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Evaluation of the Efficiency of Single-Outrigger Structural Systems in Tall Buildings

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Abstract. This study investigated the seismic behaviour of the single-outrigger frame systems and proposed the optimum location of outrigger in tall buildings compared to conventional approaches. For this purpose, a pushover analysis was carried out on different forms of the single-outrigger braced high rise buildings to capture the seismic response. An innovative Stiffness Ratio Method (SRM) technique has been utilised for small-scale 3-D modeling using Finite Element Modeling (FEM) in Abaqus/CAE software commercial program. The performance of single-outrigger systems under uniform loading was measured through lateral displacement and drift. The results confirm that by changing an outrigger's position throughout the height of the building, the strength and stiffness will experience significant changes. Placing an outrigger at the top level of the building termed Cap model led to a reduction in lateral drift by 72 percent, while it reached 84 percent, where it placed at 0.4 height of the building hereinafter called Optimal model. Overall, the results showed that the optimal form of the single-outrigger systems' efficiency is 17 percent higher than the conventional model (Cap model) in the reduction of the top displacement of the building under lateral loads.

1. Introduction

Earthquakes are the most destructive natural hazards throughout human history. Hundreds of thousands of people lost their lives, and the loss of billions of dollars' properties occurred in these disasters. Correct prediction of damage level is very useful in estimating buildings' seismic vulnerability. Results obtained from damage prediction in structure can be effectively used to manage earthquake-caused risks[1-3].

The loading capacity with higher efficiency is behind selecting the structural system of tall buildings [4]. Sufficient stiffness, strength, flexibility, and stability should be considered during the design procedure to minimize tall buildings' horizontal deflections subjected to lateral loading [5]. Such concern can be address by the application of an outrigger system [6]. It is widely accepted that by using the outrigger braced system, the lateral drift at the top of the buildings would be declined [7]. Accordingly, this research investigates the different forms of single-outrigger systems. A structural outrigger system includes a resisting central core pinned to the peripheral columns using rigid and stiff



horizontal cantilever beams. When lateral loading applies to the buildings, the outer column-restrained outrigger resists the central core's rotation. This action caused the lateral deflections and base moment in the main core to be small compared to the free-standing central core [8]. This action increases the structure's effective depth when it flexes as a vertical cantilever by inducing pulling in the windward columns and pushing in the leeward columns [6, 9]. Fig.1 demonstrates different forms of the outrigger systems (Figure 1. a and b) with core position (Figure 1. b and c).

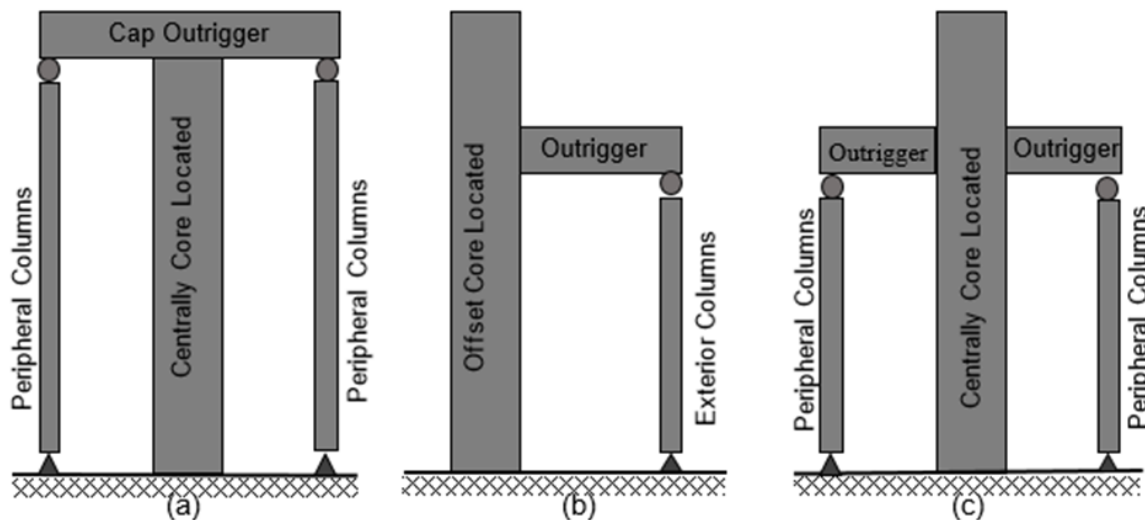


Figure 1. Types of various form and outrigger systems: (a) Cap outrigger, (b) Offset core outrigger, and (c) Centrally core outrigger

