SEISMIC DESIGN OF A SUPER HIGH-RISE HYBRID STRUCTURE

JIANG Jun[1] YOU Bing[1, 2] HU Ming[2] HAO Jiping[1] LI Yangcheng[1]

[1] *School of civil Engineering, Xi'an University of Architecture & Technology, Xi'an, China*
[2] *LANTO Consulting Architects & Engineers Co.,Ltd ,Shenzhen ,China*
Email: jiangjason@163.com

ABSTRACT :

In China, hybrid structure is frequently used for super high-rise building, and this structural system has an advantage of reducing investment. This paper is concerned with the seismic design of a super high-rise hybrid structure on a background of project by using linear elastic analysis and nonlinear elasto-plastic analysis. The hybrid structure consists of concrete shear walls, steel reinforced concrete (SRC) columns, concrete-filled square steel tubular (CFSST) columns, SRC beams and steel beams. Firstly, comparing steel structure and hybrid structure on seismic behavior and construction cost, we choose the latter system. Then, two structural design programs are utilized for elastic response spectrum analysis combined with elastic time-history analysis, and the results of two programs are quite close. Thirdly, static nonlinear analysis (pushover analysis) and dynamic nonlinear analysis (elasto-plastic time-history analysis) are performed to evaluate the seismic performance of the hybrid structure. Moreover, the important parts, such as strengthened part at bottom and hotel lobby at middle, are analyzed carefully to ensure the key columns are in elastic state under fortifiable earthquake. Conclusion can be drawn that the super high-rise hybrid structure achieves the earthquake performance objective, and the seismic design of the building can satisfy the inspection due to out-of-codes.

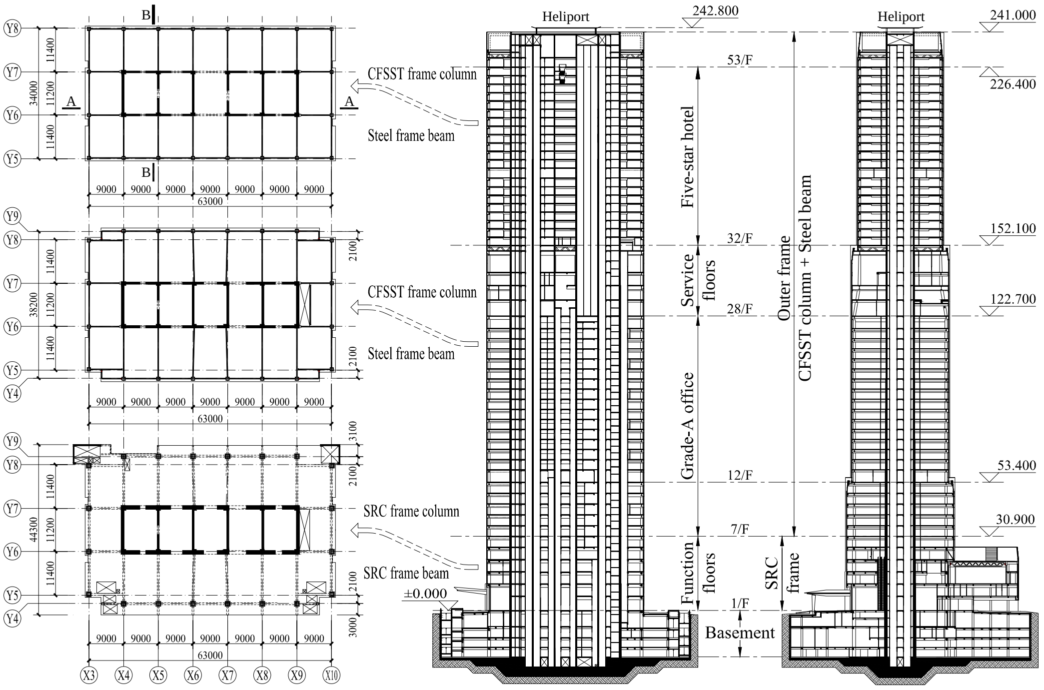
KEYWORDS: hybrid structure, response spectrum analysis, pushover, dynamic analysis

