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Optimum design of outriggers in a tall building by alternating nonlinear programming

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ABSTRACT

Optimum design of locations and areas of multiple outriggers in a tall building was performed by a newly developed method. The method proposed in this study alternates between integer nonlinear programming and real number nonlinear programming to solve mixed integer nonlinear programming. Piecewise quadratic interpolation is used to obtain a differentiable and semi-continuous constraint function using the discrete analysis results from finite element analysis. Three analysis models representing various tall buildings with outriggers were used to perform the optimum design of the outrigger, which is subject to the lateral displacement constraint. The results demonstrate that as the number of outriggers used was increased, the total volume of the outriggers decreased. However, the performance of the outriggers remained almost the same when the number of the outriggers was greater than two. The optimum locations of the outriggers were slightly higher than those from the analytical solutions with simplified assumptions. The proposed method can be effectively used in other structural engineering applications that involve FEA.

1. Introduction

Outriggers have recently been widely used to provide efficient lateral load resistance in tall slender buildings. Outriggers are horizontal structures connecting a building core or spine to distant columns. Outriggers serve to reduce the overturning moment in the core that would otherwise act as a pure cantilever, and to transfer the reduced moment to the columns outside the core using a tension-compression couple, which takes advantage of the increased moment arm between these columns [1]. Since the location of the outrigger greatly affects the effectiveness of the outrigger in terms of the lateral displacement at the top of the tall building, optimum design of the outriggers has been an attractive topic among academic researchers and practical engineers. Taranath [2] suggested that the optimum location of one outrigger to minimize the lateral displacement at the top of the building is 0.445 of the total height from the top of the building. McNabb and Muvdi [3] found that the optimum locations for two outriggers are 0.312 and 0.685 of the total height from the top of the building. In these early studies, simple conditions were assumed such as a constant section and infinite flexural rigidity of outriggers. Later studies suggested the optimum locations of the outriggers accommodating more realistic conditions such as varying section, finite flexural rigidity, and various loadings [4–6]. In recent studies, Park et al. [7] presented the optimum design of the outriggers using genetic algorithm in which sectional areas of primary structural members as well as outrigger locations are included in the design variables and two constraints are considered. However, in all of the abovementioned studies, analytic equations were used to evaluate the lateral displacement and the location of the outriggers was treated as a continuous design variable.

Finite element analysis (FEA), which is a common tool in structural engineering practice, cannot be utilized to evaluate design constraints such as the lateral displacement since the outriggers can only be installed at the beam-column joints, therefore, the locations of the outriggers should be given in discrete integers for the FEA. Meanwhile, Lee and Tovar [8] used a commercial FEA program to evaluate the lateral displacement for the outrigger placement using topology optimization. In their study, the design variables representing the sectional areas of the outriggers placed at every floor were continuous and converted to a discrete number of 0 or 1 through topology optimization. Although the design variables are the sectional areas of the outriggers, only the locations of the outriggers are determined in the optimization. Taranath [9] presented the optimum locations of one and two outriggers through a computer-assisted analysis of a realistic 46-story steel building. He used a brute force search with fixed sectional areas. Smith and Willford [10] proposed outrigger damper systems which

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employ vertical viscous dampers installed between the outrigger walls and the perimeter columns in a tall building structure to enhance structural dynamic performance. The damper locations were optimized either by manual trial and error or by automated techniques, which appears to be a modification of the brute force search.

Although the optimum design of the outriggers has been studied for over four decades, it remains a challenging problem because it includes not only continuous design variables for areas but also discrete design variables for locations. This problem is a case of mixed-integer nonlinear programming (MINLP), which is sometimes called as mixed-discrete-continuous nonlinear programming (MDCNLP) and is the optimization problem where some of the variables are constrained to take integer values and the objective function and feasible region of the problem are described by nonlinear functions. MINLPs form a particularly broad class of challenging optimization problems, as they combine the difficulty of optimizing over integer variables with the handling of nonlinear functions [11]. In the field of structural engineering, Gandomi et al. [12] developed a metaheuristic optimization algorithm for solving mixed continuous and discrete structural optimization problems. Lee et al. [13] also presented an improved genetic algorithm to solve the mixed-discrete-continuous design optimization problems. The methods used in above two studies are stochastic optimization methods which do not require gradients of the objective and constraint functions. Kravanja et al. [14] examined the MINLP optimization approach to structural synthesis and the optimization of a composite I-beam floor system was recently carried out through the MINLP [15]. In these studies, discrete variables were considered as 0–1 binary variables and analytic equations were used for the structural analysis constraints.

