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Design Optimization of a 500 m Super-Tall Building through Earthquake-Induced Collapse Analysis

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Abstract

In recent years, a combination of rapid construction of super-tall buildings and frequent occurrence of strong earthquakes worldwide demands a rational seismic design method for structures of this kind. Although earthquake-induced collapse analysis is one of the most efficient methods to quantify the collapse resistance of buildings, little research has been reported on using the collapse analysis to evaluate the seismic safety of super-tall buildings during the design stage. To optimize the design taking into account earthquake-induced collapses, a real world super-tall building with a height of greater than 500 m is investigated in this work. Throughout its design procedure, earthquake-induced collapse analyses are performed to optimize the design at three different levels (the structural system level, design parameter level and component level). At the structural system level, the influence of different lateral force resisting systems on the collapse resistance is discussed; at the design parameter level, the influence of minimum base shear force is discussed; and at the component level, the influence of high-performance shear wall on the collapse resistance is studied. Based on these discussions, the optimal design scheme of the building is established to improve the seismic safety while maintaining the cost of construction. Given more and more super-tall buildings will be constructed with new structural system and components, this work will provide important references for the seismic design of super-tall buildings and the corresponding collapse resistance research in the future.

Keywords: Super-tall building, design optimization, earthquake-induced collapse, structural system, minimum base shear force, brace-embedded shear wall

1. Introduction

Tall buildings are important symbols of construction technology and economic development of a nation. The Council on Tall Buildings and Urban Habitat (CTBUH) [1] defines “super-tall” as a building over 300 m in height. Statistics show that super-tall building construction has entered a period of vigorous development.

As a new form of architecture, very few super-tall buildings have experienced very strong earthquakes. Meanwhile, for super-tall buildings with heights over several hundred meters, studying the seismic collapse resistance by means of shaking table tests is both difficult and impractical. As a consequence, the numerical methods especially the earthquake-induced collapse analysis has become one of the best choices to directly determine the relationship between the design parameters and structural seismic safety. Nevertheless the existing work using collapse analysis mainly focuses on the collapse resistances of ordinary structural systems [2, 3, 4, 5]. Little research has been reported on using collapse analysis to ensure the seismic safety of super-tall buildings during the design stage.

Based on the above background information, a real world super-tall building with a height of greater than 500 m is investigated in this work. Throughout its design procedure, the earthquake-induced collapse analyses are performed to optimize the design at different levels: the structural system level, design parameter level and component level. Specifically, at the structural system level, the influence of different lateral force resisting systems on the collapse resistance is discussed; at the design parameter level, the influence of minimum base shear force is discussed; and at the component level, the influence of high-performance shear wall on the collapse resistance is studied. Based on these discussions, the optimal design scheme of the studied building is established to improve the safety while maintaining the cost of construction. Note that although the collapse analysis has been performed in the seismic design of ordinary buildings, a systematic collapse analysis to guide the seismic design of super-tall buildings is very rare. As a result, this work will provide important references for the seismic design of similar super-tall buildings and the corresponding collapse resistance research in the future.

2. Building Information and Numerical Models

2.1 Building information

The building concerned is a super-tall structure located in Beijing and its architectural drawing is shown in Fig.1, featuring the shape of a Chinese traditional wine cup. It will become the tallest multifunctional building with a total height of 528 m located in the high seismic region in China as well as in the world. The high seismic region is referred to as “8 degree seismic design zone” by the Code for Seismic Design of Buildings (CMC, 2010a) of China. The maximum spectral acceleration at the Maximum Considered Earthquake (MCE) level is about 0.9g (g is the acceleration of gravity) and the building site is classified as Class II (i.e., an equivalent shear-wave velocity of 360 m/s for 30 m soil (VS30)).

2.2 Numerical model of the super-tall building

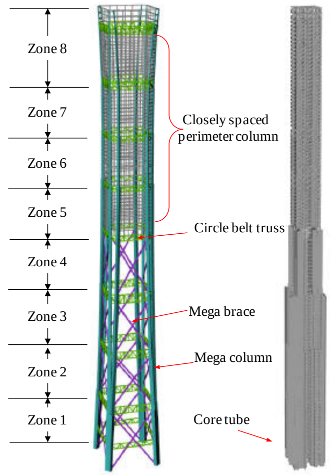
Based on the modeling approach for super-tall buildings proposed by Lu et al. [6, 7], the finite element (FE) models of this building with different design schemes are established. Details of these FE models are as follows.