1. INTRODUCTION

In recent years, hybrid structure system has been increased developed and utilized to build super high-rise buildings in China. Comparing with traditional reinforced concrete (RC) system, hybrid structure continues to use RC core walls, and introduces steel beams and columns (or SRC beams, SRC columns, CFSST columns) instead of RC beams and columns. So, hybrid structure has notable advantage in decreasing self-weight, reducing section size of structural members, and accelerating construction progress. Many domestic researchers (Gong et al., 1995; Li et al., 2001; Liang, 2005; Hou et al., 2006; Xia and Wang, 2006; Zou et al., 2006) have done research on it. From their work, conclusions can be drawn that by proper design the hybrid structure has well seismic performance. This paper introduces seismic design of a hybrid structure on a background of project. This project is a super high-rise building functioned as five-star hotel and grade-A office, with the height of 241m, 53 over-ground stories and 4 stories basement.

As we all known, super high-rise building is complex system engineering, which involving beauty, safety, and economy. However, there is another structural form, all-steel structure, which has better structural performance. According to the site condition of the region building located, and considering both performance and engineering cost, we choose the hybrid structure system, composite outer frame-RC core wall. In detail, under the sixth floor, in the range of tower building, SRC frame are utilized. From the seventh floor to the top, the CFSST columns and steel beams form the outer frame. The CFSST columns play an important role in bearing axial compression and fire resistance, as shown in the work by Han (2004). Meanwhile, SRC columns are set at the intersections of longitudinal and transversal core walls, and this method not only enhances the ductility of core walls but also facilities the rigid connections between steel beams and core walls. Fig.1 shows the typical floor plans and typical sections.

2. ELASTIC ANALYSIS



Typical floor plans Section A-A Section B-B

Fig. 1 Typical floor plans and typical sections

2.1. Response spectrum analysis

According to ‘Code for seismic design of building (GB50011-2001)’ and ‘Technical specification for concrete structures of tall building (JGJ3-2002)’, besides the basic strength and stability of structural members, other requirements in elastic state are proposed, for example, the maximum inter-storey drift is less than 1/550, the axial compression ratios of shear walls are not more than 0.5, and that of SRC frame columns do not exceed 0.7.

Then, two structural design programs, PKPM-SATWE and ETABS, are utilized to build three-dimensional structural model and to fulfill the elastic response spectrum analysis. This paper gives some basic analysis results. Table 1 shows the first six order periods; Table 2 indicates maximum top displacement and inter-storey drift; and Table 3 presents the base shear and base over-tuning moment. And the compression ratios of shear walls and SRC columns don’t exceed the limited values.

Table 1 The first six order periods of structure (sec)

No.	1	2	3	4	5	6
SATWE	6.5093(ty)	5.4096(tx)	4.7910(rz)	1.6910(tx)	1.6050(ty)	1.4316(rz)
ETABS	6.5564(ty)	4.9029(tx)	4.7436(rz)	1.6475(ty)	1.5922(tx)	1.4352(rz)

Table 2 Maximum top displacement and inter-storey drift

	Top displacement (mm)		Inter-storey drift	
Direction	X	Y	X	Y
SATWE	173.8	241.9	1/1085	1/798
ETABS	139.3	221.6	1/1244	1/798

Table 3 Base shear and base over-turning moment

	Base shear (kN)		Base over-turning moment (kN • m)	
Direction	X	Y	X	Y
SATWE	25859	25055	3644395	3240375
ETABS	25990	24363	3781019	3257016

All these data indicate that the results of two programs are quite close, except that the X-directional stiffness of structure calculated by two programs has relatively differences. The writers consider that the differences are caused by different wall models of two programs. Generally speaking, this comparison validates the correctness of the analytical model. And for simplicity, the following comparisons are only related to the results of SATWE.

