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Investigating Structural Behavior of Outrigger-braced Tall Structures

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ABSTRACT

Over the last decades due to development of large cities, tall buildings play an important role in citizen's accommodations and public centers. Design of tall buildings is a complex process which involves approximate analysis and preliminary design. In order to get the optimum design many requirements should be satisfied, criteria like strength, stability, safety of nonstructural elements and most importantly serviceability criterion. Serviceability is evaluated by the drift of the structure. Outrigger-braced tall buildings are one of the common structural systems which are economical to use. Optimum design of this structural system highly depends on the outriggers location and the number of them, also the topology of the core is a big concern to be investigated. In this research we are going to investigate the optimum location and number of the outriggers. The rigidity and optimum topology of braced core will be investigated in different examples modeled with complete details in OpenSees software linked to MatLab program. Models are under the wind loading.

***Keywords*—Tall buildings, Outriggers, Braced Core, Optimum Design.**

1. Introduction

Tall buildings are a common sight in contemporary cities, especially in those countries where land is scarce, as they offer a high ratio of floor space per area of land. Tall buildings are also, arguably, a sign of a city's economic stature.
Outrigger-braced tall building is considered as one of the most popular and efficient tall building design because they are easier to build, save on costs and provide massive lateral stiffness. Most importantly, outrigger-braced structures can strengthen a building without disturbing its aesthetic appearance and this is a significant advantage over other lateral load resisting systems. As mentioned above analyzing tall structures is a complex procedure. In order to analyze tall structures a lot of simplifications through different assumptions were made in the past studies.

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For the purpose of analyzing the outrigger-braced tall buildings researchers have done simplifications too, these assumptions may lead into an approximate solution which is the outcome of idealized behavior of tall frames. The quality of solutions that these theoretical methods produce, not only rely on the assumptions, but also on the model details. One key problem in these methods is to gather a list of structural members which are effective in the structural behavior of outrigger-braced frames.

Theoretical analysis of outrigger-braced high-rise structures started by the early works of (Tarnath 1974,1975) when the belt trusses were assumed to have infinite bending stiffness and the location up the height of structure was an important factor influencing the reduction of horizontal drift. After Tarnath's theoretical method which included a simple cantilevered beam with rotational springs on the outriggers levels, other researchers followed his simple model in their studies. Although these models were quiet simple, they represented the structural behavior of outrigger-braced systems as much as possible.

(Smith and Coull 1981) solved the equation for more outriggers and provided a graphical method which indicated the optimum locations of first, second, third and fourth outriggers. These graphical methods were the result of numerical analysis of the equations.

(HoenderKramp 2003) suggested a detailed model (Fig. 1) which included stiffness of the foundation, core and outriggers. After numerical analysis of the equations he proposed a graphical method.

(HoenderKramp 2008) suggested another graphical method and this time for observing the optimum location of second outrigger. In his second study one of the outriggers were assumed to be fixed and the other was the variable of the problem, this research like the past researches were the outcome of beam like behavior of a tall building structure.

(Zhang 2006) investigated the influence of outriggers rigidity and the effect of them on the safety of the structure. His research shows theoretical method basic assumptions are not safe in some cases. Like other scientists, his solution for the optimization process was theoretical.

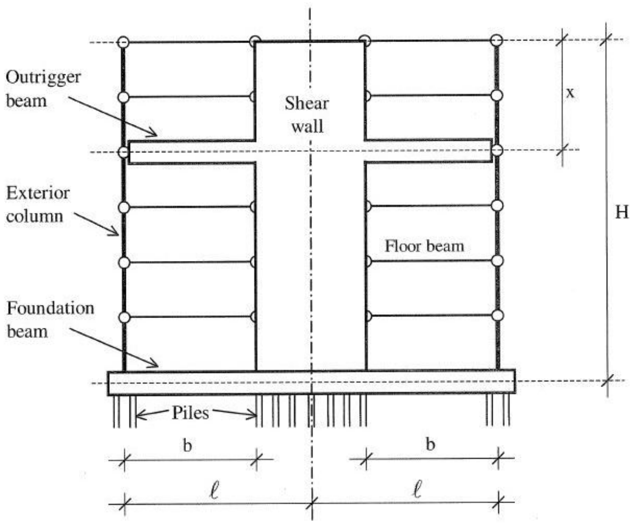

Figure 1. Analytical model of HoenderKramp

Other scientists have done investigations and all of them were quiet similar, the differences were some details like the wind load distributions and assumptions like the core and outrigger stiffness.

