Use Of Outrigger, Belt Wall And Bracing Systems In High Rise Building Subjected To Wind Loads

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Abstract - **In the fast changing and ever evolving world of today, high-rise structures with innovative designs have become the norm. Even though these structures are a marvel to look at, they have their own fair share of problems. As one goes higher, the wind forces become a huge obstacle that needs to be dealt with effectively in order to ensure the security of the residents. After extensive research and trial runs, many creative solutions have come up to tackle the effect of wind energy. In the present study, an attempt is made to effectively reduce the lateral displacement caused by wind forces with the help of a belt wall, optimally placed outriggers and a proper bracing system. In this research, with the assistance of Outrigger / Belt wall / Bracing systems, an effort has been made to assess an economical technique of decreasing lateral displacement of the structure owing to wind forces. The present study takes in consideration an elliptically planned height structure of about 320 m, the structure consists of 78 above ground level stories and 2 below. It comprises of an elliptical core as lateral load resisting system. The structure is studied with (i) Core wall (ii) Core wall with Outrigger (iii) Core wall with Belt wall (iv) Core wall with combination of Outrigger and Belt wall and (v) Core wall with Bracing systems. The thickness of outrigger/Belt wall is varied from 300mm to 500m with a step of 100. The Outrigger/Belt wall system is provided on different levels and in some cases, it is provided on two different levels. The Outrigger/Belt wall is provided only on plant floors/refuge floors/mechanical floor. The bracing system is studied only at level 70 only with cross sectional areas and with different materials (concrete and steel). There are four plant floors in the model structure, which are at level 17, 51, 70 and at roof level. The parameters discussed in this study are the lateral displacement, which occurs at the roof level of the structure along with the moment reduction shared by the elliptical core that is caused by wind forces and the moment shared by the combination system, i.e. the bracing system, outriggers and the belt wall. After much trial and error, it was established that the optimum location of a single outrigger or belt wall was level 51. For two different levels, the best location was found to be at level 17 and level 70. On the other hand, the use of bracing system drastically reduced the lateral displacement of the building right down to the permissible value but it was found to be ineffective when it came to reducing the moment shared by the core. Out of all the options and various permutations and combinations, the safest and most economical setup was found to be combination of belt wall and outrigger at two levels i.e. level 17 and level 70. This study also shows that the lateral displacement of the structure can be minimized by enlarging the size of the central core or in other words simply increasing the stiffness of the building. However, the drawback of this method is the exponential increase in the cost of the structure thereby making it profligate, because the increase in size of core directly results in the increase in volume of concrete used, which is negligible when the combination system proposed in this study is utilized.**

keywords - **Outrigger, belt wall , bracing system, wind loads**

I. Introduction

In this day and age, the construction of tall buildings has become a fast-growing trend. In order to make your presence felt in the market, companies are making it a point to construct flamboyant structures or own an office in the region's biggest skyscraper. Sky is the limit for these innovative structures as long as all proper conditions are being met. One of the biggest problems an engineer faces when designing a tall building is the considerable effect of wind on the lateral stability of the structure. This is the governing factor in the design of skyscrapers. As the building goes higher, wind pressure increases proportionally, and that is why loads associated with winds are much greater than live and dead loads. Extreme lateral displacement can cause structural and non-structural damage while too much acceleration can lead to problems to the occupants. Generally, shear walls and moment resisting frames are more than enough for low to medium height buildings, but as you go higher, these methods are rendered insufficient. At this point, belt wall system along with outriggers can be effectively used to keep the lateral displacements in check and increase the stiffness of the structure. Outriggers are a concept derived from sailing ships, which use them to resist the wind forces in their sails. Simply put, the core in the high-rise building can be related to the mast of the ship, while the outriggers act like the spreaders and the outer columns like the shroud.