The fiber-beam element is adopted to simulate the CFST mega columns [6], the secondary frames, circle belt trusses, outriggers and mega braces of the building. The constitutive models proposed by Han et al. [8] and Lu et al. [7] are used for the confined concrete and the steel, respectively. The shear walls and coupling beams in the core tube are simulated by the multi-layered shell elements [7, 9, 10].

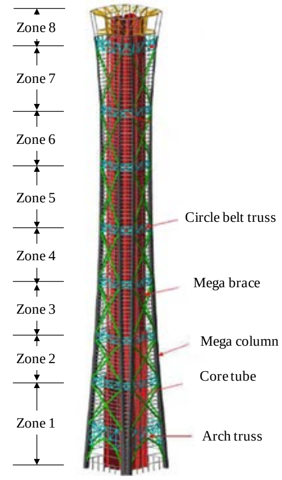
2.3 Collapse analysis methods

Based on the FE method, the authors have proposed the elemental deactivation technique in their previous studies [7] on earthquake-induced collapse simulation. The material-related failure criterion (i.e. material strain) is adopted to monitor the failure of structural elements. Specifically, the strains of the elemental integration points of the whole building are monitored. If the strain at any integration point in a fiber or layer (either concrete or steel) exceeds the material failure criterion, the stress and the stiffness of this specific fiber/layer are considered to be deactivated, which means that the fiber/layer can no longer contribute to the stiffness computation of the whole structure. If all fibers/layers of an element are deactivated, the element is considered fully deactivated from the model. The proposed method has been successfully applied in the earthquake-induced collapse simulations for two super-tall buildings that are higher than 500 m [6]. Therefore, the collapse simulation method proposed by Lu et al. [6, 7] is adopted herein to investigate the earthquake-induced collapse of the super-tall building concerned.

Fig. 1 - Architectural drawing of the super-tall building



(a) Half-braced scheme



(b) Fully-braced scheme

Fig. 2 – The sketch of the two design schemes

3. Optimal Design of Structural System

3.1 Two options for the structural system

The mega structural systems have become the best choice for the lateral force resisting systems of modern super-tall buildings according to the statistics of CTBUH [11]. Consequently, the super-tall building studied herein also adopts such a mega structural system. Two design schemes with different lateral force resisting systems are briefly described as follows. The first scheme is referred to as the "half-braced scheme", which is shown in Fig.2(a). The other design scheme is referred to as the "fully-braced scheme", which is shown in Fig.2(b).

