Review on Feasibility of High Rise Outrigger Structural System in Seismically Active Regions

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Abstract – *In the modern society, High rise buildings have become a major asset to a city or state. Major challenge in designing a high rise (Tall) structure is ensuring its lateral stability. Tall structures are usually critical to lateral loads such as wind and earthquake. Many different lateral load resisting systems are developed for tall buildings in the field of structural engineering to address the issue of its stability against heavy winds and eminent earthquakes. Outrigger Systems is one of such system which is developed especially for tall structures.*

This paper aims at providing a brief introduction to various structural systems along with elaboration on Outrigger System. The review of literature along with abstract is provided in the paper to familiarise the reader with the configurations, performance, feasibility and the current trends in the Outrigger System. A relatively latest concept of Damped Outrigger and its behaviour in an existing project in Philippines is also discussed in the paper. In addition to all of above several gaps which I have found in the literature including underestimation of performance of Outriggers under earthquake and use of three sets of Outriggers in super tall buildings are listed.

Key Words: *High-rise Structure, Outriggers, Belt Truss, Virtual Outriggers, Seismic Analysis, Damped Outrigger*

1. INTRODUCTION

Tall buildings have always been the symbol of supremacy of the nations engaged in their construction. From a scientific point of view, it has become an appealing challenge for the designers focused on the interpretation of its structural behaviour. Thereby, further goals in terms of achievable heights and unconventional shapes are expected in the next future. There are many reasons for the demands of High-rise structures in modern cities today. Some of the major reasons are listed below;

1. There is always scarcity of land in urban areas.
2. In developing cities due to rapid industrialization, there is increasing demand for residential and commercial space.
3. High-rise buildings have a significant influence on economic growth of the city.
4. Desire for aesthetics in urban settings also encourages High-rise construction.
5. High-rise effectively constitutes in the City Skyline.
6. High-rise buildings impart a certain level of sophistication and prestige to the city.

1.1 Structural systems for High-rise building design

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 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 high-rise buildings, currently there are many structural systems that can be used for the lateral load resistance. In this context, these systems can be classified based on the basic reaction mechanism/structural behaviour for resisting the lateral loads.

1.2 Lateral load Resisting Systems

Various load resisting structural systems or philosophies which are usually incorporated in multi-storied structures are discussed here. The various structural systems are:

1. Rigid frame systems
2. Braced frame and shear-walled frame systems
3. Braced frame systems
4. Shear-walled frame systems
5. Outrigger systems
6. Framed-tube systems
7. Braced-tube systems
8. Bundled-tube systems

These structural systems 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.

Interior system: 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.

Exterior system: If the major part of the lateral load-resisting system is located at the building perimeter, the system is categorized as an exterior structure.

1.3 Earthquake Resistant Design

While no structure can be entirely immune to damages from earthquakes, the goal of earthquake-resistant design is to erect structures that behave better during seismic activity than their conventional counterparts. To address the complexities in deign certain design philosophies and approaches have been developed over the years to enhance the resistance of buildings against eminent earthquakes. Technologies and design concepts, such as ductile detailing, braced frames, tubular frames; damper and base isolation are mostly involved in the Earthquake Resistant Design.

According to building codes, earthquake resistant structures are intended to withstand the largest earthquake of a certain probability that is likely to occur at their location. This means the loss of life should be minimized by preventing collapse of the buildings for rare earthquakes while the loss of functionality should be limited for more frequent ones.

2. LITERATURE REVIEW

In the field of Structural Engineering, it has been widely known that outrigger beams/truss are generally appropriate for resistance against eminent wind loads, but incorporating outriggers for earthquake resistance has been intriguing area for research. The paper aspires at summarizing the various investigations and their deductions that have been carried out in the field of Earthquake resistance of Outrigger Structures.

In 2009, N. Herath et al. worked on idea of increasing safety and stiffness of tall buildings by incorporating outrigger beams connecting core to exterior columns for regions of high seismicity. According to the author most realistic way of assessing structural damage due to earthquake was to analyse the model under same ground accelerations which were recorded in the past. The study also aimed at optimizing the location of the outrigger beams in structure in order to achieve maximum stability of design and economy in construction. The use of deep RC beams (about 3.7m deep) instead of Steel truss proved to be effective because connections of RC Outrigger beams to exterior columns worked better than its connections with Steel truss.

