SEISMIC RESISTANT PERFORMANCE ANALYSIS ON AN UNSYMMETRICAL SUPER-HIGH STEEL TV TOWER

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ABSTRACT :

Linyi TV tower located in Linyi, Shandong province is an unsymmetrical steel TV tower of 326m in height. Its main body is a circular hollow section (CHS) with big diameter which is supported by a curved truss laid in spirality. Based on the case study of this unique steel TV tower, both conventional earthquake time-history response analysis and rare earthquake nonlinear time-history response analysis of the structure are made to evaluate the seismic behavior of the tower such as weak spots and weak degrees. The results show that the seismic resistant performance of this structure is good. A few points on the tower need to be paid more attention under strong earthquake. The structure meets the requirements of no-damage under light earthquake, repairable under medium earthquake and no-collapse under strong earthquake.

KEYWORDS: Steel Tower, time-history response, conventional earthquake, rare earthquake, seismic resistant evaluation

Linyi TV tower located in Linyi Shandong province is an unsymmetrical steel TV tower of 326 m in height, which consists of four parts: a bottom building, the main structure of the tower, observation decks and a top truss for supporting antennas. The bottom building is a three-storey steel frame structure with a total construction area of 6000 m^2. The 5-storey brush pen-like observation decks with construction area of 1600 m^2, located at a height of 193m, is used for sightseeing and installing emission equipment etc. The 98m high top truss is designed to support the broadcasting and TV antennas. The main structure of the tower is a big circular hollow section (CHS) with a diameter of 8.5 meters, which is supported by three trusses laid in 'Y'. The chords of the trusses also are CHS. The three trusses are connected together by a curved truss laid in spirality to ensure the whole structural stability.

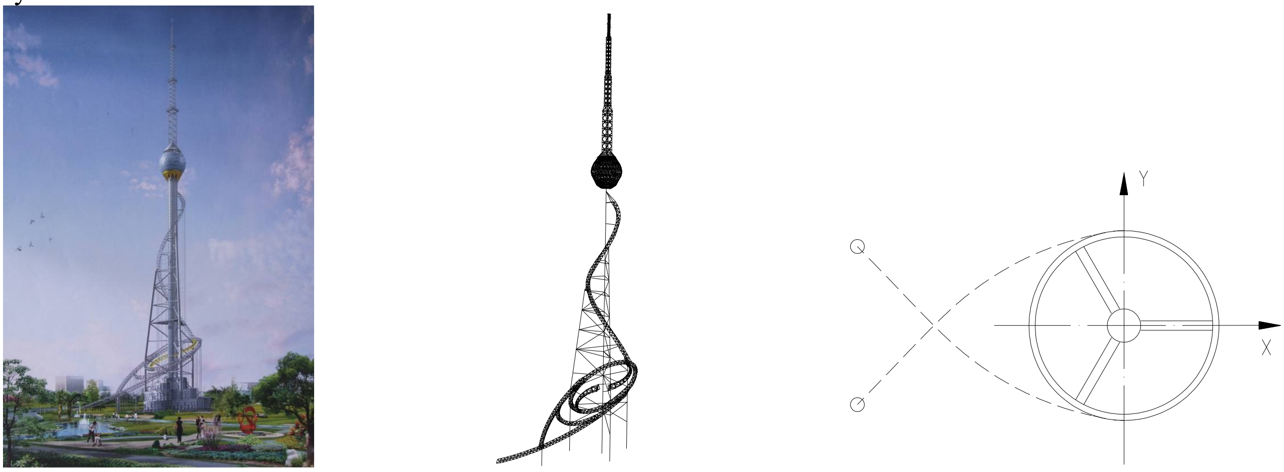
For the significant height and great flexibility of the Linyi tower as well as the complex and unsymmetrical structural type, it is necessary to analyze the structural response, especially torsional effect under earthquake. According to the seismic resistant requirement of 'three levels and two stages' in China, both conventional earthquake time-history response analysis and rare earthquake nonlinear time-history response analysis of the structure have been performed in this paper in order to evaluate the seismic resistant performance of this unsymmetrical super-high steel TV tower.

