Deflection Control in High Rise Building Using Belt Truss and Outrigger Systems

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Abstract: Structures that don’t rely on shear wall-frame interaction to resist lateral loads, in which girders are essentially pin-connected to the columns, a substantial increase in stiffness and subsequent decrease in lateral drift can result from ‘tying the exterior columns to the core at one or several levels with one or two storey stiff horizontal outriggers trusses. Outriggers trusses are usually located for architectural purposes at mechanical levels near the middle or top of building. In order to mobilize the additional axial stiffness of several columns and provide for torsional stiffness. A belt truss can be used at the outrigger levels. An outrigger-braced high rise structure consists of reinforced concrete or braced steel frame main core connected to exterior columns by flexural stiff horizontal cantilevers. The core may be located between column lines without outriggers extending on both sides or it may be located on the side of building with cantilevers connecting to the columns on the other side. When the horizontal load acting on the building, columns-restrained outriggers resist rotation of the core. Causing lateral deflections and moments in the core to be smaller than if free-standing core alone resisted the loading. The result is to increase the effective depth of the structure when it flexes as a vertical cantilever, by inducing tension in the windward columns and compression in the leeward columns. The study is to find the effect of building displacements in lateral direction with shear core, outrigger and belt truss.

Keywords: Outrigger, Belt truss system, Wind, Earthquake, Lateral displacement.

Introduction

High rise building is defined as a building 35 meters or more in height, which is divided at regular intervals in to occupiable levels. To be considered a high rise building a structure must be based on solid ground and fabricated along its full height through deliberate process. Cut off between high rise and low rise building is 35 meters. This height as chosen based on an original 12 floor cut-off. There is no absolute definition of what constitutes a “tall building.” It is a building that exhibits some element of “tallness” in one or more of the following categories:

a) Height relative to context: It is not just about height, but about the context in which it exists. Thus whereas a 14-storey building may not be considered a tall building in a high-rise city such as Chicago or Hong Kong, in a provincial European city or a suburb this may be distinctly taller than the urban norm.

b) Proportion: Again, a tall building is not just about height but also about proportion. There are numerous buildings which are not particularly high, but are slender enough to give the appearance of a tall building, especially against low urban backgrounds. Conversely, there are numerous big/large footprint buildings which are quite tall but their size/footprint rules them out as being classed as a tall building.

c) Tall Building Technologies: Number of floors is a poor indicator of defining a tall building due to the changing floor to floor height between differing buildings and functions (e.g. office versus residential usage), a building of perhaps 14 or more stories (or over 50 meters/165 feet in height) could perhaps be used as a threshold for considering it a “tall building.”
Structural Systems
In the early structures at the beginning of the 20th century, structural members were assumed to carry primarily the gravity loads. Today, however, by the advances in structural design/systems and high-strength materials, building weight is reduced, and slenderness is increased, which necessitates taking into consideration mainly the lateral loads such as wind and earthquake. Understandably, especially for the tall buildings, as the Currently there are many structural systems that can be used for the lateral resistance of tall buildings. In this context, authors classify these systems based on the basic reaction mechanism/structural behavior for resisting the lateral loads.

Structural Systems for Tall Buildings
i.) Rigid frame systems
ii.) Braced frame and shear-walled frame systems
iii) Braced frame systems
iv) Shear-walled frame systems
v) Outrigger systems
vi) Framed-tube systems
vii) Braced-tube systems
viii) Bundled-tube systems

Structural systems of tall buildings can be divided into two broad categories: interior structures and exterior structures. This classification is based on the distribution of the components of the primary lateral load-resisting system over the building. A system is categorized as an interior structure when the major part of the lateral load resisting system is located within the interior of the building. Likewise, if the major part of the lateral load-resisting system is located at the building perimeter, a system is categorized as an exterior structure. It should be noted, however, that any interior structure is likely to have some minor components of the lateral load-resisting system at the building perimeter, and any exterior structure may have some minor components within the interior of the building.