In 2012, Kiran Kamath et al. presented an investigation aimed at examining the behaviour of structures with and without outriggers with various relative flexural rigidities. Study also included performance of 3D models at various locations of outriggers along the height. The parameters under which the models were studied were bending moments, shear forces, lateral deflection, peak acceleration of the core; inter-story drifts. It was found that optimum positions of outriggers are one at top and other at centre height of the structure. This result substantiated the research done by N. Herath et al. in 2009. Several 40 storied models with different ratios of relative heights of outriggers and various relative rigidities were studied by time history analysis method. Deep and stiff outrigger beams were introduced in structures in addition to shear core wall. It was observed that the lateral displacement had been reduced by providing the outriggers at the top and the reduction was almost doubled with introduction of second outrigger at mid height. Further, it was also observed that bending moment at the base of core wall was hugely reduced with the presence of at the mid height.

In 2014, Kiran Kamath et al. presented a comparative study on behaviour of Multi-outrigger structure under Seismic loads. Their study included analysis of models with different combinations of Outriggers placed at various locations with varying axial rigidity of the shear core wall. The emphasis was given to the shear force, moments in the core, drift and displacement of the structure. Axial rigidity was considered as it was directly related to the cross sectional area and modulii of elasticity of the members. It quantified the component of rigidity of the structure to the rigidity of shear wall. Results obtained from the study confirmed that storey displacement was reduced considerably with outriggers. As the relative axial rigidity was increased displacements were further reduced but storey drift increased. Shear force in the core was observed to a maximum at lowest relative axial rigidity. Bending moment was observed to a minimum when axial rigidity of frame was half of the axial rigidity of the core.

In 2015, Srinivas Suresh Kogilgeri & Beryl Shanthapriya presented a research on steel structure incorporating outriggers to study the behavior under static and dynamic loads. In this study the authors focused on the depths of the outrigger truss. The concept involved highlighted that Outrigger reduces the overturning moment on the core and transfers the reduced moment to columns outside the core by the action of tension compression coupled, taking advantage of the increased moment arm between these columns. From the results it was observed that, maximum reductions in the storey displacement and drift were obtained for outrigger having full storey depth and behaviour of outriggers with 1/3rd & 2/3rd depths gave almost similar responses.

In 2015, Thejaswini R M and Rashmi A R published a research focused on the behaviour of building irregular in plan. The research contained seismic and response spectrum analysis of building irregular in plan keeping in view the storey deflection, drift, shear force and torsional rigidity. The study also indirectly aimed at investigating if the irregularity helped the structure behave better under lateral loads. The research was based on seven different configurations of a fifteen storied RC frame model. The various configurations selected for study, with and without outrigger, with and without shear wall, shear core wall at different locations in plan and with complete external shear wall (tube structure). From the research it was established that position of shear wall in plan had a substantial effect on the structure under seismic loads. Shear wall along the shorter walls gave superior results than shear wall along walls in longer direction. Minimum displacements were observed in the case of tube structure since peripheral shear wall inflated the rigidity of the structure from all sides. Storey drift in outrigger models were only slightly higher that the drifts in tubular structure.

In 2015, Abdul Karim Mulla and Srinivas B. N presented a research containing comparative study on behaviour of outrigger in regular as well as irregular structure. The research presented a very original concept of "Virtual Outrigger". Virtual outrigger consisted of belt truss only and there was no connection between the shear core and the exterior columns other than regular frame components such as beams and slabs. As the exterior frame swayed, the virtual outrigger came in to action by controlling the deflection and converting sway in to direct compression and tension on the exterior columns. This concept completely eliminated the complexities of design and construction of outrigger trusses and their connections with the core wall also improving the overall economy of building as well. But at the same time it also proves to be effective only under regular conditions of wind and earthquake. Virtual outrigger couldn't compete to the conventional outriggers under acute conditions of lateral loadings. That's why the scope for the virtual outrigger is limited to regions of less severe winds and earthquakes. The linear analysis methods employed in this study were Equivalent Static Load and Response Spectrum Method. It was observed through this research that natural time period was considerably reduced especially at the very first mode in both regular as well as irregular frame. The reduction on time period at the first mode had very positive impact on later modes; hence the overall displacements and drift were also noticeably reduced. In this research, outrigger trusses were tested with different materials of steel and concrete. Concrete outrigger was found to be more effective in reducing overall response. Since the concrete outriggers connected better with the RCC frame rather than steel outrigger with RCC frame, this result enhances the monolithic behavior of the structure.

