The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

A Preliminary Comparison of the Seismic Design of Tall RC Frame-Core Tube Structures between China and the United States

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Abstract

To evaluate the main differences in the structural seismic design codes of China and the United States from a structural system viewpoint, a preliminary comparative evaluation is conducted for a typical tall reinforced concrete (RC) frame-core tube building, which is a widely used structure form in both China and the U.S. Firstly, the building, for which the original design information was provided by the Pacific Earthquake Engineering Research Center (PEER), is redesigned according to Chinese seismic design codes. Next, the design load, component dimensions, dynamic characteristics, and consumption of construction materials of these two buildings are compared in detail. The results indicate that the seismic design forces, the lateral stiffness, and the material consumption of the building designed according to the Chinese seismic code are much larger than those of the building designed according to the U.S. code. These outcomes may provide useful information for further optimizing the design of tall buildings in China.

1. INTRODUCTION

Tall buildings rapidly become popular in China over the past several decades; however, China is also an earthquake-prone country located at the intersection of the Pacific and Eurasian seismic belts. Thus, the seismic safety of China's tall buildings has become increasingly significant. Although considerable progress has been made in the latest *Code for Seismic Design of Buildings* GB50011-2010 (MCPRC, 2010a) and *Technical Specification for Concrete Structures of Tall Building* JGJ3-2010 (MCPRC, 2010b), which are major seismic design codes in China, after several revisions, none of the tall buildings in China has experienced a truly strong earthquake. The lack of exposure to strong earthquakes limits the information available to improve the design

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philosophies of tall buildings in China. Therefore, it is necessary for Chinese engineers to study countries with advanced seismic design philosophies for tall buildings.

The United States (U.S.) and Japan have developed comprehensive seismic design philosophies. The tall buildings in both countries have shown good seismic performance under earthquakes. Many detailed comparisons of the seismic design codes of the U.S., Japan, and China have been performed by various researchers. However, the seismic safety of the structures in each country is ensured by the entire system of structural design specifications; therefore, a simple comparison of a single provision or coefficient may not be sufficient to fully reflect the design philosophies and the safety margin of different design code systems. Hence, a good research methodology would involve selecting a building with a specified seismic design objective, designing it based on the design specifications of different countries, and then comparing the performances of these buildings. Because such a comparative study involves a large workload and is difficult to implement, few studies using this methodology have been reported.

Therefore, based on a typical tall reinforced concrete (RC) frame-core tube building, which is a widely used structure form in both China and the U.S., a preliminary comparative evaluation is conducted to identify the differences between the seismic design practices in the U.S. and China from a structural system viewpoint. First, the building is redesigned according to the Chines seismic design codes based on the original building information provided by the Pacific Earthquake Engineering Research Center (PEER). Next, the design load, component dimensions, dynamic characteristics, and consumption of construction materials of the two buildings designed according to the Chinese and U.S. codes are compared in detail, providing useful information to enable further improvement of the design philosophies for tall buildings in China.

2. BACKGROUND OF THE STUDY CASE

To evaluate and improve the performance-based seismic design of tall buildings, PEER launched the *Tall Buildings Initiative* (TBI) research program in 2006 and then released a series of research reports (http://peer.berkeley.edu/tbi/publications-reports/). As part of the TBI program, a case study project of tall buildings was conducted in Task 12 of the program, and the final report, *Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Mean*s (Moehle et al., 2011), was released. One of the case study buildings in this report, Building 2, is an RC frame-core tube structure and the detailed design information of this building is given, providing a representative benchmark for our comparative study of the seismic design of tall buildings in China and the U.S.

Building 2 is a 42-story residential building including a 6.1-m tall penthouse and four stories below ground, located in Los Angeles. This building is a RC frame-core tube structure with a total height of 141.8 m above ground. Fig. 1 shows the three-dimensional view and typical floor plan of the prototype Building 2 presented in the case study report (Moehle et al., 2011). In this report, the prototype Building 2 was designed according to three design codes in the U.S., and the three different designs are designated as Building 2A, Building 2B, and Building 2C. Building 2A was designed according to the *International Building Code* (ICC, 2006), which requires the use of ASCE 7-05 (ASCE, 2005) and ACI 318-08 (ACI, 2008). As the *IBC 2006* (ICC, 2006) is one of the most widely used seismic design codes, the following discussion will focus on Building 2A.

