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Seismic Analysis of High-Rise RCC Building Structure with Steel Outriggers and Belt Truss System

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Abstract: In the last five years, it has been observed that high-rise buildings are built utilizing outrigger beams & truss and belt truss for transferring lateral load induced due to earthquakes and wind load. But as the height of the building increases, stiffness becomes important and the outrigger system provides lateral stiffness to the building. In this research, the high-rise RCC Structure with steel outrigger and belt truss system are provided at various positions along the height of the structure. And analyzed using linear method & non-linear method.
The modelling and analysis of the RCC building provided with an X-type & V-type bracing systems are carried out with ETABS software. The main aim of the research is to model a 40-story building to identify the optimum location of the outrigger under earthquake load. The key parameters discussed are lateral displacement, base shear and story drift. It is concluded that X-type bracings are more effective.
Keywords: Linear & Non-linear method of analysis; Outrigger system; Belt truss system; Lateral displacement; Base shear; Story drift

1 Introduction:

1.1 General Information:

Tall building development has witnessed significant global growth, leading to new engineering challenges that demand careful consideration. Modern tall structures commonly employ a system of coupled shear walls to withstand lateral loads caused by wind or earthquakes. However, as buildings increase in height, the importance of structural stiffness becomes paramount. To enhance lateral stiffness and ensure safety, outrigger beams are frequently incorporated between shear walls and external columns. The potential risk posed by earthquake ground motion is a critical concern worldwide, particularly for tall buildings that house numerous occupants. Addressing the safety and stability of these structures during severe earthquakes is of utmost importance, given their capacity to accommodate thousands of people. The possibility of structural collapse in these tall buildings could result in catastrophic consequences of intolerable magnitudes. Incorporating outrigger beams into building design requires careful consideration to ensure their optimal placement for cost-effective solutions. Various approaches have been utilized to determine the best locations of these outrigger beams when accounting for wind loads. Nevertheless, there is a notable lack of scientific research or case studies addressing the identification of optimum outrigger locations under earthquake loads.

1.2 Concept Outrigger:

An outrigger system is a structural design technique used to enhance the lateral stability of tall buildings or structures. When a building becomes taller, it faces increased lateral forces due to wind, seismic activity, or other external factors. These forces can cause the building to sway, potentially leading to discomfort for occupants and structural integrity concerns. To counteract these lateral forces, engineers employ outrigger systems, which are horizontal structures extending from the core of the building to the exterior. The outriggers are typically connected to vertical columns and linked to the building's perimeter or intermediate columns. The combination of the outriggers and the core forms a rigid system that distributes lateral forces more evenly throughout the building, reducing sway and improving stability.

1.3 Outrigger System:

In the design of tall structures, the core-wall system has proven highly effective in mitigating drift caused by lateral loads. However, as buildings grow taller, the core's stiffness may become insufficient to maintain drift within acceptable limits. To address this challenge in high-rise constructions, outriggers are introduced as horizontal structural systems. Outriggers play a crucial role in enhancing the overall lateral stability of tall buildings and effectively reducing drift. By incorporating horizontal elements that connect the core to the building's perimeter, outriggers facilitate a more balanced distribution of lateral loads. This, in turn, significantly improves the building's lateral stiffness and performance. The strategic implementation of outriggers ensures the structure's ability to withstand lateral forces, including those induced by seismic activities or wind pressure, while staying within acceptable drift limits. Consequently, outriggers provide a vital solution for constructing exceptionally tall buildings that are secure and resilient, offering enhanced structural integrity and stability. The outrigger in a building is shown in Figure 1.

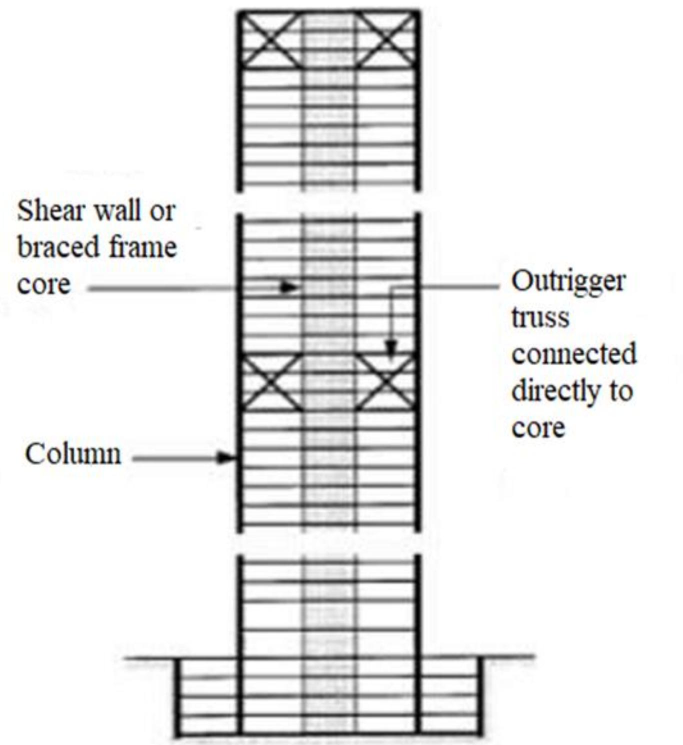

Figure 1. Conventional outriggers in tall buildings.

