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Genetic-algorithm-based minimum weight design of an outrigger system for high-rise buildings

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ABSTRACT

Outrigger systems, which consist of a core wall, external columns, and outriggers, are widely used in structural systems in high-rise buildings to control lateral displacements. This study proposes an optimal design method for minimizing the volume of the primary structural members (core wall, outrigger, and external columns) and calculating the optimal locations of outriggers using a genetic algorithm with the goal of efficiently controlling the lateral displacement of a high-rise building. The optimal solution of the outrigger system was determined based on the change in the number of stories (from one to four) at which outriggers were installed in a prototype model (a 400-m high-rise building). The results indicate that increasing the number of outrigger installations reduces the total volume of structural members needed in the outrigger system to satisfy the displacement constraint of the top floor (H/500, H: building height). Additionally, the cross-sections of the core wall and outrigger decreased and that of the external column increased, which indicated that the role of the external column in the control of lateral displacements increased as the number of outrigger installations increased. As a result, the contribution of the core wall to the bending moment decreased, which reduced the cross-section of the core wall. These results provide an optimal solution that considers the ideal locations of the outriggers and minimizes the volume of structural members within the maximum lateral displacement range, which is specified as a structural performance constraint. Therefore, this study can provide designers with a well-defined target performance level (e.g., lateral displacement or bending stress) during the initial stage of the outrigger system design process and an economical design that minimizes cost.

1. Introduction

Advancements in building materials, construction technology, and structural systems have resulted in the development of high-rise buildings. In high-rise buildings, serviceability and safety have been major issues due to lateral displacements caused by lateral loads, such as wind or earthquake loads, which increase as the building height increases. Structural systems that are typically used to control the lateral displacements of tall buildings (e.g., moment-resisting frames and coupled shear wall systems) are often unsuitable for the development of economical designs for high-rise buildings due to the large cross-sections of the structural members required to satisfy lateral drift limit conditions. Therefore, new structural systems (e.g., bundled or braced tube systems, shear wall-frame systems with haunch girders, spinal wall systems, and outrigger and belt wall systems) have been proposed, developed, and implemented to control the lateral displacement of high-rise buildings [1–7]. Among existing systems, the outrigger system performs particularly well in controlling the lateral displacement of high-rise buildings [8–12] and has been used in many such buildings around the world. The method used to control lateral displacements in outrigger systems involves connecting the core wall and external columns using rigid beams that are installed over one or two stories. The moments generated at the bottom of the core wall are made resistant by the compressive deformation and tension of the external columns connected to the outriggers, which controls the overall lateral displacements of high-rise buildings. Therefore, the outrigger system effectively reduces the moments generated by lateral loads at the bottom of the core wall. As a smart control system, it was also reported that magnetorheological (MR) dampers, which are installed between outrigger walls

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and external columns, can be effectively employed in outrigger damping systems [13]. Numerous analytical studies [14,15,11,16] have employed finite element or simplified models to simulate the linear/nonlinear responses of a high-rise building with an outrigger system subjected to static and dynamic loads, and the effectiveness of outrigger systems as structural systems for a high-rise building has been demonstrated.

For outrigger systems, the selection of the outrigger location (floor location) is an important issue in terms of ensuring the efficiency of lateral displacement control. To ensure structural efficiency and validate the importance of the outrigger system, an approximation analysis method was used to determine the optimal location of outriggers in the outrigger system [17,18], which is important for the development of an optimal design [19–24].

A study by Taranath [8] involved the selection of the optimal location of outriggers and it was found that the optimal location of an outrigger in a structure that contains one outrigger is located at 0.455H (H: building height) from the top, assuming that the outrigger exhibits an infinitely high flexural rigidity (bending stiffness). When two outriggers are used to obtain efficient lateral displacement control, the optimal locations are 0.312H and 0.685H from the top [25]. Additionally, a number of studies on selecting an optimal location for a multi-outrigger system have been performed [24,26,27]. For example, a study was conducted to determine the optimal location of a second outrigger when the first outrigger location is known [28]. Another study considered the flexural deformation of outriggers to determine the optimal location of an outrigger using non-dimensional parameters and an approximation analysis method for multi-outrigger structures [19].

A study based on a simple analysis method has also been conducted for concrete shear wall structures with one outrigger considering the rotational stiffnesses of the shear wall and column foundations [29].