Many analytical studies were conducted on the optimization of the structural outrigger systems. These researches mainly involved the optimization of outrigger's positions in which they concluded that the optimum location of the single outrigger systems was placed at a range 0.4 - 0.6 height, from the top of the building [4, 10-15]. The Finite Element Method (FEM) results confirm that by using the outrigger and belt truss system in a 60-story building, the lateral deflection was decreased by 34%, 42%, and 51% for 1, 2, and 3 outriggers systems, respectively [13, 16]. The previous research also acknowledged that the outrigger's appropriate location would be in the range of 40-60 percent of the building's height [17, 18]. Series of equations were developed to optimize the outriggers' location by reducing the drift at the top of the buildings. These equations were developed using various regressions analysis to the relative effects of mixed compatibility analyses up to four outriggers. Figure 2 provides quick hand solutions for outriggers' optimum location and to estimate top drift and moment in the building. Nevertheless, the application of such quick solutions is only limited to buildings with uniform height [19]. In this present paper, the most efficient form of the single outrigger systems, including two different models of the single outrigger locations, was investigated using 3-D FEM. The pushover analysis was utilized to calculate the lateral deflections of the studied models.

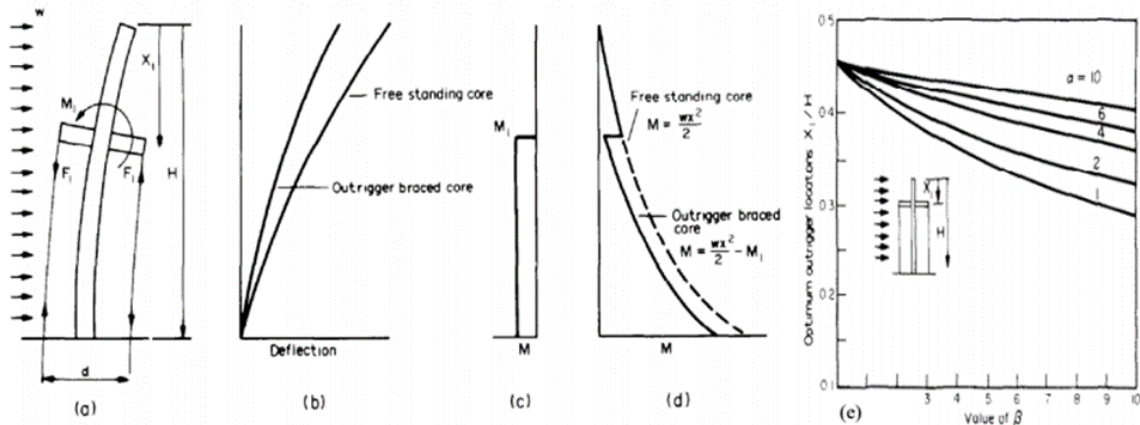


Figure 2. (a) Single outrigger structure. (b) Lateral deflection diagram. (c) The restraining moment at the outrigger level diagram. (d) Resultant bending moment diagram for core (e) Curves to obtain the optimum outrigger location in a single outrigger structure [19].

2. Analytical Study

2.1. Analytical Model

An outrigger frame system’s behavior is simplified in an idealized analytical model that is separated into parts as a central cantilever core under uniform lateral loads (W) and concentrated restoring moment due to the outrigger effect. The rotational stiffness of the outrigger, which is a restoring moment at the core, was created by the applied axial load in the peripheral columns, as shown in Figure 3.

