Parametric study of position of an outrigger-belt system through pushover analysis

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Abstract. This study revolves around the high-rise RCC buildings with lateral force resisting system (LFRS). While constructing a multi-storey building, it is necessary to survey various salient features such as lateral load resistance capacity and lateral stiffness. The LFRS is used to introduce the lateral force resistances in the building and the LFRS used for this study are core and outrigger-belt system. Since the core is applied to the whole building at once, thus application related to it are easier, but when another LFRS (outrigger belt system in this study) which is dedicated to a certain floor, is added in the building, then its position can affect the performance of the building. There has been a lot of theories regarding the optimum positions which show how the position of these storey dependent LFRS can affect the overall performance of the buildings. When a multi-storey building is prone to high intensity earthquake load or heavy wind load, the outrigger-belt and core system would resist the rotation and prevent excessive sway caused by lateral loads. Thus, if proper analysis is performed on the building for optimum position of these systems, then the overall performance can be increased significantly. For this purpose, the buildings of 20-, 25-, and 30-storeys are analysed by Pushover Analysis with two load patterns using Midas GEN. The study is also performed in buildings with different stiffness conditions to understand the overall behaviour of the building for optimum positions. A total of 285 building models are tested using two different load patterns. These buildings differ from each other in terms of position of outrigger, stiffness and number of storeys.

1. Introduction

The demand for construction of high-rise buildings has drastically increased in the 21st century, due to the surge of population and to prevent scarcity of land area. These high-rise buildings also attracted the attention for new businesses and sometimes act as a centre of attraction. To satisfy the social, economic and environmental needs, advanced analysis in the field of building technology, building material and computational structural analysis of components of buildings have been carried out by architects and engineers to create a highly efficient and safe high-rise building. In various studies, it is found that when the height of a building structure increases, an adverse effect is observed when lateral loads drastically increases, and it causes lateral displacement or sway effect on the tall building. The high-rise buildings are considered highly affected by lateral loads and need to be designed as per required of a particular seismic zone. Buildings susceptible to heavy wind loads are subjected to an oscillation effect, which may cause discomfort to the occupants. Whereas, when an earthquake occurs,
the ground motion would lead to the vibration of superstructure, causing an inertial force to act on the building. This may cause severe damage to structural and non-structural damage to the super-structure and could be highly dangerous for the occupants. Thus, to overcome these challenges, different lateral force resisting system (LFRS) are used in buildings. Outrigger is a special kind of a horizontal LFRS, which is placed between two structural systems, i.e. exterior structural framework and core system, to prevent swaying and overturning moments. The benefit of using outrigger system in a tall building at various levels is that it helps in increasing the stiffness to a building, thus increasing the overall strength of the structure, and resists the building deformation occurring due to lateral loads. Outrigger system is used as a load-resisting system in slender buildings, where they reduce storey drift and improve the comfort level of occupants during different conditions of lateral forces. From different studies conducted, it was found that the high-rise buildings containing an outrigger system would experience a major reduction in the overturning moment of about 40%, and a major reduction in the sway effect. Belt system is being provided in a building to improve the lateral system efficiency. When outriggers are used in frame systems, the belts system helps in transferring the gravity load to mega frame systems, thus helping in reducing the shear-lag effect and evenly distributing the loads across multiple columns of a building, which also distributes the load uniformly on the foundation as well. The outrigger arrangement can be introduced in form of heavily reinforced walls, deep girders, bracings etc. [1]. The outrigger-belt system used in this study was of heavily reinforced wall of specific arrangement as shown in Fig. 1, which is a simplified diagram to depict the outrigger-belt arrangement. Similar kind of arrangement of reinforcement can be seen in one of the cases discussed by Choi et al. in ref [8].

![Outrigger-belt arrangement used in the study.](image)

