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Behavior And Optimum Location Of Outrigger And Belt Truss System In High-Rise Buildings Subject To Seismic Loading

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Abstract

This study is focused on the efficient use of the lateral load-resisting system for high-rise concrete buildings subjected to earthquake load. 32-storey three-dimensional models of OMRF, SMRF, core, core with outrigger (OT), core with outrigger and cap truss, and core with belt truss (BT) and core with belt truss and their cap truss systems are analyzed and compared to find the lateral displacement, storey drift and time-period reduction. The modelling and analysis were performed using finite element software ETABS 2016. The analysis has been carried out to study the effect and performance of the outrigger system and belt truss system in the building. These systems are provided at different levels along the height of the building. The coverage of the outrigger and belt trusses are equal to the height of the typical story and maintained the same in all the models. For finding the optimum position of the outrigger and belt truss system and also with their cap truss, the result is illustrated in terms of the reduction of top-storey lateral deflection, the maximum reduction in storey drift and the maximum reduction in the time period of the building. All the parameters are obtained for the structure without an outrigger system and they are compared with the values obtained by introducing an outrigger and belt truss. A total of 51 models are studied for finding the optimum location and behaviour of the systems when introduced on the building. A comparison is made to find the best system among all the systems, which are introduced in the model. Among the entire systems, an outrigger with a belt truss is found to be the best system in terms of reducing deflection, drift, time and base shear. The optimum position is found to be at 0.375 times the height of the total structure when the user system is outrigger and its belt system in terms of reduction in deflection and time, whereas the optimum position is at mid-height when the selection criterion is lateral drift.

Keywords: *- Outrigger; Belt truss system; Earthquake; Lateral displacement. Out-outrigger; OFT-Outrigger fixed at the top and another variable; OBT-Outrigger and Belt Truss system*

Introduction

Background

Due to the increasing population in the city areas such as Kathmandu, the problem of housing has increased to a large extent (UN-HABITAT, 2010). Very few land areas are available in the core part of the town. If a taller building is constructed, then it can replace several other houses and the problem of housing can also be lowered. A large number of people can be accommodated in a tall building.

The main problem with the talls buildings is to resist lateral loads such as earthquakes and wind (Gupta et al 2020. A number of people died and structures collapsed due to the Gorkha earthquake in 2015, Nepal. The risk to the life of people and damage to the structure is more due to the collapse of such structures during an earthquake. So, it is more important to consider the lateral stiffness of the structures. One of the ways to introduce the lateral load-resisting system in high-rise buildings is to use the outrigger system (Nanduri et al, 2013) in an optimum location in a slender building to reduce the effect of the earthquake forces (Kian, 2001).

Outriggers

In the past, mainly structures were aimed to carry gravity loads only. With the advancement of building materials and new structural systems of design, building weight is largely reduced. As the building starts to grow in height, increasing the slenderness in which it is necessary to resist the majority of the lateral forces such as earthquakes by the horizontal load-resisting system of the building (Shivacharan et al 2015). One of the significant criteria for the design of a slender structure is lateral drift and deflection at the top which should be within acceptable limits. As the slenderness increases, the flexibility of the building increases. So, it becomes necessary to identify a suitable load-resisting system in such a structure to minimize the effect of lateral forces depending upon the height of the structure (Gupta et al 2020).

Some of the essential systems to resist the lateral loads in the building are rigid frame arrangement, braced frame and shear wall framed arrangement, braced framed system, shear walled framed system, outrigger arrangement, framed tube system, braced tube system, bundled tube system.

The outrigger structural system consists of a main concrete/steel core connected to the exterior column utilizing outriggers. Outriggers are relatively stiff members which may be one or two stories deep truss/deep beam/ deep walls which extend from these cores towards the exterior columns which helps in keeping the columns in their position reducing the sway and drift (Gadkari & Gore 2016). The system also helps in reducing the moment at the core base.

The core may be positioned in the middle with outriggers projecting from both sides, or it may be positioned on one side with outriggers reaching the building columns along that side (Figure 1).

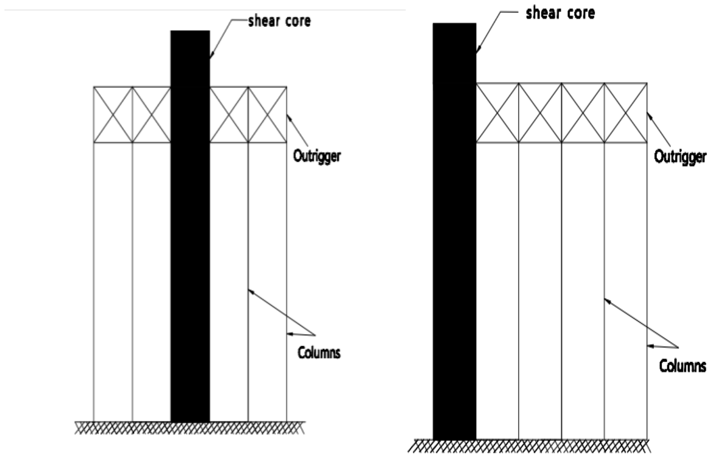

Figure 1 Outrigger with centrally located core and outrigger with an offset core

Belt truss which is one or two storeys deep ties the peripheral columns which in turn reduces the excessive deflection and drift (Gadkari & Gore 2016).. The damage level can be minimized by utilizing an outrigger and belt truss system.

Behaviour of outrigger and outrigger with belt truss

The structural response of this type of system is simple. When the building is exposed to seismic forces, the column-restrained outriggers balance the rotation of the core thus reducing the lateral deflection of the building and the moment at the base of the core also gets smaller than a free-standing cantilever structure.

If there is only a simple cantilever structure the external moment is resisted mainly by the core. By the introduction of the outriggers, the external moment is also resisted by the generation of axial compression and tension developed in the external columns connected to the outriggers (Figure 2). As a result, the effective depth of structure for resisting bending moment is enlarged by the introduction of tension in the windward column and compression in the leeward column when the core tries to flex as a vertical cantilever (Taranath 2007).

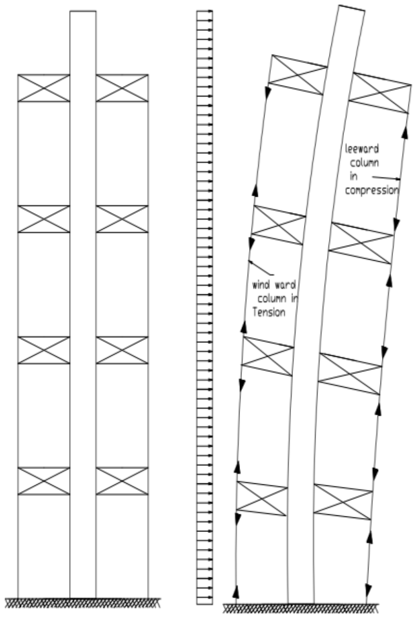

Figure 2 Behavior of outrigger when subjected to lateral load

In addition to the columns, it is also possible to mobilize the entire perimeter column to restrain the rotation of the core. It is done by tying all the perimeter columns by a one or two-storey deep beam, wall or truss referred to as a belt wall or belt truss system. Further, the belt system is connected to the outrigger and if they are not connected to the outriggers they are referred to as a virtual outrigger system. The one or two-storey outrigger and belt wall system depends on the efficiency and it should be noted that they are used in increasing the flexural stiffness; the shear resistance is not increased which must be carried out mainly by the core (Taranath 2007)..

To simply recognize the behaviour of the outrigger let us consider a one-storey deep outrigger with a truss used to stiffen the building at its top.

