Optimum location of Virtual outriggers in high rise buildings for seismic and wind responses

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Abstract - Outriggers have been used in construction of high rises since late 20th century. Outriggers provide lateral stability against wind and seismic loads. Virtual outriggers are a type of outrigger using floor diaphragms instead of deep beams which ensures space optimization. Virtual outriggers are located at suitable storeys (height) to ensure efficient performance. Parameters used for study are lateral displacement due to seismic and wind forces in X and Y direction, storey drift, base reaction, maximum overturning moment and top storey acceleration. Optimum location as determined by analyzing and comparing these parameters when outriggers are located at different heights for models of 50, 60 and 70 storeys. Models are analyzed for one, two and three outrigger systems.

Key Words: Outrigger, Virtual outrigger, wind load, seismic load, single outrigger system, multi outrigger system, lateral displacement, storey drift, overturning moment, top storey acceleration, base shear.

1. INTRODUCTION

Tall buildings form an integral part of human society and Outriggers have become an ideal structural solution to the problem of lateral instability caused in tall buildings due to winds and seismic forces. Outriggers are rigid and horizontal beams/trusses which connect the central core of the building to external peripheral columns. This improves the building strength and overturning stiffness. In spite of being structurally efficient, outriggers pose a few architectural and economic constraints which can be conveniently overcome by using Virtual outriggers.

2. LITERATURE

A number of researchers in the past have worked on the concept of outriggers and virtual outriggers as well.

R Shankar Nair (1998) in his paper gave a brief on the conventional outrigger system and problems associated with its installation and also outlined the concept of virtual outrigger system. The paper explains the virtual outrigger system with its advantages over the conventional outrigger system. The paper also gives example of Plaza Rakyat Tower in Kuala Lumpur which has two virtual outriggers.

Z. Bayati, et al (2008) worked on optimum number of outrigger systems in a building. The paper presents the results of an investigation on drift reduction in uniform belted structure with rigid outriggers, through the analysis of a model structure of 80 storeys.

S. Fawzia, et al (2011) studied the effects of cyclonic winds on 28, 42 and 47 storey buildings of L–shaped layout. The results showed that the plan dimensions have vital impact on structural heights. Increase in height with same plan dimensions, leads to reduction in lateral rigidity.

Msc. Rafael Shehu (2015) analysed the aspects of building performance designed or retrofitted by the means of conventional or virtual outrigger. The paper highlights ductile characteristics of structures post elastic phase and during seismic events. Structures of 25, 30 and 35 storeys are used to study rigid outrigger, vierendel outrigger and bracing outrigger.

Prajyot A. Kakde and Ravindra Desai (2017) used a 70 storeys building to study lateral stability and sway in case of winds. The building was modelled in ETABs 2016. The paper compares drift caused due to wind and seismic forces on tall buildings without outrigger and multiple outrigger system at located at varied heights.

The papers published conclude to the fact that use of outriggers in high rise buildings increases the stiffness by 20-30%. Optimum location of single outrigger system is at approximately mid height of the building. Also, virtual outriggers are equally structurally efficient as conventional outriggers.

3. VIRTUAL OUTRIGGER

In virtual outriggers, there is no direct connection between core and peripheral columns. The load is transferred to peripheral columns via floor diaphragms which are stiffer than usual slabs.

Virtual outriggers have a similar function to that of a conventional outrigger but the method employed varies. The working of virtual outriggers can be explained with the following two concepts.

3.1 Belt trusses as Virtual Outriggers

The overturning moment in the core is converted into a vertical couple at the exterior columns. Rotation of the core is resisted by the floor diaphragms at the top and bottom of the belt trusses; thus, part of the moment in the core is
converted into a horizontal couple in the floors. The horizontal couple, transferred through the two floors to the truss chords, is converted by the truss into vertical forces at exterior columns.

![Diagram](image1)

**Fig -1:** Working of belt truss as Virtual Outrigger

3.2 Basements as Virtual Outriggers

The principle is same as when belt trusses are used as virtual outriggers. Some fraction of the moment in the core is converted into a horizontal couple in the floors at the top and the bottom of the basement. This horizontal couple is transmitted through the floor diaphragms to the side walls of the basement, which convert the horizontal couple into a vertical couple at the ends.

![Diagram](image2)

**Fig -2:** Working of basements as Virtual Outrigger

The concept of virtual outriggers presents a reasonably unique solution to the problems posed by conventional outrigger system.

