DYNAMIC ELASTO-PLASTIC ANALYSIS OF A SUPER HIGH-RISE HYBRID STRUCTURE

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ABSTRACT :

Dynamic elasto-plastic analysis methods can actually indicate the characteristic of structure, and it is considered as an accurate method. This paper is concerned with the seismic performance evaluation of a super high-rise hybrid structure on a background of project by using nonlinear dynamic procedure (NDP). By reasonable selection of input ground motions which include three natural earthquake records and a group of artificial waves, and based on some assumptions and considerations, the nonlinear dynamic analyses are carried out by using CANNY program. Then the seismic responses of hybrid structure under three different earthquake intensities are obtained. Comparing the responses of three levels with preestablished performance objective, the results show that all responses meet the requirements. At the same time, the inter-storey shear drifts are mentioned to judge the seismic behaviors of hybrid structure. Based on the large amount of structural response information, conclusion can be drawn that the super high-rise hybrid structure achieves the earthquake performance objective.

KEYWORDS: hybrid structure, dynamic analysis, resorting force model, inter-storey drift

1. INTRODUCTION

With the development of performance-based seismic design (PBSD), the more demands for performance of buildings need to be indicated by structural engineers. At every step of PBSD, like as performance determination, performance evaluation, and performance representation, it is necessary to find out many kinds of seismic responses of structure. Dynamic analysis, also called time-history analysis, can show the internal forces and deformations of structure at every step in the whole course of seismic response. So, time-history analysis, which was only used in very important buildings, now is becoming one of the most effective tools to study seismic responses of almost all the buildings, and it is one of the basic methodologies of PBSD. This paper is concerned with the seismic performance evaluation of a super high-rise hybrid structure on a background of project by using nonlinear dynamic procedure (NDP).

Hybrid structure, consisting of steel/composite frame and reinforced concrete wall, has been developed rapidly in China. And some domestic researchers (e.g., Li et al., 2001; Hou et al., 2006; Xia and Wang, 2006; Zou et al., 2006) has applied themselves to study this hot issue. At present, hybrid structure has been the main structural form of super high-rise public buildings, such as Shanghai World Financial Center Tower(492m), Shanghai Jin Mao Tower(421m), Shenzhen Shun Hing Square(384m) and etc.

This project is a super high-rise building functioned as five-star hotel and grade-A office, with 53 over-ground stories and 4 stories basement, the height 241m. The typical floor plans and typical section are shown in Fig. 1. Under the sixth floor, steel reinforced concrete (SRC) frame is adopted to enhance the stiffness of structure. And from the seventh floor to the top, the outer frame consists of concrete-filled square steel tubular (CFSST) columns and steel beams, among which the CFSST columns have great capacity of compression resistance and fire resistance, as shown in the work by Han (2004). SRC core wall, formed by setting SRC columns at the intersections of longitudinal and transversal shear walls, is utilized to enhance the ductility of the whole structure. Some domestic researchers (Lü et al., 2006; Cao et al., 2007; Dong and Lü, 2007) have been studied the behaviors of some kinds of SRC shear walls. At the same time, the SRC columns in the core walls facility the rigid connections between steel beams and core walls.