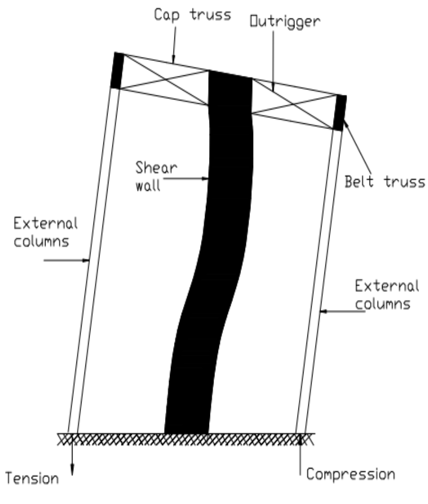

Figure 3 Cap truss outrigger with belt truss

In Figure 3, since the outrigger is used at the top, the outrigger is called a cap truss or hat truss outrigger system. The tie-down action of the cap truss creates a restoring couple at the structure's top, causing the occurrence of a point of contra flexure at some distance down the top of the building. The reversal of curvature in turn diminishes the bending moment of the core and henceforth the building drifts (Nanduri et al 2013).

Perception of Outrigger

The sailing ships use the outrigger to fight back the wind and wave force during their sails (Gadkari & Gore 2016). If we relate the various parts of the ship with the outrigger system of the building, the mast of a sailing ship is a tall spar, or arrangement of the spars, erected more or less vertically on the centerline of a ship or a boat; a spreader is a spar in a sailboat used to deflect the shrouds to allow them to better support the mast; the shrouds are pieces of standing riggings which holds the mast up from side to side; rigging is the ropes, chains, etc. that support the mast and spars of a sailing vessel, adjusting the sails.

Comparing the building structure with the sailing ship structure, the core of the building is related to the mast of the ship and the outriggers act as spreaders. Exterior columns are related to the stays or shroud of the ship (Figure 4).

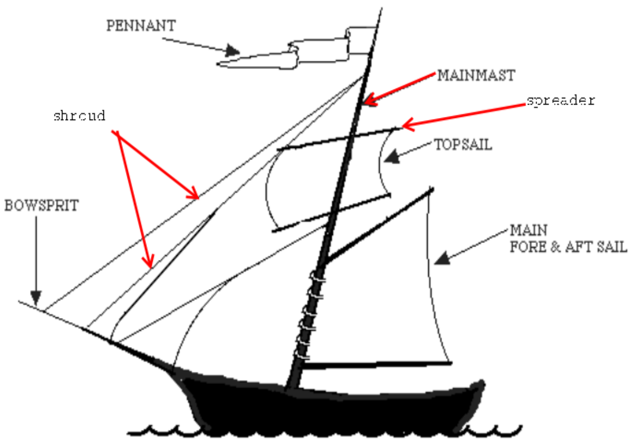

Figure 4 Parts of the sailing ship compared with the outrigger of building

The narrow boat will overturn when toss by an unexpected wave but a small amount of flotation (upward) or weight (downward) acting through the outrigger is sufficient to avoid overturning. In the same way, outriggers are connected to the columns to help in resisting the overturning of the building.

Methodology

Various research papers showed the use of outriggers in the building whose storey height was in the multiple of 5. And most of the papers showed the importance of the outrigger system only to reduce the deflection and drift of a building. A regular building of 32 storeys was selected for this study. The building is modelled in ETABS 2016.1, loading analysis was done in this software and checked if the model design passed the design criteria. Response spectrum analysis is done as mentioned in IS 1893:2002 and loading is done as per IS 875 part 1 and part 2. Firstly, the system without outriggers was modelled and named a cantilever model. The size of the elements was kept varying till the model passed the design criteria. After the model passed the design criteria, four systems were introduced to this model which are listed in Table 1. The System 1 is Table is 1 is the model without an outrigger.

Table 1 Systems to be introduced in the model

S.No.	System
1	without an outrigger (cantilever)
2	Outrigger varying at different positions in building
3	Outrigger fixed at top (OFT) and next varying at different positions of building (Outrigger with cap truss)
4	Outrigger and belt truss (OBT)
5	OBT fixed at top and next varying (OBT with cap truss)

Response spectrum analysis is carried out for all of these models by varying individual system at various locations of the building. All the models passed the design criteria. These models were created to study the optimum location of each individual system. The top storey deflection and storey drift were calculated after introducing the systems on the modelled building to find the optimum location based on their maximum reduction (Code Of Practice For Design Loads 2023). Comparisons among these systems, when they are placed at various levels of the building were made. Finally, all the five systems were compared to choose the best system among them when they are at their optimum position.

Modelling and Analysis

Model Descriptions:

Geometry: Square

Location: Nepal

Structural System: RCC frame structure with Outrigger system

No of bays: 5(in both direction)

c/c distance between columns: 5m

No. of stories:32

Floor height: 3.5m

Total Building height: 112m

Material property: M40 and Fe500

Frame sections:

Beam: 0.3mx0.5m

Column: 0.7mx0.7m (up to 15 storey)

0.6mx0.6m (16 to 32 storey)

Outrigger: 0.45mx0.45m (concrete)

Slab: 170mm

Shear wall: 350mm

Loadings:

Super Imposed Load

This comprises the floor finish, partition walls, permanent furniture etc. A floor finish of 1 N/m^2 is considered.

Live Load (LL)

The live load comprises the self-weight of humans and they are highly variable. Thus, the Indian code suggests taking 3kN/ m^2. The live load for the roof is taken 0.75KN/ m^2 (IS : 875, 2003).

Lateral load due to Earthquake:

The structure is considered in the Nepal region. The earthquake loads are calculated according to IS 1893(PART 1) – 2002.

Since the building lies in zone V the seismic zone factor is considered as 0.36. The importance factor of the building is taken at 1.5 and the response reduction factor is taken at 5. The percentage of live load considered is 0.25 (since the live load is 3kN/m^2) and the percentage of live load considered in the roof is zero (IS-1893:2002 2002).

For the analysis, ETABS version 2016 software was used. Firstly, the analysis of the cantilever structure (one without an outrigger) was done. Secondly, a single outrigger was varied in every four storeys and the optimum position of the outrigger is found.

In the third type of analysis, one outrigger was fixed at the top and the positions of other outriggers was varied in every fourth storey to find the optimum position for this type of outrigger system. In the fourth type of analysis, OBT (outrigger with belt truss) was introduced and varied on every fourth floor to find the optimum position. Finally, one OBT was fixed at the top and similarly, the other position of the outrigger is varied to find the optimum position. The summary of the various outrigger positions in given in Table 2.