Based on the design information for Building 2A, this building was redesigned according to Chinese building design codes, mainly including GB50011-2010 (MCPRC, 2010a), JGJ3-2010 (MCPRC, 2010b), and the *Code for Design of Concrete Structures* GB50010-2010 (MCPRC, 2010c). PKPM design software was employed, which is developed by the China Academy of Building Research (CABR). In the following discussion, the building designed according to the Chinese codes is referred to as Building 2N, whose three-dimensional view and typical floor plan are shown in Fig. 2. In the design of Building 2N, the overall dimensions of the structure, the position and dimensions of the core tube, the column grid array, and the story height were kept the same as those of Building 2A. In addition, the effect of the basement was not taken into account, which means that the structure was fixed at the ground level.

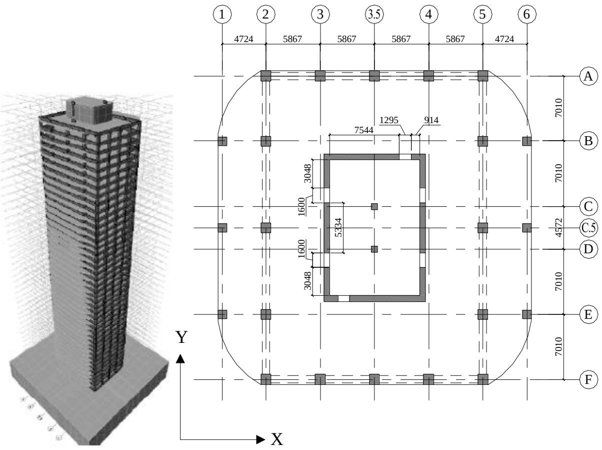

Fig. 1 Three-dimensional view and typical floor plan of Building 2A (mm)

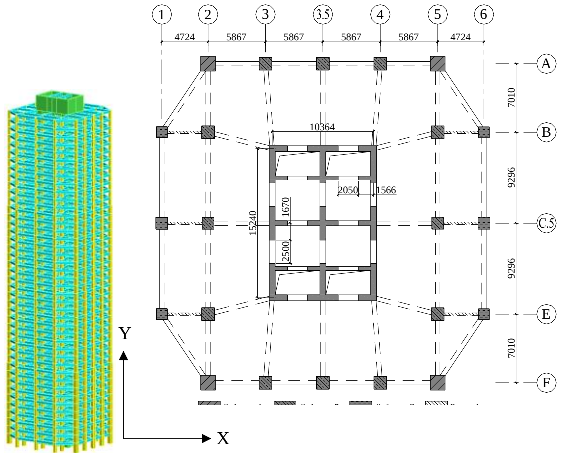

Fig. 2 Three-dimensional view and typical floor plan of Building 2N (mm)

3. VERTICAL DESIGN LOAD

To maintain the consistency of the design conditions for the two buildings mentioned above, except the self-weight of the structure, the two buildings have the same superimposed dead loads and live loads. The load combinations of Building 2N follow the provisions of 5.6.1 and 5.6.3 in JGJ3-2010 (MCPRC, 2010b). The load combinations of Building 2A follow the strength design load combinations listed in ASCE 7-05 (ASCE, 2005). The effects of the two combinations seem approximately equal overall.

4. SEISMIC DESIGN LOAD

This study focuses on the difference in seismic performance between the two structures designed according to Chinese and U.S. codes. Building 2A is located on an NEHRP site class C, with an equivalent shear-wave velocity of 30 m soil (V_{S30}), equal to 360 m/s. The characteristic period of the site is 0.455 s. This site condition is approximately equal to Site-class II and the 3rd Group in GB50011-2010 (MCPRC, 2010a).

There are some differences between the calculation methods for earthquake load in the Chinese and U.S. codes. IBC 2006 (ICC, 2006) adopts maximum considered earthquake (MCE, 2% probability of exceedance in 50 years) ground motion maps to define the earthquake intensity in different regions in the conterminous United States. However, the Seismic Ground Motion Parameter Zonation Map of China (SBQTSPRC, 2001) is defined using the fortification level earthquake, with an exceedance probability of 10% in 50 years. The action of a serviceable level earthquake (i.e., 63% probability of exceedance in 50 years), whose intensity is approximately one-third of the corresponding fortification level earthquake, is used to calculate the design lateral force. Therefore, a key problem in this study is the determination of the intensity of earthquake action for the seismic design of Building 2N to ensure identical seismic hazards between Buildings 2N and 2A.