1. ANALYTICAL MODEL DESIGN AND EARTHQUAKE INFORMATION

1.1. Analytical Model

Linyi TV tower is shown in Figure 1. It is a complicated space structure. In this paper a three dimensional framed model (Figure 1(b)) was adopted to consider its space effect (Wang & Ma, 2004). The finite element software Sap2000 was used to evaluate the structural behavior of this tower. In investigating the structural behavior under seismic action, the representation value of gravity load was taken as one time permanent load of all members and a half part of live load (Ma, Zhao and He, 2007). So the representation value of

Linyi tower is about 34000kN.



(a) The elevation of the tower (b) Analytic model of the tower (c) Section in horizontal plane

Figure 1 Linyi TV tower

When analyzing the dynamic property of the structure, one hundred characteristic periods were included. Calculation results show that the contribution of the first twenty modes in seismic response in x and y direction exceeds 94 percent, which also show that the torsion in the first several natural vibration frequencies is very small and the distinct torsion appears in the 18th mode. It is because the three trusses laid in 'Y' lead to valid space effect in the structure. Table 1 lists the first five characteristic periods and their modal behavior. In the table 1, the x and y direction was shown in figure 1(c).

Table 1 The first five characteristic periods and behavior

Vibration mode	Period/s	Modal behavior
1	5.3607	Displacement in x direction
2	3.9288	Displacement in y direction
3	1.4573	Displacement in x direction
4	1.4515	Displacement in y direction
5	1.2998	Displacement in x direction

1.2. Earthquake Action

According to the geology condition of Linyi city, the basic seismic intensity is degree 7; the horizontal design basic acceleration value of ground motion is 0.15g. It is a class II ground, and group I in design earthquake grouping, therefore the design characteristic period of ground motion is 0.35s (Lu & Zhou, 2002). Since TV tower belongs to a very important structure for a city, its seismic intensity was increased to degree 8 and the horizontal design basic acceleration value of ground motion was increased to 0.2g. Here the maximum horizontal earthquake influence coefficient under conventional earthquake is 0.16 with the ratio of damping of 0.02, while the maximum of horizontal earthquake influence coefficient under rare earthquake is 0.90 with the ratio of damping of 0.03. The maximum values of earthquake acceleration in time-history analysis are shown in Table 2.

Table 2 Maximum values of earthquake acceleration in time-history analysis

Earthquake action type	Maximum value
Conventional earthquake	70cm/s^2
Rare earthquake	400cm/s^2

1.3. Seismic Resistant Performance Verify

In the code for seismic design of building, the elastic drift angle under conventional earthquake with the allowable value of 1/300 and the elastoplasticity drift angle under rare earthquake with the allowable value of 1/50 should be checked. Besides, due to the code for design of high-rising structures, the maximum horizontal displacement under load nominal combination with the earthquake action as the main load also need to be verified to meet the allowable value of h/100, where h is the height of the structure. The members' stress under load fundamental combination with the earthquake action as the main load still should be less than design value of load-carrying capacity of members with the regulation factor of 0.75. The load combinations adopted for seismic resistant analysis are shown as following:

(1) Nominal combination: $1.0D+0.5L+1.0Q_E+0.2W$;

(2) Fundamental combination: $1.2D+0.6L+1.3Q_E+0.5Q_{EV}+0.28W$.

Where D is the dead load; L is the live load; W is the wind load; for Q_E and Q_{EV} are the horizontal and vertical earthquake load required in the code for seismic design of building.

2. CONVENTIONAL EARTHQUAKE RESPONSE ANALYSIS

The Lin Yi tower is a complicated structure and has a great significance. In order to evaluate its seismic resistant performance against conventional earthquakes, this paper adopted the response spectrum analytic method by mode displacement superposition, and this paper also adopted the linear time-history response analytic method to verify the calculation results. The analysis details are summarized below.