1.4 Working Principle of Outrigger:

The primary purpose of outriggers is to mitigate the global deformation of a building, stemming from the flexural behaviour of its resistant core. This is accomplished by reducing the overturning moment within the cantilever design and redirecting the diminished moment to the outer structural members through highly rigid horizontal beams known as outriggers. These outriggers are precisely connected to the core at specific levels. The effectiveness of the outrigger system hinges on two critical factors: the flexural stiffness of girder and axial stiffness of vertical columns in building's perimeter. Furthermore, the incorporation of deep spandrel girders, functioning as belts encircling the entire structure, enables the engagement of additional peripheral columns to support and reinforce the outriggers. This additional support can lead to a significant improvement in stiffness, often up to 25-30 percent. To ensure adequate stiffness in both flexure and shear, outriggers and belt girders are commonly designed with a vertical extension that spans at least one or two stories. This design strategy allows these elements to effectively contribute to the building's overall lateral stability and enhance its capacity to withstand lateral forces, such as those induced by seismic or wind loads. Figure 2 shows the structural behaviour and mechanics of buildings with and without outriggers.

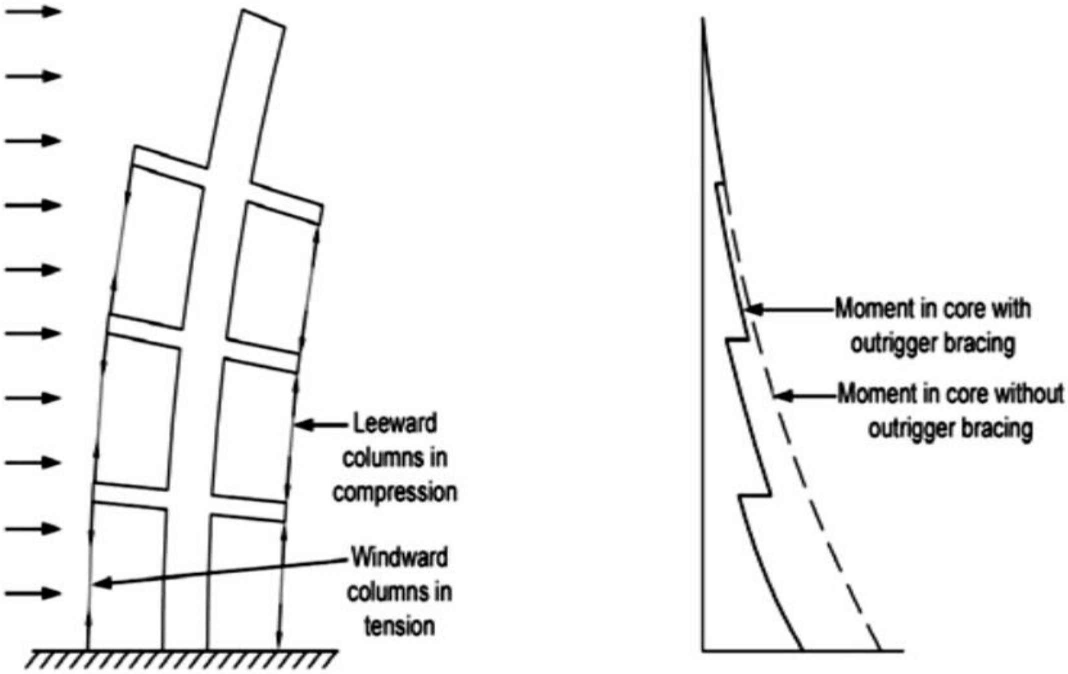

Figure 2. Structural behaviour of an outrigger system is depicted, along with a comparison of moment diagrams with and without outrigger bracings

2. Methodology:

2.1 General:

The methodology essential for accomplishing the project's intended goals and objectives. It provides a comprehensive description of the analysis method and the model used in this inspection. The study focuses on examining how the outrigger structural system influences the response of a high-rise reinforced concrete (RCC) building under seismic forces. The seismic analysis methods employed for estimating the demand on the structure can be categorized into the following two types,

- Linear Dynamic Method
- Non-Linear Time History Analysis Method

2.1.1 Linear Dynamic Method:

Linear Dynamic Method is employed assess structural demand a building when its response is predominantly influenced by multiple vibration modes. This approach enables the estimation of the building's dynamic behaviour under such complex conditions, allowing for a comprehensive analysis of its response to various excitations and loading scenarios.