Most previous studies on the lateral displacement control of outriggers have indicated that, for a constant structural volume, the top displacement control effect improved as the number of outrigger installations increased or the location of the outriggers approached its optimum. However, considering the overall structural performance and economics of structures, unconditionally minimizing the top displacement does not necessarily result in an ideal design. Therefore, assuming that the specific limit conditions for structural performance (e.g., limitations on the top displacement or bending stress at the bottom of the core specified in the design code) are satisfied using design methods, such as optimization techniques [30,31], the lateral displacement control effect due to outrigger installations can be utilized to reduce the volume of the structural members, which results in a more economical and efficient design.

Using a genetic algorithm (GA) approach [32–35], this study proposes an optimal design that selects the optimal location of an outrigger and minimizes the volume of the primary structural members (core wall, external column, and outrigger) of the outrigger system to efficiently control the lateral displacement of the outrigger system. In this optimal design, the objective function was to minimize the volume of the primary structural members, and the constraint parameters were the bending stress generated at the bottom of the core wall and the top displacement. Additionally, the bending stiffness of the core wall and outrigger, the axial stiffness of the external column, and the locations (which are based on the number of outriggers) were used as design variables for the optimization.

In this study, an optimal GA-based design was developed as a prototype by considering a sample building with a height of 400 m and a width of 50 m, which corresponds to a slenderness ratio (height/width) of eight. Based on the optimization results satisfying the constraint condition on the top drift and bending stress, we studied the relationships between the minimum volume of the structural members and the optimum location of the outrigger, the change in the volume and bending stress of core walls resulting from the outrigger installation, and the number of installations.

2. Simple analysis method

A simple analysis method for outrigger systems [5] was adopted in this study. *N* outriggers were used, and a constant cross-section was assumed regardless of the installation location in the vertical direction. Only the axial behavior of the external column was considered, and the flexural deformations of the outrigger and core wall were considered to be a deformation component. However, shear deformation was not considered in the structural members. Additionally, all the structural members were assumed to exhibit linear elastic behavior. The joint conditions for the three primary structural members were as follows: the outrigger and core wall were assumed to be connected by a rigid joint, and the outrigger and column were assumed to be connected by pin joints.

In this simple analysis method [5], it is assumed that both the section sizes of the core and columns are uniform regardless of the building height. However, these assumptions are not applicable to a real structure, whose member sizes vary with the building height. Therefore, in the structure considered, the flexural rigidity of the core wall and the axial rigidity of the external column vary linearly with respect to height, as shown in Fig. 1 [36]. Additionally, a trapezoidal wind load was used as the load exerted on the structure. Based on the studied section sizes of the members (i.e., core and columns) and the shape of the wind load as a function of height, the simple analysis method proposed by Smith and Coull [5] was modified in [36] and used in this study.

We assume a building of height, H, and width, B, with n outriggers at a distance x_i from the top to the i th outrigger; second moments of inertia of the core walls, I_t and I_b; cross-sectional areas of the columns, A_t and A_b; horizontal loads of w_t and w_b at the top and bottom ends of the structure, respectively; a restraining moment applied to the core by the ith outrigger, M_i; and a Young's modulus, E.

The rotations of the core at the levels of the outriggers ($\theta_1, \ldots, \theta_n$ in Fig. 1) can be expressed using both the flexural deformation of the core and the bending deformation generated by the differential axial deformation of the external columns and the bending of the outrigger. In addition, the compatibility condition should be satisfied between these two rotations.

Initially, the rotation of the core, $(\theta_i)_c$, at the point of contact of the i th outrigger and the core can be calculated using the moment area method, which is given in Eq. (1). The first term on the right-hand side of Eq. (1) represents the rotation of the core generated by a wind load with a trapezoidal shape (Fig. 1), and the second and third terms with a negative sign indicate the rotations reduced by the restraining moments of the outriggers, M_k, on the core.

In addition, the rotations of the outriggers, $(\theta_i)_o$, at the point where they are connected to the core can be represented by Eq. (2), where the first and second terms are related to the axial deformation of the external column and the last term indicates the bending deformation of the outrigger.

$$(\theta_i)_{core} = \int_{x_i}^{H} \frac{H}{E(I_t(H-x)+I_b x)}\left(\frac{w_t x^2}{2}+\frac{(w_b-w_t)x^3}{6H}\right)dx - \sum_{k=1}^{i}\int_{x_i}^{H}\frac{HM_k}{E(I_t(H-x)+I_b x)}dx - \sum_{k=i+1}^{n}\int_{x_k}^{H}\frac{HM_k}{E(I_t(H-x)+I_b x)}dx \quad (1)$$