1.1 Lateral Load Resisting Systems

1.1.a Outrigger System

An outrigger is a rigid horizontal structure, which is a part of a boat's rigging, which extends beyond the gunwale providing stability to the main hull preventing it from capsizing. Taking inspiration from this concept, high-rise structures are installed with outriggers and a central core. Stiff in flexure, these horizontal cantilevers connect the central core to the peripheral columns. The moment arm of the core is increased due to this connection, which in turn increases the lateral stiffness of the system. When wind forces act on the structure, the column-restrained outriggers on the windward side restrain overturning moment through tension and the outriggers on the leeward side through compression. This minimizes lateral displacement drastically when compared to a structure without outriggers. Outrigger systems are not only efficient in controlling the lateral displacements occurring at the top, they are also significant in reducing the inner storey drifts of the structure. This is one of the most efficient system of designing a high-rise structure as it increases the structural depth of the building when it behaves as a vertical cantilever. A horizontal deep girder joins all the exterior columns, which are not directly connected to the ends of the outriggers.

Types of Outrigger Systems

- **Conventional Outrigger System** - This system consists of outrigger girders connected directly to the braced frame or the shear wall at the central core and to the peripherally located columns. These exterior columns are most commonly located at the outer edge of the building. These outrigger trusses, which are connected on one side with the central core and the exterior columns on the other side, convert the moment at the core into a vertical couple at the columns thereby resisting rotation at the core. The core is subjected to reverse curvature below the outrigger, as the rotation is minimal in most designs. In other words, the outrigger truss moves up and down due to overturning and rotation of the core caused by the wind forces. The peripheral columns restrict this movement and produce opposing forces.
- **Virtual Outrigger System** - One of the biggest problems associated with conventional outrigger system is the decline of usable space on the working floor. Functional and architectural constraints create many hurdles. To overcome these problems, virtual outrigger concept is used. The direct connection between the central core and the exterior columns used in the conventional outrigger system is eliminated which in turn solves many problems concomitant with the use of outrigger systems. The working behind the virtual outrigger concept is to make use of stiff diaphragms, which are resilient in their own plane. The moment is transmitted in the form of horizontal couple from the central core to the outrigger trusses and from there to the peripheral columns. Belt truss/walls and basements can be used as virtual outriggers

1.1.b Belt Walls

Belt walls eliminate many of the hurdles that arise when working with the outrigger system. They are provided to improve the axial and torsional stiffness of the columns. Belt walls are quite useful in controlling the settlement of columns as well as shortening and differential elongation. Extra peripheral columns are constructed in order to support restraining the overturning of the outriggers.

To achieve this phenomenon, exterior columns are tied to a wall running around the circumference of the building in the form of a belt, hence the name belt wall. The floor diaphragms are flexible in the out-of-plane vertical direction even though they are quite stiff in their own plane and are thus unaffected by differential settlement of columns.

1.1.c Bracing Systems

Bracing is a highly economical and efficient system of resisting lateral displacement in a high-rise building. This system is most suited for buildings of medium height and are generally used in steel construction. The number of bracings and their location is the most important factor during architectural planning Bracing systems usually form a triangulated vertical truss in which the diagonal members form the web and columns acting as chords. The biggest advantage of this system is that it can be used repetitively leading to a highly economical design and cost cutting in fabrication. Large-scale bracing systems are highly efficient in reducing drift ratio and uplift forces in the foundation.

1.2 Need for Present Study

It comes as no surprise that the cost of owning a piece of land these days is through the roof. To compensate for this exponential increase, builders have started going higher and higher, which presents its own set of problems. Larger height to width ratio will cause huge overturning moments while the structure deflects considerably. Taller buildings have created a need for unconventional, innovative and efficient structural systems. As fewer exterior columns are preferred, the central core wall is the one that is fully responsible of resisting lateral forces. For this concept to work, high-rise structures consist of floor spaces free of columns between the peripheral columns and the central core. This type of setup sanctions for varied utilization of the floor space, at the cost of sacrificing the core and peripheral column system, which is vital for repelling the overturning forces and moment. To overcome this hurdle, one needs some form of structural system to connect these two components in order to increase the overall resistance of the structure. The best option here is to make use of outriggers, which increase the resisting moment to overcome the lateral forces acting on the structure. They are also quite economical as the use of outriggers directly influences the quantity of steel used and it is common knowledge that controlling the cost of steel increases the overall economy of the structure.

