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Dynamic characteristics of novel energy dissipation systems with damped outriggers

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ABSTRACT

This study proposes complex rotational stiffness for modeling multiple damped outriggers in a tall building. The complex rotational stiffness considers interaction between peripheral columns and the dampers in damped outriggers. By combining the complex rotational stiffness into a dynamic stiffness matrix, the dynamic characteristics of a building with multiple outriggers can be derived in accordance to the Benoulli–Euler beam theory. These dynamic characteristics subsequently provide a guideline for designing outriggers in a building. In this study, the proposed method is verified in comparison with a finite element model. An in-depth parametric study is then conducted by the proposed method to evaluate a building with outriggers with respect to the stiffness ratio of the core to perimeter columns, position of damped outriggers, and damping coefficient of linearly viscous dampers. The investigation shows that the modal damping is significantly influenced by the ratio of core-to-column stiffness, as well as is more sensitive to the damping coefficient of dampers than to the position of damped outriggers. All of the results obtained are non-dimensional and convenient for analysis and applications of designing damped outrigger systems.

1. Introduction

In the recent years, cities around the world have seen a plethora of new supertall buildings (i.e., with a height greater than 300 m). One of the tall building types is the frame-core structure. However, large drifts in these traditional frame-core buildings raise concerns for structural design that result in a higher demand of the core stiffness. Smith and Coull [1] proposed an outrigger system in a 47-story building. An outrigger system connects the building core to perimeter columns by rigid shear walls or deep beams. The outrigger system resists the later loads through perimeter columns to improve building performance without significantly increasing the core dimensions.

A number of studies explored the methods to design outriggers in tall buildings. Moudares [2] utilized a pair of coupled shear wall as an outrigger to reduce lateral displacements. Taranath [3] introduced a simplified model to describe an outrigger system, which consists of a bending beam, infinite rigidity outriggers, and axial force of perimeter columns. He also determined 0.555 of the building height as an optimal location of a belt truss for a single outrigger. McNabb et al. [4] further extended the same idea to two outriggers in a building. Lee et al. [5] used topology method to attain an optimized outriggers placement. All these studies are focused on the stiffness enhancement through outriggers.

In addition to static analysis, Smith et al. [6] investigated dynamics of tall buildings with an outrigger with respect to its location. By specifying an appropriate transformation, the dynamics of bracing outriggers with shear walls were derived, with results that were similar to Moudarres and Coull [7]. The dynamic characteristics of the frame core walls with one or two outriggers were later investigated by Shen et al. [8,9]. His study considered the compatibility for outriggers in terms of displacements and forces. Through these methods, the traditional outriggers are dynamically modeled.

In recent years, supplemental energy dissipation devices have been widely accepted as effective means for protecting tall buildings from strong wind and severe earthquake [10,11]. Typically, most supplemental damping systems are installed between floors and distributed over the height of a building. For tall buildings, this approach is not cost-effective. Moreover, performance of dampers is also limited due to low interstory drifts and velocities in these buildings. Inspired by the development of outriggers, dampers have been proposed for placement between outriggers and perimeter columns, using the outriggers to amplify building responses [12]. Tan [13] tested a damped outrigger system using

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shaking table testing, and the results showed better performance over the convectional outriggers. Additionally, Zhou [14] numerically investigated seismic performance of a high-rise building with damped outriggers. The study discussed five connection types of viscous dampers in damped outriggers. Fang [15,16] analyzed damped outriggers with viscous dampers and BRB bracing systems in the reliability perspective. Due to the comparable performance of MR dampers [17,18], Chang et al. [19] numerically investigated a single outrigger with MR dampers in a tall building and Asai et al. [20] further examined the performance of such smart outriggers system experimentally using real-time hybrid simulation. Until now, damped outrigger systems have been successfully applied to real-world tall buildings, i.e., Saint Francis Shangri-La Towers with a height of 210 m high in Philippine [21] and Gate of South Asia Tower with a height of 366 m in Yunnan, China [22]. All these studies and applications focused on a specific structure and lacked of a generally theoretical analysis.

A damped outrigger system can be simplified as a cantilever beam with energy dissipation devices. For cantilever beams, the dynamic analysis can be accomplished by the Bernoulli–Euler beam theory [23,24]. A continuum beam with dampers has been theoretically studied, i.e., with a viscous damper in the longitudinal [25] and in the transverse direction [26], with rotational dampers at the free end [27], and with a viscous damper attached intermediately [28,29]. For damped outrigger systems, Chen and Wang [30] explored a single damped outrigger in a building based on the principle of virtual work. Another theoretical approach is to utilize a series of compatibility equations to analyze damped outriggers [31]. Furthermore, most theoretical studies ignored the influence on stiffness of perimeter columns and its contribution to modal damping. For multiple damped outriggers, a complete analysis should include the perimeter columns in modeling.