2.1. Response Spectrum Analysis by Mode Displacement Superposition

2.1.1 Parameters for response spectrum analysis

During adopting response spectrum analytic method by mode displacement superposition (Clough & Penzien, 2006) to investigate the seismic resistant performance under conventional earthquake, the interrelated parameters are the same as the values described above. The maximum seismic influence coefficient is 0.16, the damping ratio equals 0.02. The remaining parameters of seismic influence coefficient curve were decided by the given values. Otherwise, the horizontal and vertical earthquake load should be combined together.

2.1.2 Analysis results

(1)Base shear and moment

The results of response spectrum analysis are summarized in Table 3.

Table 3 Base shear and moment values in response spectrum analysis

Cases	Fx（kN）	Fy（kN）	Fz（kN）	Mx（10^8 kN.m）	My（10^8 kN.m）	Mz（10^8 kN.m）
X100Y085	996	951	168	0.35	1.2	1.2
X085Y100	854	1111	147	0.38	1.1	1.1
Z065	106	32	2868	3.5	3.5	0.13

In the table 3, case X100Y085 represents the horizontal earthquake loads in two directions, the factor in x direction is 1.0, and the factor in y direction is 0.85. Case Z065 represents the vertical earthquake load and the factor equals 0.65. Table 3 indicates that the base shearing forces are lower than the allowable values in the code of seismic design of buildings. Furthermore, due to the asymmetry of the structure, the twist moment values are relatively large.

(2)Peak displacement values of key points

Concerning about the structure response of response spectrum analysis, there are several key points in the tower such as the top floor of the observation decks, the rotating platform of the observation decks as well as the top spot of the truss for supporting antennas. The maximum displacement values of these parts are listed in Table 4. The displacements in x and y direction are similar that is consistent with relatively small torsion in the first several natural vibration frequencies.

Table 4 Maximum displacement values of key spots(mm)

Cases	On the top floor of the observation decks		On the rotating platform of the observation decks		On the top spot of the truss for supporting antennas	
	x	y	x	y	x	y
X100Y085	493	250	495	245	775	518
X085Y100	464	280	460	265	727	551

(3) Drift angle on the observation decks spots

For the observation decks belong to the necking locations of the structure, the drift angle values are relatively large. Maximum drift angle values in x and y direction are 1/468 and 1/402, which satisfy the allowable value shown above.

2.2. Linear Time-history Response Analysis against Conventional Earthquake

This paper choose three kinds of natural seismic wave records including El_Centro, Northridge and Taft earthquake records as well as an artificial earthquake wave record (Lanzhou earthquake record) according to the soil condition in Linyi. Also, the time-history acceleration records in three directions are input with decided peak values ratios, which is 1:0.85:0.65 for case 1, 1:0.65:0.85 for case 2. Otherwise, the duration of all groups of earthquake records should not be smaller than five to ten times basic characteristic periods, here authors choose 30s, and the peak value of the input acceleration should be adjust to be $70cm/s^2$. The ratio of damping equals 0.02.

2.2.1 Results comparisons between response spectrum analysis and linear time-history response analysis

In order to ensure the correctness of two analytic methods, calculated results are listed in Table 5. The base shear values of each time-history curve are larger than 65% of the value got by response spectrum analysis, and the average value of time-history analysis is greater than 80% of the response spectrum analytic result. So the average value of time-history analysis is used to verify the members' strength. We also find that the stress of all the members is low, so the earthquake load doesn't play an important role in structure design.

2.2.2 Displacement and drift angle verification

Maximum displacement values and drift angle values of the key points against conventional earthquake in condition of two kinds of worst-cases are shown in Table 6 and Table 7. They all meet the requirement of the allowable values.