4. MODEL

Models of a structure of 50, 60 and 70 storeys are made in ETABS software. The plan is triangular in shape with each side measuring 36 m. The shape is chosen to take into consideration the critical loads at the edges. The plan with location of columns at the bottom storey is shown in the figure below.

![Diagram](image3)

**Fig -3:** Model plan used for analysis

The building is assumed to be a commercial building located in Mumbai, India, with floor to floor height of 4 m.

4.1 Structural configuration

The structural configuration of the structure is as follows:

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Special R.C. Moment resisting frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number for storeys</td>
<td>50, 60, 70</td>
</tr>
<tr>
<td>Slab Thickness</td>
<td>150 mm</td>
</tr>
<tr>
<td>Slab thickness at Virtual outrigger level</td>
<td>200 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame elements</th>
<th>Storey range</th>
<th>Exterior peripheral column (Cp)</th>
<th>Interior columns (Ci)</th>
<th>Perimeter beams (Bp)</th>
<th>Interior beams (Bi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(All dimensions are in m)</td>
<td></td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61 – 70</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61 – 70</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>41 – 50</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>31 – 40</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21 – 30</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11 – 20</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Base – 10</td>
<td>0.8 x 0.8</td>
<td>0.6 x 0.7</td>
<td>0.45 x 0.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam dimensions at outrigger level</th>
<th>0.8 x 1.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of internal wall</td>
<td>150 mm</td>
</tr>
<tr>
<td>Thickness of sheath core</td>
<td>450 mm</td>
</tr>
<tr>
<td>Grade of reinforcing steel</td>
<td>Fe500</td>
</tr>
<tr>
<td>Grade of concrete</td>
<td>M50</td>
</tr>
</tbody>
</table>

4.2 Loading

The loads considered for the structure are as follows:

1) Dead load: Unit weight of concrete: 25 kN/m³
   Unit weight of floor finish: 1 kN/m³
Unit weight of masonry : 20 kN/m³

2] Live load:  
Commercial area : 4 kN/m²  
Staircase : 3 kN/m²  
Terrace : 2 kN/m²

3] Seismic load:  
Zone factor : 0.16 (Zone III)  
Response reduction factor: 5  
Importance factor : 1.5  
Frame type : SMRF

4] Wind load:  
Basic wind speed : 44 m/s  
Design wind speed : Vb * k1 * k2 * k3  
Probability factor : k1 = 1  
Terrain factor : k2 (category 2)  
Topography factor : k3 (class C)

4.3 Virtual outrigger storey configuration

The model works on the principle of using belt trusses as virtual outrigger. The core moment is transferred to peripheral columns using floor diaphragms. The peripheral columns which are connected by a belt truss or belt walls then equally transmit the moment to the foundation.

Thickness of floor diaphragms : 200 mm  
Grade of concrete : M50  
Reinforcement : Fe 550  
Size of perimeter beams : 0.8 x 1 m

Fig -4: 3D Model for virtual outrigger storey at top

5. ANALYSIS

Models of 50, 60 and 70 storeys are subjected to seismic and wind loads. The models are analysed for one-outrigger system, two-outrigger system and three-outrigger system. The placement of virtual outriggers in each of the system is based on work of past researchers. The details of models are as follows:

1] One outrigger system

2] Two outrigger system

3] Three outrigger system

Each of the above models are analysed for the following parameters:

- Lateral displacement for seismic and wind loads in X and Y direction
  - Top storey displacement
  - Floor wise displacement
  - Average displacement
- Storey drift for seismic and wind forces in X and Y direction
  - Maximum drift
  - Floor wise drift
  - Average drift
- Top storey acceleration
- Base shear
- Maximum overturning moment

The given parameters form the base to draw patterns and variations so that results can be concluded.

6. RESULTS

The following results are obtained in each of the outrigger system cases.
Lateral displacement due to seismic forces in X direction for 50, 60 and 70 storey models is shown and analyzed below.

**Chart -1:** Lateral displacement for 50 storey model

**Chart -2:** Lateral displacement for 60 storey model

**Chart -3:** Lateral displacement for 70 storey model

The contents of the graph are analyzed in the following table. The displacements with least values are highlighted.