Interior Structures

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Material/Configuration</th>
<th>Efficient Height Limit</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Frames</td>
<td>-</td>
<td>Concrete</td>
<td>20</td>
<td>Provide flexibility in floor planning. Easily moldable</td>
<td>Expensive form work. Slow construction.</td>
</tr>
<tr>
<td>Shear Wall/ Hinged</td>
<td>-</td>
<td>Concrete Shear wall + Steel Hinged Frame</td>
<td>35</td>
<td>Effectively resists lateral shear by concrete shear walls.</td>
<td>Interior planning limitations due to shear trusses.</td>
</tr>
<tr>
<td>Shear Wall (or Shear Truss – Frame Interaction System)</td>
<td>Shear wall / Rigid Frame</td>
<td>Concrete Shear wall + Steel Rigid frame</td>
<td>60</td>
<td>Effectively resists lateral loads by producing shear wall – frame interacting system.</td>
<td>Interior planning limitations due to shear walls.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete Shear wall + concrete frame</td>
<td>70</td>
<td>Effectively resists lateral loads by shear wall – frame interacting system.</td>
<td>Interior planning limitations due to shear walls.</td>
</tr>
</tbody>
</table>
Outrigger Structure-s

<table>
<thead>
<tr>
<th>Material/Configuration</th>
<th>Efficient Height Limit</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Cores (Steel Trusses or Concrete shear walls) + Outriggers (Steel Trusses or Concrete walls) + Belt Trusses + Steel or Concrete Composite (Super) Columns</td>
<td>150</td>
<td>Effectively resists bending by exterior columns connected to outriggers extended from the core.</td>
<td>Outrigger structure does not add shear resistance.</td>
</tr>
</tbody>
</table>

Exterior Structures

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Material/Configuration</th>
<th>Efficient Height Limit</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube</td>
<td>Framed Tube</td>
<td>Concrete</td>
<td>60</td>
<td>Effectively resists lateral loads by locating lateral systems at the building perimeter.</td>
<td>Shear lag hinders true tubular behavior. Narrow column spacing obstructs the view.</td>
</tr>
<tr>
<td>Tube</td>
<td>Braced Tube</td>
<td>Concrete</td>
<td>100</td>
<td>Effectively resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. Reduced shear lag.</td>
<td>Bracing obscures the view.</td>
</tr>
<tr>
<td>Tube</td>
<td>Bundled Tube</td>
<td>Concrete</td>
<td>110</td>
<td>Reduced shear lag.</td>
<td>Interior planning limitations due to the bundled tube configuration.</td>
</tr>
<tr>
<td>Tube</td>
<td>Tube in Tube</td>
<td>Ext. Frame tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete)</td>
<td>80</td>
<td>Effectively resists lateral loads by producing interior shear core – exterior framed tube interacting system.</td>
<td>Interior planning limitations due to shear core.</td>
</tr>
<tr>
<td>Diagrid</td>
<td>-</td>
<td>Concrete</td>
<td>60</td>
<td>Effectively resists lateral shear by axial forces in the diagonal members.</td>
<td>Expensive form work. Slow construction.</td>
</tr>
<tr>
<td>Super frames</td>
<td>-</td>
<td>Concrete</td>
<td>100</td>
<td>Could produce super tall buildings.</td>
<td>Building form depends to a great degree on the structural system.</td>
</tr>
</tbody>
</table>

Introduction to Outrigger

Although outriggers have been used for approximately four decades, their existence as a structural member has a much longer history. Outriggers have been used in the sailing ship industry for many years. They are used to resist wind. The outriggers are like the spreaders and the exterior columns are like the shrouds or stays. Innovative structural schemes are continuously being sought in the field. Structural Design of High Rise Structures with the intention of limiting the...
Drift due to Lateral Loads to acceptable limits without paying a high premium in steel tonnage. One such is an Outrigger System, in which the axial stiffness of the peripheral columns is invoked for increasing the resistance to overturning moments. This efficient structural form consists of a central core, comprising either Braced Frames or Shear Walls, with horizontal cantilever trusses or girders known as outrigger Trusses, connecting the core to the outer columns.

**Fig 1: Outrigger system with central core**

**Literature Review**

1. Minsik Bang And Jaehong Lee “An Analytical Model for High-Rise Wall-Frame Building Structures”

   In this paper, the governing equations of a wall-frame building are formulated through the continuum approach and the whole structure is idealized as a shear–flexural cantilever. The effect of shear deformation of the wall and flexural deformation of the frame are considered and incorporated in the formulation of the governing equations. A displacement-based one-dimensional finite element model is developed to predict lateral drift of wall-frame structures under horizontal loads. Numerical results are obtained and compared with previously available results and the values obtained from the finite element package MIDAS. The study indicates that the effect of shear deformation of the wall as well as the flexural deformation of the frame should be considered especially for tall and/or slender buildings. The proposed method is found to be simple and efficient provides reasonably accurate results in early design stage of tall building structures.