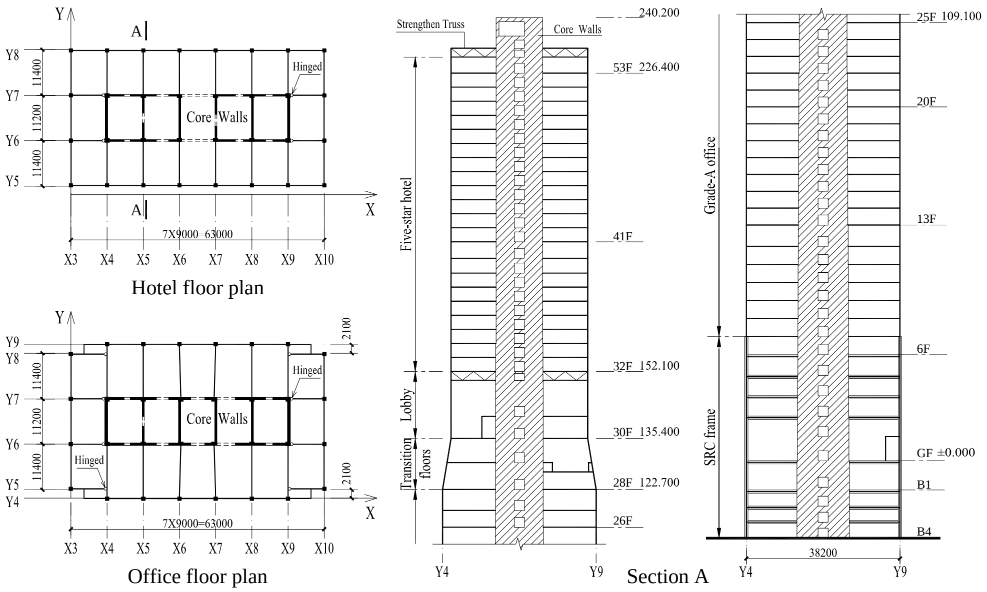


Fig. 1 Typical floor plans and typical section

2. PERFORMANCE OBJECTIVE

Based on the importance of building and category of seismic fortification, moreover considering the balance between safety and economy, the seismic performance objective of the building can be established as follow:

(1) Under frequent earthquake, all the members of the structure are in elastic working range. The inter-storey drift values don't exceed 1/550.

(2) 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.

(3) Under severe earthquake, the limbs of core walls do not present shear failure. The inter-storey drift values don't exceed 1/120.

Furthermore, the more detail about performance objective and level can be acquired from some references (e.g., CECS-160, 2004; Xu et al., 2005).

3. DYNAMIC ANALYSIS

Although dynamic elasto-plastic analysis is considered as an accurate method to indicate the behavior of structure, the accuracy of seismic response of building depends on the input ground motions. In other words, to time-history analysis, the selection of proper earthquake waves is very important.

3.1. Selection of input ground motions

Compared with the artificial wave which is synthesized according to the site measurement and standard response spectrum, this paper chooses three natural earthquake records based on their spectrum characteristics. The artificial waves contain three contents corresponding different level earthquake intensities: frequent (LV1), fortifiable (LV2) and severe (LV3). The three natural ground motions are El Centro-EW (1940), WufengNE-NS (1999), and YunlincitySE-NS (1999), among which the latter two records come from Chi-Chi earthquake of Taiwan in 1999. All the waves are figured in Fig. 2. Moreover, the peak ground acceleration (PGA) of every natural record and the scaling factors for three different levels on the basis of specific site condition and category of seismic fortification are shown in Table 1.

However, it is worth mentioning that there is no need to scale artificial records since they are already spectrum-compatible. With the standard acceleration spectrum, the acceleration response spectra of the artificial record and scaled natural records for severe earthquake (LV3) are shown in Fig. 3. According to the elastic response spectra analysis, it is found that the first basic natural vibration period is about 6.5 second. So we care about the value of spectra accelerations when the period is around 6 second. It can be found that the spectral acceleration of El Centro-EW record at 6 second is less than the other records.