Table 2 List of models analyzed

SN	Model	
1	Cantilever (freely standing model without outrigger)	Cantilever
2	Outrigger at storey 32	Outrigger variable
3	Outrigger at storey 28	
4	Outrigger at storey 24	
5	Outrigger at storey 20	
6	Outrigger at storey 16	
7	Outrigger at storey 12	
8	Outrigger at storey 8	
9	Outrigger at storey 4	
10	Outrigger fixed at the top and storey 28	Outrigger fixed at top and variable at other storeys
11	Outrigger fixed at the top and storey 24	
12	Outrigger fixed at the top and storey 20	
13	Outrigger fixed at the top and storey 16	
14	Outrigger fixed at the top and storey 12	
15	Outrigger fixed at the top and storey 8	
16	Outrigger fixed at the top and storey 4	
17	OBT at storey 32	OBT variable
18	OBT at storey 28	
19	OBT at storey 24	
20	OBT at storey 20	
21	OBT at storey 16	
22	OBT at storey 12	
23	OBT at storey 8	
24	OBT at storey 4	
25	OBT fixed at the top and storey 28	OBT fixed at the top and variable at other storeys
26	OBT fixed at the top and storey 24	
27	OBT fixed at the top and storey 20	
28	OBT fixed at the top and storey 16	

29	OBT fixed at the top and storey 12	
30	OBT fixed at the top and storey 8	
31	OBT fixed at the top and storey 4	

Table 3 lists of models for final optimization

SN	Model	
1	Outrigger at storey 13	Outrigger variable
2	Outrigger at storey 14	
3	Outrigger at storey 15	
4	Outrigger at storey 17	
5	Outrigger at storey 18	
6	Outrigger fixed at the top and storey 13	Outrigger fixed at top and variable at other storeys
7	Outrigger fixed at the top and storey 14	
8	Outrigger fixed at the top and storey 15	
9	Outrigger fixed at the top and storey 17	
10	Outrigger fixed at the top and storey 18	
11	OBT at storey 13	OBT variable
13	OBT at storey 14	
13	OBT at storey 15	
14	OBT at storey 17	
15	OBT at storey 18	
16	OBT fixed at the top and storey 13	OBT fixed at the top and variable at other storeys
17	OBT fixed at the top and storey 14	
18	OBT fixed at the top and storey 15	
19	OBT fixed at the top and storey 17	
20	OBT fixed at the top and storey 18	

For finding the optimum position total number of the model created is 51 (Table 2 and 3).

The plan view of the building model is shown in Figure 5. The Figures 6 to 11 show the model nodes for the systems listed in Table 1.

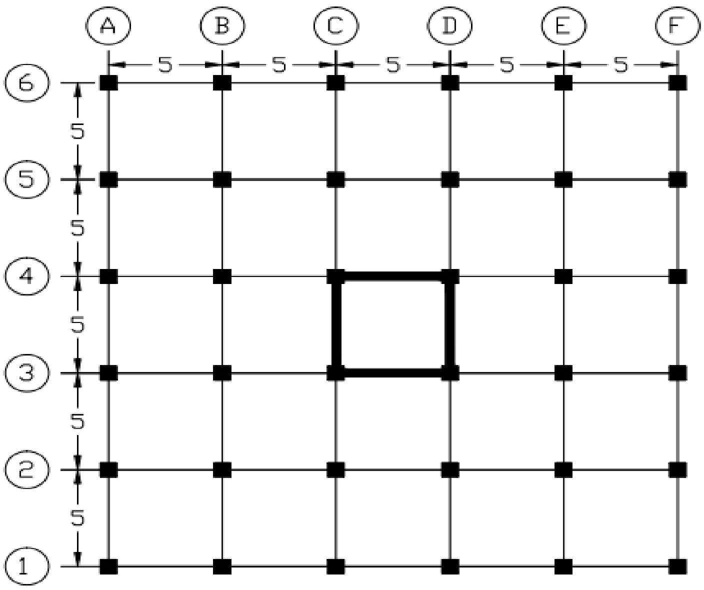

Figure 5 Plan of Model

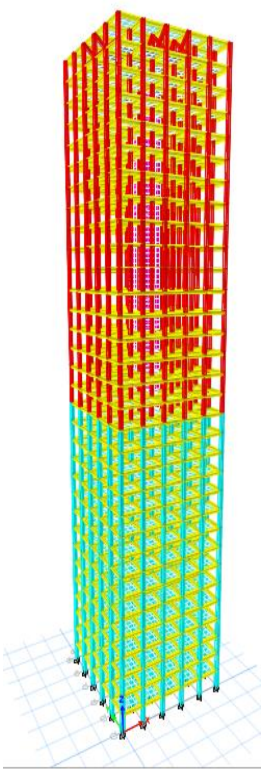

Figure 6 Cantilever Model

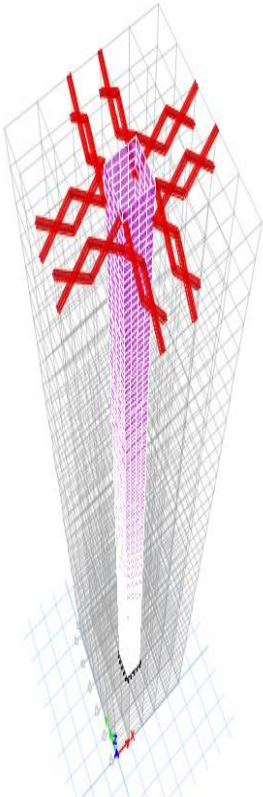

Figure 7 Outrigger Cap truss

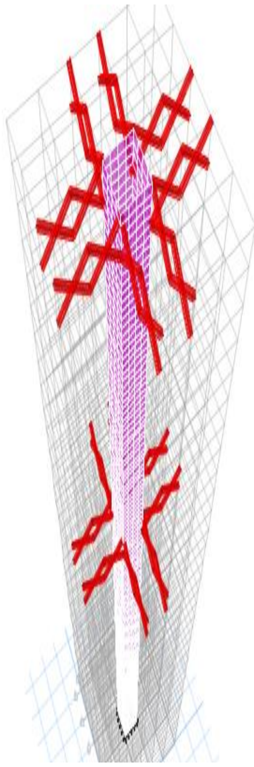

Figure 8 Cap truss fixed and other outrigger varying

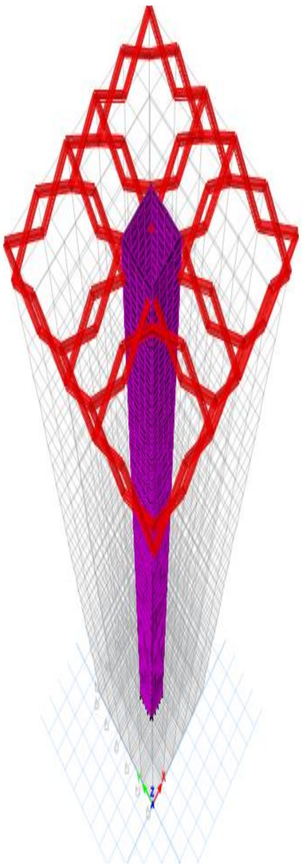

Figure 9 OBT with cap truss

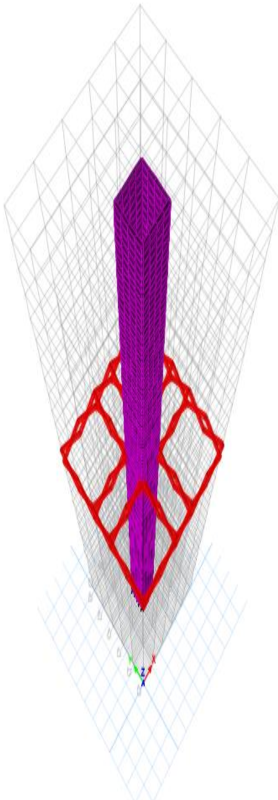

Figure 10 OBT varying along building height

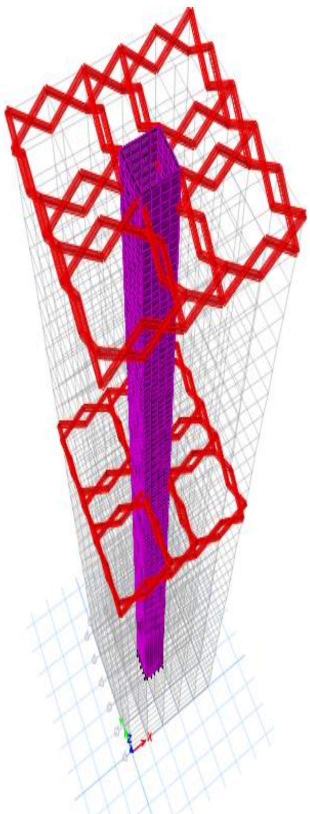

Figure 11 OBT varying along building height with cap OBT fixed

1 RESULT AND DISCUSSION

Deflection

Figures 12 to 15 show the variation of deflection in a storey where the outrigger is placed. The nature of the curve for each system is quite similar. The main observations to be noticed in these figures is the variation of the deflection at the top of the building.