- **Response Spectrum Method**

The Response Spectrum Method serves as a widely adopted approach in seismic analysis and structural design, particularly in cases where actual time history records for a specific location are not available. This method goes beyond relying solely on peak ground acceleration by incorporating frequency content of ground motion and dynamic properties of structure to predict its response to seismic forces. In practical terms, using smooth design spectra produced from the average of several seismic motions, the approach computes the maximum displacements and member forces for each vibration mode. These response spectra are graphical representations that plot greater response of a Single Degree of Freedom (SDOF) system against its time period (or frequency) for a given damping ratio. By employing response spectra, engineers can ascertain the peak structural responses under linear conditions, thereby aiding in the design of earthquake-resistant structures and calculation lateral forces induced by seismic events. This analytical process entails conducting frequency domain analysis to determine response of the SDOF system for various time periods, followed by plotting the results to create response spectra for specified damping ratios and input ground motion. Through this iterative approach, incorporating different damping ratios, engineers can obtain comprehensive response spectra that provide valuable insights into the structural behavior under seismic loads. These response spectra play a critical role in ensuring the structural integrity and safety of buildings and other infrastructure subjected to seismic forces.

2.1.1 Non-Linear Time History Analysis Method:

Non-linear Time History Analysis method holds significant importance in seismic estimation of structures, particularly when their response exhibits non-linear behaviour. This technique involves a step-by-step examination of dynamic response of a structure subjected time-varying loading, typically represented by a seismic event's time history. By conducting this analysis, engineers can accurately assess how a structure will react to the dynamic forces imparted by a representative earthquake. This approach considers the non-linearities inherent in the structural system, such as material yielding and other non-linear effects, leading to more realistic and precise predictions of the structure's performance under seismic conditions. To execute the Non-linear Time History Analysis, it is necessary to have an acceptable earthquake time history that represents the expected ground motion at the structure's location. Armed with advanced computational tools and expertise, engineers can simulate and analyze the structure's response at each time step, gaining valuable insights into its behaviour during seismic events. This rigorous evaluation enables the design and implementation of robust structures capable of withstanding the challenges posed by seismic forces effectively. Due to this the problem of design is confined only to determine the area of diagonal members. As per the design suggested by Moon et al. (2007), the area of members along web and flange are calculated.

2.2 Problem Statement for Dissertation:

The proposed study aims to analyze seismic resistance of high-rise G+40 RCC building with a structural system comprising coupled shear walls. To enhance the building's ductility and provide adequate stiffness, steel outriggers will be incorporated between the shear walls and external columns. The outrigger system will consist of X-type and V-type bracings, along with a belt truss system. The primary objective is to determine the optimal placement of these outriggers within the high-rise building to effectively withstand lateral loads induced by earthquakes. ETABS software is used to prepare models and analysis it.

2.2.1 Input Data of Building:

- Type of Structure- G+40 Story High-Rise RCC Building
- Outrigger Bracing System- V-type and X-type
- Section of Bracing- Square Box Section
- Size of Beam- 400x800mm
- Size of Column- 900x900mm
- Height of Floor- 3m

2.2.2 Material Properties:

The following basic material properties are utilized in the analysis:

- Modulus of Elasticity of Steel, Es- 20,0000 MPa
- Modulus of Elasticity of Concrete, Ec-27386.12 MPa
- Grade of Concrete of Column- M40
- Grade of Concrete of Beam and Slab-M30

2.3 Model Details:

A high-rise RCC building structure's seismic reactivity, specifically a G+40 storied building with an outrigger structural system, is the focus of this study. The modelling and analysis were conducted using ETABS software.