1.3 Objectives of the Study

The primary objective of the present thesis is to find out the efficiency of belt walls, bracing systems and outriggers in resisting lateral forces at various storeys in a high-rise structure exposed to wind loads. The aim of the study is

- To observe and study the way in which displacement at roof level is reduced and how the high-rise structure behaves with the addition of belt walls and outrigger
- To study the reduction of moment shared by the central core wall by the application of outriggers and belt wall.
- To calculate the moment shared at the base of the high-rise structure.

II. LITERATURE REVIEW

Gerasimidis and Efthymiou (2009) "Optimum outrigger locations of high-rise steel buildings for wind loading" In this paper a two-dimensional model was analyzed with a concrete core at the middle of the building model and two columns at the edges of the structure. One of the outriggers was placed at the top level of the building while the study was carried out in finding the optimum location for the second outrigger. The second outrigger was moved along the height of the building and placing it on every floor level. A uniform wind loading was considered for the two-dimensional model. The number of stories were thirty with a constant story height of 3m. It was found that when the second outrigger was placed at the middle of the model, the optimum location of the outrigger was achieved, taking into consideration only the drift criteria.

Abbas and Mohsin (2012) "Optimization of outrigger locations in steel tall buildings subjected to earthquake loads**"** This paper compared the optimum outrigger locations obtained by response spectrum and nonlinear time history analysis. 3D models of 20 and 25 storey steel frame braced by outrigger and belt truss system were considered. The paper concludes that optimum outrigger and belt location resulting from response spectrum analysis are at storey 10 and 14 respectively for 20 and 25 storey models whereas for time history analysis the optimum locations were at storey 14 and 16 respectively.

Raj Kiran, Ihtesham and Suresh (2013) "Optimum position of outrigger system for high rise reinforced concrete buildings under wind and earthquake loads" The paper studied nine 30 storey 3d models of outrigger and belt truss system for both wind and earthquake loads. The paper concludes that the use of outrigger and belt truss system in high rise buildings increased the stiffness of the building and made it efficient under lateral load. The drift at the top with only core is 50.63mm when outrigger was provided at top, this reduced to 48.2mm and 47.63mm with and without belt truss. There was no reduction in drift with belt truss. Using second outrigger with cap truss gives the reduction of 18.55% and 23.01% with and without belt truss. The optimum location of the second outrigger is middle height of the building.

II.a Critical Appraisal

- Much of the literature copes with the study of steel outrigger trusses and belt trusses, no journal is studied using reinforced concrete outriggers and reinforced concrete belt walls.
- Many of the researchers studied only the optimum location of outriggers so far attempt is not made for reducing lateral displacement by providing RCC outrigger and belt walls.
- Thus, the present study is an attempt for the analysis of high-rise structure with concrete outriggers, belt walls, combination of outriggers and belt walls along with bracing systems.

III. CASE STUDY

High-rise structures are vulnerable to oscillate under high winds for long natural periods. These structures are prone to the phenomenon of dynamic resonance in wind. Vortex shedding is another type of dynamic response in wind. In vortex shedding phenomenon when high winds blown across the surface of a high-rise structure, vortices are alternately shed from one side to the other giving rise to low pressure zones on the downward side of the structure which generates a fluctuating force acting perpendicularly to the direction of the wind. For buildings higher than 40 storeys, the dynamic resonance in wind has a huge impact on the design of the building. In simpler words, the dynamic resonance in a building can be compared to that of a tuning fork. The taller the structure, the lower is the frequency. It means that as the building goes higher, its frequency is lowered proportionally which results in a structure which resonates more by the wind. At the end of the day, the biggest factor governing the design of a tall structure is the drift of the building due to wind forces and not the fully stressed state as is the common misconception.