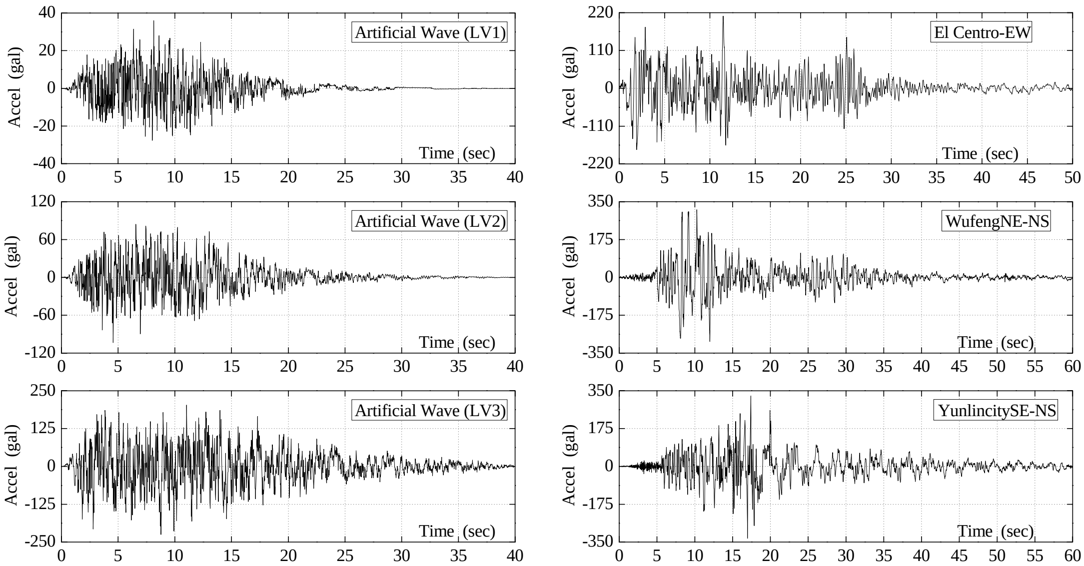


Fig. 2 Acceleration time-histories

Table 1 PGA values of natural records and scaling factors for three levels

Natural records	El Centro-EW	WufengNE-NS	YunlincitySE-NS
PGA (gal)	210.1	312.9	332.8
Scaling factor to LV1 (35 gal)	0.1666	0.1119	0.1052
Scaling factor to LV2 (100gal)	0.4760	0.3196	0.3005
Scaling factor to LV3 (220gal)	1.0471	0.7031	0.6611

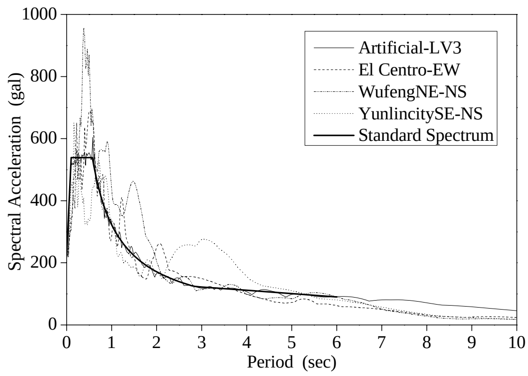


Fig. 3 Acceleration spectra for severe earthquake (4% damping)

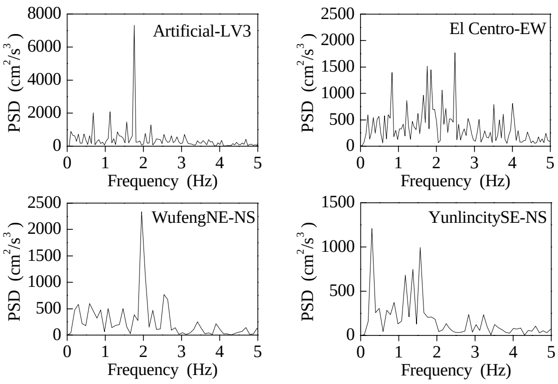


Fig. 4 Acceleration power spectral density of scaled records for LV3

On the other hand, the power spectrum can reflect the spectral characteristics of input ground motions. When the predominant period of ground motion is close to the characteristic site period (T_g), which lies on the focal mechanism, earthquake magnitude, epicentral distance, and site condition of the region building located, the response of structure will be remarkable. Additionally, 'Report of seismic safety assessment' provides T_g=0.57sec under severe earthquake. From Fig. 4, the acceleration power spectral density of scaled records for severe earthquake, we can find that the artificial (LV3) and WufengNE-NS records have notable predominant component, and the other two records contain relatively abundant frequency component. Furthermore, these PSD curves indicate better applicability to the characteristic site period (T_g).