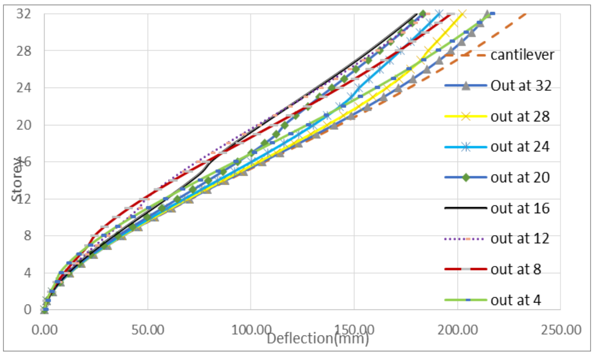

Figure 12 Lateral deflection of building with outrigger

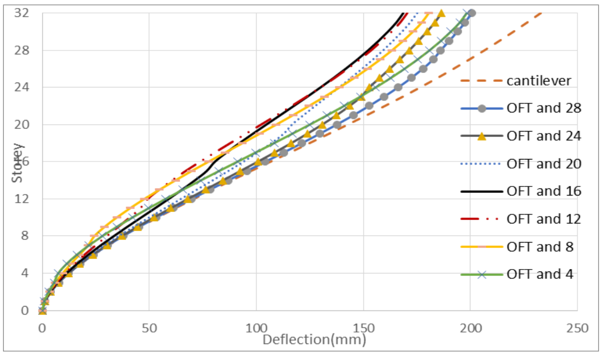

Figure 13 Lateral deflection of building with cap truss and outrigger

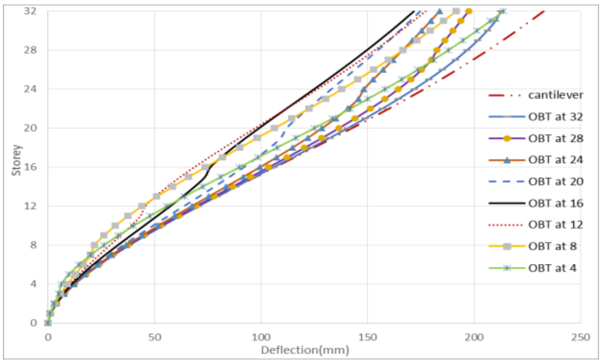

Figure 14 Lateral deflection of building with OBT

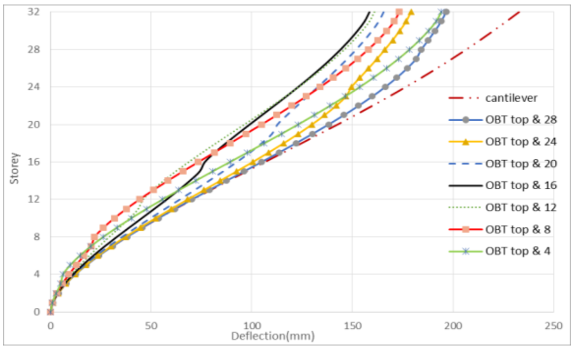

Figure 15 Lateral deflection of building with OBT cap truss and OBT

The maximum deflection at the top of the building is seen when there is no outrigger and belt truss systemin the building as seen from the above graphs. The structure without an outrigger and the belt truss system is referred to as a cantilever structure. In this structure, the maximum deflection at the top of the building is 232mm.

From Figure 12, when the outrigger is varied at various levels of the building it is noticed that the deflection is reduced where the outrigger is used. In each location where an outrigger is used, there is a reduction in building deflection. The deflection at the top is gradually reduced till it reaches the position of 16th storey. The model was again run by moving the outrigger to lower stories and it is noticed there is an increase in top deflection. Hence outrigger at 16th storey provided a minimum deflection of 180mm. So, it can be considered an optimum position. When the outrigger is used at the top it reduced the deflection at the top by 8%. The deflection produced when the outrigger is at storey 12, 16 and 20 is quite similar. When the outrigger is at the 12th storey it reduced the deflection by 20.7% and when the outrigger is at the 20th storey it reduced the deflection by 21.3%. Thus, it is observed that the 20th-storey position of the outrigger is more efficient than 12th storey outrigger. Similarly, the outrigger at 4th and 32nd storey also shows a similar type of result; the outrigger at 32nd storey is more efficient compared to the outrigger at 4th storey. At the optimum level of the outrigger, the deflection is reduced by 23%. The following list shows the percentage reduction in deflection, compared to the deflection in caltilever system, in decreasing order when the outrigger is used at various locations of the building.

a. Outrigger at storey 16 (22.6%) optimum position
b. Outrigger at storey 20 (21.3%)
c. Outrigger at storey 12 (20.7%)
d. Outrigger at storey 24 (17.9%)
e. Outrigger at storey 8 (15.5%)
f. Outrigger at storey 28 (13.1%)
g. Outrigger at storey 32 (8%)
h. Outrigger at storey 4 (7.2%)

Figure 13, shows the maximum deflection of the storey when one outrigger is fixed at the top and the next outrigger is varied at various storeys of the building. This is a two-outrigger system in which one is fixed at a position and the next is variable. The top position is used as a fixed outrigger position. Generally, an outrigger is used in place of a mechanical floor, plant floor, or refuse floor. The top floor is less used by the public and various plants of water supply, electricity, and lift mechanical floor are made in this part. So, the top part of the building is fixed. Also placing the outrigger at the top of the building eliminates the differential movement between the exterior columns by providing a compressive restraint of the exterior column in expansion and a tension restraint when the columns are in tension (Taranath, 1988). The minimum deflection is obtained at 16^{th} storey and hence considered as the optimum position of the outrigger having one fixed at the top. The outrigger at 16^{th} storey reduced the deflection from 232mm (cantilever) to a value of 168.571mm at the top. The top deflection is reduced by almost 28%. Again, the top deflection produced by the outrigger being at storey 4 and 28 is quite similar. The deflection produced by 12 is nearer to that of the optimum position i.e. (storey 16). One can also check if the optimum position lies between 20 to 16 or between 16 to 12, due to very less change in deflection for this system the optimum position is at the 16th storey of the building. As moving down or up from 16 the increase in deflection is observed. The following list shows the percentage reduction of deflection in decreasing order when one outrigger is fixed at the top and the second is used at various locations of the building.

a. Outrigger fixed at the top and at storey 16 (27.6%) optimum position
b. Outrigger fixed at the top and at storey 12 (26.8%)
c. Outrigger fixed at the top and at storey 20 (24.8%)
d. Outrigger fixed at the top and at storey 8 (22.5%)
e. Outrigger fixed at the top and at storey 24 (19.9%)
f. Outrigger fixed at the top and at storey 4 (14.9%)
g. Outrigger fixed at the top and at storey 28 (13.9%)