One of the chief factors influencing the design of high-rise structure is the behaviour of the structure under the application of lateral loading. Lateral drift at roof level or top of the structure is one of the most essential condition for the design of high-rise structures. According to Indian Standard Code 456, the tolerable displacement also known as top deflection for analysis of wind loading is 1/500 of the height of the structure. It is difficult to truly understand how drift affects the structure unless one experiences acceleration. There are several methods to reduce the drift caused due to lateral loads, one of them being the core wall system which has been found to be quite effective. The main drawback of this system is that when the building increases in height, the stiffness of the core is not enough to keep the wind drift in check. As stiffness of the building increases in significance as one goes higher, the core wall system is combined with outrigger beams connected to shear walls or belt walls which are then connected to the peripheral columns. With this particular system in place, the lateral forces are controlled, wherein the rotation of the core is resisted by outriggers and columns thereby reducing the deflection at top and moment at the base which would have been present in free core system. Quite a number of studies have been carried out on this combination system.

An RCC shear walled structure of 320 m height is considered in the current study. The structure considered here is proposed building which is under construction, however the general layout, height and various other dimensions of the buildings have been greatly exaggerated to make the building susceptible to failure under wind forces so as to make use of outriggers and belt walls. In other words, a scenario is created in which the use of belt walls, bracing system and outriggers seems like a good solution.

Gust factor method is the most commonly used method for determining the way a building will behave under the dynamic effects of wind in both parallel and perpendicular directions, however, to avoid unnecessary complications, a 2 kN/m_2 uniform wind pressure is assumed to act on the building in y direction only. In high-rise structures, it has been seen that the wind base shear effect is much more substantial than the effect of seismic base shear, therefore, in this study, static wind analysis is performed on the structure. The building model was created according to the exact specifications in ETABS. The model was created using several different position combinations of outriggers, bracings and belt walls at various levels in the building. The purpose of placing the lateral force resisting systems on different levels is to investigate and govern the assortment of options that are going to be optimal to endure the loads.

III.a Description of Structure Model

The present thesis comprises of a spiral building in the shape of an egg whose dimensions are 43.2m in X-direction and 55.9m in Y-direction encompassing an area of 2415m2. The total height of the building is 292m. There are 70 floors with different heights above the ground along with 3 floors underground (12m). The structure is surrounded by a radial grid system of columns placed at regular intervals.

The central core installed in the building is of elliptical shape which will be able to comfortably house various amenities and elements like staircase, MEP risers and other forms of vertical transportation. The lateral force resisting system functions on the fundamental principle of central core wall system. Not counting the elliptical core, the structure consists of 14 different shear walls. It is common knowledge that the lower floors of the building require stronger concrete whereas the higher levels can make do with lower grades, keeping that in mind the lower levels use M45 grade and the higher levels use M85 grade.