(Kameshki and Saka 2001) investigated the behavior of different topologies of bracings. They realized X-bracing system yields the lightest frame among the other bracing systems like: V-bracing and Z-bracing. Their optimization process also revealed drift is not a dominating constraint through the optimization process for the X-bracing systems. Although Kameshki's model were a 15 story frame, it might illustrate the effect of topologies of different braced cores in tall frames.

In the present study, besides proposing a new methodology for fast and precise analysis of outrigger-braced frames, the effect of different topologies of brace cores will be evaluated. X-bracing system and V- bracing system will be compared, also the optimum location of the outriggers will be investigated through different examples including 20, 30, 40 story models. Static analysis will be performed due to wind loading with exact details.

1. Proposed Methodology

The program has been written as m-file in MatLab program. Inputs are a short list containing basic geometrical data needed for OpenSees and a list of steel sections based on the experience. Core type (only braced cores) ,sections assigned to core , outriggers and finally the range of outriggers locations are the secondary list to be defined to the program. Assigning sections to the core and outrigger is one of the key features of this method, this is mainly because in theoretical method sectional properties of core is supposed to be constant for the full height. The program is capable of calculating the inter-story deflection, bending moment and axial force in structural members. Precise results will be obtained from the analysis.

Selection of OpenSees software is because of fast and reliable analysis. OpenSees scripts will be written in m-file. MatLab program is employed because of creating secondary loops, pre and post processing of data. Wind load and the distribution of it will be calculated in MatlLab according to ASCE 7-05 (American Society of Civil Engineers). Despite theoretical method this feature enables the designer to calculate most accurate wind load distribution and assign it to the frame.

Employing this script lets the designers not only to obtain the optimum location of the outriggers, but also consider the effect of each structural member in the calculations. Theoretical methods contain time consuming procedures compared to the proposed methodology and this is remarkable superiority.

2. Design of Analysis Model Structures

The outrigger-braced frame is assumed to be located in Boston where basic wind speed is 49.1744 m/s (110 mph).

Wind load will be calculated according to ASCE 7-05. Several assumptions as following were made:

- Basic wind speed = 49.1744 m/s
- Exposure category : B
- Building plan dimensions = 22.5 × 22.5m and 27 × 27 m (5 @ 4.5m for X-bracing and 6 @ 4.5m for V-bracing)

Several factors like gust-effect factor must be calculated and finally the design wind speed will be calculated.

Box sections are the group of the sections to use as column members and W-sections are the list of sections to use for beam members (Table I) .Note that the local buckling of the box members should be resisted through proper arrangements. Building's plan is supposed to be symmetric including five bays (six bays in case of V-bracing). Building's height depends on the model of analysis. Fig. 2 and Fig. 3 illustrate 30 story models.

Table I. Section lists

Section Type	Section Details	
	Section Dimensions	*Member type*
Box	60×2:4 , 65×2:4 , 70×2:4 , 75×2:4 , 80×2:4 (cm)	Columns
IPE	IPE33 , IPE 36 , IPE 40 , IPE 45 (cm)	Beam (20 Story)
W-section	W18×8:6 ,W21×9, W21×7, W24×9, W24×7 (in)	Beam