2.2. Elastic time-history analysis

As a supplement of elastic response spectrum analysis, it is necessary for super high-rise building to perform elastic time-history analysis under frequent earthquake. This paper chooses one artificial wave, which is synthesized according to the standard response spectrum, and three natural earthquake records, which are El Centro-EW (1940), WufengNE-NS (1999), and YunlincitySE-NS (1999). And the latter two come from Chi-Chi earthquake of Taiwan in 1999. All these waves are shown in Fig. 2. Corresponding frequent earthquake, the peak ground acceleration (PGA) of the construction site is 35 gal. Hence, scaling the three natural records to be compatible with frequent earthquake is necessary. Fig. 3 shows the acceleration response spectra of the artificial record and scaled natural records for frequent earthquake. And Fig.4 indicates the average acceleration response spectrum of the four input ground motions and the standard acceleration spectrum. These two figures bear out that the average response spectrum of ground motions matches the standard response spectrum in a statistical sense.

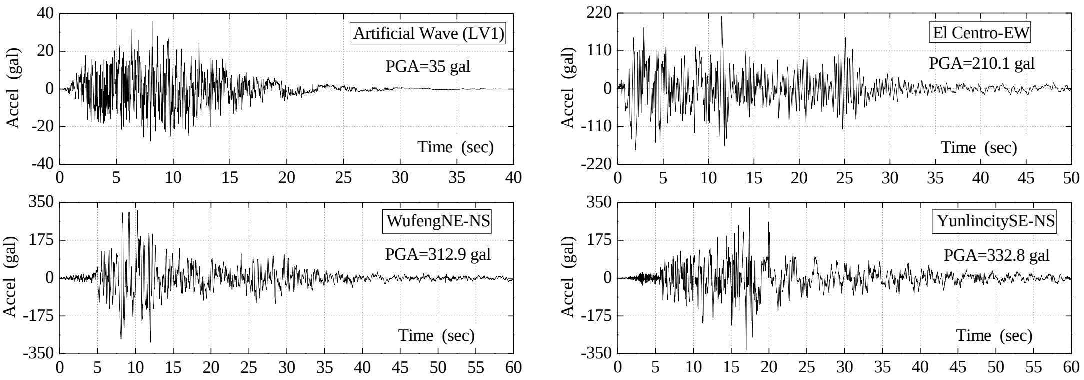


Fig. 2 Input ground motions

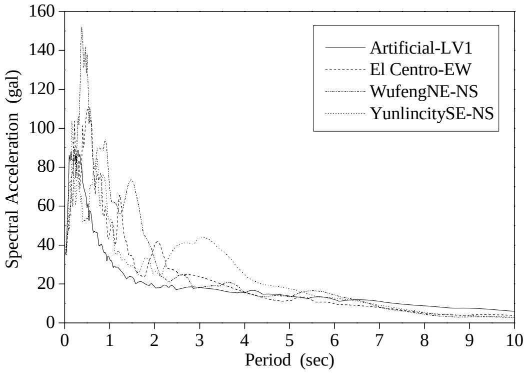


Fig. 3 Acceleration spectra for frequent earthquake (4% damping)

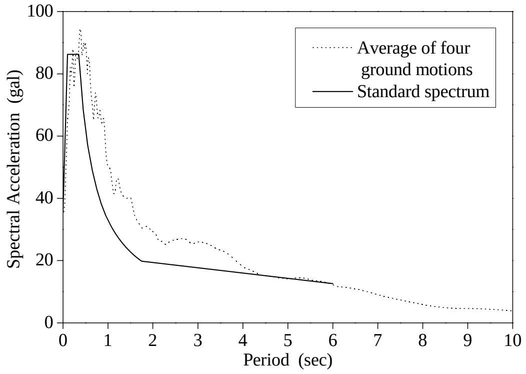


Fig. 4 Average acceleration response spectrum and stand spectrum (4% damping)

Using the results of response spectra design, such as the size of reinforcement members, the three-dimensional structural model is built by CANNY program. Based on some simplification and assumptions, the elastic time-history analysis is performed. Some responses of structure are obtained which are presented in Table 4. Comparing these responses with those of response spectrum analysis, it can be found that they are compatible in average sense. So, we can utilize the envelope responses of time-history analyses and response spectrum analysis to fulfill the elastic seismic design.