Figure 3. Plane of building

2.3.1 Given Data:

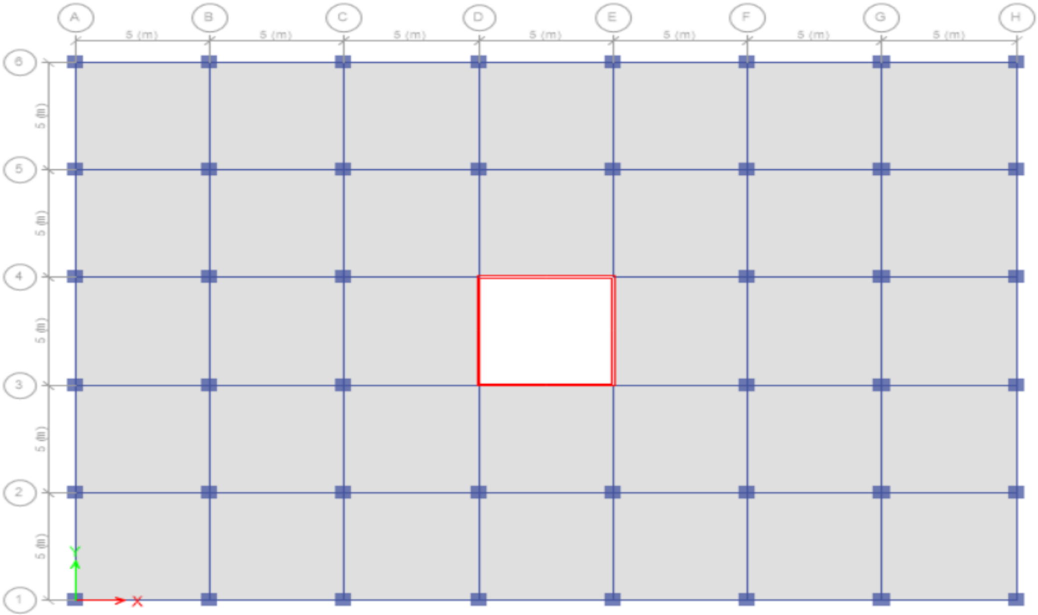

Table 1. Details of G+40 story RCC building

Type of Frame	Ordinary Braced Frame
Building Plan Dimensions	35 x 25 m
Bays in X- & Y- Direction	X-direction – 7 bays of 5m each Y-direction – 5 bays of 5m each
No. of Floors	G+40 (41storied)
Seismic Zone	IV
Seismic Zone Factor	0.24
Soil Type	Medium case
Importance Factor	1.2
Response Reduction Factor	5
Height of Floor	3m

Slab Thickness	200mm
Type of Outrigger Brace	Tube Section
Thickness of Tube Section	25mm
Size of Brace	400x400mm

2.4 Modelling and Analysis:

The main objective of work is to examine and analyze impact by employing an outrigger structural system in reaction to the response behaviour earthquake stresses on a high-rise Reinforced Concrete (RCC) structure. The computational modelling for this investigation is conducted utilizing ETABS software, which relies on the finite element method of analysis for accurate simulations. By employing this advanced software and methodology, the study aims to gain valuable insights into how the outrigger system influences the overall seismic performance of tall RCC structures.

2.4.1 Modelling of Building:

The modelling and analysis of a 40-story building using the ETABS software. The primary focus is to conduct a comparative study between two structural configurations: one with an outrigger system and the other without. The outrigger system is implemented using V-type and X-type bracing systems, along with belt trusses. Through this meticulous investigation, the study's goal is to examine and contrast seismic performance & behaviour of the building under these two distinct structural schemes. The use of ETABS software ensures accurate and reliable simulations, providing valuable insights into the effectiveness and benefits of employing outrigger systems in high-rise construction.

- Model 1 - Conventional model using no outriggers. (Fig.4)
- Model 2 - Model using V type braced outriggers positioned 12h, 27th, 41th story. (Fig.5)
- Model 3 - Model using X type braced outriggers positioned12h, 27th, 41th story. (Fig.6)
- Model 4 - Model using V type braced outriggers positioned 8th, 19th, 30th, 41th story. (Fig.7)
- Model 5 - Model using X type braced outriggers positioned 8th, 19th, 30th, 41th story. (Fig.8)
- Model 6 - Model using V type braced outriggers positioned 9th, 17th, 25th, 33th, 41th story. (Fig.9)
- Model 7 - Model using X type braced outriggers positioned 9th, 17th, 25th, 33th, 41th story. (Fig.10)

2.4.2 Software Modelling of G+40 story Conventional Building:

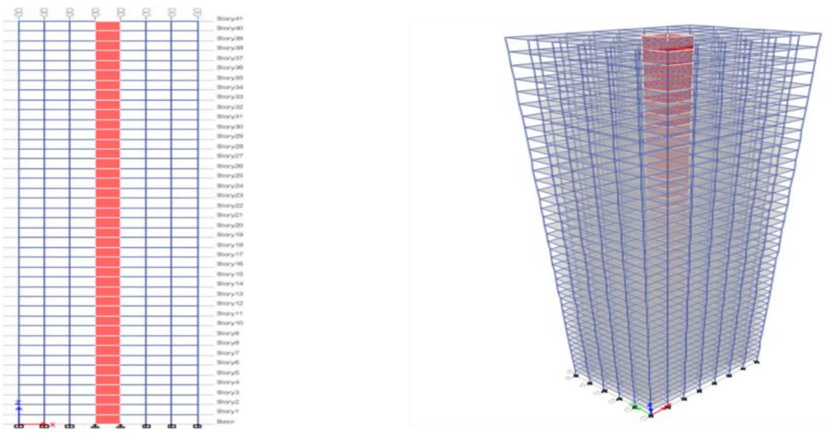

Figure 4. Model of G+40 Conventional Building

2.4.3 Software Modelling of G+40 story Building with Outrigger using er using V type and X type bracing located at 12th, 27th, 41th Story