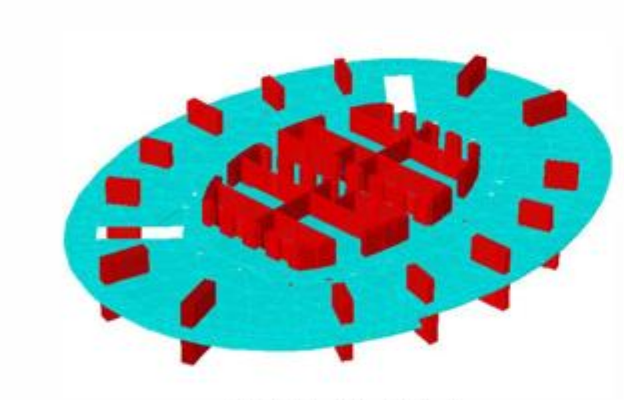


Fig. 3.B Floor plate of the Structure

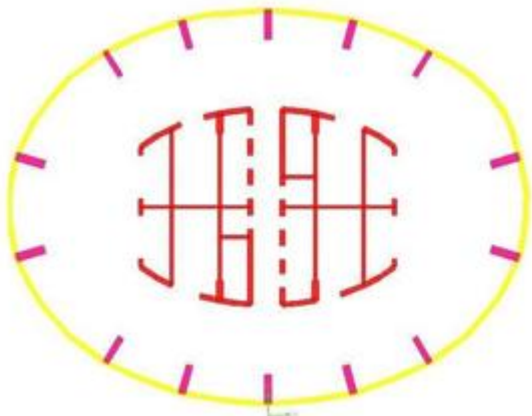


Fig. 3.A Plan of the Structure

III.b Building model analysis using ETABS

The stresses developed along with moment and displacements are calculated by using the method of static wind analysis including and excluding outriggers. The software used for this analysis is ETABS which stands for Extended Three-Dimensional Analysis of Building Systems. The points to be considered for this software are

- The slab and walls were taken as shell type to deliver plane stiffness.
- The rigid diaphragm option was used to model the slab sections and they are modelled only to take in plane diaphragm forces.
- Due to cracks appearing in the slabs at supports and also because of the effect of shrinkage and creep, the out of plane bending stiffness of slabs is neglected.
- The building was analyzed carefully after Uniformly Distributed Load was properly disturbed among all floors.

After detailed consultation and feedback from experienced engineers who are in practice, for preliminary calculations, only uniform wind pressure was adopted. After the option of outrigger is accepted by the client and architect, the calculation of different loads will be incorporated in the final detailed design. The structure is studied only for wind acting in the Y direction.

The results which were compared are as follows:

- Displacement at the roof level
- Moment shared by the elliptical core
- Moment shared by the outrigger system
- Moment shared by the belt system
- Moment shared by the outrigger and belt system

IV. RESULTS AND DISCUSSIONS

IV.a. Outrigger System

The stresses and moment shared by the elliptical core along with drift of the building under the presence of outriggers are studied carefully in this thesis. The static wind analysis was carried out in ETABS software wherein outriggers were placed in certain places with different thicknesses varying from 450mm to 650mm. The behaviour of the building was observed and appropriate results were documented.

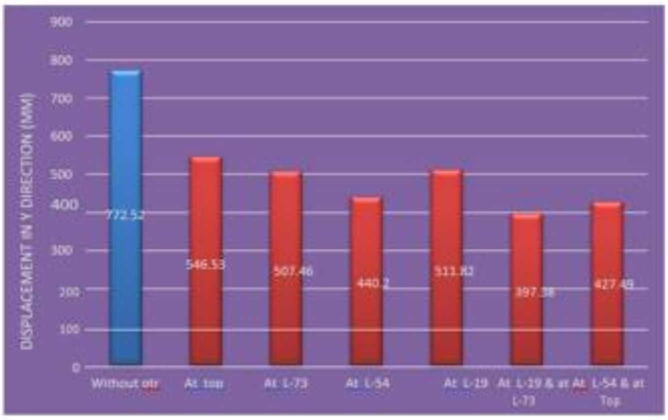


Fig 4.1 Comparison of lateral displacement at roof level with different outrigger locations.

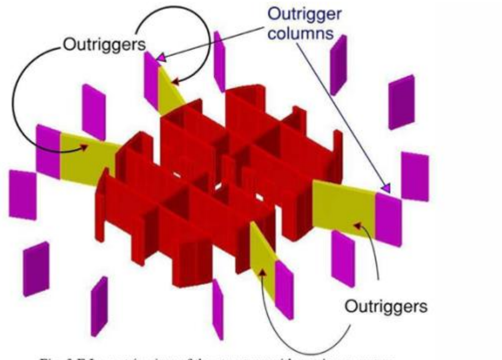


Fig. 3.E Isometric view of the structure with outrigger system

IV.b Belt Walls

The belt wall system was modelled similarly on the same floors i.e. the 73rd, 54th, and the 19th floors and a combination of 19th floor and 73rd floor along with 54th floor and the roof level.

The structure consists of a combination of outriggers along with belt wall. This system was modelled in ETABS with the thickness varying from 450mm to 650mm and its subsequent effect on the behaviour of the building i.e. drift of the building along with stresses and moment shared by the elliptical core is studied.