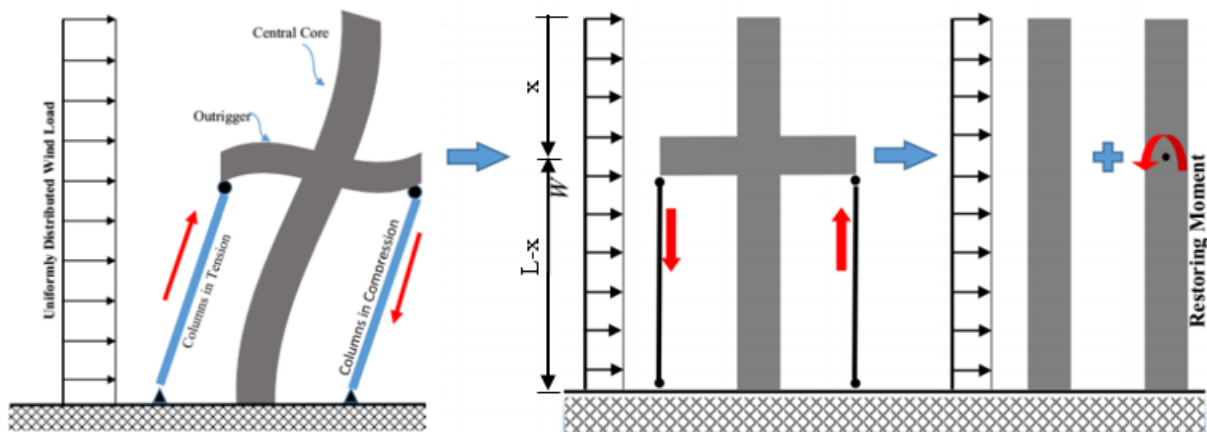


Figure 3. The idealized analytical model of the single outrigger frame system under lateral loads.

The interaction between the rotation of central core and outrigger located at a distance (x) from the top of the building subjected to lateral load can be written:

$$\theta_x = \theta_c - \theta_o \tag{1}$$

Where

θ_c is the rotation of the core, θ_o is the outrigger rotation, and θ_x is the final rotation of the cantilever outrigger structure system at $z = x$ (rad).

According to Fig.3, the restoring moment (M_x), as a result of outrigger placed at a distance (x) from the top of the calculated model is:

$$M_x = \frac{WL^2}{6EI} (x^2 + x + 1) \quad (2)$$

where

$$C = \frac{1}{EI} + \frac{2}{AEd^2}$$

Where EI is flexural rigidity, A is the area of the column, E is the modulus of elasticity, d is the horizontal distance between the peripheral columns in the outrigger direction, and L is the height of the building or columns. The rotational stiffness of the outrigger K when it placed at a distance x from the top of the core can be calculated by

$$K_x = \frac{AEd^2}{2(L-x)} \quad (3)$$

The rotational stiffness of the outrigger significantly depends on its location, measured from the top of the building [20, 21]. The lateral deflection at the top of the core is derived by an algebraic equation based on M_x . Accordingly, the lateral drift at the top of the core due to M_x would be

$$Y_{out} = \frac{W}{12(EI)^2(c)} (L^3 - x^3)(L + x) \quad (4)$$

Subsequently, the lateral drift at the top of the building as a result of lateral load and effect of the M_x , at ($Z = L$ or $x = 0$) is

$$Y_{(x=0)} = \frac{WL^4}{8EI} - \frac{W}{12(EI)^2(c)} (L^3 - x^3)(L + x) \quad (5)$$

Therefore, Eq.5 will be minimized if Eq.4 be maximized. Using the first differentiating the Eq.4 and assuming x equal to zero ($\frac{dY_{out}}{dx} = 0$), the Eq.5 is minimized at $x = 0.455L$. Therefore, a single outrigger system is optimized if it is placed at $0.455L$ from the top of the building [21].