To solve this problem, a proper fortification level earthquake should be chosen for Building 2N to achieve an equivalent probability of exceedance to Building 2A. As the exceedance probability of MCE defined in the U.S. design code is approximately equivalent to that of a severe earthquake (i.e., 2%~3% probability of exceedance in 50 years) as defined in the Chinese design code, the corresponding seismic design load for Building 2N can be determined via a comparison between the response spectrum for the MCE hazard level of Building 2A and the response spectrum for a severe earthquake prescribed in Chinese code. The seismic design of Building 2A is mainly based on the site-specific response spectrum for the MCE hazard level, which is denoted as site-specific MCE spectrum provided by the seismic hazard analysis for the Los Angeles site. The response spectrum for severe earthquakes in an 8.5 degree seismic intensity zone and 9 degree seismic intensity zone in China are plotted in Fig. 3 in contrast to the site-specific MCE spectrum. It should be noted that the corresponding peak ground acceleration (PGA) value of the fortification level earthquake (i.e., 10% probability of exceedance in 50 years) is 300 cm/s^2 in the 8.5 degree seismic intensity zone and 400 cm/s^2 in the 9 degree seismic intensity zone.

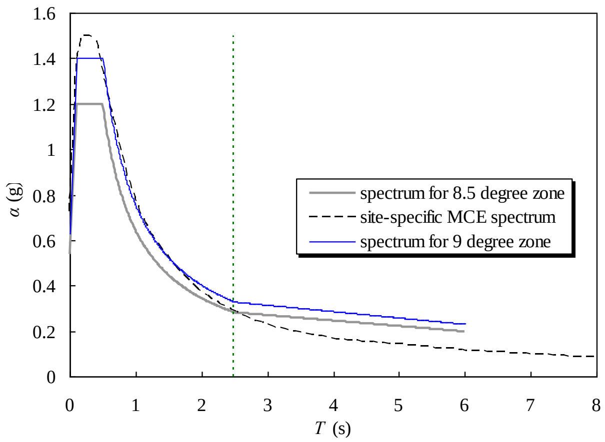

Fig. 3 Comparison between the site-specific MCE spectrum and the two Chinese response spectra.

Fig. 3 shows an approximate match between the site-specific MCE spectrum and the two Chinese response spectra. It is obvious that the response spectrum for the 9 degree seismic intensity zone better matches the site-specific MCE spectrum for short periods;

the response spectrum for 8.5 degree seismic intensity zone better matches the site-specific MCE spectrum for moderate periods (approximately 2.5 s); and the values of the two Chinese response spectra are both greater than the value of the site-specific MCE spectrum for long periods (beyond 2.5 s). Therefore, the 8.5 degree seismic intensity specified in the Chinese seismic code is selected as the design intensity for Building 2N and is used for the seismic design of Building 2N for the following reasons.

(1) As specified in the Chinese code JGJ3-2010 (MCPRC, 2010b), the height limit for RC frame-core tube structures, such as Building 2N, is notably strict in zones of 9 degree seismic intensity (no more than 60 m). Therefore, a 9 degree seismic intensity is not suitable for the design intensity of Building 2N.

(2) According to the empirical formula of the fundamental period for RC frame-core tube structures in China, the estimated fundamental period of Building 2N is approximately 2.52 to 5.04 s. Fig. 3 shows that the response spectrum for a severe earthquake in the 8.5 degree seismic intensity zone is closer to the site-specific MCE spectrum in this period range.

5. COMPARISON OF THE MATERIALS AND DIMENSIONS OF MAIN COMPONENTS

The layouts of Building 2A, designed according to U.S. code, and Building 2N, designed according to Chinese code, are shown in Fig. 1 and Fig. 2, respectively. The materials and dimensions of the main components between the two buildings are compared in Table 1. It is evident that Building 2N has larger columns and more internal walls in the core tube than Building 2A. This difference is mainly due to the stricter inter-story drift limit in Chinese code, which requires higher structure stiffness.