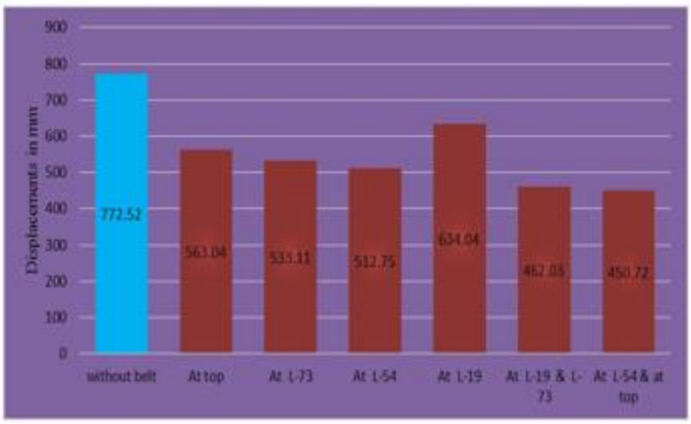


Fig 4.D.1 Comparison of lateral displacement at roof level with different belt locations

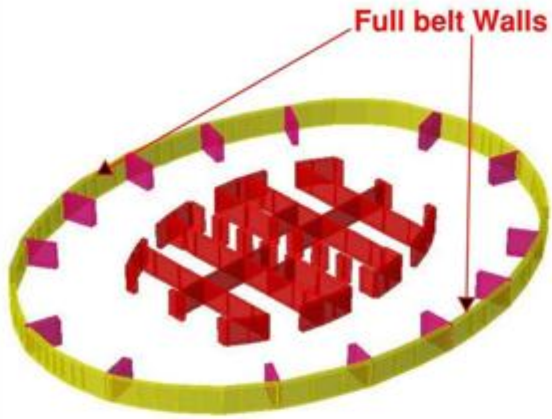


Fig. 3.N Isometric view of the structure showing belt wall system

IV.c. Bracing System

The behaviour of the building is observed by providing bracings or x-bracing of varying sizes such as 0.7mx1.75m, 1.1mx1.1m, 1.3x1.3m of grade M60 at the 73rd Floor with its ends released. The subsequent results obtained such as moment reduction and deflection in the core are studied carefully.

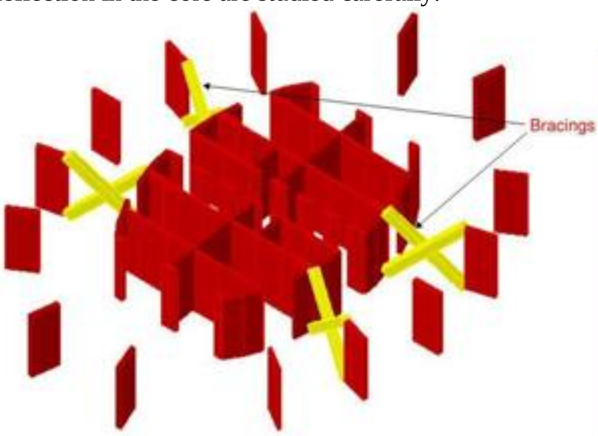


Fig. 3.Q Isometric view showing bracing system in the structure

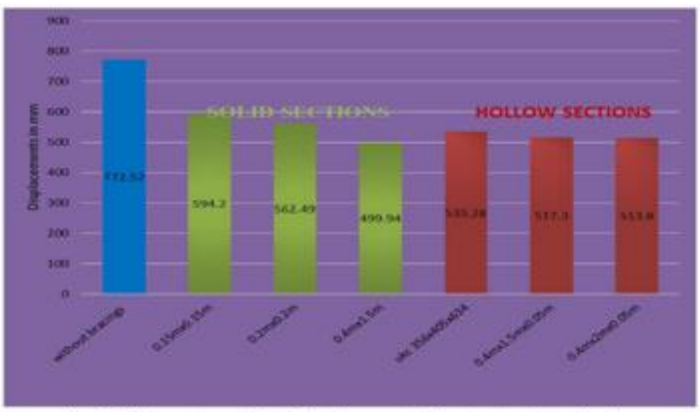


Fig 4.K.1 Comparison of lateral displacement of the structure at roof level with steel bracing of different cross sections.

