign at that level. Storey shear distribution along the height of structure is parabolic (2^{nd} degree curve) in nature.

6.1.2 Pushover Curve

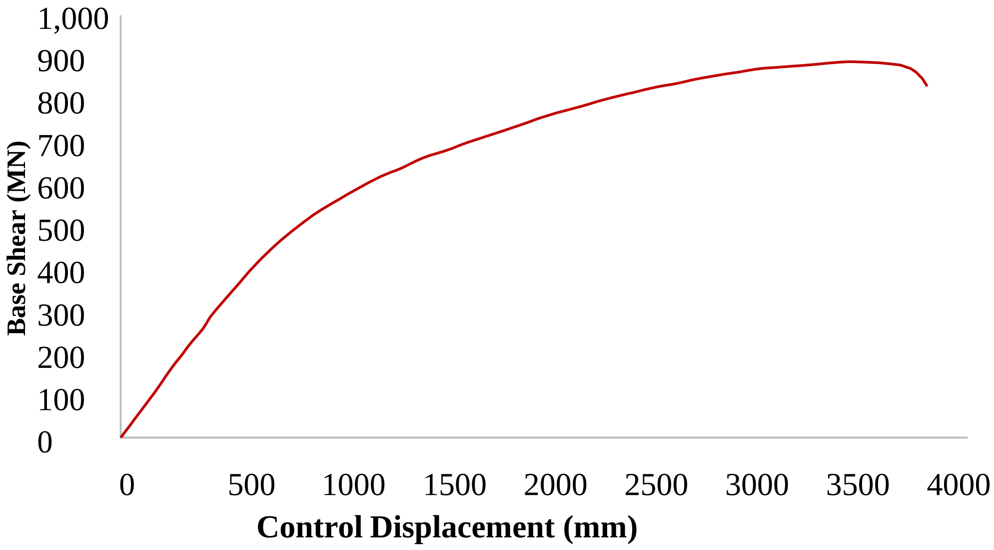


Figure 21 Pushover curve for bare frame

Discussion Of Results

Following are some key points discussed on basis of the results:

1) As the number of outrigger(s) increases, there is overall reduction in lateral displacement of high rise structure.

2) The lateral displacement of structure with the outrigger(s) located at bottom level storey is less as compared to structure with the outrigger(s) located at top level storey.

3) From Figure 9, it is observed that, there is sudden reduction in lateral displacement upto three numbers of outriggers but after that there is uniform reduction in lateral displacement.

4) It is observed that there is only 6.42% reduction in lateral displacement of the top storey for structure with one outrigger which is located at 40th storey.

5) Reduction in lateral displacement for structure with two outriggers (i.e. 20th and 40th storey) and structure with three outriggers (i.e. 20th, 40th and 60th storey) are 13.19% and 17.02% respectively.

6) There is no significance difference in percentage reduction in lateral displacement of the top storey for structure with four outriggers (i.e. located at 20th,40th,60th and 80th storey) and structure with five outriggers (i.e. located at 20th,40th,60th, 80th and 100th storey).

7) From Figure 10 it is observed that, as height of structure increases, lateral displacement also increases. There is sudden drop in lateral displacement at the level of outrigger(s) due to enhancement in lateral stiffness at that level.

8) As the number of outrigger(s) increases, the storey drift ratio of structure reduces.

Conclusions

Total 32 models are modeled and studied with varying the location of the outrigger(s) in this study. As number of outrigger increases, all the response parameters viz. top storey lateral displacement, storey drift ratio reduced. So, overall structural performance is improved. Finally, it is concluded that; the optimum outrigger location of a high rise building under the action of wind load is between 0.20-0.40 times the height of the building (from the bottom of the building). Also, structural performance of structure with more than four outriggers is not efficient.

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