In 2007, Rob J. Smith and Michael R. Willford presented a paper on a new concept known as the Damped Outrigger. The paper described a new philosophy in design for tall structures exposed to extreme wind loads, such as cyclones and typhoons. In such extreme conditions tall structures with conventional outrigger were not proficient enough in controlling the deflection and moments. As a solution to these excessive responses, the concept of Damped Outrigger was developed.

The research proved to be very cost-effective since, it reduced the requirement of high strength and stiffness resulting in lighter frame. Apart from this investigation on typhoon winds, authors also brought to attention the significance of reliability, maintenance and replacements of Dampers from time to time for safe functioning of the building. The authors also indicated that, Damped Outrigger concept could also be incorporated for Earthquake Resistant Design where Performance-based approach is preferred. Dependable structural damping was enhanced by a factor of 5 by incorporation of Damped Outrigger.

2.1 Summary of Literature

1. Outriggers have a significant impact on behaviour of structure under lateral loads, such as wind and earthquake. The behaviour of outrigger structure under earthquake load is different form earthquake to earthquake. The optimum position of outrigger under earthquake load in a grid frame is between 0.4-0.48 times the height of the structure (from the bottom of the building).
2. Positioning of outriggers in a structure alters many parameters, such as storey displacement, drift, core bending moment etc. Therefore, it is most necessary to optimise the location of the outrigger beams/truss in the elevation of the building. Single outrigger is placed at top when reducing storey displacement is the primary concern. It is placed at mid height to minimize the storey drift to a lowest amount. In general, placing Outrigger at the top is less efficient, but when dominant criterion is peak acceleration, top position is optimum.
3. Relative Axial Rigidity has a significant impact on the bending moment of the core wall. In multi-outrigger system, maximum reduction in displacement is achieved when the ratios of heights of the two outriggers is 1.5 and relative axial rigidity of 0.75.
4. Comparative performance of the outriggers by varying depths has marginal impact on the lateral displacement and drift of the high-rise structure. Depth of the outriggers and the displacements are indirectly proportional.
5. Increasing the density of the exterior columns enhances the stiffness of the outrigger structure resulting in decrease in deflections. Outrigger behaves as high drift controller when provided at storey which has maximum drift.
6. The concrete outrigger is more efficient in reducing the lateral storey displacement than the steel outrigger in a tall RC building. The load resisting capacity of the tall building structure increases by providing outriggers due to its strength characteristics.
7. Damped Outrigger is the new philosophy for the design of high-rise buildings to introduce a high level of dependable supplemental damping for the primary purpose of reducing dynamic wind effects. Its influence

of structures subjected to severe seismic load is yet to be investigated.

2.2 Gaps in Literature

After scrutinizing the literature available in the area of Outrigger Structural system, the gaps or problems which are not yet investigated are established and discussed as follows;

1. Most of the research work is based on the performance of outrigger system under eminent wind loads. Seismic resistance offered by outrigger systems is underrated.
2. The models analysed in various research are grid models rather than actual building plan.
3. Outrigger has a potential of acquiring heights up to 350 meters (70 - 80 stories) and yet very rarely, models up to only 60 stories are investigated with research work mostly being carried out for models below 40 stories.
4. Multi-outrigger concept has proved very efficient but the performance of employing three sets of outriggers in a super high-rise building (about 80 stories) is yet to be studied.
5. For outrigger system, performance based designs are not much emphasized. Nonlinear dynamic analysis is rarely performed in the literature available.
6. Analysis using Time History method for super high-rise (around 80 stories), especially for regions of high seismicity such as Seismic zone-V is never studied.
7. Relatively recent concepts in Outriggers viz. Virtual outriggers and Damped outriggers are not yet analysed for super high-rise structures.
8. System of 'Damped Outrigger' as of today is only analysed for typhoon winds in Philippine. Its behaviour under seismic load is not yet studied in any literature available.