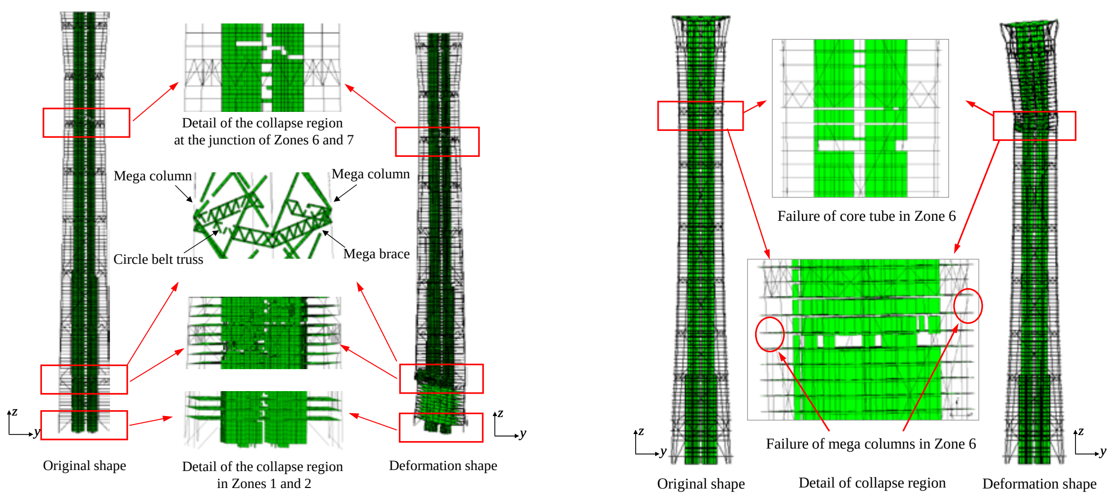
3.2 Material consumption

The fundamental vibration periods of the half-braced and fully-braced design schemes are 7.44 s and 7.38 s, respectively. This implies that the lateral stiffness of the fully-braced scheme is larger than that of the half-braced scheme. The material consumption of these two schemes is compared in Table 1. The comparison shows that the total material consumption (concrete and steel) of the fully-braced scheme is 11.19% less than that of the half-braced scheme. This is mainly because the mega columns and shear walls in the fully-braced scheme have smaller cross sections, which results in a reduction of 13.44% in concrete consumption. The steel consumption of the two design schemes, on the other hand, is very similar. Specifically, the steel consumption of the mega columns in the fully-braced scheme is 17.68% less than that of the half-braced scheme; while the steel consumption of the mega braces increases 13.04% comparing to the half-braced scheme. Consequently, the total steel consumption of the fully-braced scheme is only 3.16% larger than that of the half-braced scheme. Overall, although the mega braces in the fully-braced scheme result in a larger steel consumption, due to more uniform lateral stiffness in the fully-braced scheme, the cross sections of other components have been reduced and in turn resulted in a similar amount of the total steel consumption of these two design schemes. In addition, the total mass of the fully-braced scheme is smaller than that of the half-braced scheme.

Table 1 – Comparison of the total material consumption of the two design schemes

	Half-braced scheme	Fully-braced scheme	Relative deviation
Total mass (ton)	753 720	669 382	-11.19%
Concrete consumption (ton)	652 938	565 211	-13.44%
Steel consumption in mega columns (ton)	29 074	23 934	-17.68%

Steel consumption in all steel components (ton)	65 408	73 936	13.04%
Steel consumption in slab (ton)	6 300	6 093	-3.29%
Total steel consumption (ton)	100 783	103 963	3.16%



(a) Half-braced scheme (b) Fully-braced scheme

Fig. 3 – Typical collapse modes of the two design schemes subjected to extreme earthquakes

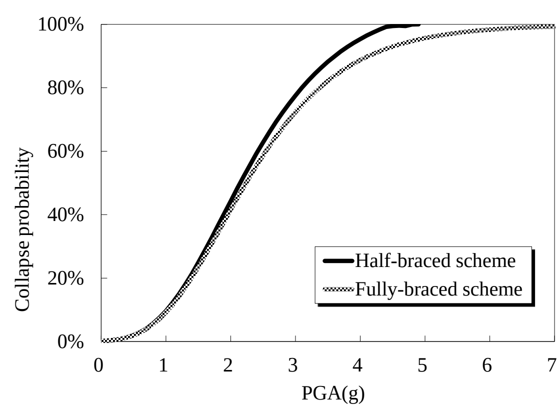


Fig. 4 – The collapse fragility curves for the two design schemes

3.3 Collapse analysis

The widely used 22 far-field ground motion records suggested by FEMA P695 [2] and the El-Centro EW 1940 ground motion are adopted as the basic seismic input.

The earthquake-induced collapses of these two design schemes subjected to extreme earthquakes are conducted using the proposed method presented in Section 2.3. The collapse modes of the two schemes subjected to the ground motion of El-Centro EW 1940 are compared in Fig.3. The collapse fragility curves for these two schemes are compared in Fig.4. For both design schemes, the PGA corresponding to the MCE level is 0.4 g as specified in the design code, and the PGAs inducing a 50% of the building collapse are 2.35 g and 2.70 g, respectively, for the half- and fully-braced schemes. Consequently, the *CMR*s (collapse margin ratio) of the two schemes are 5.88 and 6.75, respectively. Note that the fully-braced scheme exhibits a higher collapse resistance, having a *CMR* 14.8% higher than that of the half-braced scheme. Furthermore, the total material consumption of the fully-braced scheme is 11.2% lower than that of the half-braced scheme. As a result, the fully-braced scheme is suggested as the lateral force resisting system for the super-tall building studied herein.

4. Optimal Design of Key Design Parameters

4.1 Adjustment method for base shear force

Base shear force is one of the most important design parameters in seismic design. To ensure the structural seismic safety, a lower bound (minimum) of the base shear force ($V_{\min}$) has been specified in different international building codes [12]. An alternative and better strategy is necessary to be proposed to rationally adjust the base shear force of super-tall buildings to meet the minimum base shear force requirement. Three methods in adjusting the base shear force are listed in Table 2, represented by three models (Models A, B and C). The typical components of Models A, B and C are given in Table 3. The material consumptions of the lateral force resisting system in these three models are compared in Table 4. The comparison clearly shows that the material consumption of the mega columns in Model A is much larger than that of the other models. Meanwhile, the total material consumption of Model B is slightly larger than that of Model C.