   An analytical model was developed to study the deflection of wall-frame structures. The model is capable of predicting accurate deflection for various configuration including core types and aspect ratios of the structures. To formulate the problem, a one-dimensional displacement-based finite element method is employed.

2. Tolga Akiš “Lateral Load Analysis Of Shear Wall-Frame Structures”

   The purpose of this study is to model and analyze the nonplanar shear wall assemblies of shear wall-frame structures. Two three dimensional models, for open and closed section shear wall assemblies, are developed. These models are based on conventional wide column analogy, in which a planar shear wall is replaced by an idealized frame structure consisting of a column and rigid beams located at floor levels. The rigid diaphragm floor assumption, which is widely used in the analysis of multistorey building structures, is also taken into consideration. The connections of the rigid beams are released against torsion in the model proposed for open section shear walls. For modeling closed section shear walls, in addition to this the torsional stiffness of the wide columns are adjusted by using a series of equations. The results of these analyses are compared with the results obtained by using
common shear wall modeling techniques.

3 P. Jayachandran, “Design Of Tall Buildings Preliminary Design And Optimization”
The design of tall buildings essentially involves a conceptual design, approximate analysis, preliminary design and optimization, to safely carry gravity and lateral loads. The design criteria are strength, serviceability, stability and human comfort. The strength is satisfied by limit stresses, while serviceability is satisfied by drift limits in the range of H/500 to H/1000. Stability is satisfied by sufficient factor of safety against buckling and P-Delta effects. The factor of safety is around 1.67 to 1.92. The aim of the structural engineer is to arrive at suitable structural schemes, to satisfy these criteria, and assess their structural weights in weight/unit area in square feet or square meters. This initiates structural drawings and specifications to enable construction engineers to proceed with fabrication and erection operations. The weight of steel in lbs/sq ft or in kg/sq m is often a parameter the architects and construction managers are looking for from the structural engineer. This includes the weights of floor system, girders, braces and columns. The premium for wind, is optimized to yield drifts in the range of H/500, where H is the height of the tall building.

4. Kenneth Arnott, “Shear Wall Analysis – New Modelling, Same Answers.” Engineers now routinely have access to highly capable 3D analysis packages often including the ability to use finite elements (“FE” shell elements). More and more structures are being analyzed in 3D, and as suppliers of such software we at CSC are certainly being faced with increasingly frequently asked questions relating to the modeling of shear and core wall systems using shell elements within the context of a 3D model. Personally it had not identified any useful text until the recently published “Finite Element Design of Concrete Structures” which it would thoroughly recommend to anyone seeking a more pragmatic engineering view of the issues together with a very realistic review of the options which should be considered.

Bear in mind that just 25 years ago very few engineers had access to any sort of computing capability. When dealing with concrete frames and shear walls the estimation of such properties dictates that all resulting deflections and forces should be regarded as best estimates and engineers should consider the use of alternative runs to assess sensitivity to design assumptions.

5. Hou Guangyu, Et Al’. “Design And Research On Composite Steel And Concrete Frame-Core Wall Structure” This paper presents the design, research and related joints’ details of a 31-storey composite frame-core wall structure, which is located in Beijing City, a region of seismic fortification of 8 degree. In order to improve the ductility bearing capacity of the core walls and to ensure inelastic deformation capacity of the longitudinal coupling beams carried steel trusses, proper steel frames were embedded within the longitudinal core walls. Experimental results show that there are no obvious cracks in the core walls, spelling of concrete and local buckling of reinforcement at the bottom of the core wall’s boundary elements and the composite columns at the perimeter have not been observed, even the elasto-plastic storey drift angle has reached 1/101, the whole structure has better seismic performance.

