Effect of Optimal Outrigger Location on the Structural Performance of Tall Buildings under Wind Loads

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ABSTRACT

As the height of the structure increases, the amount of lateral force applied to the structure by the wind load increases. As the lateral load entering the structure and the height increase, the amount of moment created at the base of the structure and the maximum displacement created in the structure increase. Using Outrigger and belt trusses is one of the methods to reduce the maximum moment and maximum displacement created in the structure. One of the basic points in the Outrigger and belt truss system is the optimal location of the outriggers. In this research, the effect of the optimal location of the outriggers on the efficiency of reducing the structure's base moment and the efficiency of reducing the maximum displacement created in the structure has been investigated. To investigate the number of Outriggers, a structure with 1 to 4 Outrigger with two different wind load intensities has been considered. For this purpose, first the mathematical relations required to calculate the optimal location of the outriggers to minimize the structure's base moment, the efficiency of reducing the structure's base moment, and the efficiency of reducing the maximum displacement of the structure for a structure with n Outriggers were obtained, and then the required values were obtained using the written MATLAB code. The results show that by using an Outrigger in the structure, the efficiency of reducing the structure's base moment will increase by 60% and the efficiency of reducing the maximum displacement will increase by 50%. With increasing wind load intensity, the performance of the Outriggers will increase and the efficiency of the structure will increase. By increasing the ratio of the flexural rigidity of the Outriggers to flexural rigidity of the central core of the structure, the efficiency of the structure will incre

KEYWORDS

Outrigger, Structural performance, Optimal location, wind load, Base moment.

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1. Introduction

In recent years, high-rise buildings have been widely constructed and continue to be built. Given their significance in urban communities, high-rise buildings have become a common infrastructural element in urban areas worldwide [1–3]. As structural height increases, wind resistance becomes a pivotal design consideration—particularly due to vibrations induced by crosswinds and vortex shedding, which can generate significant structural motion [4, 5]. As buildings become taller and more slender, their natural frequencies decrease, reaching a range where large-amplitude vibrations can easily occur. The slenderness of a high-rise building is typically characterized by the ratio of its height to its minimum plan dimension [6, 7]. Furthermore, as building height increases, the bending moment generated at the base of the structure under wind and seismic loads also rises [8]. The use of outrigger and belt-truss systems to reduce structural displacement and moments dates back several decades [9]. Figure 1 illustrates an outrigger system combined with a belt truss. In this type of system, exterior columns at a specific height function as a belt, while outriggers connect this belt to the structural core. The belt truss system links the exterior columns to the core; consequently, both the exterior columns and the inner core resist rotation, thereby reducing structural displacement and the moment generated at the base of the inner core.

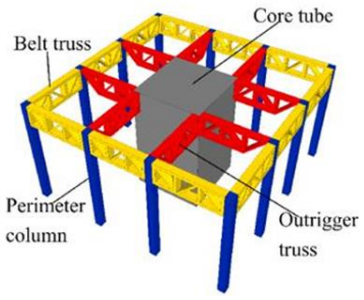

Figure 1. Structure with outriggers and a belt truss

The use of outriggers is an effective method for reducing both the maximum structural displacement and the bending moment at the structure's base. While previous studies have largely focused on determining the optimal outrigger location to minimize maximum displacement or drift, further investigation is needed regarding the optimal location based on the criterion of minimizing the base moment and the simultaneous evaluation of how this location affects both the base moment and maximum displacement particularly when considering varying wind load intensities and different numbers of outriggers. The primary objective of this paper is to examine the impact of the optimal outrigger location (determined by the base moment minimization criterion) on the efficiency of reducing both the base moment and maximum displacement. Accordingly, this research aims to present an analytical method for determining the optimal location of outriggers in high-rise buildings subjected to wind loads and to investigate the effect of this location on the lateral performance of the structure.

2. Mathematical relationships

To investigate the optimal placement of outriggers which minimizes the base moment of the structure mathematical relationships are first derived for a structure with two outriggers and subsequently generalized for a structure with *n* outriggers. Figure 2 illustrates the wind force distribution on a structure equipped with two outriggers.

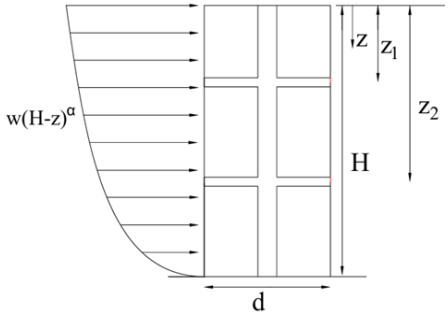

Figure 2. Wind force distribution and moment diagram for a structure

w is the reference wind load intensity, H is the total height of the structure, d is the spacing between adjacent columns, and α is the wind load distribution coefficient that governs the variation of wind load with building height. The coefficient α depends on the structure's location and the terrain characteristics of the area, with values ranging from 0.14 to 0.5 [10]. In this study, it is assumed that the outrigger braces are connected to a rigid central core, while their connection to the perimeter columns is pinned. By calculating the rotation induced in the outrigger brace at its connection point to the central core and equating this value to the rotation of the central core, the reduction in the moment developed within the outrigger braces is determined using Equation 1.