In this current paper, the optimum design of the outrigger, including areas as well as locations, is performed. FEA rather than analytic equations is utilized to calculate the lateral displacement of tall buildings. The optimization is formulated as a problem of MINLP and a novel algorithm is proposed to solve the MINLP problems.

2. Optimum design of outriggers

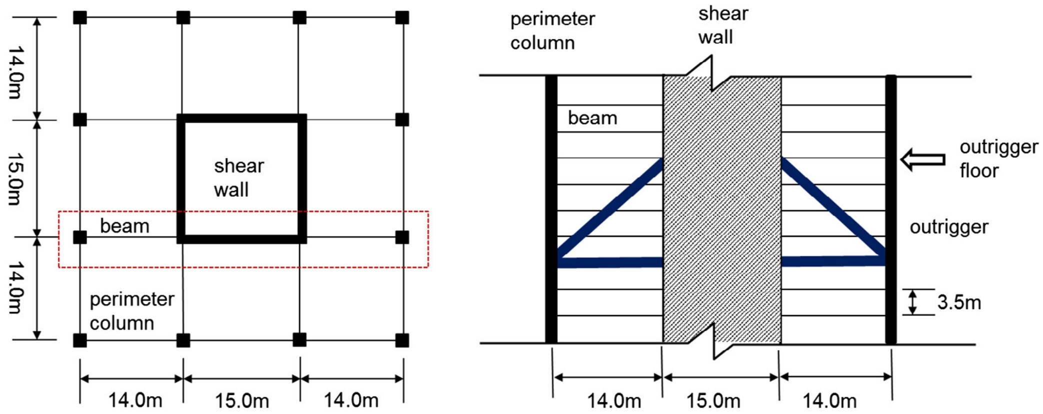
2.1. Effect of outrigger on lateral displacement

The outriggers are key components in the efficient and economic design of tall buildings. Coupling the shear wall with the perimeter frame results in an increase in the overall resistance of the structure to the overturning forces caused by the wind or earthquake loads.

The effects of an outrigger on the lateral displacement of tall buildings were investigated prior to the optimization of the outriggers. Three 80-story reinforced concrete building structures with the single outrigger as shown in Fig. 1 were analyzed. The columns and shear walls have three different sectional profiles, as listed in Table 1. The constant-section model has the same column and wall sections for all stories. In the constant-stress model, the sectional areas of the column and wall were adjusted so that the members developed equal axial stresses from the gravity loads. The general model had four different section groups for the columns and walls. Although the constant-section model and constant-stress model were not suitable for an actual tall building, they represented extreme cases of the column and wall sectional profiles used in tall building structures. The four-story high outrigger truss has two inclined members and two horizontal members as shown in Fig. 1(b). The sectional area of the inclined member in the outrigger was $\sqrt{2}$ times that of the horizontal member so that the same axial stresses can be developed in both members. The sectional area of the horizontal members was normalized to the reference value of 0.1256 m^2, which is equal to 100 in the scale of the normalized

Table 1
Analysis models.

Analysis model	Member	Floor level	Section size width × depth (m)
General model	Column	1F–20F	1.5 × 1.5
		21F–40F	1.5 × 1.2
		41F–60F	1.5 × 1.0
		61F–80F	1.0 × 1.0
	Shear wall	1F–30F	1.0 × 15.0
		31F–50F	0.8 × 15.0
		51F–70F	0.7 × 15.0
		71F–80F	0.6 × 15.0
Constant-Section model	Column	1F–80F	1.5 × 1.2
	Shear wall	1F–80F	0.8 × 15.0
Constant-Stress model	Column	1F	1.755 × 1.755
		2F–79F	Varying
		80F	0.196 × 0.196
	Shear wall	1F	1.205 × 15.0
		2F–79F	Varying
		80F	0.015 × 15.0



(a) Typical floor plan (b) Elevation at outrigger floor

Fig. 1. Analysis model (only part of the structure is shown for clarity).