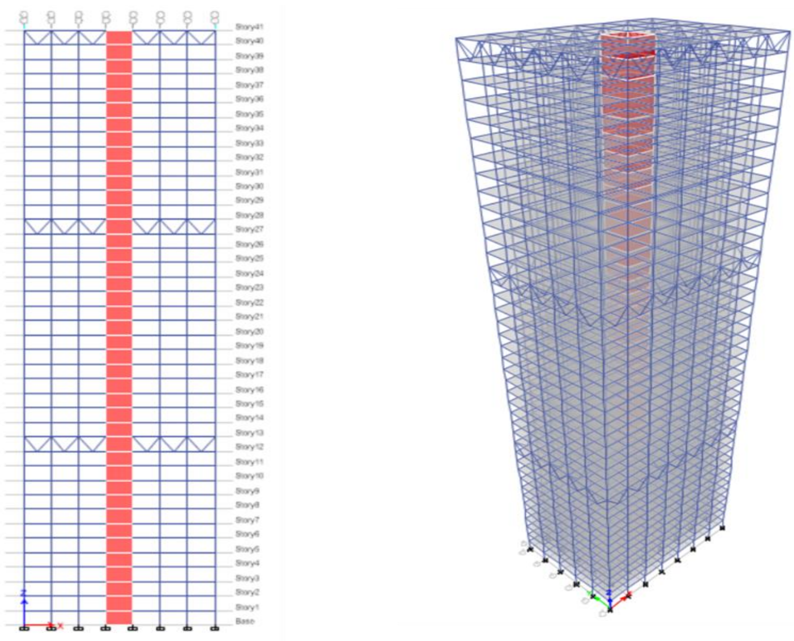

Figure 5. Model of G+40 Building with outrigger using V type bracing positioned at 12th, 27th, 41th Story

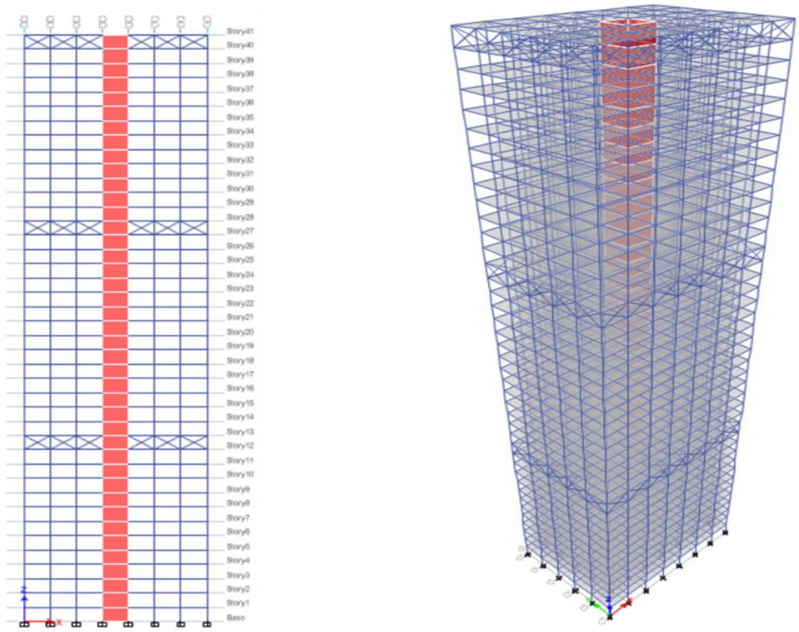

Figure 6. Model of G+40 Building with outrigger using X type bracing positioned at 12th, 27th, 41th Story

2.4.4 Software Modelling of G+40 story Building with Outrigger using er using V type and X type bracing located at 8th, 19th, 30th, 41th Story

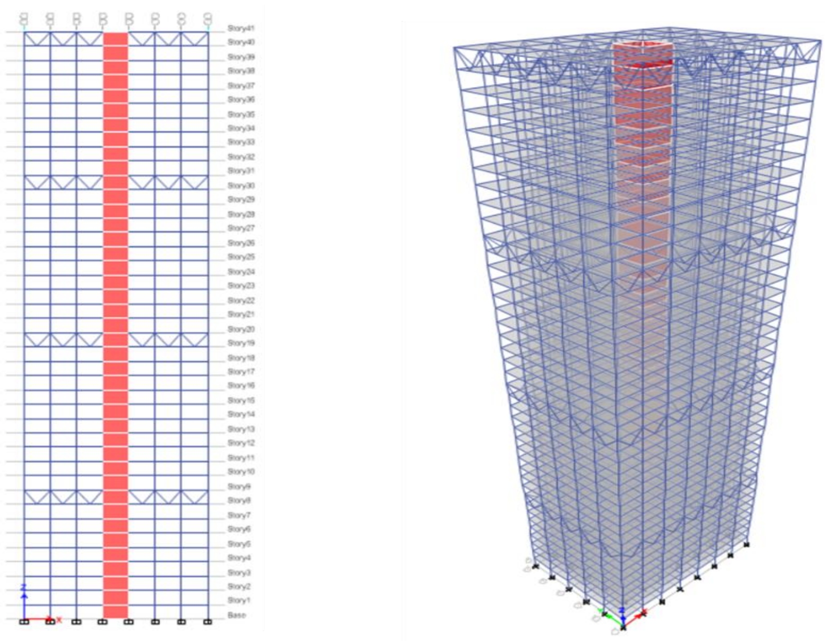

Figure 7. Model of G+40 Building using outriggers by V type bracing positioned at 8th, 19th, 30th, 41th Story