In this paper, complex rotational stiffness is derived to model damped outriggers in a tall building. In this method, the effects of damper, peripheral column and interaction between outriggers are taken into account. The main equation governing the dynamic characteristic of damped outrigger system is then obtained from complex rotational stiffness and dynamic stiffness matrix based on the Bernoulli–Euler beam theory. To understand the behavior of damped outriggers in a building, an in-depth parametric study is carried out which considers the stiffness ratio of the core to perimeter columns, position of damped outriggers and damping coefficient of dampers. The proposed complex rotational stiffness method is also validated by a finite element model. Through a series of analyses, a building with two damped outrigger can be optimally designed.

2. Complex rotational stiffness

A simplified model used in analysis of a damped outrigger system with a uniform core and perimeter columns is shown in Fig. 1. Note that the axial stiffness of peripheral columns is taken into account and characterized by E_cA_c. The core is approximated as an Euler–Bernoulli beam, with bending stiffness characterized by EI and mass m per unit length. Outriggers are located at a height of $\alpha_1 L, \ldots \alpha_j L \ldots \alpha_n L, j = 1, \ldots, n$, from the bottom of the building, and these outriggers are cantilevered from the core. The outrigger cantilever beams to the dampers are assumed to be infinitely rigid. Linear viscous dampers with a damping coefficient, denoted by C_d, are vertically installed between the end of outriggers and perimeter columns. x_j is local axial coordinate at the j-th segment which is separated by outriggers.

For a traditional outrigger system, resisting moments reduce the lateral displacements by a force couple, which is induced by the tension and compression in the windward and leeward

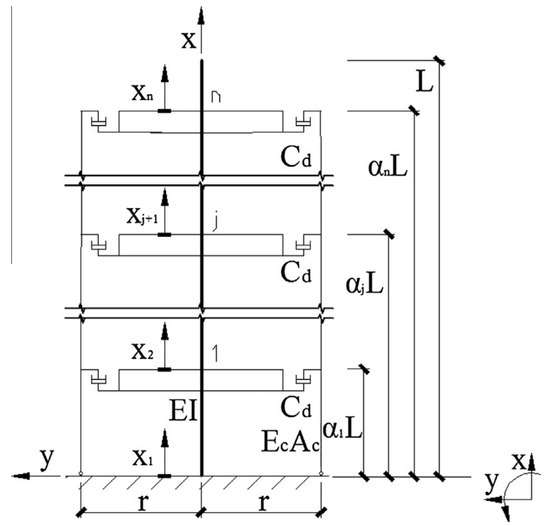

Fig. 1. Simplified analytical model.

columns. With additional dampers in outriggers, the resisting moments can be further generated. This damped outrigger can be seen as a complex rotation stiffness that consists of stiffness and damping per outrigger. Thus, complex rotational stiffness is proposed to model a damped outrigger system, as illustrated in Fig. 2.

The complex rotational stiffness considers both effects of the dampers and axial stiffness of perimeter columns for damped outriggers. For convenience, the derivation of the complex rotational stiffness begins with a structure having two damped outriggers. The following derivation can be further extended to a structure with more than two damped outriggers. Thus, the resisting moments to the core are given by

$$M_1 = 2F_{d1}r = -2C_d\Delta\dot{U}_{d1}r = -2i\omega C_d\Delta U_{d1}r^2 \quad (1)$$

$$M_2 = 2F_{d2}r = -2C_d\Delta\dot{U}_{d2}r = -2i\omega C_d\Delta U_{d2}r^2 \quad (2)$$

where U_{d1} and U_{d2} are relative displacements on the viscous dampers at the heights of $\alpha_1 L$ and $\alpha_2 L$, respectively; ω is exciting circular frequency; $i = \sqrt{-1}$; r is the length of outrigger beam. The displacements along the perimeter columns can be expressed by

$$\Delta U_1 = -\frac{F_1\alpha_1 L}{E_cA_c} = -\frac{(F_{d1}+F_2)\alpha_1 L}{E_cA_c} = -\frac{(M_1+M_2)\alpha_1 L}{2E_cA_cr} \quad (3)$$

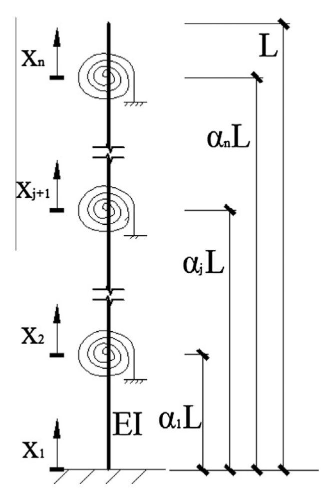

Fig. 2. Illustration of complex rotational stiffness.