Dynamic Analysis of High-Rise Structures with Outrigger Structural System Subjected To Lateral Loads

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Abstract. In this age of urban development and rapid modernization the need of high-rise structures is rapidly increasing as buildings have gotten taller and narrower, the structural engineering has been increasingly challenged to meet the desired stability requirements. In tall buildings, stiffness is the key to sustainability, among various types of structural systems available for tall buildings, outrigger system is one of the majorly used efficient system. The present study aims to identify the efficiency of outrigger shear walls and to find out the optimum position of outriggers in high rise structures under lateral loads. The outrigger systems are required to have additional stiffness and adequate damping, by which outrigger can be used as a structural fuse to protect the building under severe earthquake and wind conditions.

This research work aims to study the dynamic analysis of high-rise structures with outrigger structural system, for this research two regular buildings of 36 & 50 storeys situated in seismic zone V having a constant area of 900sqm(30mx30m) with a typical storey height of 3m were analysed using ETABS 2018. Optimum position of outrigger is determined by considering 8 models in which positions of outriggers is varied along the building height. Response spectrum analysis is carried out to evaluate the performance of structure for earthquake loads and the Gust factor method is used for the dynamic analysis of wind loads. Parameters such as Modal Mass Participation, Base Shears, Storey Displacements, Storey Drift, Time-periods, and acceleration are compared. Upon comparison it was found that among all 36 storey models outriggers placed at extreme ends performed better than other models and among all 50 storey models’ outriggers placed at regular intervals has performed better to all other models.

Keywords: Outrigger Structural System, High Rise Structure, Linear-Dynamic statistical analysis, Gust Factor Analysis.

1. Introduction

Over the last few years, the process of designing high-rise structures has evolved. In recent years, comprehensive three-dimensional finite element models of structures have become a commonplace. This is owing to more advanced software capabilities and higher computational power. However, these models generate a large amount of data and outputs, making it easy to ignore any flaws, especially if the model is large and sophisticated. It's simple to accept these conclusions without question if the designer isn't diligent and doesn't understand structural behaviour or finite element modelling. Furthermore, differing modelling methods have a significant impact on the force and stress distribution, which can lead to lengthy arguments and disagreements between engineers, as they often generate different results on the same building.

The never-ending human desire to reach the sky has progressed well beyond its historical milestones. Continuous research in the fields of materials, construction technology, and analysis software and operating systems has aided in the construction of the 21st century’s modern marvels. These high-
High-rise structures have come to symbolise human supremacy and have effectively become a symbol of a country's prestige and socio-economic well-being. High-rise buildings, though fancy on the outside, are the result of pioneering architecture, calculative engineering, and sheer hard work. As a building's height increases, it is vulnerable to lateral (horizontal) loads such as seismic and wind forces. Seismic force is one of the most unexpected forces, as it varies depending on the height and seismic weight of the structure. Wind forces grow in a parabolic relationship with building height. Tall buildings are primarily built to resist lateral loads acting on them, in addition to vertical loads (dead and imposed loads).

Core and Outrigger structural system is designed for improving building overturning, stiffness, and strength by connecting the core or spine to closely spaced outer columns. Outrigger systems work by linking two structural systems together - a core system and a perimeter system - and causing the building to act like a composite cantilever. Outriggers can be found in the form of walls in a reinforced concrete structure and trusses in steel structures.

2. Literature Review
Huge collection of literature is available on the application of Outrigger Structural System (OSS) in the tall buildings. It has also been observed that the OSS has performed considerably better than belt truss system in an RCC high rise structure of 210m height when subjected to wind loads as stated by Akash Kala[1] in their research work, similar work has also been carried out by Varsha Virde[2] on the assessment of high rise building with steel outriggers under the influence of wind loads by gust factor method for along and across conditions, model considered in this study was a 40 storey regular building. Saif Azhar[3] has conducted research for optimal location of steel outrigger bracing system in tall buildings, in this paper he has studied the behaviour of structure under the influence of earthquake loads for zone IV conditions. Models considered for analysis are 20 storeys, 40 storeys, and 60 storeys which are further classified into 5 different types. His study has concluded by prescribing top and H/2 positions as the optimum position.

From the present literature we can assess that most of the study done by earlier researchers is based on behavioural assessment of the high-rise buildings in Zone IV only and present work is limited to 120mts of height and had been performed with the use of steel outriggers and belt truss systems. There is an absence of research work on Concrete Structures with the use of only core wall and shear walls as outriggers connecting the peripheral columns.

3. Objectives
Objective of the study is:
1. To evaluate the response of structures subjected to Lateral loads and to assess its behaviour for outrigger structural system.
2. To understand the behaviour of structures, present in seismic zone V.
3. To determine the responses of structure by varying positions of outriggers in high rise buildings.
4. To study the effect of outriggers in different locations along the height of the structure.
5. To find the optimum position of outrigger for a high-rise structure under both seismic and wind loads.
6. To assess the behaviour of outriggers beyond the height limit of 120m as stated by IS code.