2.2. Evaluation of a Single Outriggered Frame System

Concerning the analytical model and derived equations, the obtained analytical result [21] show that using a single outrigger at the top of the building “Cap Form” was reduced the lateral drift at the top of the building by 67% while using an outrigger placed at the optimum location by $x = 0.455L$, “Optimal Form” declined the lateral drift by 88%. Accordingly, it can be concluded that the lateral drift at the top of the building, 32% declined by using the outrigger system’s optimum location.

3. Numerical Study

3.1. Numerical Simulation Models

The lateral performance of a tall slender building equipped with a single outrigger system was investigated using 3-D FEM using Abaqus/CAE 6.11 program. The Stiffness Ratio Method (SRM) is an innovative procedure which been utilized in this research. The use of the SRM technique to three-dimensional down-scaled modelling is created by the stiffness ratio of the structural members. This technique entirely enhances and follows the two-dimensional theory model of basic formulas mentioned in the analytical portion of the paper. Accordingly, the models include a resisting central core (double rectangular Aluminum profile sections $2 \times (101.6 \times 44.45 \times 1.2)$ mm), outrigger beams (single size of the core section), and exterior columns (section size $38.1 \times 38.1 \times 1.2$ mm). The boundary condition of the core element is fixed to the base as a vertical cantilever part. The outriggers were fixed at the core through the height and were pinned to the facade columns at the other end. The exterior columns have simply connected to the base as vertical members to transfer carrying axial loads. The model’s total height is considered 2550 mm, width 850 mm (center-to-center of the peripheral columns), as shown in Figure 4.



Figure 4. Cap outrigger structure, optimal outrigger structure, the central core alone, section size of the components.

The quadrilateral shell element (S4R) was selected for the element type, and uniform lateral loads were applied step by step (Pushover analysis) to the model to examine its non-linear behavior [22].

Table 1. shows the material properties of Aluminum (Al) material that was tested at the structures laboratory of Universiti Teknologi Malaysia (UTM). The material properties comply with the true stress-strain relationship recommended by ASTM E 8 – 04 [9]. The universal tension test was carried out on the three specimens of the Aluminium with a similar thickness of 1.2 mm and a loading rate of 2 mm/min at Structures Lab of UTM. The results show that the maximum values of the engineering stress observed to be 15% less than that of the maximum values of the true stress, whereas the maximum failure values of the engineering strain are 1.5% more than the maximum failure values of the true strain. The comparison Stress-strain curves for engineering and true results are given in Fig.5. The true material properties computed values were imported to Abaqus/CAE program to analyze the prototype 3-D models.