3. SYSTEM OF OUTRIGGER

The literature survey carried out has refined the philosophy of outrigger system to control the response of the high-rise buildings, especially in region of eminent wind and high seismicity. It is observed that outriggers are deep and stiff beam/truss which connects the central core to the exterior most columns in a frame which helps in keeping the columns in their position in turn reducing the sway. This system helps in reducing the movement of the core when compared against lateral loads to the system with freely standing core without outriggers. The restrain caused by the outrigger reduces the lateral drift at top. The stiffness of the structural system increases by 20 to 30% by introducing the outrigger structural system. The use of outriggers in high-rise buildings started about 5 decades ago.

3.1 Concept of Outrigger

Originally, the concept of outrigger was employed in the sailing ship in order to increase the stability and the strength of the masts subjected to wind forces. From this point of view, a tall building could be considered analogous to the mast of a ship in presence of further elements similar in behaviour to the spreaders and stays. Thus, the engineers understood that it was possible to couple the internal core of the building with the exterior columns.

The major factor that affects the design of tall structures is its sensitivity to the lateral load. One of the important criteria for the design of tall buildings is lateral drift at top. The acceptable drift limit (top deflection in tall building) for wind load analysis (according to the IS code) is 1/500 of the building height. The use of core-wall system has been a very effective and efficient structural system used in reducing the drift due to lateral load. However, as and when the height of the building increases, the core does not have the adequate stiffness to keep the drift down to acceptable limits. For such high-rise structures, structural system known as outriggers may be introduced.

3.2 Working principle of Outriggers

When horizontal loading acts on the structure, the rotation of the core is reduced by the axial force that arises in the external columns, in particular tensile force in the windward columns and compressive force in the leeward ones. The efficiency of the outrigger system depends upon the flexural stiffness of the girder and the axial stiffness of perimeter vertical columns. In addition, including deep spandrel girders, which work as belts surrounding the entire building, it is possible to mobilize also the other peripheral columns to assist in restraining the outriggers, providing an improvement up to 25-30 per cent in stiffness.

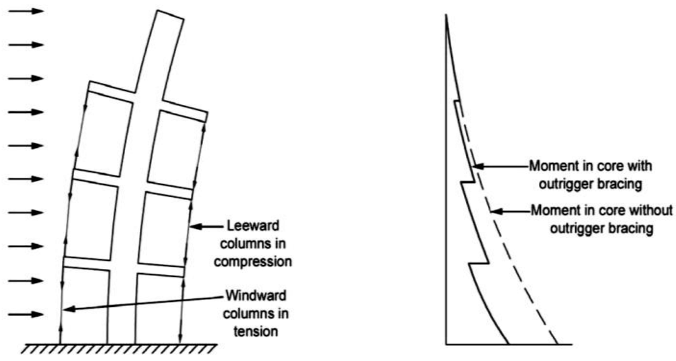

Fig -1: Structural behaviour of an outrigger system; comparison in terms of moment diagram between systems with or without outrigger bracings
(*Source- Dr. K. S. Sathyanarayanan, 2012*)

3.3 Outrigger Configurations

Outriggers are used with many different configurations and combinations depending upon the location of building, type of loading expected to resist and materials used. Based on these considerations, different types of configurations are developed by various researchers to enhance the overall response of the structure. The most efficient configurations are stated below:

1. Conventional Outrigger
2. Virtual Outrigger
3. Damped Outrigger

1. Conventional Outrigger:

In the conventional approach, two outrigger beams/truss are connected to the central core on one side and to peripheral columns on the other side. The same configuration is repeated for both sides of the building and a total 4 numbers of outriggers are fixed. The connection of outriggers with core wall is rigid and on the other ends the connection with exterior column is hinged or moment free. This configuration is designed as propped cantilever beam with infinite stiffness.