4. Methodology
4.1 Response Spectrum Method
It is a representation of the maximum response of idealized single degree of freedom system having certain period and damping, during earthquake ground motions. The maximum response plotted against undamped natural period, for various damping values, can be expressed in terms of maximum absolute acceleration, maximum relative velocity or maximum relative displacement.
This method is applicable for those structures where modes other than fundamental mode affect significantly the response of the structure. With this method, the multiple modes of response of a building are taken into consideration. In this method the response of multi-degree-of-freedom (MDOF) system is expressed as the superposition of modal response, each modal response being determined from the spectral analysis of single degree-of-freedom (SDOF) systems, which are the combined to get the total response. Computer analysis can be used to determine the modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide an estimate of the total response of the structure. The modal combination methods used are:

- Absolute - peak values are added together
- Square root of sum of squares (SRSS)
- Complete quadratic Combination (CQC)

4.2 Gust Factor Method

As per IS 875, gust is defined as positive or negative departure of wind speed from its mean value, lasting for not more than, say, 2 minutes with the peak occurring over a specified interval of time. Gust Factor is defined as the ratio between a peak wind gust and mean wind speed over a period, can be used along with other statistics to examine the structure of the wind. Gust factors are heavily dependent on upstream terrain conditions (roughness), stability, height etc., In the calculation of structural response (whether modal analysis or otherwise), the structure should be so represented by means of an analytical or computational model that reasonable and rational results can be obtained by its behaviour.

\[ F_z = C_t \times A_e \times p_z \times G \]

- \( F_z \) = along wind load on the structure at any height \( z \) corresponding to strip area.
- \( C_t \) = force coefficient for the building.
- \( A_e \) = effective frontal area considered for the structure at height.
- \( p_z \) = design pressure at height \( z \).
- \( G \) = Gust Factor.

This study is conducted on Eight different regular buildings having Core Shear Wall(SW) and RC Outrigger Structural System(OSS) which are modelled in ETABS 2018 software. The Modal analysis also performed before Response spectrum analysis to check the mode shapes, mass participation ratios, and time-period of structures. In this study, parameters such as maximum displacement, storey shear and storey drift ratio of every model are tabulated and studied. The seismic effects as well as Wind effects in both X & Y direction are studied, and the above-said parameters are presented in a table format and graphs are drawn for easy comparison between the models, using these graphs and values, the optimal position of outrigger has been determined and structural performance of the models is studied.
5. **Model Information**

5.1 **Model Details**

In this study two structures are considered whose height is varied i.e., 36 storeys model of height 108mts and 50 storeys model of height 150mts. Structures considered here are regular in plan geometry of 30m x 30m. Models are classified as follows:

5.1.1 **36 Storey Model**
- Model with Structural core walls (BFS)
- Model with SW and OSS at 12\textsuperscript{th} Storey (M1)
- Model with SW and OSS at 18\textsuperscript{th} Storey (M2)
- Model with SW and OSS at 6\textsuperscript{th} and 30\textsuperscript{th} Storey (M3)
- Model with SW and OSS at 12\textsuperscript{th} and 24\textsuperscript{th} Storey (M4)

5.1.2 **50 Storey Model**
- Model with SW and OSS at 10\textsuperscript{th} and 40\textsuperscript{th} Storey (M5)
- Model with SW and OSS at 20\textsuperscript{th} and 30\textsuperscript{th} Storey (M6)
- Model with SW and OSS at 10\textsuperscript{th}, 25\textsuperscript{th} and 40\textsuperscript{th} Storey (M7)

Figure 2 provides graphical representation of Model considered.

![Flow Chart Representation of Model Details](image)

**Fig. 2.** Flow Chart Representation of Model Details

5.2 **Material Details**
- Grade of Concrete:- M30
- Grade of Steel:- HYSD 550
5.3 Section Details

5.3.1 36 Storey Model
- Beam Sizes: 250mm x 350 mm
- Column Sizes: 600mm x 600mm
- Total Height: 108 m
- Storey Height: 3m
- Each Panel Size: 5m x 5m
- Core Shear Wall Thickness: 150mm
- Outrigger Wall Thickness: 150mm

![3D View of 36 Storeys models](image)

Fig. 3. 3D View of 36 Storeys models

5.3.2 50 Storey Model
- Beam Sizes: 250mm x 350mm
- Column Sizes: 750mm x 750mm
- Total Height: 150m

![3D View of 50 Storeys models](image)