2. Literature review
The main focus of this study is to determine the optimum position of the outrigger belt arrangement in a high-rise RCC building and to study the effect of change in position if the stiffness of the building is varied along height, or as whole. Various researchers have performed several structural analyses and modeling on related topics. A framed tube Structural system is being modeled using computational method and an effect of outrigger-belt system on a three-dimensional building structure is being modeled using a rotational spring under lateral load conditions [1]. While conducting various studies, it is found that optimum location of the outrigger system is dependent upon a type of loading on a building, moment of inertia and axial stiffness acting on the exterior walls [1], [6], [8]. As a result, when there is an increase in axial stiffness, the optimum location of outrigger system will move in the downward direction. A research was conducted in which an ideal location of outrigger-belt system was determined using various arrangements of single and double outrigger levels on various sizes, height and shape of a building [2], [5]. Reference [2], conducted an analysis on buildings with various stories such as 28, 42 and 57-storey buildings using the finite element method, where it was observed that placing the double outrigger system at middle height, i.e. 42-storey, would help in maximizing the reduction of lateral deflection in the building. When a multi-storey building is subjected to seismic
loading like earthquake loads, the behavior of outrigger location is studied and the efficacy of placing an outrigger in a tall building is examined [3], [4]. From their investigation on a 20-storey and 30-storey building, both finite element method and component-mode synthesis method were used for building analysis and found that the component-mode synthesis method is effective in minimizing the analysis time and addition of outrigger-system helps in improving the stiffness of the building in [3]. In reference [4], an analysis on G+3 building was performed to evaluate its performance under the seismic loads acting upon the building. After conducting a non-linear pushover analysis on G+3 building, it was observed that curve, formed between base shear and displacement, was linear initially and then started to diverge from linearity as the columns and beams of the building was subjected to inelastic forces of action in [4]. This indicates that static loading is the key factor in governing the pushover computational analysis and failure of building structure during earthquake loads may occur as a consequence of using bad quality of construction materials. Reference [5] conducted structural analysis of a outrigger braced frame system, to obtain the optimal location of outrigger-belt and core system of a building subjected to lateral loads. After conducting various studies, it was observed that the outrigger system placed in tall building helps in improving the stiffness of structure and makes the structure more resilient against severe lateral loads, by reducing 33% and 66% drift and top displacement using one outrigger-system and two outrigger-system respective in [5]. Reference [6], conducted several studies regarding the analysis of 40-storey tall building for ideal position of outrigger system, using Sap2000 software. The author conducted a 40-storey building analysis, performance analysis have been done by placing a central shear wall and found that stability and stiffness of a structure increases by placing an outrigger system when earthquake of magnitude 7.8 was acting on building in [6]. After performing analysis on three-dimensional building using ETABS, the conclusion drawn was that after placing an outrigger and decreasing the dimension of columns at certain levels, the building stiffness improves and the structure becomes more comfortable for occupants [1-3]. Various analyses are being conducted to prepare a comparison between the optimal location of outrigger and time-history analysis, so as to assess the behaviors of structural analysis on building [7]. After several observations, the results of analysis on 20 and 25 storeys buildings was taken out and the optimum location came out to be 10 and 14 simultaneously, showing that outrigger has influence on behavior of building susceptible to lateral loads in [7]. Reference [8], performed analysis of a high-rise building and studied the effects of building behavior by placing an outrigger system, including effect of using structural systems like differential column shortening. After performing several analyses, it was observed that by reducing the core overturning, it helps in reducing flexural and shear forces across the foundation, and tall buildings with mega-columns gives an aesthetic and flexible system to the occupants [1], [2], [8]. It should be noted that the conventional outrigger connects the core of the building to its exterior column, whereas the virtual outrigger or belt system connects the exterior columns with each other, forming a belt type system [8]. Thus, through all the literature discussed, it is evident that outrigger systems can improve the performance of the building and the optimum position of these LFRS can improve the performance and to make it simpler.

3. Methodology and nomenclature
The building of 20-, 25-, and 30-storeys were modelled in Midas GEN software and they were analysed through Pushover Analysis. The Pushover Analysis is a static non-linear analysis procedure, which is well known to give the seismic vulnerability of a structure. This analysis is known to give good results, although it is also known as an analysis which is highly dependent on the type of loading selected. The building models are tested in 2 phases, which are explained properly in the later portion of this section. In brief, the models in Phase 1 either have a constant stiffness or the stiffness varies along the height. The variation of stiffness along the height is achieved by varying the cross-sectional area of beams and columns after every floor, which can be observed in Fig. 2, as in Midas GEN, different cross-sections, are represented by different colours, thus showing different models from Phase 1 with constant stiffness and varying stiffness.
As for nomenclature of building models, three types of models have been considered, which is SC, 3C and 5C, where SC is a building with the constant cross-section area of columns and beams, 3C is a building having cross-sectional area of columns and beam that changes after every 3 storeys and 5C is a building having cross-section of beams and columns that change after 5 storey levels. So, according to this nomenclature, a SC25 model means a building contains 25 storeys with same cross-sectional areas, while a 3C30 model means that a building has 30-storeys and its cross-sectional area would decrease after every three storeys. In Phase 1, core and outrigger-belt (COB) thickness is 200mm for all models, thus it is not mentioned in the name. Although in Phase 2, the COB thickness varies to vary overall stiffness of the buildings, thus if A is used as a suffix, it means wall thickness is 200mm and if B is mentioned then it stands for 300mm thickness of the COB. So, B-3C30-24 building model means 30-storey building which has a COB thickness of 300mm and the cross-sectional area of beam and column reducing at every three levels, with outrigger at 24th storey.