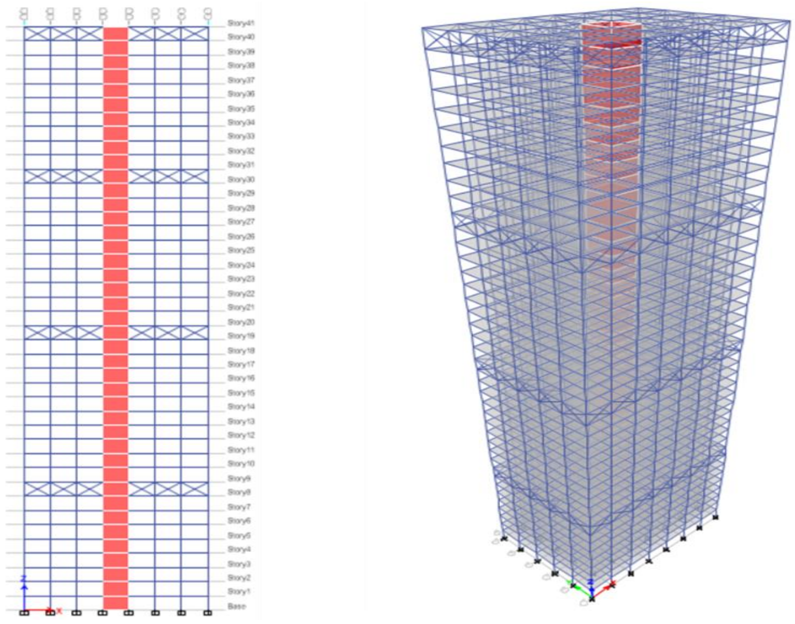

Figure 8. Model of G+40 Building using outriggers by X type bracing positioned at 8th, 19th, 30th, 41th Story

2.4.5 Software Modelling of G+40 story Building with Outrigger using er using V type and X type bracing located at 9th, 17th, 25th, 33th, 41th Story

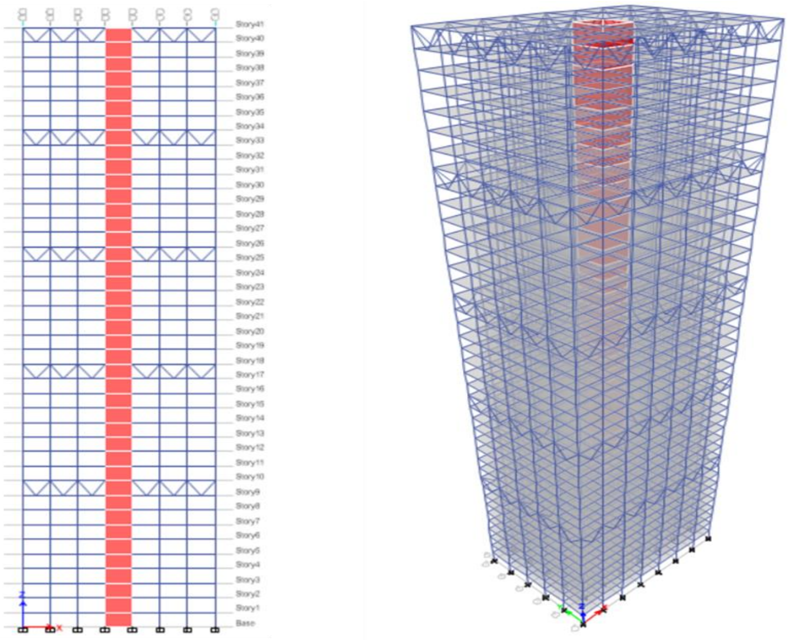

Figure 9. Model of G+40 Building using outriggers by V type bracing positioned at 9th, 17th, 25th, 33th, 41th Story

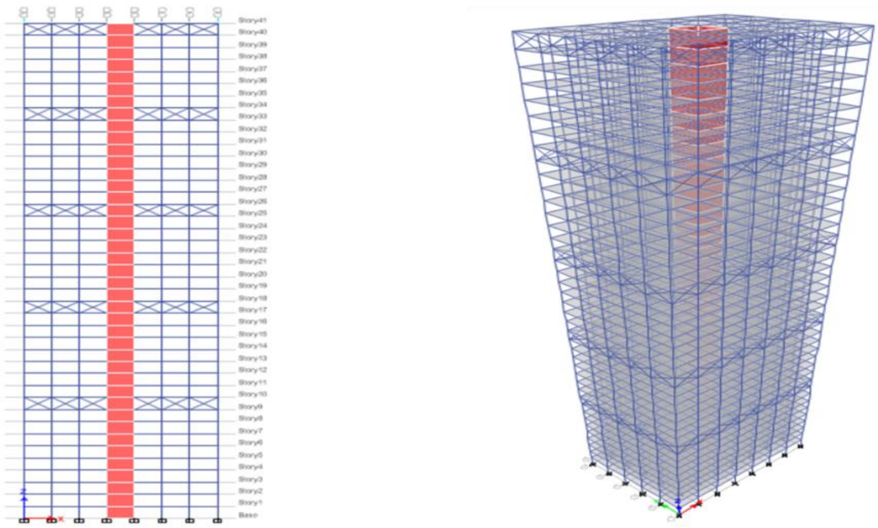

Figure 10. Model of G+40 Building using outriggers by X type bracing positioned at 9th, 17th, 25th, 33th, 41th Story