Figure 14, shows the maximum storey deflection when the OBT (outrigger with belt truss) system is used at various locations of the building. In this system, the exterior column is attached by means of the belt truss along the perimeter and the belt is indirectly connected to the core by means of outriggers running transversely from the central core. Again, varying the position of the outrigger with the belt truss system, the performance of the outrigger when placed at storey 32 and storey 4 are similar in nature regarding the reduction of deflection at the top of the building. In Figure 14, it is observed that on moving below the top it is found that the deflection decreases till the system moves to storey 16. On moving below storey 16 further downward it is observed that the deflection again increases. Thus, in this system also the optimum position of OBT is obtained at storey 16. The reduction in deflection is about 26%. But when the OBT is used at the top it reduced the deflection by about 9%. Also, when only the OBT is used at storey 4 it reduced the top deflection by 8%. It is because the exterior columns also take part in reducing the deflection of the central core as it is achieved by using the belt system at the exterior part of the building. The following list shows the percentage reduction of deflection in decreasing order when one OBT is used at various locations of the building.

a. OBT at storey 16 (26.2%) optimum position
b. OBT at storey 20 (24.9%)
c. OBT at storey 12 (23.8%)
d. OBT at storey 24 (21%)
e. OBT at storey 8 (17.6%)

f. OBT at storey 28 (15.2%)
g. OBT at storey 32 (8.7%)
h. OBT at storey 4 (8.1%)

Figure 15, shows the maximum storey deflection when one OBT is fixed at the top and the next OBT is varied at various locations of the building. It is a system where two OBT is put at the same time in the structure. The deflection at the top is less than that of the outrigger and belt truss. For this system, the minimum deflection is seen when the outrigger is at the level of storey 16. Hence from the graph where one OBT is fixed at the top the next optimum position of the outrigger is located at storey 16. Storey 16 reduced the deflection by 32 per cent. It is because both the OBT are resisting the lateral movement of the building and core and more columns are involved to resist the deflection. The following list shows the percentage reduction of deflection in decreasing order when one OBT is fixed at the top and the second is used at various locations of the building.

a. OBT fixed at the top and at storey 16 (32%) optimum position
b. OBT fixed at the top and at storey 12 (31%)
c. OBT fixed at the top and at storey 20 (29%)
d. OBT fixed at the top and at storey 8 (25.5%)
e. OBT fixed at the top and at storey 24 (23.1%)
f. OBT fixed at the top and at storey 4 (16.6%)
g. OBT fixed at the top and at storey 28 (15.6%)

The analysis of the modeling results, as shown in Figures 12 to 15, shows that there is a curvature change at the levels where the outrigger and outrigger with belt truss are used. It is due to the fact that at the level of

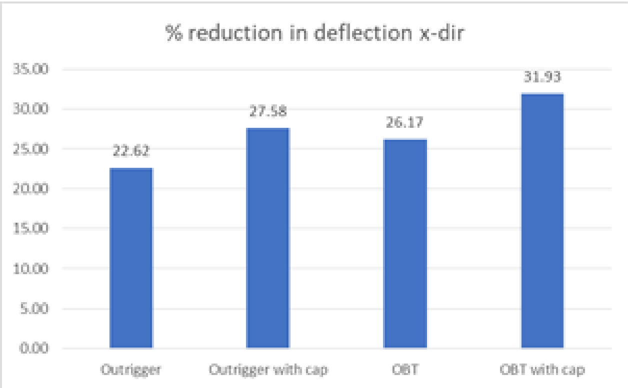

Figure 16 Comparison system in reducing deflection when they are at their optimum location

the outrigger and outrigger with the belt truss, the rotation of the core is restricted at those points by column outrigger interaction. Comparing the four systems when the outrigger and OBT are placed at their optimum position the following bar diagram shows the percentage reduction in top deflection of these systems.

Figure 16 shows which system of outrigger is more efficient in reducing the maximum storey deflection when they are at their optimum position. The system with the outrigger only can reduce the storey deflection but is less efficient than the rest of the three systems. If one outrigger is fixed at the top and the next is at its optimum position it can perform better than the case first. It is because two systems of outrigger are used and the top is fixed. The top fixed outrigger reduces the deflection at the top which is further reduced by the outrigger at storey 16 i.e. optimum location. It can be observed that this two-outrigger system is better at reducing the deflection than the deflection produced at the top by a single OBT system though exterior columns are also involved in reducing deflection. It is also because the deflection is reduced at the two places when one is fixed at the top and the next is at the optimum position. Apart from these when one OBT is fixed at the top and the next is at the optimum position, it proved to be more efficient than other systems in terms of reducing the top deflection. This system utilized more the number of columns to reduce the deflection than the rest of the three systems. Also, this system is increasing the lateral stiffness at two places. So more lateral stiffness of the overall building is increased by two outrigger systems than single outrigger and OBT systems. Thus, the efficiency of the building in terms of reducing the top deflection is in the order of:

Only outrigger <OBT only < one outrigger fixed at the top and next at other < One OBT fixed at the top and next at other position.

From Figure 12 to 15, it can be observed that the least deflection occurs at a distance of 0.5H. It is found, on moving down, the top deflection deceased till storey 16 and again increased on moving downward from it. Though it is observed that the difference in deflection between 20, 16 and 12 is very less, there may also exist the minimum deflection when the outrigger is placed between storey 20 to storey 16 or storey 12 to storey 16. Following graphs shows the changes in deflection when the outrigger is placed up and down from storey 16 at a step of 1 storey.

System Optimization

The figures 17 to 20 show that there is very less reduction in top deflection when the outrigger is at position storey 18 to storey 13. So, the before-obtained position of the outrigger to be considered at an optimum is fine. In the 1st and 3rd figures, the minimum deflection is obtained at storey 16. But in the 2nd and 4th figure minimum deflection is at the 14th storey though the change in deflection is very small. Hence, it can be said that the optimum position is at a distance of 0.5H when a single outrigger and single OBT system are used. But when the top is fixed the next optimum position of the outrigger is at a distance of 0.44 times the height of the building. Thus, in summary, it can be concluded that the optimum position of these systems varies from 0.44 to 0.5H.

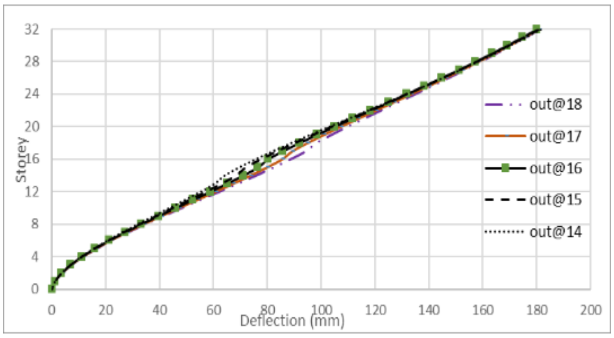

Figure 17 Storey Vs lateral deflection to find final outrigger position

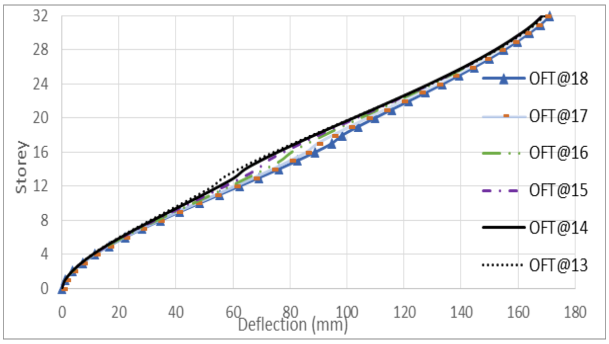

Figure 18 Storey Vs lateral deflection to find final outrigger optimum position with cap

