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Development and application of a simplified model for the design of a super-tall mega-braced frame-core tube building

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ABSTRACT

Resilience-based earthquake design for next-generation super-tall buildings has become an important trend in earthquake engineering. Due to the complex structural system in super-tall buildings and the extreme computational workload produced when using refined finite element (FE) models to design such buildings, it is rather difficult to efficiently perform a comparison of different design schemes of super-tall buildings and to investigate the advantages and disadvantages of different designs. Here, a simplified nonlinear model is developed and applied to compare two design schemes (i.e., the fully braced scheme and half-braced scheme) of a super-tall mega-braced frame-core tube building, which is an actual engineering project with a total height of approximately 540 m. The accuracy of the simplified model is validated through a comparison of the results of modal analyses, static analyses and dynamic time history analyses using the refined FE models. Subsequently, the plastic energy dissipation of different components and the distribution of the total plastic energy dissipation over the height of the two design schemes are compared using the proposed simplified model. The analyses indicate that the fully braced scheme is superior because of its more uniform energy distribution along the building height and the large amount of energy dissipated in the replaceable coupling beams, which enables rapid repair and re-occupancy after an earthquake. In contrast, the potential damage in the half-braced scheme is more concentrated and more severe, and the damage in the core tubes is difficult to repair after an earthquake.

1. Introduction

In recent years, studies on the resilience-based seismic design of super-tall buildings have become increasingly popular [1–5]. To design an earthquake-resilient super-tall building, the performance of super-tall buildings subjected to various earthquake intensities should be accurately simulated; such simulations are used to predict the seismic energy dissipated in replaceable and repairable components as well as the structural damage in key components that are difficult to repair.

Numerous studies have been conducted using three-dimensional (3D) refined FE models to investigate the nonlinear seismic performance and predict the potential collapse modes of super-tall buildings. Nonlinear time-history analyses of various super-tall buildings, including the Taipei Financial Center ($H = 508$ m) [6,7], the Shanghai Tower ($H = 632$ m) [8–12], the Republic Plaza ($H = 280$ m) [13], and the Shanghai World Financial Tower ($H = 420.5$ m) [14], were conducted using refined FE models, which were established using various general-purpose FE software packages (e.g., ANSYS [15], Perform 3D [16], LS-DYNA [17] and ABAQUS [18–23]) and open-source software packages (e.g., OpenSees [24]). The seismic performances of these super-tall buildings subjected to various seismic intensities were predicted to optimize the seismic designs. More recently, collapse simulations of super-tall buildings subjected to extreme earthquakes were successfully performed by Lu et al. [25,26] using MSC.Marc [27]. The potential collapse modes of these super-tall buildings were predicted, and the critical zones that might induce collapse were identified, which could serve as a reference for future improved designs.

As described above, the refined FE model has been widely applied to investigate the seismic performance and reveal the potential collapse modes of tall and super-tall buildings with various structural systems [6–14,25,26,28–31]. However, such simulations have several drawbacks: first, the refined FE model cannot be accurately established without specific structural design details, which are typically unavailable at the preliminary design stage, thus restricting the applications of this type of model at this

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stage. Moreover, super-tall buildings are typically composed of many different components, thereby leading to an extremely large computational workload and low efficiency when using the refined FE models. Such models restrict the implementation of parametric analyses or incremental dynamic analyses (IDAs). In particular, several different design schemes are typically proposed at the preliminary design stage. Due to the lack of specific design details and the large computational workload, the comparison between various design schemes, which is essential for the design of super-tall buildings, cannot be easily performed using the refined FE models.

In contrast, a simplified model that represents the key nonlinear and dynamic characteristics of super-tall buildings and effectively reduces the computational effort has the potential to facilitate the comparison of different preliminary design schemes. Moreover, if the engineering demand parameters are available through the analysis of the simplified model during the preliminary design stage, such a model can also be used to guide and optimize the preliminary design.