3. Results and Discussion:

3.1 Comparative Results:

- **Lateral Displacement**

Table 2. Maximum Lateral Displacement from Linear Dynamic Analysis

No. of Model	Max displacement at top story (mm)	depletion (%)
Model 1	483.53	-
Model 2	371.49	23.16%
Model 3	368.42	23.80%
Model 4	352.46	27.10%
Model 5	350.33	27.54%
Model 6	346.63	28.31%
Model 7	344.23	28.80%

The variation of lateral displacement has been graphically represented below in figure 11,

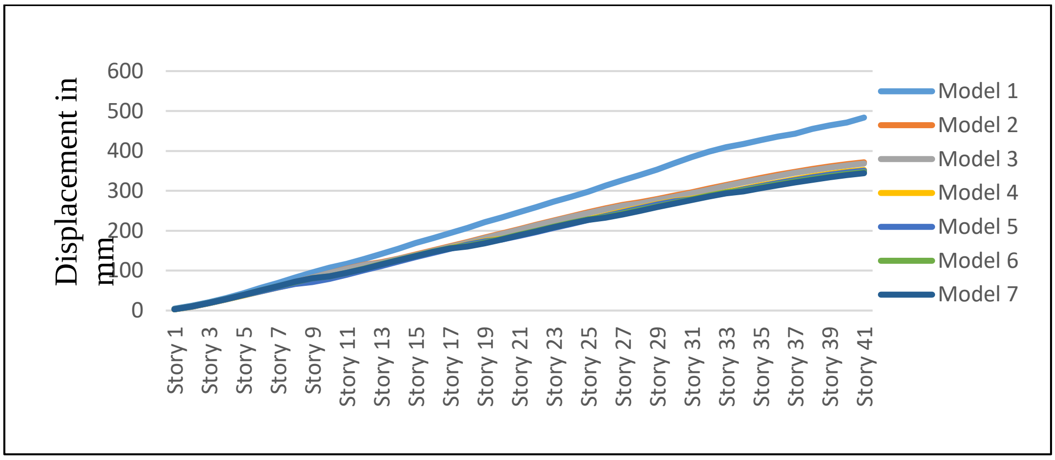

Figure 11. Comparison of lateral Displacement from Linear Dynamic analysis

From this graph, it is observed that RCC building with X-type outrigger bracing system along with belt trusses provided at 9th, 17th, 25th, 23th, 41th stories reduces the lateral displacement by 28.80% compared to conventional building and gives minimum result values than building with V-type bracing outriggers.

Table 3. Maximum Lateral Displacement from Non-Linear Time History Analysis

No. of Model	Max displacement at top story (mm)	depletion (%)
Model 1	452.72	-
Model 2	353.34	21.95%
Model 3	344.25	23.96%
Model 4	337.52	25.44%
Model 5	330.81	26.92%
Model 6	329.27	27.26%
Model 7	324.16	28.39%

The variation of lateral displacement has been graphically represented below in figure 12

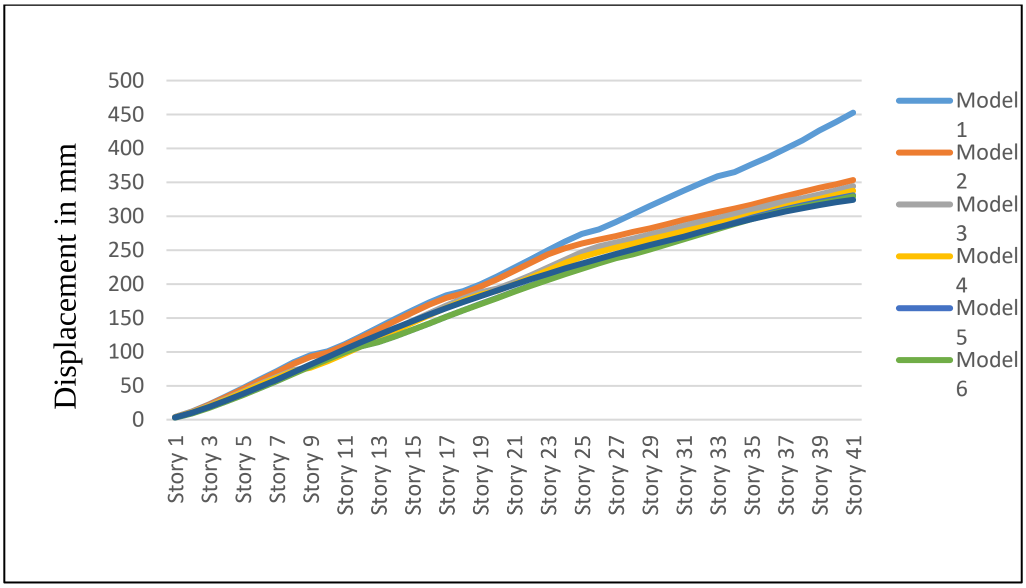

Figure 12. Comparison of lateral Displacement from Non-Linear Time History analysis

From this graph, it is observed that RCC building with X-type outrigger bracing system along with belt trusses provided at 9th, 17th, 25th, 23th, 41th stories reduces the lateral displacement by 28.39% compared to conventional building and gives minimum result values than building with V-type bracing outriggers.