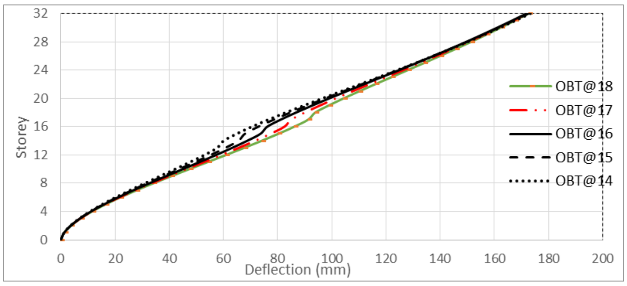

Figure 19 Storey Vs lateral deflection to find final OBT optimum position

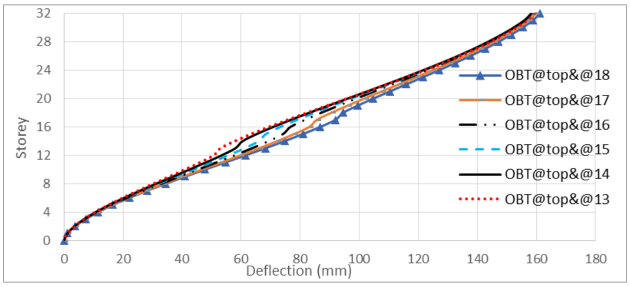

Figure 20 Storey Vs lateral deflection to find final OBT optimum position with cap OBT

Storey Drift

Story drift is the lateral displacement of one level relative to the level above or below. The story drift ratio is the story drift divided by the story height.

The **Error! Reference source not found.**Figure 21 to 24 show the effect of providing outriggers and OBT in reducing the inter-storey drifts of a building. It is known from the figures that for all the cases, there is a maximum reduction in drift where the outriggers and OBT systems are introduced. The higher the position of the outrigger lower the storey drift ratio at the top. Also providing the outrigger at the top reduces the top-storey drift for any position of the outrigger and OBT system. The top curve tries to converge at a single point in this system.

In all**Error! Reference source not found.**, maximum storey drift is observed in the cantilever structure. When the outrigger is used at any position the inter-storey drift is decreased. This outrigger reduced the drift at the top and at the level of the outrigger. The inter-storey drift at the base of the structure is zero. The inter-storey drift is reduced by 49.24% when the outrigger is used at the top as seen from Figure 21. But it is not able to reduce the deflection at the lower levels of the building by a large amount. It almost follows the cantilever drift index curve below the middle height of the building. The overall inter-storey drift of the building is reduced when the outrigger is used at the position of 16. It is capable to reduce the overall drift of the building below and above the outrigger position in a uniform manner. For other positions of outrigger,

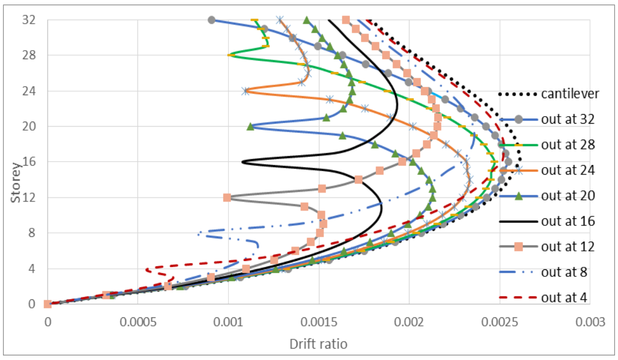

Figure 21 Storey drift index with outrigger

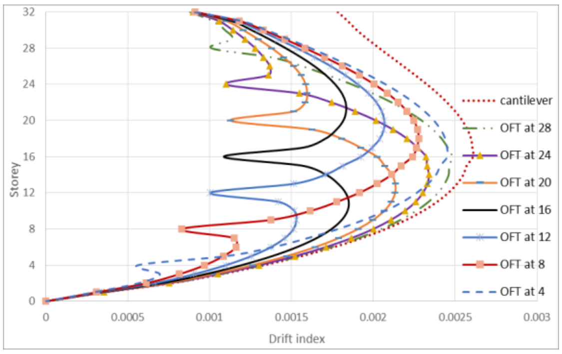

Figure 22 Storey drift index with outrigger and cap truss

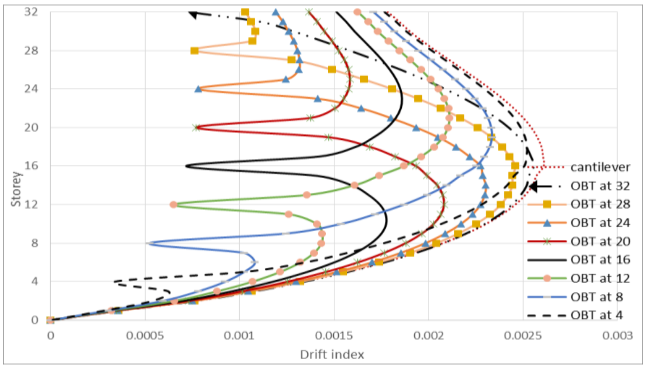

Figure 23 Storey drift index with OBT

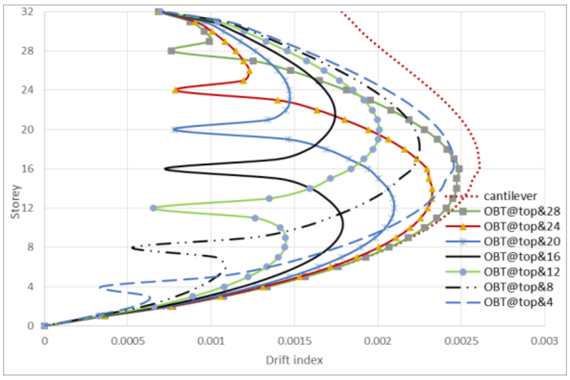

Figure 24 Storey drift index with OBT and Cap OBT

there is no such uniformity seen in reducing the inter-storey drift.

So, storey 16 can be taken as an optimum position to reduce the storey drift of the structure. At storey 16 the reduction in building drift at this level is 59%. Storey 16 also reduced the top storey drift by 13%.

The storey drift of One outrigger fixed at the top and the next variable at various positions of the building is shown in Figure 22. When the top is fixed, the storey drifts at the top was reduced and almost converge to a single point for any position of the next outrigger. The top drift was reduced by more than 50% when the outrigger was used at any position of the building. There is a uniform reduction in the drift when the outrigger was a storey 16. At the level of storey 16, the reduction in storey drift is 59% at that level when compared to the cantilever structure.

Figure 23 shows that the plot of storey versus storey drift index when only the OBT system is kept at various levels of the building. Similar to the outrigger system when only OBT is kept at various levels of the building there can be seen diverged inter-storey drift curve at the top of the building. There is more reduction in the inter-storey drift at each level of OBT than shown in Figure because it utilized the peripheral columns to reduce the drift of the storey. The reduction in the drift at the top when the outrigger is at a storey level of 16 is found to be 60%. It reduced the storey drift at storey 16 by an amount of 72.32% when compared with the cantilever structure. The reduction in inter-storey drift is more than 60% at any level of OBT.

Figure 24, shows the plot of storey vs maximum drift index after one OBT is fixed at the top and the next OBT is variable at various storeys of the building. When one OBT is fixed at the top then it helped in reducing the top drift and all the OBT system drift was reduced to almost a single point. It reduced the top-storey drift by more than 62%. At the level of 16, the drift was reduced by 72.5%.