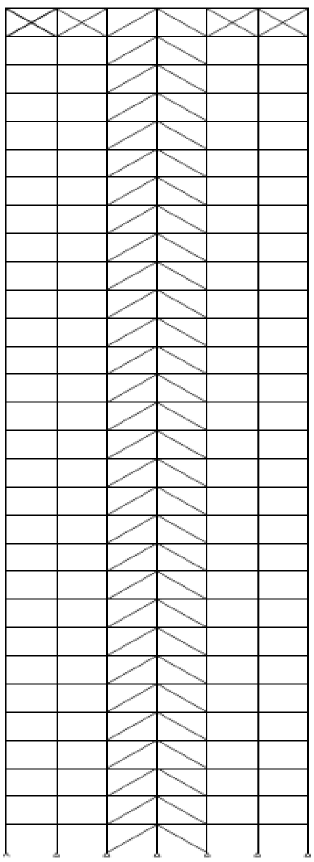

Figure 2. 30 Story V-bracing model

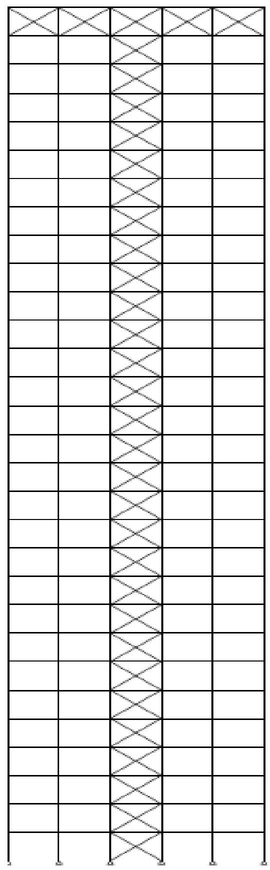

Figure 3. 30 Story X-bracing model

3. Case Study

20 story V-Bracing Model

Single Outrigger-Braced Frame

An outrigger-braced frame consisting of 20 stories and 6 bays with a V-bracing core is the first model to investigate. This model has been occupied because of a higher level of core rigidity when comparing to the other core topologies like X-bracing. Deflection reduction is defined by the following:

Deflection reduction = 1- (Maximum horizontal deflection of the frame with outriggers / Maximum horizontal deflection of the frame without outrigger) (1)

A list of I-shaped sections is assigned to the beam and column members. The maximum horizontal deflection for the frame without outriggers at the top story is 0.295677 m. Analyze indicates 16.45% of deflection reduction when the outrigger is placed at the 11th story.

30 story V-Bracing Model

Single Outrigger-Braced Frame

The higher the structure gets, the more arrangements needed to resist the lateral loads like wind. Use of an outrigger in a twenty story model may not be logical but when the frame gets higher it is more usual to place outriggers. Beam members in this model are selected from W-sections because they have more axial and flexural stiffness compared to the IPE sections assigned to the twenty story frame. Box sections are assigned to the column members in groups which alter every five stories. Due to higher level of axial force core surrounding columns and exterior columns are selected from stronger range of box sections, this trend remains the same for the other models.

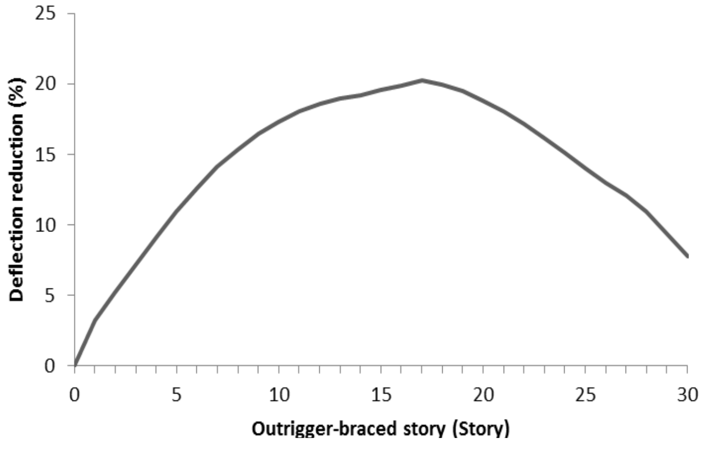

Figure 4. Deflection reduction for 30 story model (V-bracing core)

Maximum deflection without outriggers in this case is around 30cm. This is mainly because of the stronger beam sections which the effect of them were neglected in the previous researches. Result of the analysis is shown in a graphical format in Fig. 4. This diagram suggests the first outriggers location to be around 17^{th} story which is almost the same solution when using theoretical analysis of Tarnath. Meanwhile, the maximum bending moment of column members increases 107.46%. maximum axial force for the columns almost remains the same with the reduction rate of 7.48%.