IV.c. Belt wall and Outrigger System

The structure consists of a combination of outriggers along with belt wall. This system was modelled in ETABS with the thickness varying from 450mm to 650mm and its subsequent effect on the behaviour of the building i.e. drift of the building along with stresses and moment shared by the elliptical core is studied.

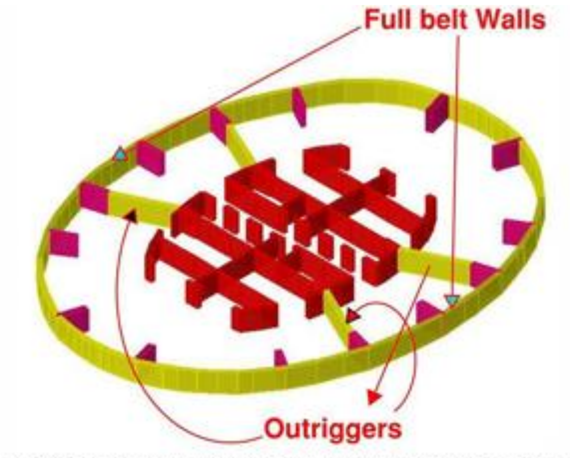
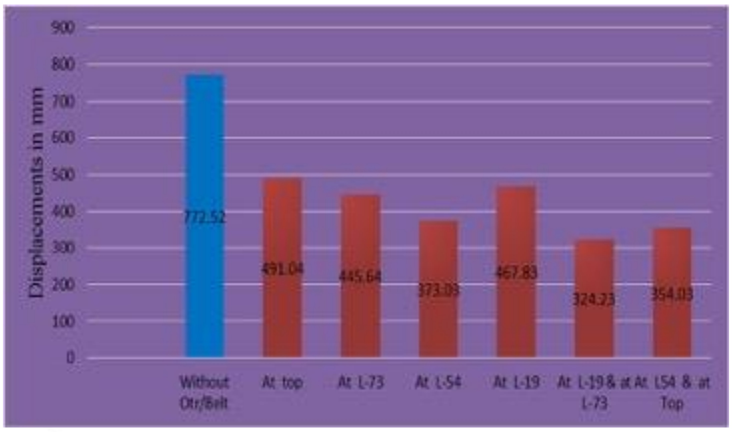


Fig. 3.P Isometric view showing outrigger and belt wall system in the structure



V. CONCLUSIONS

- The tall buildings with core wall as lateral load resisting system (LLRS), a large amount of moment caused by wind forces is shared by core wall. For the structure to be safe the size of the core wall should be sufficient enough, making the structure highly uneconomical.
- The addition of Outrigger makes the structure stiff to a very high level and it allows the structure to be spacious unlike if we use “Tubular Structures” which reduces the portability of the structure.
- It was observed that with the use of a 600mm outrigger at two locations (L-73 & L-19) the lateral displacement due to wind-y forces of the structure reduces by almost 50%, reduces moment shared by central core by 38% and stresses on core by 29%. The moment shared by outrigger system is about 41% of the total moment developed due to wind-y forces.
- With the use of belt walls at two level (L-73 & L-19), the lateral displacement of the structure reduces by 52%, moment shared by the central core also reduces by almost 40%. The moment shared by belt wall system in this particular model is about 40% of the total moment developed due to lateral loads.
- The combination of outrigger and belt wall reduces the lateral displacement of the structure by almost 60% when the combo was placed at two level (L-73 & L-19), the moment shared by the central elliptical core reduces by 48% and stress on core by 39%. In this model the moment shared Outrigger Belt system is of about 49% of the total moment developed.
- With the use of bracing of different cross-sectional areas, the lateral displacement of the structure reduces to the permissible limits, but the bracing fails in axial forces.

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