Structural Behaviour
The multistorey building systems analyzed in this study are considered to be rigid frame structures. In such systems, all structural elements of the system are assumed to have infinitely rigid moment resistant connections at both ends. Another assumption about the structural system is the linear elastic structural system behavior, in which the deformations are proportional to the loads. One of the most important assumptions in this study is the ‘rigid diaphragm floor’ assumption, a common assumption which simplifies the problem significantly and reduces computing time. This results in three displacement degrees of freedom at each floor level (translations in two orthogonal directions and rotation about vertical direction), and in-plane displacements of the diaphragm can
be expressed in terms of these displacements. All the other nodes on that floor are called slaved nodes and their three displacement components (translation in x-direction, translation in y-direction and rotation about z-direction) can be represented using the displacements of the master node and the distance to the master node as in the following equations:

\[
\begin{align*}
    u(i)_x &= u(m)_x - y(i)u(m)_y \\
    u(i)_y &= u(m)_y + x(i)u(m)_x \\
    u(i)_\theta &= u(m)_\theta
\end{align*}
\]

In the above equations, \(u(i)_x\), \(u(i)_y\) and \(u(i)_\theta\) are the three displacement components of the slaved node, \(u(m)_x\), \(u(m)_y\) and \(u(m)_\theta\) are the displacement components of the master node and \(x(i)\) and \(y(i)\) are the components of distance between master and slaved node at that floor. This method is called the master–slave technique.

**Problems with Outriggers**

1. The space occupied by the outrigger trusses (especially the diagonals) places constraints on the use of the floors at which the outriggers are located.
2. Architectural and functional constraints may prevent placement of large outrigger columns where they could most conveniently be engaged by outrigger trusses extending out from the core.
3. The connections of the outrigger trusses to the core can be very complicated, especially when a concrete shear wall core is used.
4. In most instances, the core and the outrigger columns will not shorten equally under gravity load. The outrigger trusses, which need to be very stiff to be effective as outriggers.

**Objectives and Details of the Present Study**

The objective of the present work is to study the use of outrigger and belt truss placed at different location subjected to wind or earthquake load. The design of wind load was calculated based on IS 875 (Part 3) and the earthquake load obtained using IS 1893 (Part-1): 2002. The location of outrigger and belt truss for reducing lateral displacement, building drift and core moments can be obtained. The ETABS software program is selected to perform analysis. The present study is limited to reinforced concrete (RC) multi-storied symmetrical building. All the building models analyzed in the study have 15,20,25 storeys with constant storey height of 3 meters. This building does not represent a particular real structure that has been built or proposed. However, the dimensions, general layout and other characteristics have been selected to be representative of a building for which the use of outriggers would be a plausible solution.

The model considered for this study is a 45,60,75 mts high rise reinforced concrete building frame. The building represents a 15,20,25 storied office building. The Plan area of the Structure is 40x40m with columns spaced at 5m from center to center. The height of each storey is 3.00m and all the floors are considered as Typical Floors. The location of the building is assumed to be at Hyderabad. An elevation and plan view of a typical structure is shown in fig.

![Building plan dimensions & column centre spacing](image1)

![Building elevation view with central core portion](image2)
locations of outrigger beams and belt truss as shown in fig.

**Structure 1**: Building frame outrigger beam locations as shown in fig

**Structure 2**: Building frame same as structure-1 with belt truss.

**Structure 3**: Building frame outrigger beam locations as shown in fig

**Structure 4**: Building frame same as structure-3 with belt truss.

**Structure 5**: Building frame without any outrigger beams as well as belt truss.

The analysis is carried with all the load combinations. But the wind load is governing. Out of that, the load case (0.9 DL + 1.5 WL Y) is giving maximum values. Hence the above load case is considered for taking the values of forces, moments and the load case (D.L+0.8(LL+WLX) considered for taking the values of Displacement and drift.

Columns considered for comparison of analysis are C21, C23, C30, C38, C40, C43, C53 & C57.

All wall piers are identical with a uniform wall thickness of 350mm over the entire height. The Bracing beams (outriggers) and all other beams are 230mm wide and 600mm deep, Grade 40 (Mix – M40) concrete is considered (Compressive strength 40 N/mm²) throughout the height of the building. The outer and inner columns sizes are considered as 800 x 800 mm and shear wall thickness is considered as 350 mm. The Outrigger Beams are flexurally rigid and induce only axial forces in the columns; the lateral resistance is provided only by the bending resistance of the core and the tie down action of the exterior columns connected to the outrigger;

Since the building is assumed to be a office building live load is considered as 3 kn/m². A floor load of 1.5 kN/m² is applied on all the slab panels on all the floors for the floor finishes and the other things. A member load as u.d.l. of 6 kn/m is considered on all beams for the wall load considering the wall to be made of Light Weight Bricks.