From the above figures, it can be interpreted that the system with a top fixed can reduce the inter-storey drift more than without the system having a top fixed. The other position where the outrigger is variable except at the top is similar in reducing the drift. Similar is the result with OBT fixed and not fixed at the top. Hence from the figures, we can conclude that the OBT system is far better than the outrigger system for reducing the inter-storey drift of the building. The top fixed system reduces the storey drift at any level by a small amount than the top, not fixed condition. Hence from the figure, it can be confirmed that the lateral stiffness of the building and lateral stiffness of the storey is increased which has ultimately reduced the storey drift by a large amount.

System optimization

On further varying the position of the outrigger and OBT above and below storey 16, the obtained storey drift results are as follows (Figure 25 to 28); the results are given in Table 4.

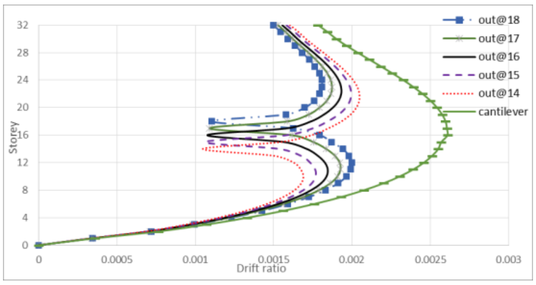

Figure 25 Storey drift index with outrigger for optimization

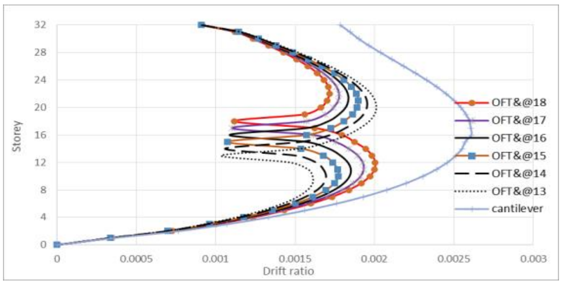

Figure 26 Storey drift index of outrigger with cap truss for optimization

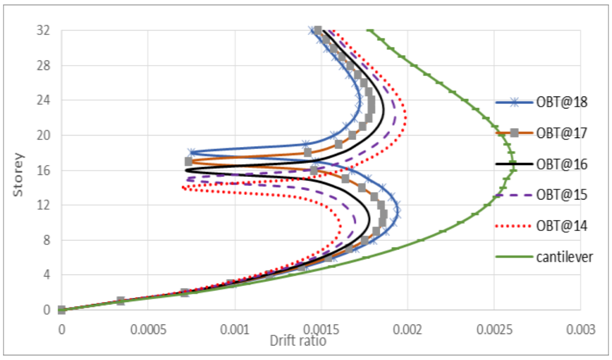

Figure 27 Storey drift index with OBT for Optimization

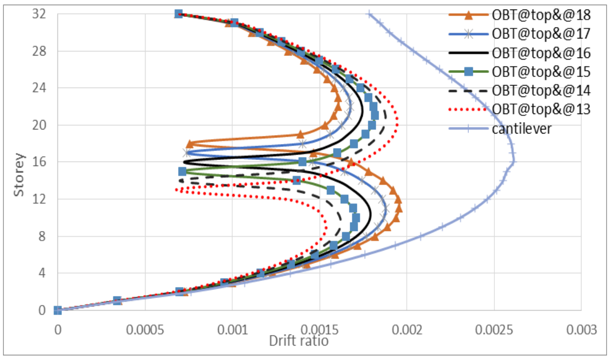

Figure 28 Storey drift index with cap OBT and OBT for optimization

Table 4 Storey drift with various systems for optimization

Storey	Drift ratio		difference	% reduction
	cantilever	Outrigger		
story18	0.002597	0.001106	0.001491	
story17	0.002605	0.001091	0.001514	
story16	0.002609	0.001087	0.001522	58.34
story15	0.00257	0.001062	0.001508	
story14	0.00255	0.001048	0.001502	

Storey	Drift ratio		difference	% reduction
	cantilever	Outrigger with cap truss		
story18	0.002597	0.001116	0.001481	
story17	0.002605	0.001102	0.001503	
story16	0.002609	0.001077	0.001532	58.72
story15	0.00257	0.001072	0.001498	
story14	0.00255	0.001058	0.001492	

Storey	Drift ratio		difference	% reduction
	cantilever	OBT		
story18	0.002597	0.000748	0.001849	
story17	0.002605	0.000732	0.001873	
story16	0.002609	0.000722	0.001887	72.32
story15	0.00257	0.000706	0.001864	
story14	0.00255	0.000692	0.001858	

Storey	Drift ratio		difference	% reduction
	cantilever	OBT with cap truss		
story18	0.002597	0.000753	0.001844	
story17	0.002605	0.000738	0.001867	
story16	0.002609	0.000717	0.001892	72.52
story15	0.00257	0.000711	0.001859	
story14	0.00255	0.000697	0.001853	

Fluctuating the Outrigger and OBT system with and without top fixed condition as seen from the optimization graphs there is a uniform reduction in storey drift at storey 16. Hence from these data storey, 16 can be considered as an optimum storey to reduce the storey drift of a building. Storey 15 and storey 17 also tried to show a similar result but their uniformity is less than that of storey 16.

The optimum position by deflection criteria, when the outrigger and OBT system was variable, was found to be at storey 16. Also, when their top is fixed the optimum position is found to be at storey 14. From inter-storey drift criteria, the optimum position of all the systems was found to be at storey 16. But if both the deflection and drift are considered then storey 16 can be considered as the optimum position which can show efficient performance for all the systems. Therefore, the optimum position lies at a distance of 0.5 times the building's height

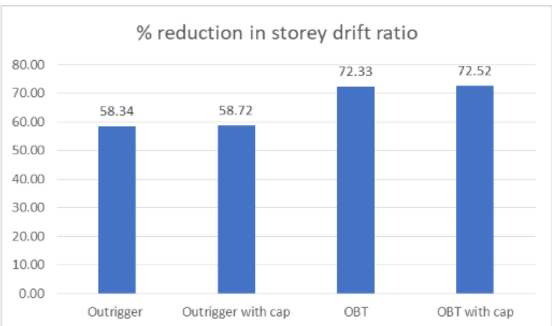

Figure 29 Comparing the systems for reducing storey drift ratio

Comparing the system in terms of reducing the storey drift ratio it can be concluded that the belt truss systems are far better than the outrigger system. Cap truss systems are suitable for reducing the upper-level drift ratio but at the same level, they show the same reduction in an inter-storey drift that is obtained with an outrigger only.