Second Outrigger

In order to obtain the second outriggers optimum location, the first outrigger is fixed on a specific story. The first outriggers location alters every 5 stories. In most of the models the second and third outriggers optimum locations are obtained according to the outputs from the first step analysis for the first outrigger. The result shows that the best options for placing the first outrigger are in 10^{th}, 15^{th} and 17^{th} stories. The graph in Fig. 5 suggests the second outrigger optimum location for three models. Discontinuities in the curves are in the locations of first outriggers. Table II includes the result of the analysis for five models. Analysis clearly shows that besides deflection reduction, factors like maximum moment on columns should be considered. This is mainly because with the outriggers shifting location in each stage of analysis the moment on core and main elements alters. The script written in Matlab and OpenSees is capable of considering these factors.

Table II. result of the analysis for five models

Model Code	Story		
	First Outrigger (Fixed)	***Second Outrigger range***	***Maximum reduction(%)***
(5,1:4,6:30)	5^{th}	17^{th}	28.47 %
(10,1:9,11:30)	10^{th}	18^{th}	30.84 %
(15,1:14,6:30)	15^{th}	20^{th}	29.29 %
(17,1:16,18:30)	17^{th}	10^{th}	30.67 %
(25,1:14,26:30)	25^{th}	12^{th}	27.84 %

Third Outrigger

For a thirty story model, more than two outriggers is not economical, similarly as an structural view it won't necessarily reduce the deflection noticeably. In some cases adding more outriggers might even add to the bending moment of core and lower stories columns. Fig. 5 includes the graph which is the result of the analysis for three different models. By comparing the graphs of Fig. 5 and Fig. 6 it is concluded, adding more outriggers to this frame is no longer efficient.

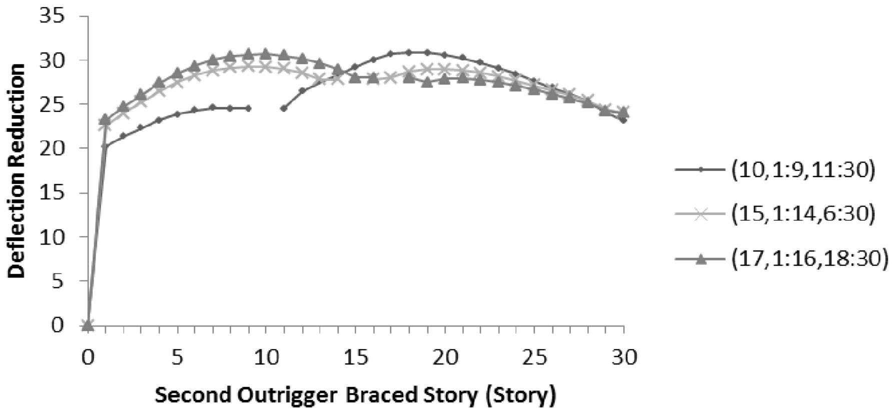

Figure 5. Deflection reduction caused by second outrigger for 30 story model (V-bracing core)