- **Story Drift**

Table 4. Maximum Story Drift from Linear Dynamic Analysis

Model No.	Max story drift	depletion (%)
Model 1	0.00531	-
Model 2	0.00407	23.35%
Model 3	0.00406	23.54%
Model 4	0.00393	25.98%
Model 5	0.00392	26.17%
Model 6	0.00388	26.93%
Model 7	0.00386	27.31%

From above, it is observed that 27.31% reduction in story drift is occurred in building with X-type outrigger bracing system with belt trusses provided at 9th, 17th, 25th, 23th, 41th story than conventional building and gives minimum result values than building with V-type bracing outriggers.

Table 5. Maximum Story Drift from Non-Linear Time History Analysis

No. of Model	Max story drift	depletion (%)
Model 1	0.00476	-
Model 2	0.00367	22.89%
Model 3	0.00366	23.10%
Model 4	0.00354	25.63%
Model 5	0.00353	25.84%
Model 6	0.00348	26.89%
Model 7	0.00347	27.10%

From above, findings are 27.10% reduction in story drift is occurred in building with X-type outrigger bracing system with belt trusses provided at 9th, 17th, 25th, 23th, 41th story than conventional building and gives minimum result values than building with V-type bracing outriggers.

- **Base Shear**

Base shear is largest anticipated lateral force resulting from earthquake ground motion that acts as base of building structure. Base shear is depending on soil conditions, dead weight of structure, seismic ground motion etc.

Table 6. Maximum Base Shear from Linear Time Dynamic Analysis

No. of Model	Max base shear (KN)
Model 1	62256.51
Model 2	66671.01
Model 3	66706.19
Model 4	69196.18
Model 5	69760.22
Model 6	70582.28
Model 7	71294.37

Table 7. Maximum Base Shear from Non-Linear Time History Analysis

No. of Model	Max base shear (KN)
Model 1	56668.44
Model 2	62766.06
Model 3	63423.69
Model 4	71357.15
Model 5	71658.04
Model 6	74721.17
Model 7	77790.47

The analysis reveals that the inclusion of belt trusses and outriggers in the structure results in only a marginal increase in base shear compared to conventional buildings. The presence of steel outriggers in an RCC building leads to minimal changes in base shear due to higher dead weight of reinforced concrete when compared to steel. Given that weight of the outriggers is considerably lower than that of building structure, there is no significant alteration in the base shear values.

3.2 Discussion:

This chapter presents the comprehensive results obtained from both the models with outriggers and the models without outriggers. A detailed comparison is conducted, focusing on key parameters such as displacement, drift, and base shear. The objective is to analyze and assess the performance differences between the two structural configurations, shedding light on the impact of outriggers on the overall behaviour of the building under various loading conditions. By meticulously examining these results, valuable insights can be gained, aiding in the understanding of the effectiveness and advantages of incorporating outriggers in tall building design for enhanced seismic resistance and reduced lateral deformations.

4. Conclusion

Based on results obtained from seismic analysis of the G+40 storey RCC building, with and without the outrigger structural system, yields following conclusions.

- Seismic analysis of G+40 storey building with an outrigger system reveals a significant reduction in responses, including lateral displacement, storey drift, and base shear. These findings align well with the conclusions drawn from the existing literature study. The incorporation of outriggers proves to be an effective approach in enhancing the overall structural behaviour, resulting in improved seismic performance and reduced lateral forces.
- Linear and non-linear analysis of RCC building incorporating outrigger systems, utilizing both V and X type bracing, reveals that X type bracings exhibit

superior performance compared to V type bracings. The observations indicate that X type bracings yield the minimum values for both displacement and drift. These results underscore the heightened effectiveness of X type bracings in enhancing the building's lateral stability and mitigating structural deformations during seismic loading.

- Linear dynamic method of analysis for RCC building equipped using an outrigger system using X type bracings, lateral displacement, and greatest storey drift experience a decrease of 28.80% and 27.31%, respectively, in comparison to values derived by analysis of a conventional RCC building. In nonlinear method of analysis, lateral displacement, and greatest storey drift undergo a reduction of 28.39% and 27.10%, respectively, in comparison to values obtained from the analysis of the conventional RCC building. These findings demonstrate the consistent and notable effectiveness of the outrigger system using X type bracings in reducing lateral deformations and improving the building's overall structural response to seismic forces.

The linear dynamic method of analysis holds more significance than the non-linear method because it accounts for the maximum peak ground acceleration. In linear analysis, the consideration of peak ground acceleration is crucial for understanding the building's response to seismic forces. This information is essential in assessing the structural behaviour and ensuring the safety of the building under seismic loading conditions.

The optimal placement of outriggers, resulting in minimum lateral displacement and storey drift values for the building structure under seismic forces, is identified to be within the range of 0.20-0.30 times the building's height from the bottom. This specific location demonstrates its effectiveness in enhancing the building's lateral stability and reducing structural deformations during seismic events.

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