The terms LC-1 and LC-2 is used in the study are related to the load cases used for the pushover analysis, which corresponds to load case 1 and load case 2, respectively. The load case 1 is a static load case derived from the equivalent static method derived using the IS1893 [9], it is the most commonly used load case for pushover analysis. Whereas the load case 2 corresponds to the N2 method, which is known as one of the most accurate methods of analysis [10]. All 285 models are pushed using these two load cases for the pushover analysis and their corresponding results noted accordingly.

![Figure 2. Isometric view of: (a) SC25-14, (b) 3C25-07, (c) A-3C30-24 or 3C30-24, (d) A-SC30-22 or SC30-22, (e) 5C30-20.](image)

In Phase 1 of this study, there are overall 225 models, which can be divided into 3 categories; SC, 3C, and 5C. Differences in these are mentioned in previous part of nomenclature. These categories are later divided into subcategories based on number of storeys, and the buildings are of 20-, 25-, and 30-storey and such category has as many models as its number of storey which differs from each other on the basis of the storey at which the outrigger-belt arrangement is place. The storey to storey height is
3.2m that gives the height of 20-storey building as 64m and 30-storey buildings as 96m. Thus, they satisfy all the criteria set by IS16700 [11]. These buildings are then analysed through Pushover analysis using the two load cases mentioned above. The results corresponding to each model with varying positions of outrigger-belt system is recorded. The parameters selected are base shear (BS) and roof displacement (RD). These are converted into unitless and relative numbers and the plotted in form of graph.

In Phase 2, the change in optimum positions is observed in the models when the COB thickness is introduced. So as to study the effect on the optimal location of outrigger-belt system caused by the change in overall stiffness of buildings. This phase conducts change in the thickness of COB in models, which results in change in overall stiffness. 30 storey models are analysed in this phase, which contain an analysis of SC and 3C models for determining the optimum position and the effects due to change in stiffness corresponding due to COB thickness. This phase helps in giving precision and accurate data, and also provides a series of graphs which help in determining the overall view of change in displacement occurring after using outrigger-belt. So, SC30 and 3C30 models are selected from phase one and are renamed as A-SC30 models and A-3C30 models, respectively. Suffix A is used as the core and outrigger-belt arrangement used in them are of 200mm thickness. Along with them, 60 more models are formed by using a thickness of 300 mm for COB, which are added with a suffix of B. So, it can be said that the thickness of COB is increased by 50% to study the change in optimum position due to change in overall stiffness. The results obtained in this phase are also converted in unitless and relative form, in a similar manner as Phase 1. It should be noted that all models that are analysed here have the same plan and same plan dimensions. It should also be notes that effect of “strong columns and weak beams” are also taken in consideration for modelling.

4. Results

The results obtained from the Phase 1 and Phase 2 is converted to graphs. The obtained results are presented in unitless and comparative manner. The individual dots in a graph represent an individual building model corresponding to relative storey at which outrigger-belt is present along with the base shear (BS)/ roof displacement (RD) for that model. Graphs have been plotted by using the data collected from the analysis of all 285 building models. It should be noted that the Pushover Analysis load cases, LC-1 and LC-2 are applied in X-direction of loading which is also a stiffer direction in this study. The values on Y-axis of all the graphs represent the storey level in a relative manner which corresponds to the building having outrigger-belt arrangement at that level. Whereas the X-axis of the graph corresponds to RD or BS depending on the graph is being observed. In Phase 1 of the study, a total of 225 models were analysed through Pushover Analysis. The three category models that they have are of SC, 3C, and 5C, every category has 75 models each, out of which 20, 25, and 30 models are of 20-, 25-, and 30-stories, that differ from each other on the basis of storey level of outrigger-belt.