Table 4 Responses of elastic dynamic analysis

Input ground motion		Artificial wave	El Centro-EW	WufengNE-NS	YunlincitySE-NS
Base shear (kN)	X	19845	28165	19315	19729
	Y	24932	24620	27801	21782
Base over-turning moment (kN • m)	X	2408350	2120070	2605770	2464880
	Y	2870820	2357630	3325710	2664480
Inter-storey drift	X	1/1069	1/1237	1/1032	1/977
	Y	1/1171	1/1399	1/928	1/909

3. NONLINEAR ANALYSIS

Because this project is an out-of-codes high-rise building, it is necessary to perform nonlinear analyses to evaluate the seismic performance of the hybrid structure under fortifiable and severe earthquake. This paper adopts static and dynamic nonlinear procedure to investigate the structural behavior by using CANNY program, which has been developed for more than twenty years by Dr. Li Kangning.

In the nonlinear analysis course, there are some assumptions and considerations. The fixing point of structure is in the underground first floor (B1F). Using rigid diaphragm assumption, so the DOFs of beam elements and floors are reduced. Core walls are simplified to bidirectional in-plane column elements, working together with the SRC columns in core walls by the assumption of plane-section. Furthermore, elasto-plastic uniaxial springs: rotation springs at element-ends, shear spring located in mid-span, are used to simulate the plastic hinges. Column elements have bending, shear, and axial deformations, also using uniaxial spring model for its computational efficiency. The nonlinear flexural and shear deformations of RC elements, considering concrete cracking, use Takeda restoring force model having trilinear skeleton curve. Steel beams and CFFST columns use trilinear hysteresis model to express flexural deformation. The shear deformation of steel beams use degrading bilinear model. The nonlinear flexural deformations of SRC elements make use of quadri-linear restoring force model. And the nonlinear axial deformations of peripheral core walls under the interaction of axial force and bending moment use asymmetric restoring force models to present axial stiffness degradation.

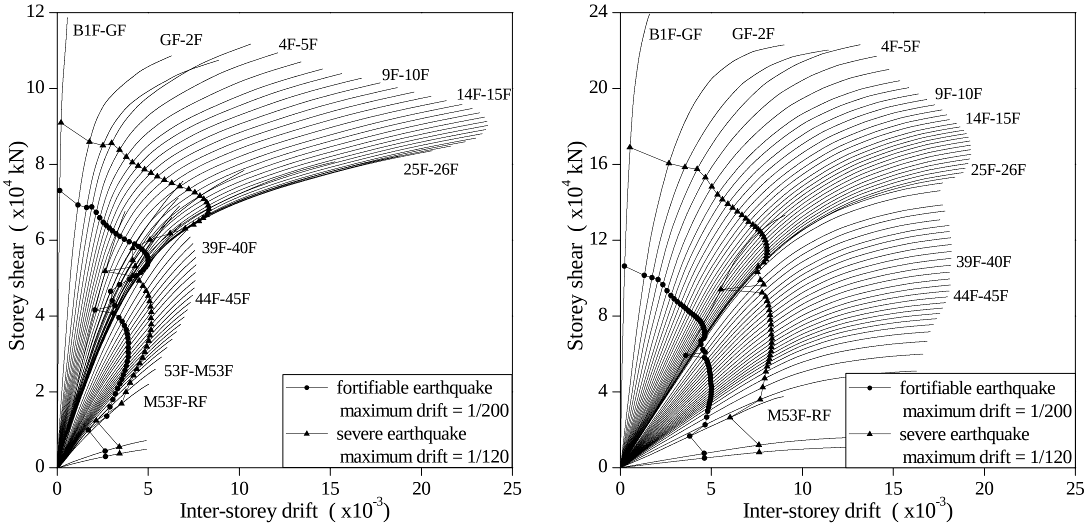
Moreover, seismic performance objective is established. Under fortifiable earthquake, the limbs of core walls do not appear the whole tension, and all the vertical members do not yield. The inter-storey drift values don't exceed 1/200. Under severe earthquake, the limbs of core walls do not present shear failure. The inter-storey drift values don't exceed 1/120.