Table 2 – Three adjustment methods for base shear force

Models	Adjustment method
Model A	Altering the structural layout and increasing the component dimensions until $V_{\mathrm{t}} \geq V_{\min}$
Model B	Using the scaled shear force $V_{\mathrm{t},i} \cdot V_{\min}/V_{\mathrm{t}}$ to perform the story drift displacement evaluation and component design
Model C	Using the calculated shear force $V_{\mathrm{t},i}$ for story drift displacement evaluation; and using scaled shear force $V_{\mathrm{t},i} \cdot V_{\min}/V_{\mathrm{t}}$ to conduct the component design

Table 3 – The typical component parameters of Models A, B and C

		Model A	Model B	Model C
The mega columns at the bottom	Size (m)	6.5 × 6.5	5.2 × 5.2	4.8 × 4.8
	Concrete strength (MPa)	44.5	44.5	44.5
	Steel ratio (%)	10	5.9	5.9
The shear wall at the bottom	Wall thickness (m)	1.5	1.2	1.2
	Concrete strength (MPa)	38.5	38.5	38.5
Mega braces	Size (m)	3.4 × 1.7 × 0.015 × 0.01	1.8 × 0.9 × 0.01 × 0.01	1.8 × 0.9 × 0.01 × 0.01
	Steel strength (MPa)	350	350	350

(*Note: The section of the H-shaped steel is described as the width × height × web thickness × flange thickness.)

Table 4 – The material consumptions and fundamental vibration periods of Models A, B and C

Material consumption		Model A	Model B	Model C
Mega column	concrete consumption (m^3)	65 408	35 077	31 761
	steel consumption (ton)	47 070	16 482	14 017
Core tube	concrete consumption (m^3)	59 524	51 064	51 101
	steel consumption (ton)	33 376	15 423	15 132
Mega brace	steel consumption (ton)	4 532	1 236	1 236
Circle belt truss	steel consumption (ton)	3 072	995	995

Total concrete consumption (m^3)	124 932	86 141	82 862
Total steel consumption (ton)	88 050	34 136	31 380
Fundamental vibration period (s)	5.957	7.589	7.669

4.2 Collapse analysis

To study the rationality of the three adjustment methods for base shear force (Table 2), the earthquake-induced collapse analysis is performed to determine the collapse resistance of the above three models.

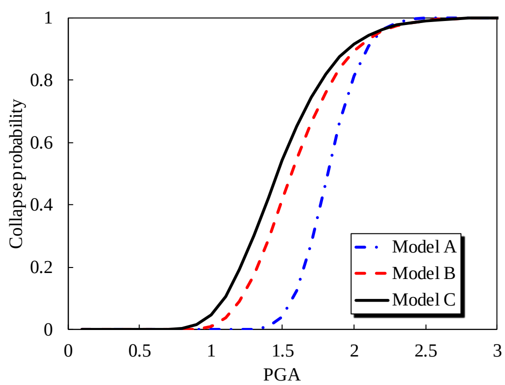


Fig. 5 – The fitted collapse fragility curves of the three models

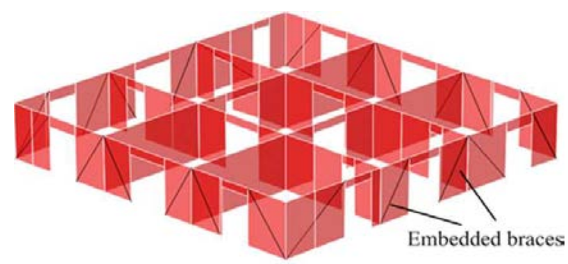


Fig. 6 – Typical layout of the brace-embedded shear walls

With progressing of the design, seven site-specified ground motion records suitable for this super-tall building are provided by the Beijing Earthquake Bureau according to the building site condition. Among these ground motions, there are five natural ground motion records and two artificial ground motion records. The fitted collapse fragility curves of the three models using the seven site-specified ground motion records are shown in Fig.5. The *CMR*s of Models A, B and C are 4.53, 3.91 and 3.66, respectively. The material consumption of Model A is much larger than Model B and Model C. However, the safety margin of three models is at the same level. Therefore, taking into consideration both the structural safety and construction cost, the committee believes that Model B is deemed to represent the best base shear force adjustment method for this super-tall building. In the subsequent design and analysis, Model B is selected to be further optimized.