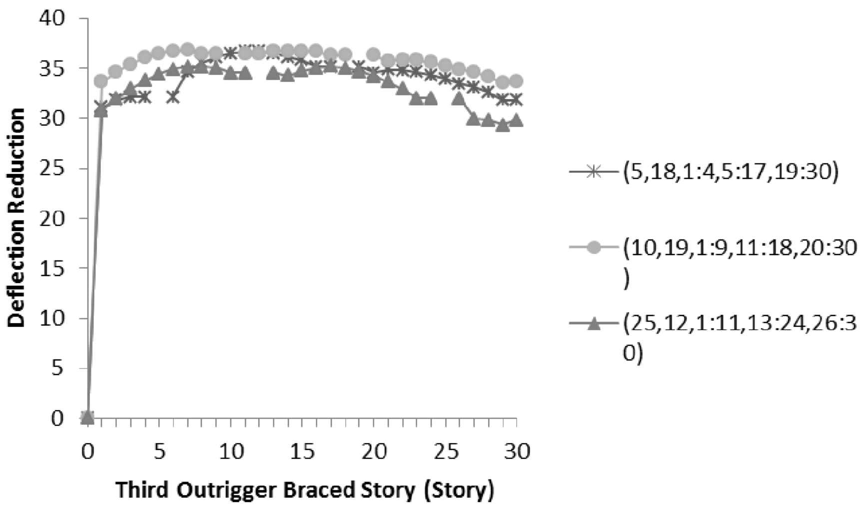

Figure 6. Deflection reduction caused by third outrigger for 30 story model (V-bracing core)

40 story V-Bracing Model

Single Outrigger-Braced Frame

Strong range of W-sections are assigned to the beam members. Maximum deflection of the frame without outriggers is 0.7737 cm. As the frame gets taller, more concluding of this research will be possible. As it is notable horizontal deflection is increasing considerably by adding to the stories of the structure. The results indicate that for this height, outriggers tend to be placed on lower stories. In order to investigate this fact, we are going to compare the results with an X-bracing frame.

30 story X-Bracing Model

Single Outrigger-Braced Frame

As mentioned before this type of bracing is not as rigid as V-bracing (Fig. 2 and Fig. 3). Fig. 7 is a diagram which indicates that the first outrigger for this frame should be located at the 12th story. Placing outrigger on this location will result in the 33% decrement rate of deflection reduction. This rate of decrement is remarkable compared to the V-bracing frame with the same stories, it is concluded by the core getting less rigid the effect of using outriggers in high-rise frames is more noticeable. In the common solution for such problems the effect of core rigidity is neglected or when it is considered, it is not detailed. But in the suggested method using a reliable and exact analysis script in OpenSees every single detail is modeled and the results are showing serious contrasts between the approximate method and the exact method.

For a 30 story single outrigger-braced frame, analysis shows that the optimum location for the first outrigger should be around 14th story. Fig. 2 displays the effect of first outrigger shifting in a range of 30 story. Vertical axis indicates deflection index and horizontal axis is the range of stories.

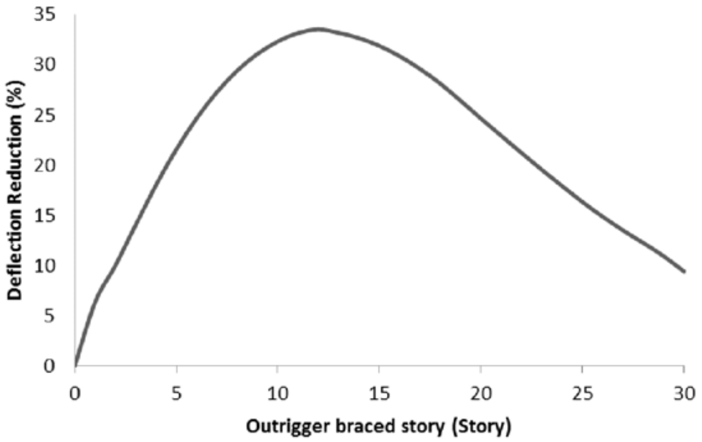

Figure 7. Deflection reduction for 30 story model (X-bracing core)

Second Outrigger

In order to investigate the location of the second outrigger, the first outrigger is placed on the potential optimum locations. Comparing the analysis results with the same stage analysis for the V-bracing core system illustrates the effect of less rigid core. In this case outriggers tend to be placed on the lower half of structure. This can be realized from the results of placing the first outrigger on 15th story. In this model maximum deflection reduction will be obtained if the second outrigger be placed on 8th floor. Fig. 8 is a diagram including the analysis results of this part. Placing the first outrigger on the 10th floor will result in the second outrigger to be placed on the 17th floor. This will cause 46.44% of deflection reduction. Although this model is an ideal solution for the least possible deflection, it is not an optimum solution when taking bending moment of columns as an important factor. Placing the second outrigger at the

17th floor will increase the maximum bending moment 149% compared to the model without outriggers.