3.1. Nonlinear static analysis

Nonlinear static analysis, also called pushover analysis, is a simplified methodology to evaluate structural inelastic behavior by applying monotonically increased lateral loads to every floor. The applied lateral load patterns have studied by many researchers (e.g., Mwafy and Elnashai, 2001; Wang and Zhou, 2003; Lü and Zhu, 2005; Kalkan and Kunnath, 2006). This paper applies the lateral load based on seismic storey shear according to the response spectrum analysis. By carrying out pushover analyses respectively along X- and Y-direction, the relationships of inter-storey drifts and storey shears are achieved. Fig. 5 shows the storey performance curves.

From this family curves we can simply estimate that there are no obviously weak stories in the structure. And it is also found that the Y-directional ductility of the whole structure is better than the X-direction, because the X-directional core walls are coupled shear walls while the Y-direction has several pieces of solid shear walls. Hence, the carrying capacities of structure along two directions are different. Then finding the limited values: 1/200, 1/120, corresponding fortifiable and severe earthquake, and its relevant storey shear, which appears firstly, the other stories' inter-storey drifts and storey shears at the certain step can be obtained. Drawing these points at the storey performance curves, the distribution of inter-storey drifts is achieved, from which we can find that the maximum inter-storey drift of X-direction is located in 20F-21F and that of Y-direction is in 42F-43F.

Investigating the detailed damage information of elements, it is found that when the maximum inter-storey drift reaches 1/120 there is no shear failure. And the important failure model is embodied in bending yield of coupling beams.



X-directional Pushover Y-directional Pushover

Fig. 5 The storey performance curves

3.2. Nonlinear dynamic analysis

Nonlinear dynamic analysis can show all kinds of responses of structure under fortifiable (LV2) and severe (LV3) earthquake by inputting ground motions at the fixing point. Besides the aforementioned three natural records, here are the other two artificial records shown in Fig.6. The PGA corresponding LV2 and LV3 are 100gal and 220gal respectively. When calculating, Newmark's numerical integration method is utilized, and the time interval is set to be 0.005 second. The viscous damping matrix is assumed to be Rayleigh's damping, and the modal damping ratio is 4%.

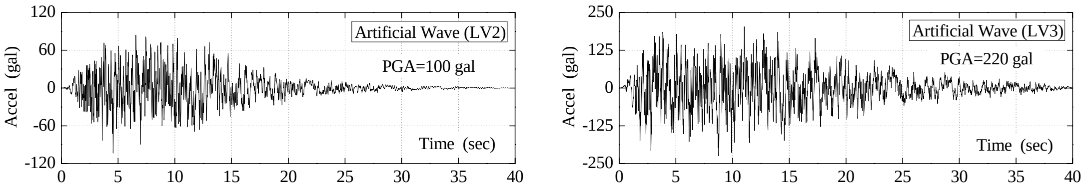


Fig. 6 Artificial waves for fortifiable and severe earthquake

By calculation, the responses of structure are obtained, among which the maximum inter-storey drifts under LV2 and LV3 are shown in Table 5 and the distribution of extreme inter-storey drift along the height is indicated in Fig. 7. Observing the envelope of extreme inter-storey drifts under four input ground motions, it can be found that the locations where the maximum inter-storey drift is obtained are almost identical with pushover analysis. This testifies, from one aspect, that the selection of input ground motions is reasonable and the results of static and dynamic methods are comparable. Moreover, under fortifiable earthquake (LV2), many coupling beams yield due to flexure, but most of the ductility ratios are less than 3.0. All the vertical members do not yield. Under severe earthquake, almost all coupling beams appear flexural yielding, and some ductility ratios exceed 6.0. Some frame beams located under 27F appear slightly flexural yielding. And the outside of core walls present partly local flexural yielding; the corner of core walls located in the bottom show yielding because of flexural tension. Generally, the hybrid structure does not appear shear failure, and the building shows well seismic performance.