Wind load in this study is established in accordance with **IS 875(part 3-Wind loads)**. The location selected is Hyderabad. The basic wind speed as per the code is Vb =44m/s. The coefficients K1 and K2 are taken as 1.0. The terrain category is taken as „Category 4” with structure class C.

Taking internal pressure coefficient as ±0.2 the net pressure coefficient Cp (windward) works out as +0.8 and Cp (leeward) as -0.5 based on h/w and l/w ratio of table 4 of IS 875 (part3). Using the above data the ETABS automatically interpolates the coefficient K3 and eventually calculates lateral wind load at each storey.

Earthquake load in this study is established in accordance with **IS 1893(part 1)-2002**.The city of Hyderabad falls in “zone 2” (Z=0.10). The importance factor (I) of the building is taken as 1.0. The site is assumed to be hard/rocky site (Type I). The response reduction factor R is taken as 3.0 for all frames. The fundamental time period (Ta) of all frames was calculated as per clause 7.6.1 of the aforementioned code.

\[ Ta = 0.075*b*0.75 \]

Based on the above data the ETABS calculates the design horizontal seismic coefficient (Ah) using the Sa/g value from the appropriate response spectrum. The Ah value calculated is utilized in calculating the design seismic base shear (VB) as,

\[ VB = Ah * W \]

Where, \( W \) = seismic weight of the building.

\[ Qi = VB * (Wi*hi2)* (∑j Wi*hj2)-1 \]

Where, \( Qi \) = Design lateral force at floor i.

\( Wi \) = seismic weight of the floor i

\( hi \) = height of the floor I measured from base

\( j \) = 1 to n, n being no. of floors in the building.

The structure is analyzed as per the loading combinations provided in **IS: 456-2000**. The following load combinations are used to determine the maximum lateral deflection in the structure.

i) DL+LL
ii) DL+LL±WL(x or y)
iii) DL±LL±EL(x or y)
iv) DL±WL(x or y)
v) DL±EL(x or y)
RESULTS AND DISCUSSIONS

1. Storey axial forces:

![Fig 9: elevation view with central core & outriggers in different stories](image)

![Fig 5: Plan view of the model with central core and extended outriggers on three sides](image)

![Fig 6: 3D view of structure without any Outrigger & Belt Truss](image)

![Fig 7: 3D view of structure with Belt truss](image)

![Fig 8: Sectional elevational view of 25 storey structure with Outriggers](image)

2. Diaphragm CM Displacement:

![Fig 3: Diaphragm CM Displacement](image)

3. Storey Drift:

![Fig 4: Storey Drift](image)
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4. Natural time period:

Moments

Another very important factor that is monitored is the moments along the height of the concrete core. The moments that were monitored as shown in figure.

1. The moments below the first outrigger (cap truss).
2. The moments above the second outrigger.
3. The moment below the second outrigger.
4. The core base moments.

Comparison of results of Structure 4 with Structure 3: will give the effect of floor rigidity. Comparison of results of structure 4: with structure: 2 will give the effect of double core shear wall.

From the analysis of the Data the following conclusions have been made.

i) Due to presence of the additional stiffness in terms of double core shear wall + stringer beam + floor rigidity, structure 4 is a stiffer structure.

ii) It can be concluded that floor rigidity is not required to be increased beyond that required for the load carrying of Dead load and Live load on floors.

iii) Column forces and moments are minimum in case of “Building frame with Double Core arrangement of shear wall and Stringer beams” for which drift and displacement are also comparatively less.

iv) Moments in Corner column are less compared to the middle column.

v) Moments in outer periphery columns are less compared to the moments in interior columns.

Conclusions

The study has been carried out to find the effect of Building displacements in Lateral direction with shear core, stringer beam and floor rigidity. The following four structures are considered for study for 25 Storey ‘L Shape’ building.

**Structure 1:** Building frame without shear wall and with stringer beams.

**Structure 2 :** Building frame without shear wall and with stringer beams & floor rigidity.

**Structure 3:** Building frame with Double Core arrangement of shear wall and stringer beams.

**Structure 4:** Building frame with Double Core arrangement of shear wall, Stringer beams and floor rigidity.

References


Structures” Bureau of Indian Standards, New Delhi, 2002.