Although limited research has been reported on establishing a simplified model of super-tall buildings, many researchers have conducted studies on establishing simplified models for conventional tall buildings. For example, a simplified model for the framed-tube structure proposed by Connor and Pouangare [32] was applied to analyze its elastic response subjected to static lateral loads and subsequently used to guide the preliminary design. Luco and Cornell [33] developed a simplified model involving the interconnection of two shear beams to predict the seismic performance of tall buildings. Meftah et al. [34] presented a simplified approach for the seismic analysis of a tall building braced by shear walls and thin-walled open section structures, and a simplified formulation for the vibrational frequencies and internal forces subjected to earthquakes was obtained based on D'Alembert's principle. An important achievement in the simplified modeling of super-tall buildings was accomplished by Lu et al. [35]; specifically, a two-dimensional (2D) simplified model encompassing nonlinear beam-column elements and nonlinear spring elements for the Shanghai Tower ($H = 632$ m) was proposed. The reliability of this model was validated by comparing the results of the simplified model with those of the refined FE model. The analyses of the plastic energy dissipation indicated that the outrigger was the primary plastic energy dissipation component, and the total plastic energy distribution along the height of the building subjected to three seismic intensities was identified. Despite these efforts, the simplified model has only been used for the Shanghai Tower (which is a mega-column/core-tube/outrigger system), in a study by Lu et al. [35]. Additional validation of the reliability of this model is required for other types of super-tall buildings. In addition, further studies should also be performed on the application of the simplified model at the preliminary design stage and the comparison of different design schemes.

Therefore, based on the simplified model and associated parameter determination approaches proposed by Lu et al. [35], a simplified model is developed for the seismic analysis of an actual super-tall mega-braced frame-core tube building. In addition, this simplified model is used to perform the comparison of two preliminary design schemes for this building in terms of its resilient performance. The studies indicate that this simplified model is also capable of efficiently and reliably predicting the key seismic characteristics of this building, thereby laying a foundation for the further comparison of different design schemes. Subsequently, the energy dissipation characteristics of these two structural schemes are investigated and discussed through nonlinear time-history analyses using the simplified models. The plastic energy dissipation contribution of each component as well as the total plastic energy distribution along the height of the building are compared for both schemes, thereby conclusively providing a reference for the selection of a better option among the various considered schemes. The analytical results indicate that the fully braced scheme induces a more uniform plastic energy dissipation distribution than the half-braced scheme. Furthermore, the fully braced scheme effectively enables the energy dissipation to be located in the readily replaceable components (e.g., coupling beams and perimetric trusses) instead of the key components that are difficult to repair (e.g., mega columns, core tubes and mega braces). As a result, the fully braced scheme provides a better seismic resilient performance than the half-braced scheme. The outcome of this study serves as a guideline for a method to reliably and efficiently understand the seismic performance of different preliminary design schemes of super-tall buildings, which can provide guidance and serve as a reference for the performance-based and resilience-based earthquake design of super-tall buildings.

2. Introduction of two design schemes and the associated refined FE models

The project studied in this research is a multi-functional super-tall office building with a total height of approximately 540 m. The building adopts a hybrid lateral-force resisting system named as "mega-braced frame-core tube" [26]. Two design schemes are proposed at the preliminary design stage, which are referred to as the "fully braced scheme" and "half-braced scheme". The fully braced scheme involves the use of mega columns, mega braces within the full height of the structure (i.e., Zones 1–8), perimetric trusses, concrete core tubes and secondary frames, as shown in Fig. 1. In contrast, the half-braced scheme involves the use of mega columns, mega braces in the lower four zones of the structure (i.e., Zones 1–4), outer frame tubes in the higher four zones (i.e., Zones 5–8), perimetric trusses, outriggers, concrete core tubes and secondary frames, as shown in Fig. 2. Further details of the half-braced scheme are presented in Lu et al. [26]. The differences between these two schemes are listed in Table 1.

This super-tall building is located in Beijing, a relatively high seismic region in China [36] (with a maximum spectrum acceleration of 0.9g for the Maximum Considered Earthquake (MCE) level, where g is the acceleration of gravity); both the wind and seismic loads play important roles in the structural design. An elastic analysis of the building indicates that the maximum drift ratios when

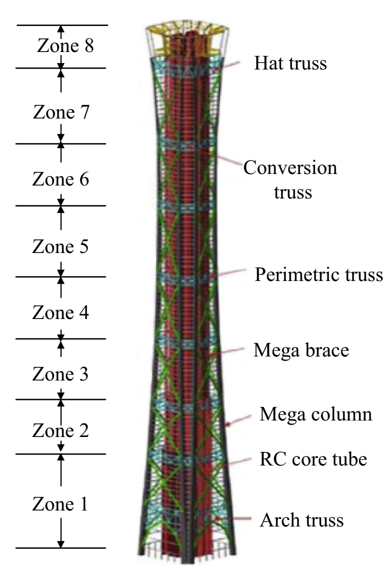

Fig. 1. Fully braced scheme.