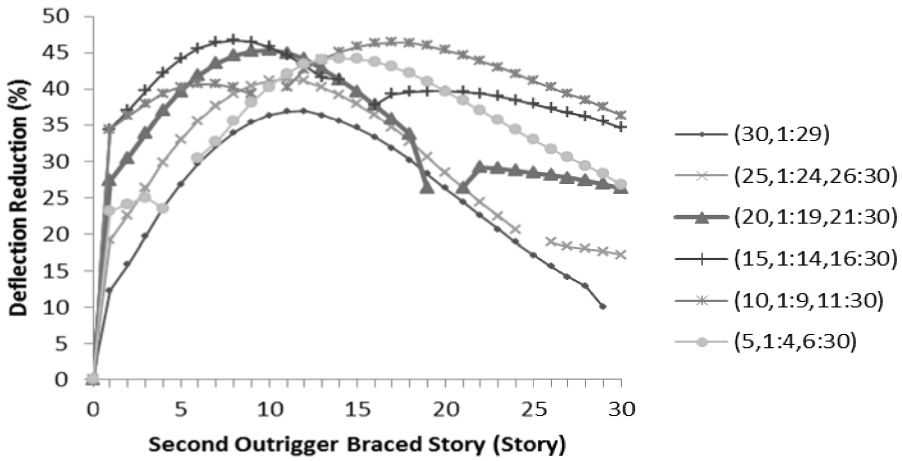

Figure 8. Deflection reduction caused by second outrigger for 30 story model (X-bracing core)

Third Outrigger

With the first and second outriggers assumed to be fixed Fig. 9 displays the influence of third outrigger. As mentioned before discontinuities in the curves are in the locations of first and second outriggers. It can be concluded that third outrigger's optimum location is moving to the lower stories. Assuming the first and second outriggers to be placed respectively in 18th and 10th floor, third outriggers optimum location is 6th floor. This location will cause 53.86% of deflection reduction. This surprising result indicates balancing between core, outrigger, beams and columns rigidity is most important factor in getting the best result.

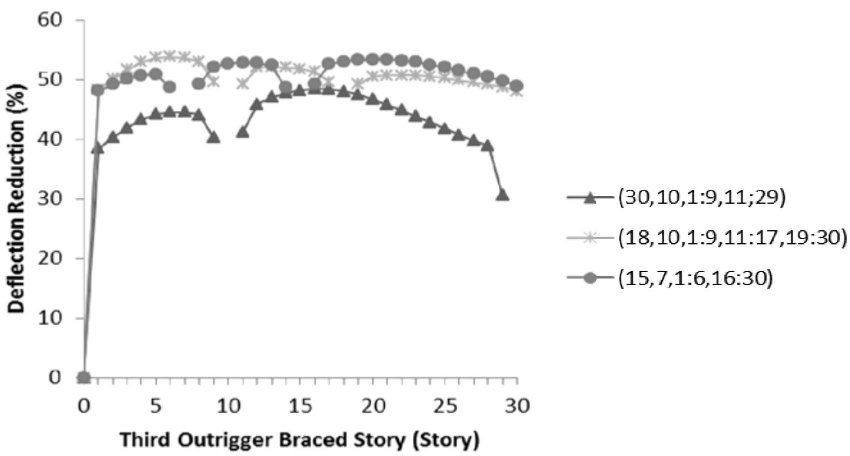

Figure 9. Deflection reduction caused by third outrigger for 30 story model (X-bracing core)

As mentioned this frames core is less rigid compared to V-bracing core. Placing three outriggers in optimum locations will cause noticeable amount of deflection reduction.