Time Period

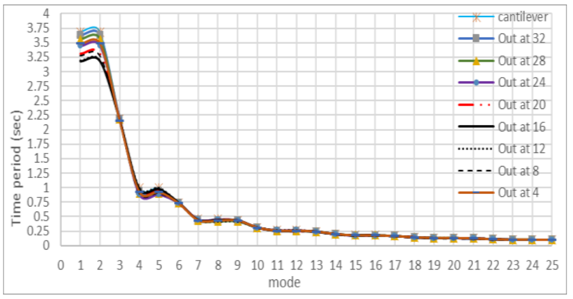

Figure 30 Modal time period with Outrigger

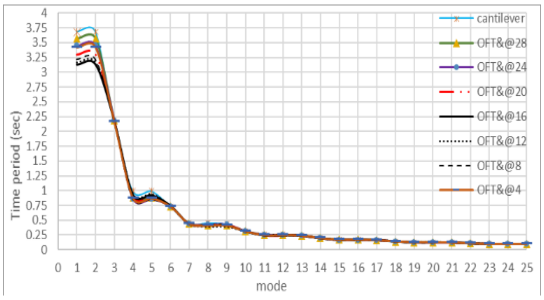

Figure 31 Modal time period Outrigger with Cap

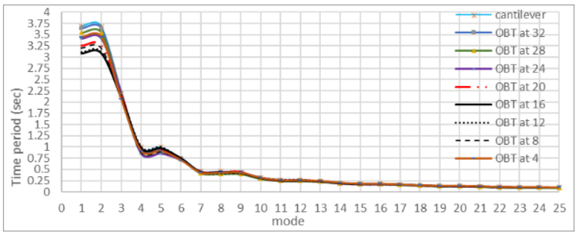

Figure 32 Modal time period with OBT

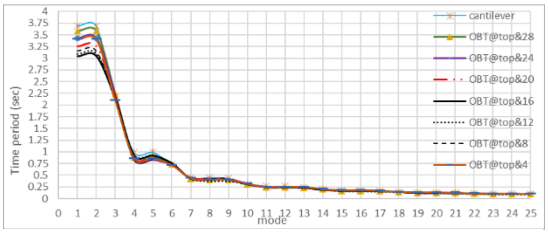

Figure 33 Modal time period of OBT with Cap

As the number of modes increases the time period of oscillation of a building decreases. Altogether 25 numbers of modes have been considered during the analysis of the structure. From the plot of the modal time period, it is observed that the maximum time period of the building has occurred under mode 1 of the building. Further, the time period of the building is reduced when the outrigger is at various locations of it. The maximum modal time period is found for the cantilever structure. It is found to be 3.688 seconds. As a symmetric structure, the modal time period in both directions is the same. So, mode 1 and mode 2 have the same time period. A slight variation might be found in the time period of mode 4 and mode 5. The rest of the remaining mode exhibits similar behaviour..

Figure 30 shows the variation in the modal time period of the building when the outrigger is kept at various stories of it. The minimum time period is found when the outrigger is located at storey 16. The time period reduced by the outrigger at the level of storey 16 and storey 12 is nearly the same. The maximum reduction in the time period is by 0.515 seconds when the outrigger is used at storey 16. The reduction in the time period when the outrigger is at storey 12 is by 0.492 seconds. Therefore, the outrigger at 12 reduced the time period by 13.34% while the outrigger at 16 reduced it by 13.96% than that of the cantilever.

Figure 31 shows the variation in the modal time period when an outrigger is fixed at the top and another is variable. Under the first and second mode outrigger at 12 reduced the time period by 14.1% while the outrigger at storey 16 reduced the time period by 15.05%. Storey 16 and storey 12 show the maximum reduction in the modal time period. When the outrigger is at other storeys the modal time period increases.

Figure 32 shows the variation in the modal time period when OBT is present at various locations of the building. Providing the outrigger at storey 12 reduced the modal time period (mode 1 and mode 2) by 15.32%. Outrigger at 16 reduced the time period by an amount of 15.46%. The maximum time reduction is by outrigger at storey 16 and then it is reduced next by storey 12 by the maximum amount. The outrigger at storey 32 shows the minimum variation in the modal time period.

Figure 33 shows the variation in the modal time period when the building has one OBT fixed at the top and the next is variable at various positions of the building. This system reduced the time period more than the other systems. When the next OBT is at storey 12 it reduced the maximum modal time period by 17.22% and when the OBT is at storey 16 it reduced the time period by 17.32%.

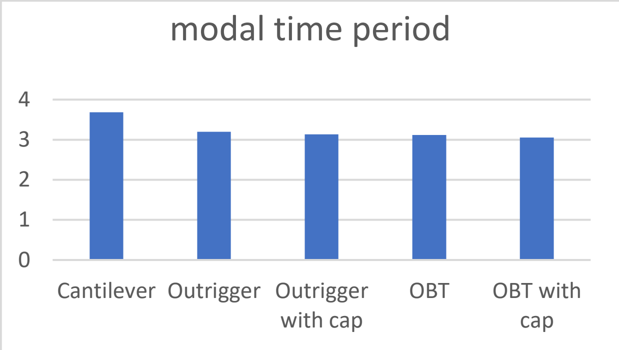

Figure 34 Comparison of the modal time period

There is very less reduction in the time period when the outrigger is at the top of the building. Providing the outrigger and OBT near the middle position reduces the modal time period by a significant amount. Among storey 16 and storey 12, the storey 16 outrigger and OBT system can be considered more beneficial in reducing the modal time period by a maximum amount. Among the systems OBT fixed at the top is considered the most efficient in reducing the time period of the building. The OBT system is better at reducing the modal time period than the outrigger system.

The following shows the system in decreasing order which provides better performance in reducing the modal time period.

OBT fixed at top system > OBT system > outrigger fixed at top system > outrigger system

Base Shear

The value of the base shear of a building is largely affected by the weight. The more the weight of the structure the more the base shear generated. Also, stiffness of the structure also affects the base shear generated. The higher the period of the structure means the more flexible the structure inhibits. A flexible assembly experience lesser acceleration compared with a stiff structure. The flexible structure is difficult to excite, it will have lower base shear compared with a stiff building.

Table 5 Base shear

System	Base Shear(kN)
cantilever	3887.277
Outrigger	3906.0191
outrigger with cap truss	3920.6908
OBT	3925.4195
OBT with cap truss	3971.5684

The weight of the structure is added when the outrigger and OBT system are added to it. So, the base shear is more in the OBT system. Cap truss systems generate high base shear because their weight is also more. From a stiffness point of view, the system without an outrigger and OBT is more flexible than the structure with an outrigger and OBT. The base shear of the OBT system is more than that of the outrigger system. The largest base shear is obtained when the same structure has the highest stiffness. The systems with cap truss show more increase in base shear than without cap truss system (Table 5). It is because the system is being used in two places.

Conclusion

From the above analysis and their result intepretation it can be seen that the lateral stiffness of the building can increased by placing the outrigger at various places. Also, OBT systems are more efficient in increasing the lateral stiffness of the building than the outrigger system. The belt and cap truss system is proven to be better than the outrigger system in reducing deflection. The optimum position of a single outrigger and single OBT is at the mid-height of the building when the criterion for selection is deflection. In the system with a cap truss, lower stories needed to be stiffer and the optimum position is not at the mid-height of the building. It is some distance below the mid-height of the building. The optimum position of the outrigger and OBT with cap truss is at 0.44H of the building when the selection criterion is deflection. Also, two outrigger systems are are more suitable than a single outrigger system. The cap truss helps in reducing the top deflection at the upper level and the next outrigger further helps in reducing the deflection at the places where they are used.

When various outrigger and OBT systems are introduced, they can reduce inter-storey drift by a large amount. In places where outrigger and OBT systems are introduced, inter-storey drift is reduced at the place by a maximum value and it also reduces the inter-storey drift of the whole building. Cap truss systems help in reducing the upper stories drift ratio by a large amount but quite less reduction is seen in lower stories. The optimum position of the Outrigger and belt truss with and without cap truss is at 0.5H of the building when the selection criteria are inter-storey drift.

Outrigger and OBT systems are very useful in reducing the period of a slender structure. The minimum time period occurs at the place of the optimum position of the outrigger and OBT.

With the introduction of the outrigger and OBT the base shear of the building is increased. Increased base shear shows the increment in the stiffness and weight of the structure when the outrigger and belt truss is used.

Recommendation

The construction of taller buildings is the most to eradicate the problem of housing in the core city areas. And it is important to introduce a lateral load-resisting system like an outrigger in such a building. The effect of the earthquake can be minimized using outrigger-type systems at various locations of the building.

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