3.2. Method and assumptions

This paper utilizes CANNY program, which has been developed for more than twenty years by Dr. Li Kangning, to perform dynamic analyses. This program specialize elasto-plastic analyses of all kinds of structures for seismic studies. In the analytical course, the three-dimensional member model is based on some assumptions and considerations. Rigid diaphragm assumption is utilized, thus beam elements only consider in-plane (out of floor-slab plane) nonlinear flexural and shear deformations except that those connecting free joints need to append the axial nonlinear deformation. All the frame columns have bidirectional flexural and shear nonlinear deformations as well as axial deformation. And 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, to RC elements, considering concrete crack, the deformations of bending and shearing use Takeda restoring force model having trilinear skeleton curve; to steel beams and CFSST columns, taking into account the first outmost fiber yielding of steel and section yielding, the flexural deformation use trilinear hysteresis model, and the shear deformation of steel beams use degrading bilinear model; to SRC elements, considering concrete cracking, the first yielding of steel or rebar and section yielding, use the quadri-linear restoring force model to express the nonlinear flexural deformation. The peripheral core walls under the interaction of axial force and bending moment, having certain stiffness degradation, use asymmetric restoring force models to show the nonlinear axial deformation. In addition, making use of section analysis, the flexural bearing capacities of elements are obtained. This paper assumes that the bending yield bearing capacity of RC, SRC and CFSST elements correspond to the yielding of 50 percent steel and rebar of cross-section, and that of steel elements accord with the yielding of 75 percent steel of cross-section.

3.3. Time-history analysis

While the 3-D calculating model is established by CANNY program, adding all the dead load and 50 percent live load, inputting acceleration time-histories along X- and Y-direction respectively at the fixed end of structure (underground first floor), the dynamic analyses are performed. During the analytical courses, 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%.

After analysis, the responses of structure are obtained. Table 2 and Table 3 present the base shear-weight ratios and the maximum inter-storey drifts respectively under three level earthquake intensities.

Table 2 Base shear-weight ratio (%)

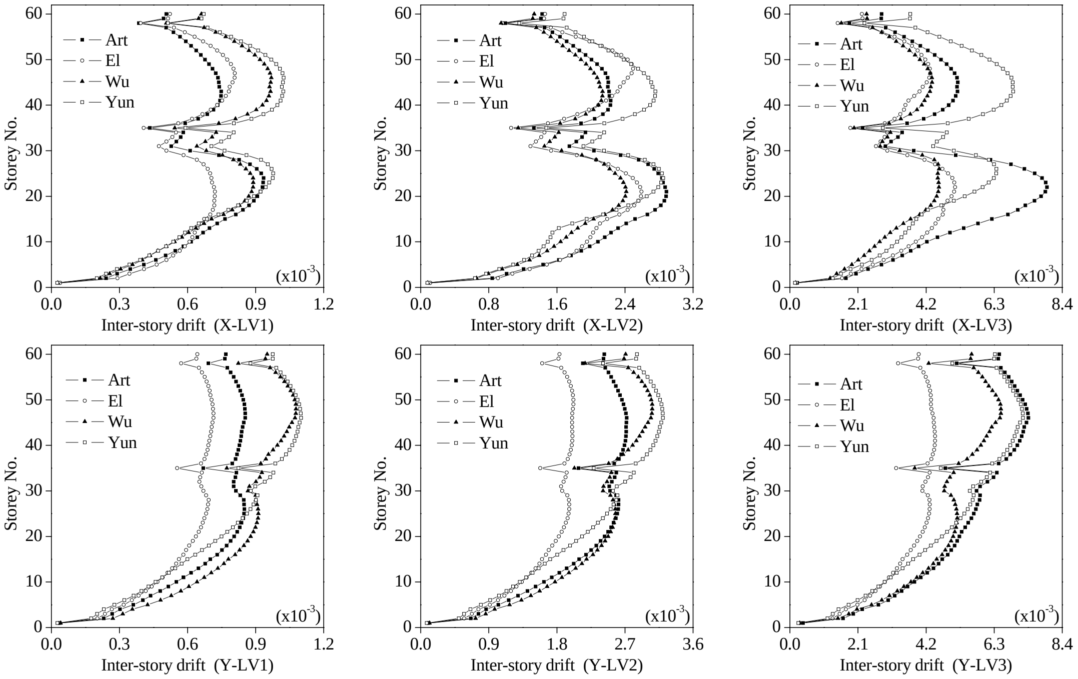
Earthquake records	X-directional input			Y-directional input		
	LV1	LV2	LV3	LV1	LV2	LV3
Artificial	1.024	3.166	5.322	1.242	3.317	8.200
El Centro-EW	1.365	3.663	5.403	1.188	3.315	7.104
WufengNE-NS	0.967	2.559	4.630	1.407	3.873	7.398
YunlincitySE-NS	0.951	2.658	4.320	1.084	3.127	6.783