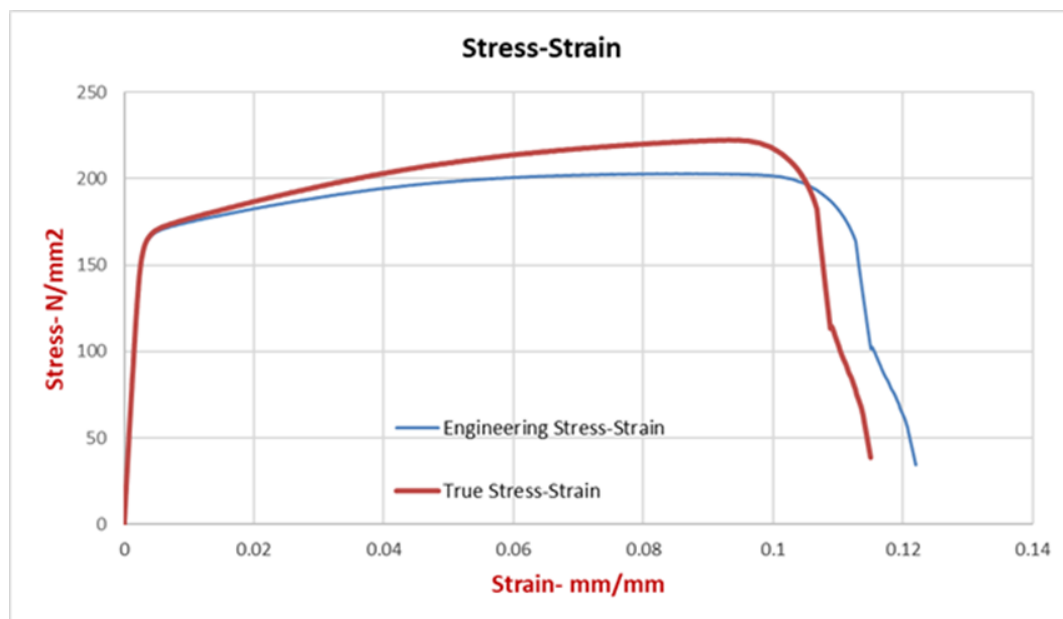


Figure 5. The stress-strain curves of Engineering and True data from the laboratory test of the used material.

Table 1. Material properties of Aluminum (Al)

Elasticity modulus E	68356.78 MPa
Poisson's ratio ν	0.33
Yield stress F_y	168 MPa

4. Results and Discussion from Numerical Analysis

In the first phase of the study, a single-core model (a free standing-core alone, no outrigger) was analyzed under uniform linear lateral load ($W = 13.63 \text{ KN/m}^2$), which was distributed through the height. As shown in Fig.6, the model failed at the base when the stress of the specimen elements experienced by 175.55 MPa at the early stage of pushover analysis (based on the yield stress in Table.1). The second phase of the study concerned a single outrigger system where an outrigger placed at the different levels throughout the building's height ($x=0, 0.25, 0.40, 0.45, 0.50, 0.55, 0.60,$ and $0.75,$ of the height) subjected to the same uniform loading protocol. The results indicated that the 3-D single outrigger model when the outrigger placed at 0.40 height from the top of the model provided minimum lateral drift. Nevertheless, it was observed that the Cap outrigger model was failed by uniform lateral loading by $W = 23 \text{ KN/m}^2$ while the optimal model “ $x=0.4 \text{ H}$ ” experienced failure at $W = 31 \text{ KN/m}^2$, as shown in Fig.6. Moreover, the results confirmed that the free-core model and the Cap outrigger model failed as a result of local buckling at the base. In comparison, the yield mechanism was the governing failure mode for the Optimal outrigger system that occurred at the upper level at the outrigger place instead of the base.

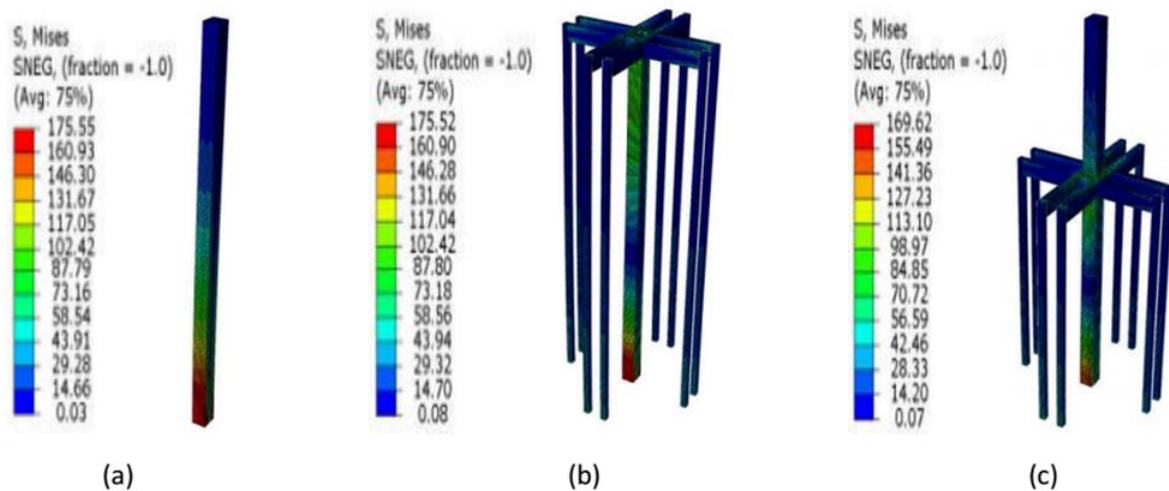


Figure 6. Stress Contour Plot (MPa) at the failure Zones for three models (a) a free single-Core alone model, (b) Cap outrigger model, and (c) Optimal outrigger model.