Table 1 Comparison of the materials and dimensions of the main components

		Building 2A	Building 2N
Beams	material	f_c'=5 ksi (~34.5 MPa)	C40
	dimension (mm)	762×914	250×500, 450×900
Columns	material	f_c'=5, 6, 8, 10 ksi (~34.5, 41.4, 55.2, 69.0 MPa)	C60, C50, C40
	dimension (mm)	1170×1170 - 915×915	1500×1500 - 800×800
Shear walls	material	f_c'=5, 6 ksi (~34.5, 41.4 MPa)	C60, C50, C40
	dimension (mm)	610, 460	600-400

Note: The standard compressive strengths for
C40, C50, and C60 concrete prisms are 26.8 MPa, 32.4 MPa, and 38.5 MPa, respectively.

6. COMPARISON OF THE DESIGN RESULTS

6.1 Total weight and free vibration periods of the buildings

The seismic weight and free vibration periods between the two buildings are compared in Table 2. It is evident that the stiffness of Building 2N is much larger than that of Building 2A. As the stiffness requirement is stricter in Chinese code, more lateral-force-resisting components are needed, resulting in the total weight of Building 2N being greater than that of Building 2A.

Table 2 Comparison of the seismic weight and free vibration periods

		Building 2N	Building 2A	
Seismic weight (ton)		57,306.0	46,267.2	
Period (s)	1	2.565	4.456	Translation mode in the X direction
	2	2.383	4.026	Translation mode in the Y direction
	3	1.992	2.478	Torsion mode

6.2 Comparison of the design lateral force and inter-story drift ratio

The design lateral forces of the two buildings are shown in Fig. 4 and Fig. 5. The maximum design shear force of Building 2N is 1.47 times that of Building 2A. Note that these design shear forces are the standard values for component design, which will contribute to the higher material consumption of Building 2N (see Section 6.3 for a detailed discussion).

The design inter-story drift ratio in two directions of the two buildings and the corresponding inter-story drift ratio limitations are shown in Fig. 6 and Fig. 7, respectively. The maximum story drift ratio of Building 2N under the serviceability level earthquake is approximately 1/809, just satisfying the acceptance limit of 1/800 for the elastic inter-story drift ratio specified in the Chinese code. In contrast, the maximum story drift ratio of Building 2A at the design level is approximately 1/152, which is much smaller than the acceptance limit of 1/50 for the elasto-plastic inter-story drift ratio specified in ASCE 7-05 (ASCE, 2005). Overall, even considering the differences between the two design methods, the Chinese code for the seismic design of buildings specifies a stricter inter-story drift ratio requirement than ASCE 7-05 (ASCE, 2005).