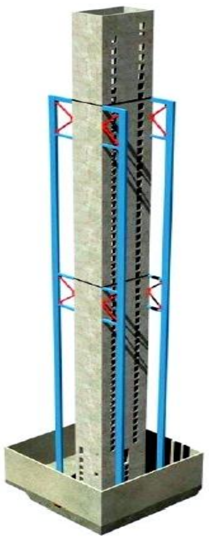

Fig -2: Shear core connected to exterior column via Outrigger truss system
(*Source- Kiran Kamath, 2014*)

2. Virtual Outrigger:

This is a relatively new concept wherein the outrigger beams that connect the core to columns are completely eliminated. The conventional outrigger is replaced by a Belt truss system. The truss connects all the peripheral columns via truss or deep beam thus generating a couple over the rigid storey which is formed by the belt truss. This couple helps in reducing the core moment and drift in a structure. The concept of Virtual outrigger system eliminated the complexities related to connection of the core with outrigger beams. Absence of outrigger beams increases the usable space and improves planning and design of Outrigger storey. The peripheral belt truss engages all the columns due to which the sway is converted into axial force and transferred to the columns resulting in enhanced efficiency of structure.

3. Damped Outrigger:

Damped outrigger is the most recent of all the other philosophies concerned to Outriggers. In this concept, a system is introduced to increase the dependable structural damping by a factor of 5–10. The damping is achieved by incorporating passive and semi-active damper into the outrigger system. By doing so the dynamic response of the building to wind effects (buffeting and vortex shedding) is virtually eliminated, leading to substantially reduced lateral design forces and assured occupant comfort. The dampers are installed at the connection of outrigger beam with exterior column as shown below in the figure 3.6. This improves the reliability of dynamic response predictions and, by supplying higher levels of damping, substantially reduces the required stiffness of the building while at the same time improving performance. The concept of damped outrigger is developed to enhance the damping of the structure to reduce dynamic response unlike the other configurations aiming at increasing the stiffness and strength of the structure. The researches so far have e employed viscous dampers and visco-elastic dampers into outrigger system.

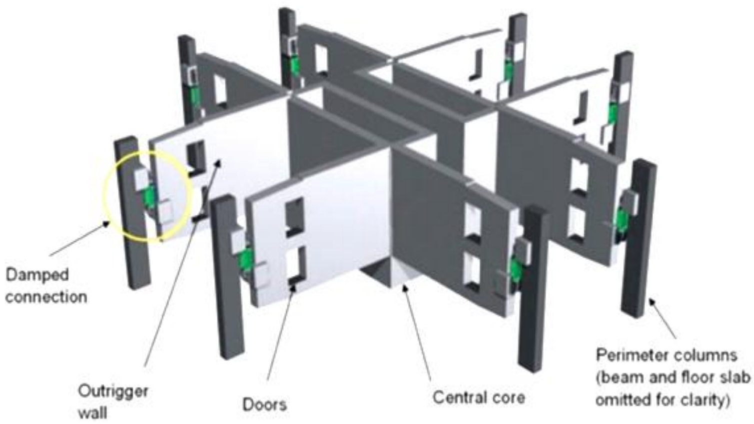

Fig -3: Layout of Outrigger storey with installation of dampers
(*Source- Rob J. Smith, 2007*)

3.4 Factors affecting the effectiveness of Outrigger system

From the studies carried out so far it has become evident that the behaviour of Outrigger system is dependent upon many factors. Some of the major factors of influence are listed below;

1. The stiffness and location of the outrigger truss system.
2. The stiffness and location of the Belt truss system.
3. Geometry of the tall building
4. Stiffness of the central core
5. Floor-to-floor height of the tall building

3.5 Various advantages and disadvantages of Outrigger System

Like all other structural system, Outrigger system also possesses certain advantages and disadvantages over other structural systems which are as follows:

Advantages:

1. Outrigger system can be incorporated into steel, concrete or composite structures.
2. Rigid frame connections can be avoided on the exterior frame of the structures, bringing out economies.
3. Considerable reduction or complete elimination in the net tensile forces in the columns and foundations.
4. The external column spacing is not governed by structural consideration and can easily be spaced according to aesthetic and functional perspective.

Disadvantages:

1. Outrigger systems interfere with the planning and utility of usable or rentable space.
2. Connection at the interface between core and foundation is expensive and involves intensive work.
3. Labour intensive and expensive rock anchors are required alternative to simple spread footing.
4. Expensive foundations solely required to resist overturning moment.

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