The capacity curves have been plotted for all three studied specimens, as illustrated by Figure 7. The capacity curve clearly shows that the optimal single-outrigger model ($x=0.4\text{H}$) provided higher base shear and lateral stiffness. The lateral stiffness in the optimized outrigger system is $K_e=134.69 \text{ N/mm}$ compared to $K_e=89.23 \text{ N/mm}$ and $K_e=27.97 \text{ N/mm}$ for the cop-outrigger model and free-core model, respectively.

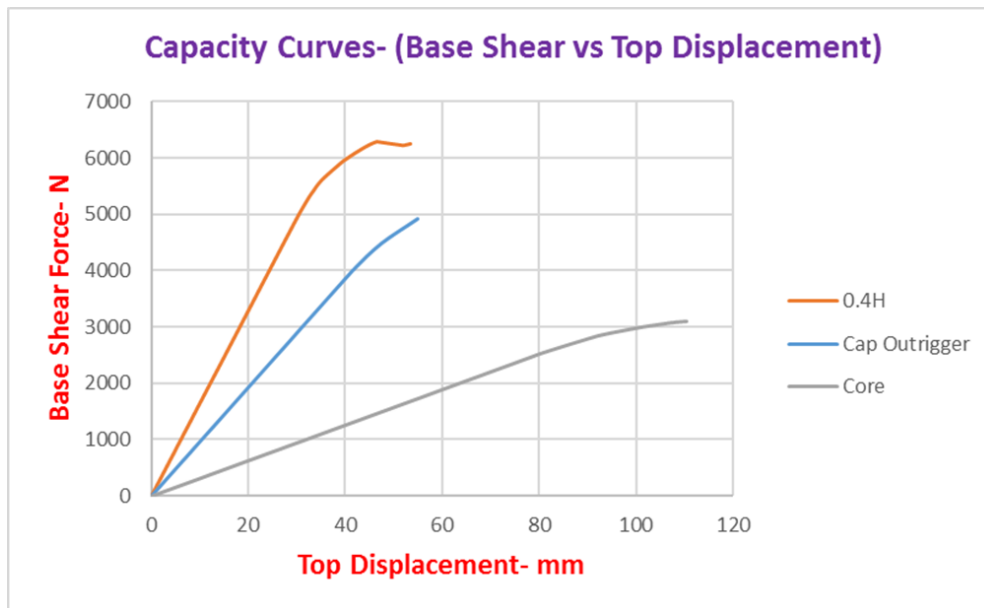


Figure 7. Capacity curves of all three studied 3-D modeling through FEA

Figure 8. shows the lateral stiffness versus the level of the single-outrigger forms and free standing-core alone (no outrigger). The figure clearly shows that the maximum stiffness can be achieved by using an optimized outrigger system.