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$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = \frac{w}{EI} A_1^{-1} B_1$$

$$A_1 = \begin{bmatrix} S_1 + S(H - z_1) & S(H - z_2) \\ S(H - z_2) & S_1 + S(H - z_1) \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{2(H - z_1)^{\alpha+3} + (\alpha+3)(H - z_1)H^{\alpha+1}(\alpha(H + z_1) + 2z_1}{2(\alpha+1)(\alpha+2)(\alpha+3)} \\ \frac{2(H - z_2)^{\alpha+3} + (\alpha+3)(H - z_2)H^{\alpha+1}(\alpha(H + z_2) + 2z_2}{2(\alpha+1)(\alpha+2)(\alpha+3)} \end{bmatrix} \quad (1)$$

$$S = \frac{1}{EI} + \frac{2}{d^2 (EA)_C}, \; S_1 = \frac{d}{12(EI)_o} \quad (2)$$

By considering the load applied to the structure and the moment reduction in the outrigger braces, the moment generated at the base of the structure and the maximum displacement within the structure can be determined using Equation (3).

$$M_e = \frac{wH^{\alpha+2}}{\alpha+2} - M_1 - M_2 \quad (3)$$

$$\Delta_o = \frac{w(2\alpha+9)H^{\alpha+2}}{6(\alpha+3)(\alpha+4)EI} - \frac{1}{2}(M_1(H^2 - z_1^2) + M_2(H^2 - z_2^2))$$

where Me and oΔ are the bending moment at the base of the structure and the maximum displacement created in the structure, respectively. The efficiency of reducing the structure's base moment and the efficiency of reducing maximum displacement are defined according to Equation 4.

$$E_M = \frac{\frac{w}{EI} B^T (A^{-1})^T e^T}{\frac{wH^{\alpha+2}}{(\alpha+2)EIS}} = \frac{S(\alpha+2)}{H^{\alpha+2}} B^T (A^{-1})^T e^T \quad (4)$$

$$E_\Delta = \frac{\frac{1}{EI}\frac{w}{EI} B^T (A^{-1})^T C}{\frac{w(2\alpha+9)H^{\alpha+4}}{6(\alpha+3)(\alpha+4)EI}\frac{1}{EIs}} = \frac{3S(\alpha+3)(\alpha+4)}{(2\alpha+9)H^{\alpha+4}} B^T (A^{-1})^T C$$

$$C^T = \left[H^2 - z_1^2 \;\; H^2 - z_2^2 \;\; \ldots H^2 - z_n^2\right], \; e = [1 \;\; 1 \;\ldots 1]$$

where E_M represents the efficiency of reducing the structure's base moment, and E_Δ represents the efficiency of reducing the structure's maximum displacement.

3. Results

Figures 3 and 4 illustrate the effect of the number of outrigger braces on the efficiency of reducing the structure's base moment and maximum displacement across various load intensities.

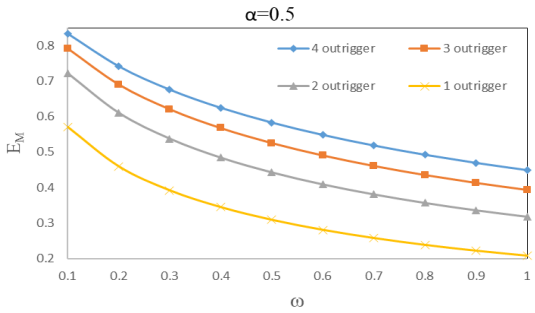

Figure 3. Efficiency of reducing the structure's base moment with varying numbers of outriggers

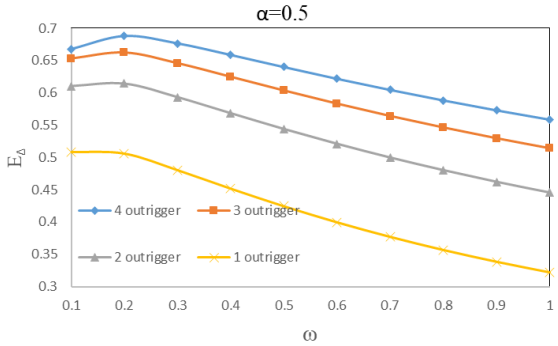

Figure 4. Efficiency of reducing the maximum structural displacement with varying numbers of outriggers

Increasing the number of outrigger braces from two to three enhances the effectiveness of reducing the structure's base moment by 10% to 23% and the maximum structural displacement by 7% to 16%, depending on the flexural stiffness of the outrigger braces, the flexural stiffness of the central core, and the axial stiffness of the columns. Increasing the number of outrigger braces from three to four further improves the effectiveness of reducing the base moment by 5% to 14% and the maximum displacement by 2% to 9%.

1- Conclusion

In this study, the effect of the optimal location of outriggers determined by minimizing the structure's base moment on the performance of tall buildings under wind loads was investigated. To this end, buildings equipped with one to four outriggers were analyzed under two different wind load intensities; the study examined the influence of the number of outriggers, the ratio of outrigger flexural stiffness to central core stiffness, and the axial stiffness of perimeter columns on the efficiency of base moment reduction and maximum displacement. Based on the results obtained, the key findings of the research are as follows:

- use an outrigger at a location that minimizes the structure's base moment can increase the efficiency of base moment reduction to approximately 57% and the efficiency of reducing maximum structural displacement to about 50%. This result demonstrates

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that even the use of a single outrigger provided its location is suitably chosen can have a significant impact on controlling the lateral response of a tall building.

- Increasing the number of outriggers from one to two depending on the flexural stiffness of the outriggers, the flexural stiffness of the central core, and the axial stiffness of the columns—results in an increase in the efficiency of base moment reduction by approximately 25% to 50% and an increase in the efficiency of maximum displacement reduction by approximately 20% to 40%.

- By increasing the number of braces from one to three, the efficiency of reducing the base moment of the structure increases in the range of 40-90% and the efficiency of reducing the maximum displacement increases in the range of 30-60%. Therefore, increasing the number of braces in this range can lead to a significant improvement in the lateral performance of the structure.

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