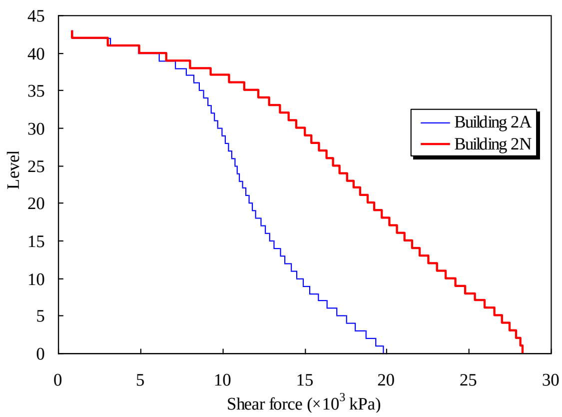

Fig. 4 The design lateral force in the X direction of the two buildings

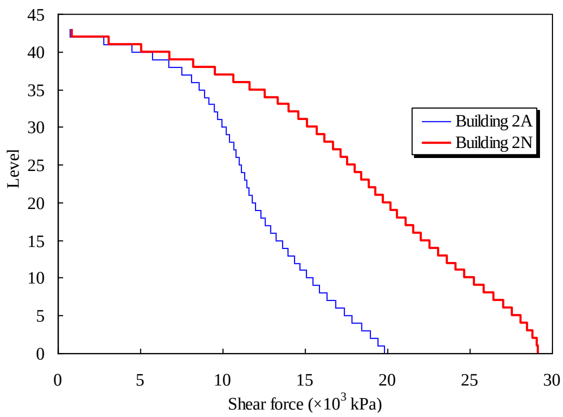

Fig. 5 The design lateral force in the Y direction of the two buildings

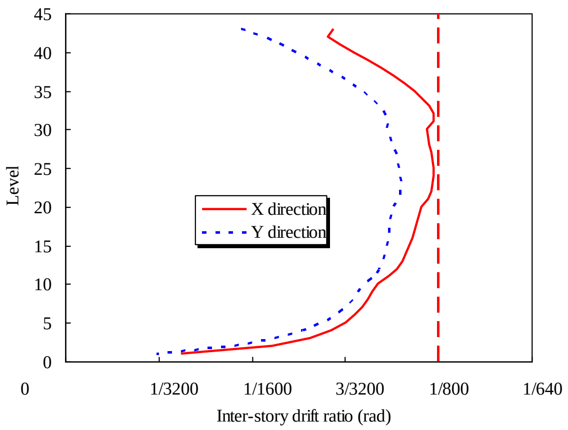

Fig. 6 The design story drift ratio from design lateral forces for Building 2N (at the serviceability level)

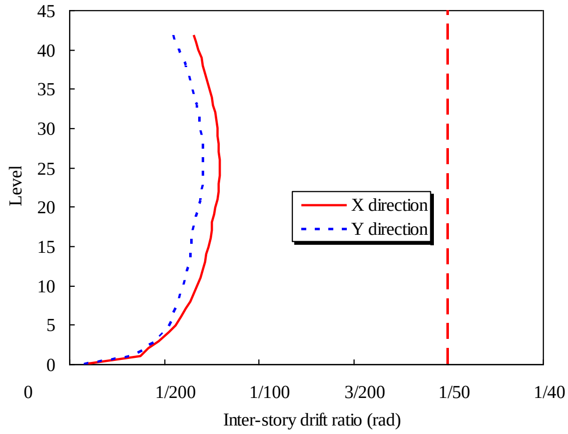

Fig. 7 The design story drift ratio for Building 2A (the story drift ratio of elastic analysis from design lateral forces × C_d)

6.3 Comparison of material consumption

The material consumptions of the two buildings are compared in Table 3. The comparison reveals that the total concrete consumption of Building 2N is roughly the same as that of Building 2A. However, the concrete consumption of the main lateral-force-resisting system including the beams, columns, and shear walls of Building 2N is significantly higher than that of Building 2A. On the other hand, because post-tensioned slabs are adopted in Building 2A, the number of beams is smaller and the slabs are thicker than those of Building 2N. Therefore, the concrete consumption of slabs in Building 2A is higher than that in Building 2N. Similarly, the reinforcing bar consumption of Building 2N is clearly higher than that in Building 2A, and the additional reinforcing bar is mainly distributed in the shear walls. Note that the design shear force of Building 2N is larger than that of Building 2A, which contributes to the higher reinforcement in the shear walls of Building 2N.

Table 3 Comparison of the material consumption of Buildings 2N and 2A

		Core walls	Columns	Beams	Slabs	Sum
Concrete consumption (m^3)	Building 2N	5916.9	3651.2	4247.8	5368.6	19184.5
	Building 2A	4194.6	2587.9	3610.9	9967.3	20360.7
Reinforcing bar consumption (ton)	Building 2N	1657.1	786.0	947.4	643.2	4033.8
	Building 2A	196.6	647.7	708.0	541.2	2093.6

7. CONCLUSIONS AND REMARKS

This study redesigned a typical tall RC frame-core tube building according to the Chinese seismic design code based on the original building information provided by PEER and compared the design results between the two buildings designed according to Chinese and U.S. design codes. The outcomes indicate that the lateral stiffness, the design seismic forces, and the material consumption of the building designed according to the Chinese seismic design code are much larger than those of the building designed according to the U.S. seismic design code. The inter-story drift limit under the serviceable level earthquake (i.e., 63% probability of exceedance in 50 years) in Chinese seismic code is notably strict, being the dominant factor in many cases; therefore, further studies on this issue should be performed to optimize the design of tall buildings in China.

ACKNOWLEDGEMENT

This study is financial supported by the National Nature Science Foundation of China (No. 51222804, 51178249, 51261120377) and the Fok Ying Dong Education Foundation (No. 131071).

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