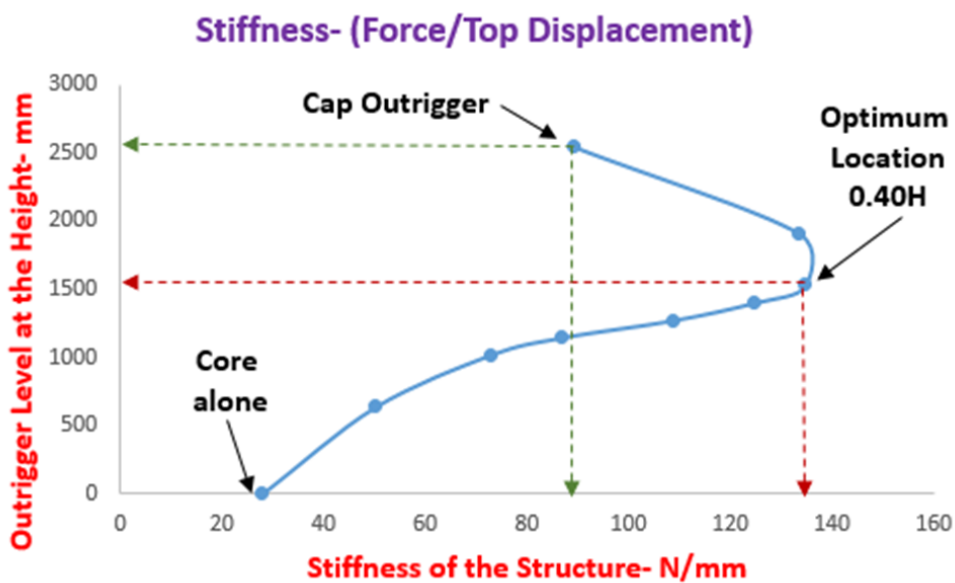


Figure 8. Lateral stiffness versus outrigger level and Core model (no outrigger)

Figure 9. shows the base moment versus outrigger level. The figure clearly shows that the maximum base moment can significantly decline using an optimized outrigger system compared to the free core-alone.

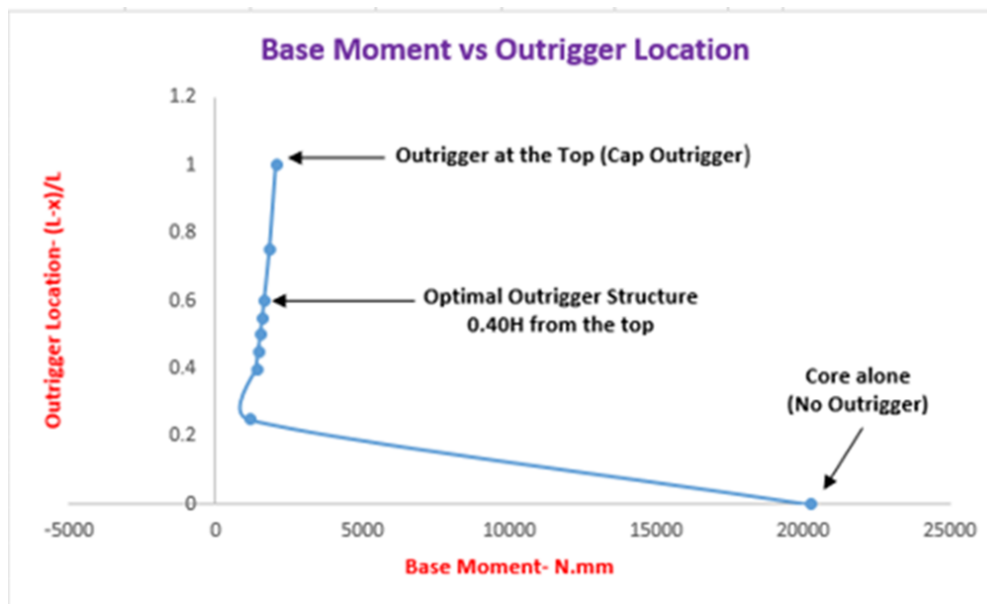


Figure 9. Base moment reduction versus outrigger level

5. Conclusions

The following conclusions have been drawn:

- The efficiency of previous analytical results in the reduction top displacement of the optimal model ($x=0.455H$) is 32% higher than the cap model by lateral uniform loading.
- The FEM results indicated that the optimum form of the single-outrigger systems ($x=0.40H$) provided minimum lateral drift by 17% efficiency higher than the same loading cap-outrigger form.
- The numerical 3D models increasing the stiffness (K_c) efficiency of the optimal model is 51% higher than the Cap model by the ultimate uniform loading.
- The numerical 3D models in the optimal model reduction base moment efficiency are 24% higher than the cap outrigger model.
- This study concluded that the efficiency of the single-outrigger systems is independent of the structure's height, and it depends on the location of the outrigger placing.

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