40 story X-Bracing Model

Single Outrigger-Braced Frame

This model is selected because of investigating the effect of height while dealing with a less rigid core. Maximum top deflection in case of not having any outriggers for the 40 story model is 0.954 m. Fig. 10 is a diagram which shows the deflection reduction for the first outrigger. Placing the first outrigger on the 10th story causes deflection reduction rate of 15%. It is concluded that current X-bracing core is not efficient anymore. Adding any more outriggers will not reduce the horizontal deflection of top stories seriously. Fig. 11 displays the effect of third outrigger for current structure. As it is noticeable maximum reduction is 25%, while placing three outriggers in 6th, 10th and 20th stories. In conclusion, with the building getting higher, stronger cores seem to interact better with outriggers in order to resist lateral loads. Proposed method helps to balance between the core rigidity and the height of structure in order to get the optimum solution.

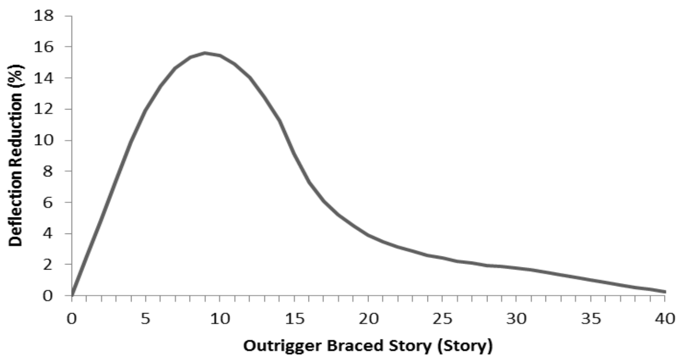

Figure 10. Deflection reduction for 40 story model (X-bracing core)

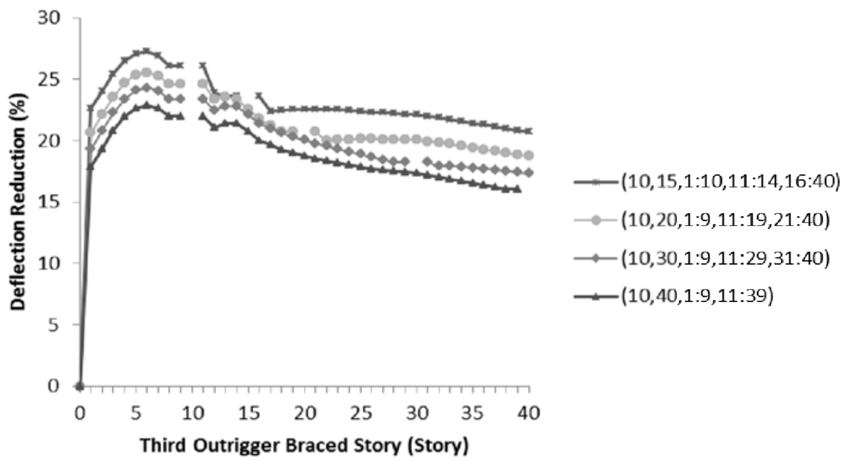

Figure 11. Deflection reduction caused by third outrigger for 40 story model (X-bracing core)

4. Conclusions

- Outrigger-braced system is efficient and reliable system. Outrigger efficiency highly depends on the rigidity level of core. Balancing between core, outriggers, beams and columns rigidity not only lowers the horizontal top deflection, but also results in noticeable amount of reduction in internal forces of structural members.
- Optimum locations of outriggers depends on many factors including core rigidity, outriggers rigidity, beams and columns rigidity and the wind loading distribution. Theoretical methods of investigating optimum locations of outriggers were the outcome of assumptions which ignored the effect of most of the factors mentioned. Proposed methodology utilizes a computer program which is a Matlab script capable of linking to OpenSees. Program is simple, fast, accurate and reliable.
- By the core getting upper levels of rigidity, outriggers tend to be placed on the higher levels of the structure. While outrigger gets more rigid, the optimum location should be on lower stories.
- Serviceability is not the only factor to consider while investigating the optimum location of outriggers. Internal forces should be considered as an important factor too.

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