Fig. 4. 3D View of 50 Storeys models
- Storey Height: 3m
- Each Panel Size: 5m x 5m
- Core Shear Wall Thickness: 200mm
- Outrigger Wall Thickness: 200mm

5.4 Loading Details
- Live Load: 4 KN/m
- Wall Load: 4.2 KN/m
- Seismic Load
  - Seismic Zone Factor: V
  - Response Reduction Factor: -5
  - Damping: 5% self-damping
  - Importance Factor: 1.5
  - No. of Modes Considered: 12
  - Mass Source: 1DL + 0.5LL
- Wind Load
  - Basic Wind Speed: 44 m/s
  - Terrain Category: 4
  - Probability Factor K1 = 1
  - Height Factor K2 = Depends on height
  - Topography Factor K3 = 1
  - Importance Factor K4 = 1

Fig. 5. Without outrigger frame
Fig. 6. With outrigger frame
6. Results

36 Storey Model

![Fig. 7. Time Period](image1)

![Fig. 8. Spectral Acceleration vs Time period](image2)

![Fig. 9. Base Shear Variation](image3)

![Fig. 10. Displacements for Seismic Analysis](image4)

![Fig. 11. Storey Drifts for Seismic Analysis](image5)
Fig. 12. Displacements and Storey Drifts for Wind Analysis

50 Storey Model

Fig. 13. Time Period

Fig. 14. Spectral Acceleration vs Time Period

Fig. 15. Base Shear Variations

Fig. 16. Displacements for Seismic Analysis
Fig. 17. Storey Drifts for Seismic Analysis

Fig. 18. Displacements and Drifts for Wind Analysis

Table 1. Modal Mass Participation for 36 Storey Models

| MODES | MASS PARTICIPATION % |
|--------|-----------------------|
|        | BFS | M1    | M2    | M3    | M4    |
| 1-UX   | 94.04 | 93.98 | 94.22 | 95.01 | 91.75 |
| 2-UY   | 94.04 | 93.98 | 94.22 | 95.02 | 94.18 |
| 3-RZ   | 95.28 | 95.19 | 95.17 | 95.6  | 96.35 |
Table 2. Modal Mass Participation for 50 Storey Models

| MODES | MASS PARTICIPATION % |
|-------|-----------------------|
|       | M5       | M6       | M7       |
| 1-UX  | 94.04    | 93.98    | 94.22    |
| 2-UY  | 94.04    | 93.98    | 94.22    |
| 3-RZ  | 95.28    | 95.19    | 95.17    |

7. Discussions

1. As the position and number of outrigger levels are varying the time periods, acceleration, base shear, displacements, storey drifts are changing relatively.
2. For the dynamic earthquake analysis of a 36-storey model using 1 level outrigger i.e., at 12th storey reduced the displacement by 10% but inter storey drift had increased by 3% and base shear is increased by 21%.
3. For the dynamic earthquake analysis of a 36-storey model using 2 level outriggers i.e., at 6th and 30th storeys reduced the displacement by 21%, inter storey drift had reduced by 11% and base shear is increased by 25%.
4. For the dynamic wind analysis of a 36-storey model using 1 level outrigger i.e., at 18th storey reduced the displacement by 34%, inter storey drift had reduced by 35%.
5. For the dynamic wind analysis of a 36-storey model using 2 level outriggers i.e., at 12th and 24th storeys reduced the displacement by 46%, inter storey drift had reduced by 45%.
6. For the dynamic earthquake analysis of a 50-storey model using 2 level outriggers i.e., at 20th and 30th storey reduced the displacement by 49%, inter storey drift had reduced by 51% and base shear is increased by 21%.
7. For the dynamic earthquake analysis of a 50-storey model using 3 level outriggers i.e., at 10th, 25th and 30th storey reduced the displacement by 54%, inter storey drift had reduced by 56% and base shear is increased by 25%.
8. For the dynamic wind analysis of a 50-storey model using 2 level outriggers i.e., at 20th and 30th storey reduced the displacement by 6%, inter storey drift had reduced by 20%.
9. For the dynamic wind analysis of a 50-storey model using 3 level outriggers i.e., at 10th, 25th and 30th storey reduced the displacement by 54%, inter storey drift had reduced by 13% and base shear is increased by 20%.

8. Conclusions

Based on the observations and the results obtained during this study, we can arrive at the following conclusions: The best performing model for dynamic assessment subjected to earthquake and wind load cases in a 36-storey model is the M3 and M4 respectively and in a 50-storey model it is the M7. When compared to seismic and wind loads outrigger structural system has performed well in the case of Wind Loads.
9. Limitations

Following are the limitations of the present study

- The buildings which were modelled were regularly shaped having constant square area of 900sqm.
- Irregular plan geometry cases are not considered here.
- No Vertical Irregularities were considered in this dissertation.

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