Table 3 Maximum inter-storey drift

Earthquake records	X-directional drift			Y-directional drift		
	LV1	LV2	LV3	LV1	LV2	LV3
Artificial	1/1069	1/346	1/126	1/1171	1/367	1/136
El Centro-EW	1/1237	1/385	1/196	1/1399	1/495	1/223
WufengNE-NS	1/1032	1/414	1/217	1/928	1/327	1/154
YunlincitySE-NS	1/977	1/351	1/145	1/909	1/312	1/139

Further, the distribution of maximum inter-storey drifts along the height can reveal the stiffness distributing of stories in the height direction. Fig. 5 shows the absolute values of extreme inter-storey drifts which envelope the responses of inter-storey drift during the time-history analysis. The above data illustrate that the responses of structure under the excitation of several ground motions are close, and that the selection of ground motions is reasonable. On the other hand, we can find that, in X-direction, the responses under all the input motions are closer than those of Y-direction. The responses of El Centro-EW along Y-direction are less than the others. And the seismic responses of the upper part of structure are almost dominated by YunlincitySE-NS wave, but that of lower part depend on artificial waves and WufengNE-NS wave.

In general, the responses of structure under all the earthquake waves are comparable and the selected input ground motions based on the above method can satisfy the dynamic analyses.



Note：Art: Artificial, El: El Centro-EW, Wu: WufengNE-NS, Yun: YunlincitySE-NS

Fig. 5 Distribution of extreme inter-storey drift

Moreover, this paper gives the following summary damage of structural elements. Under frequent earthquake (LV1), the maximum inter-storey drifts of X- and Y-direction approximately 1/1000, and all the members of structure are basically in elastic state except that some RC and SRC members crack due to vertical load. Under fortifiable earthquake (LV2), the maximum inter-storey drifts of two principal directions are less than 1/300. When inputting earthquake waves along X-direction, many X-directional coupling beams yield due to flexure, and most of their ductility factors are less than 3.0. However, there are about fifteen coupling beams whose ductility factors exceed 3.0. When inputting earthquake waves along Y-direction, some Y-directional coupling beams present slightly bending yield, and their ductility factors are similar to those of X-direction. All the vertical members do not yield under fortifiable earthquake. Under severe earthquake (LV3), the maximum inter-storey drifts of two principal directions reach 1/130. In X-direction, almost all coupling beams appear flexural yielding some of which accompanying shear cracking, and there are approximately 15 percent ductility factors exceed 6.0. A few X-directional steel frame beams yield slightly for bending; frame columns present concrete cracking and stiffness degradation; some frame beams appear flexural yielding and the ductility factors are less than 3.0; the outside of core walls appear partly local flexural yielding. In Y-direction, the behaviors of coupling beams are similar to those of X-direction, but mostly ductility factors exceed 6.0. All the vertical elements do not present shear failure except that the corner of core walls located in the bottom show yielding because of flexural tension. Generally, the whole hybrid structure show well seismic capacity under three level earthquake intensities.

4. PERFORMANCE EVALUATION

Investigating all the responses of dynamic analyses and comparing with the preestablished performance objective, it can be conclude that the super high-rise hybrid structure can satisfy the performance objective.

However, it is important to recognize that the inter-storey drifts under severe earthquake include the flexural and shear deformations, among which the flexural deformation causes remarkable rotation of the storey, while the shear deformation (harmful deformation) is relatively small. For example, when inputting Artificial-LV3, the X-directional maximum inter-stoery drift reaches 1/126, but the maximum inter-storey shear drift is only 1/592; similarly the Y-directional maximum harmful inter-storey drift is 1/454, the extreme total inter-storey drift 1/136. So, these data reveal that the SRC core walls present well seismic behavior.

5. CONCLUSIONS

This paper studied the seismic performance of a super high-rise hybrid structure by NDP, and carried out the structural elasto-plastic design by using PBSD method. Based on the above analyses, the following conclusions can be drawn:

(1) According to both the spectra acceleration under given period and the predominant period of ground motion, the selected ground motions can give structure proper seismic responses. And the reference standard is the artificial waves.
(2) The super high-rise hybrid structure achieves the performance objective.
(3) By proper designing, the hybrid structures also have excellent seismic performance.

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