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition</th>
<th>Lateral displacement in X direction (seismic) when Virtual Outrigger is located @</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 storey</td>
<td>Top storey</td>
<td>0.045522 0.045992 0.045904 0.045916</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.024593 0.024128 0.024013 0.024589</td>
</tr>
<tr>
<td>60 storey</td>
<td>Top storey</td>
<td>0.053928 0.053816 0.053409 0.053932</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.039393 0.038611 0.038682 0.038689</td>
</tr>
<tr>
<td>70 storey</td>
<td>Top storey</td>
<td>0.153226 0.156731 0.150869 0.150667</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.060808 0.059436 0.058743 0.059102</td>
</tr>
</tbody>
</table>

Storey drifts due to wind forces in Y direction for 50, 60 and 70 storey models are shown in the charts below.

**Chart -4:** Storey drift for 50 storey model

**Chart -5:** Storey drift for 60 storey model

**Chart -6:** Storey drift for 70 storey model
The table below analyses the data for storey drift.

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition</th>
<th>Storey drift in Y direction (when Virtual Outrigger is located @)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 storey</td>
<td>Spec X</td>
<td>$\delta_a$, $\delta_b$, $\delta_c$, $\delta_d$</td>
</tr>
<tr>
<td>60 storey</td>
<td>Spec Y</td>
<td>$\delta_a$, $\delta_b$, $\delta_c$, $\delta_d$</td>
</tr>
<tr>
<td>70 storey</td>
<td>Spec Z</td>
<td>$\delta_a$, $\delta_b$, $\delta_c$, $\delta_d$</td>
</tr>
</tbody>
</table>

The top storey acceleration in $U_x$ direction analysis is as follows:

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition</th>
<th>Top storey acceleration ($U_x$ direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 storey</td>
<td>Spec X</td>
<td>0.2557</td>
</tr>
<tr>
<td>60 storey</td>
<td>Spec Y</td>
<td>0.1268</td>
</tr>
<tr>
<td>70 storey</td>
<td>Spec Z</td>
<td>0.2758</td>
</tr>
</tbody>
</table>

The top storey acceleration is analyzed for $U_y$ and $U_z$ direction as well.

The table below shows base reaction due to seismic forces in $X$ direction.

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition</th>
<th>Base Reaction (in kN) when Virtual Outrigger is located @</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 storey</td>
<td>Spec X</td>
<td>$F_x$, $F_y$, $F_z$, $R_{resultant}$</td>
</tr>
<tr>
<td>60 storey</td>
<td>Spec Y</td>
<td>$F_x$, $F_y$, $F_z$, $R_{resultant}$</td>
</tr>
<tr>
<td>70 storey</td>
<td>Spec Z</td>
<td>$F_x$, $F_y$, $F_z$, $R_{resultant}$</td>
</tr>
</tbody>
</table>

Base reactions due to seismic forces in $Y$ direction are also analyzed.

The table below presents maximum overturning moment.

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition</th>
<th>Maximum overturning moment (in kNm) when Virtual Outrigger is located @</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 storey</td>
<td>Spec X</td>
<td>$M_{resultant}$</td>
</tr>
<tr>
<td>60 storey</td>
<td>Spec Y</td>
<td>$M_{resultant}$</td>
</tr>
<tr>
<td>70 storey</td>
<td>Spec Z</td>
<td>$M_{resultant}$</td>
</tr>
</tbody>
</table>

Similar analysis is done for all the models in two-outrigger system and three outrigger system.

### 7.1 One-Outrigger system

For each parameter, optimum location varies. This is mainly due to variation in height, impact of seismic and wind loads and layout of the structure.

- Lateral displacement: Mid-height
- Storey drift: Mid height
- Top storey acceleration: No clear interpretation
- Base reaction: 2-3rd height
- Maximum overturning moment: No clear interpretation

### 7.2 Two-Outrigger system

The optimum locations in case of two outrigger system are:

- Lateral displacement: 2-3rd and 1-3rd height
- Storey drift: 3-4th and 1-4th height
- Top storey acceleration: 2-3rd and mid-height
- Base reaction: No clear interpretation
- Maximum overturning moment: 3-4th and 1-4th height

### 7.3 Three-Outrigger system

The optimum locations in case of three outrigger system are:

- Lateral displacement: 3-4th, mid and 1-4th heights
- Storey drift: 3-4th, mid and 1-4th heights
- Top storey acceleration: No clear interpretation
- Base reaction: Top, 3-4th and mid-height
- Maximum overturning moment: 3-4th, mid and 1-4th height

**REFERENCES**


7. **CONCLUSION**

The following conclusions can be drawn for each of the outrigger systems.