| Building models | BS     | RD     | BS     | RD     |
|-----------------|--------|--------|--------|--------|
| SC20            | 9 to 12| 5 to 6 | 9 to 12| 6 to 7 |
| SC25            | 9 to 13| 3 to 7 | 10 to 14| 5 to 8 |
| SC30            | 11 to 16| 3 to 7 | 11 to 16| 6 to 8 |
| 3C20            | 10 to 15| 7 to 15| 10 to 15| 9 to 15|
| 3C25            | 13 to 19| 18 to 23| 13 to 18| 14 to 21|
| 3C30            | 18 to 22| 22 to 27| 16 to 23| 19 to 26|
| 5C20            | 10 to 14| 6 to 14| 9 to 14| 7 to 14|
| 5C25            | 12 to 17| 4 to 8 | 12 to 16| 5 to 15|
| 5C30            | 18 to 23| 22 to 27| 17 to 23| 19 to 26|

Table 1. Optimum storey positions of outrigger-belt system for models of phase 1.
The Phase 2, in which the change in optimum position is being observed with change in stiffness of the building, although, in this phase the change in stiffness of the buildings are introduced by changing the thickness of COB. The models in series SC30 and 3C30 from Phase 1 are use in this phase with the names of A-SC30 and A-3C30 respectively. The 60 new models in this phase correspond to series B-SC30 and B-3C30. All new models are also analysed by two load cases and they corresponding BS and RD are noted and graphs are plotted in Figures 12-13. Thus, for this stage, the figure under observation is figures 5, 8, 12, 13. The optimum positions are inferred and written in table 1 and table 2 for Phase 1 and Phase 2, respectively.

Figure 3. Graph of buildings in SC20 showing variation in (a) BS, (b) RD.

Figure 4. Graph of buildings in SC25 showing variation in (a) BS, (b) RD.
Figure 5. Graph of buildings in SC30 or A-SC30 showing variation in (a) BS, (b) RD.

Figure 6. Graph of buildings in 3C20 showing variation in (a) BS, (b) RD.

Figure 7. Graph of buildings in 3C25 showing variation in (a) BS, (b) RD.
Figure 8. Graph of buildings in 3C30 or A-3C30 showing variation in (a) BS, (b) RD.

Figure 9. Graph of buildings in 5C20 showing variation in (a) BS, (b) RD.

Figure 10. Graph of buildings in 5C25 showing variation in (a) BS, (b) RD.
Figure 11. Graph of buildings in 5C30 showing variation in (a) BS, (b) RD.

Figure 12. Graph of buildings in B-SC30 showing variation in (a) BS, (b) RD.

Figure 13. Graph of buildings in B-3C30 showing variation in (a) BS, (b) RD.
Table 2. Optimum storey positions of outrigger-belt system for models of phase 2.

| Building models | LC-1 BS | LC-1 RD | LC-2 BS | LC-2 RD |
|-----------------|---------|---------|---------|---------|
| A-SC30          | 11 to 16| 3 to 7  | 11 to 16| 6 to 8  |
| A-3C30          | 18 to 22| 22 to 27| 16 to 23| 19 to 26|
| B-SC30          | 12 to 17| 3 to 7  | 11 to 17| 3 to 8  |
| B-3C30          | 17 to 21| 21 to 26| 16 to 22| 18 to 25|

5. Conclusions
The study is carried out for optimum position of outrigger-belt system in the building in which the stiffness of the building is varied with height and as a whole. The following conclusions can be drawn from the study:

- The graphs generated show that with change in position of outrigger and belt system, the performance of the building can be affected and optimum positions can improve the performance by 5-10%.
- If the buildings have a constant stiffness throughout the height (ignoring the additional stiffness introduced due to outrigger-belt system), then the optimum positions based are usually at 0.40-0.50H for base shear and 0.15-0.30H for roof displacement.
- If the stiffness of the building is decreasing with the increase in height, then the optimum position based on base shear shifts a little upwards to a region of 0.55-0.70H of the building, whereas if the roof displacement is taken as a parameter, then the 0.65-0.80H becomes the optimum positions. Although the same buildings, lower region of 0.20-0.35 also gave good (and sometimes better) results.
- It can be inferred that if the overall stiffness of the building is increased at once (for example in Phase 2), then it will surely increase the performance and decrease the roof displacement of the building, but it may not have any major impact on the optimum position of the outrigger-belt system.

Here H stands for the total height of the building and data is mentioned from the bottom of the building. Since fewer models were used in assessing the effect of outrigger-belt system in these high-rise buildings, thus, author would like to suggest more work in this area using a bigger data set.

6. References
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