On the other hand, some key members of the hybrid structure, such as the ground floor columns, the inclined columns between 28F to 30F, and the slender columns located in hotel lobby, are checked carefully under fortifiable earthquake. Examining the responses of frame columns under fortifiable earthquake, it can be found that the key columns at the middle part of building only show concrete cracking due to bending, some of which accompanying shear cracking, while the ground floor columns are in elastic state without cracking and yielding.

To conclude, responses of the hybrid structure, calculated by nonlinear procedure, indicate that the structure can satisfy the performance objective.

Table 5 Maximum inter-storey drift

Earthquake records	X-directional drift		Y-directional drift	
	LV2	LV3	LV2	LV3
Artificial	1/346	1/126	1/367	1/136
El Centro-EW	1/385	1/196	1/495	1/223
WufengNE-NS	1/414	1/217	1/327	1/154
YunlincitySE-NS	1/351	1/145	1/312	1/139

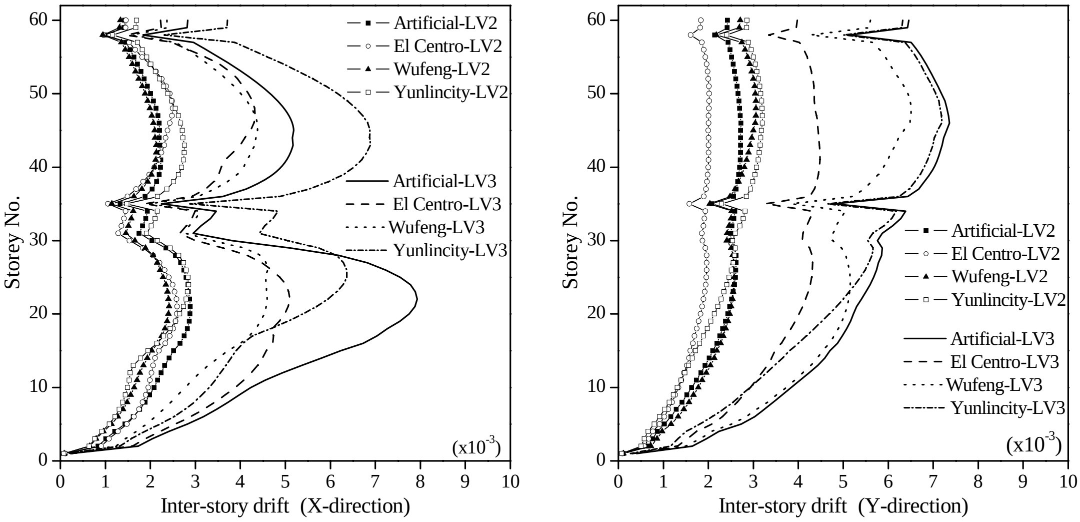


Fig. 7 Distribution of extreme inter-storeydrift

4. CONCLUSIONS

This paper introduced the design procedure of a super high-rise hybrid structure. Elastic analysis including response spectrum method and elastic time-history analysis, and nonlinear analyses including static and dynamic procedures are conducted. There are some conclusions can be drawn:

(1) The results of elastic response spectra analyses calculated by two structural programs show the correctness of the calculating model. And the results of elastic time-history are basically identical with that of response spectra analyses.

(2) Nonlinear elasto-plastic analyses under fortifiable and severe earthquake are performed to indicate the behavior of structure. The results show that the hybrid structure has well seismic performance and achieves the performance objective.

ACKNOWLEDGEMENTS

The writers would like to gratefully acknowledge Dr. Li Kangning, who provided CANNY program and the original analyses data, and LANTO Consulting Architects & Engineers Co.,Ltd , which supplied the opportunity of participating design.

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