5. Optimal Design of Structural Components

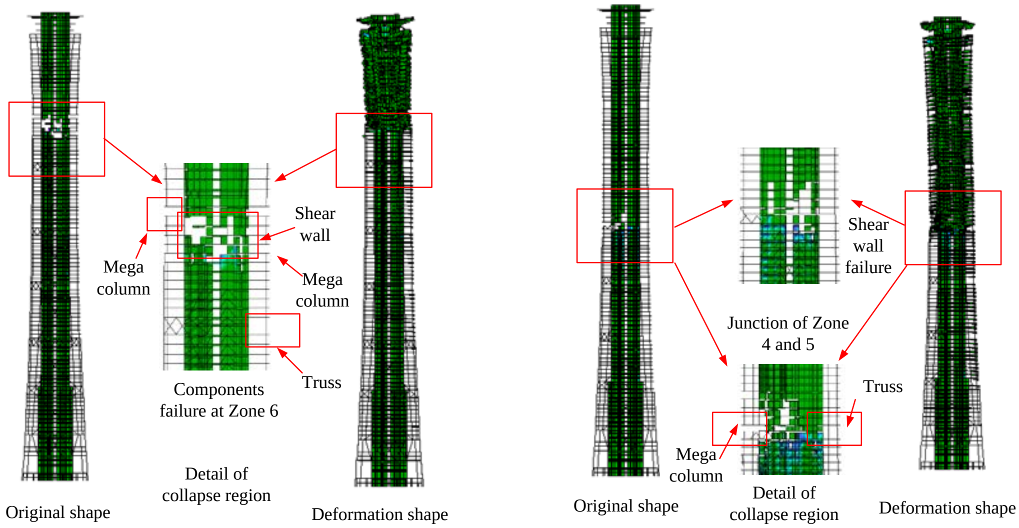
5.1 Layout of the embedded braces

Previous analysis indicates that Zone 6 has the largest possibility to become the initial collapse region in Model B. Therefore, the high-performance brace-embedded shear walls [13, 14] can be used between 78th and 95th stories in Zone 6 to increase the collapse resistance. Two models with different shear wall arrangements are designed. For Model B1, traditional RC shear walls are used between 78th and 95th stories; for Model B2, brace-embedded shear walls are adopted. Note that in order to make full utilization of the bracing capacity, the V-shaped embedded braces are uniformly distributed in the external shear walls, as shown in Fig.6.

5.2 Comparisons of different wall arrangements

The fundamental vibration periods of these two models are 7.513 s and 7.458 s, respectively, which are very similar. This implies that the embedded braces in 78th-95th stories have little influence on the lateral stiffness of the structure and in turn the demand of the seismic force remains the same.

The same seven ground motion records are also used for the collapse analysis, through which the typical collapse modes of Models B1 and B2 are compared in Fig.7. It can be concluded that after enhancing the shear walls by embedded braces, Zone 6 is no longer the typical weak region in this building and the global collapse resistance, i.e., *CMR*, of Model B2 has been increased by 12.7% comparing to Model B1. Note that the increased amount of steel due to the embedded braces is less than 0.1% of total steel consumption, which means that such an enhancement method is very cost-effective. In the final design, brace-embedded shear walls are indeed used in 78th-95th stories in the super-tall building concerned.



(a) Model B1 (b) Model B2

Fig. 7 – Typical collapse modes of Models B1 and B2 subjected to extreme earthquake

6. Conclusions

In this study, an actual super-tall building with a height larger than 500 m is investigated. With the earthquake-induced collapse analysis, the optimal seismic designs of this super-tall building are conducted at the structural system level, the design parameter level and the component level. The following comments are concluded:

(1) The optimal design of the structural system indicates that the fully-braced scheme results in lower cost and higher level of safety.

(2) The adjustment method of scaling the calculated base shear force to the minimum value for component design and story drift displacement evaluation will find a balance between the seismic collapse resistance and the overall construction cost.

(3) The optimal design of structural components indicates that enhancing the shear walls in 78th-95th stories by embedded braces has a significant effect on increasing the seismic collapse resistance of the super-tall building.

Conclusively, the earthquake-induced collapse analysis can quantitatively study the influence of different design factors on the safety of the building. Given more and more super-tall buildings to be constructed with new types of structural systems and components, the collapse analysis presented in this study will provide important references for both seismic design of similar super-tall buildings and future collapse resistance research.

7. Acknowledgements

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8. Copyrights

9. References

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