Table 5 Base shear values in response spectrum analysis and linear time-history response analysis

Cases		Base shear of x direction（kN）					Base shear of y direction（kN）				
		(1) Time-history analysis results	(2) Average value of time-history analysis	(3) Response spectrum analysis result	(3)×0.65	(3)×0.80	(1)' Time-history analysis results	(2)' Average value of time-history analysis	(3)' response spectrum analysis result	(3)'×0.65	(3)'×0.80
El_centro seismic wave	1	2572	1500	925	601	740	2451	1700	1030	670	825
	2	2213					2876				
Northridge seismic wave	1	1830					2024				
	2	1522					2553				
Lanzhou seismic wave	1	1311					1093				
	2	1110					1291				
Taft seismic wave	1	784					607				
	2	662					711				

Table 6 Maximum displacement values of the key points against conventional earthquake（mm）

Seismic wave	Cases	On the top floor of the observation decks		On the top spot of the truss for supporting antennas	
		X	Y	X	Y
Elcentro	X100Y085	392	307	668	617
	X085Y100	390	340	659	669
Northridge	X100Y085	360	225	664	497
	X085Y100	342	240	626	529
Lanzhou	X100Y085	414	195	657	434
	X085Y100	390	207	625	447
Taft	X100Y085	399	171	616	397
	X085Y100	379	181	589	414

Table 7 Maximum drift angle values on observation decks against conventional earthquake

Seismic wave	Cases	Maximum values	
		x direction	y direction
Elcentro	X100Y085	1/584	1/408
	X085Y100	1/615	1/351
Northridge	X100Y085	1/601	1/550
	X085Y100	1/718	1/478
Lanzhou	X100Y085	1/623	1/1007
	X085Y100	1/724	1/888
Taft	X100Y085	1/750	1/1500
	X085Y100	1/900	1/1125

3. RARE EARTHQUAKE NONLINEAR TIME-HISTORY ANALYSIS OF THE STRUCTURE

In the code for seismic design of building, the whole structure mustn't collapse under rare earthquake. That means the tower is allowed to be damaged without overall collapse. This principle was the guideline of the seismic design under rare earthquake.

Here the same data of seismic wave records and the worst-cases as the data of linear time-history response analysis were used to analyze the rare earthquake response. For Linyi TV tower, the peak value of the input acceleration equals $400cm/s^2$, and the entire seismic wave records should be adjust to meet this requirement.

The nonlinear characteristic of the material as well as the load-displacement second-order effects were both taken into account during calculating the rare earthquake response. Considering the requirements of the feasibility, accuracy and efficiency in calculations, fiber PMM hinge, PMM hinge and P hinge were respectively adopted for the main structural CHS, truss members and the truss for supporting antennas (Jiang, 2004). In order to ensure the calculation process to be convergent, the Wilson-θ method was used, where θ equals 1.4. The duration of the seismic wave records is about 30s; the time step is 0.02s; and the ratio of damping equals 0.03.

The peak displacement results of key spots and the base shear data are listed in Table 8 and Table 9, which are following the requirement of the allowable values in the seismic design code. On the other hand, ratios of shear and gravity values for all structural members also meet the requirement.

Table 8 Maximum displacement values and maximum drift angle values against rare earthquake

Seismic wave	Cases	On the top floor of the observation decks（mm）		On the top spot of the truss for supporting antennas（mm）		Maximum values of drift angle	
		X	Y	X	Y	X	Y
El_centro	X100Y085	638	910	961	1581	1/281	1/118
	X085Y100	633	1057	971	1811	1/321	1/97
Northridge	X100Y085	613	486	1046	900	1/204	1/187
	X085Y100	558	526	976	1124	1/236	1/173
Lanzhou	X100Y085	802	378	1123	696	1/204	1/375
	X085Y100	959	448	1339	757	1/225	1/346
Taft	X100Y085	885	473	1125	889	1/182	1/264
	X085Y100	1003	530	1310	984	1/151	1/228

Table 9 Base shear values in the nonlinear time-history analysis

Seismic wave	Cases	X direction		Y direction	
		Base shear(kN)	Ratio of shear and gravity	Base shear(kN)	Ratio of shear and gravity
El_centro	X100Y085	5799	0.17	5807	0.17
	X085Y100	4969	0.15	6679	0.2
Northridge	X100Y085	5009	0.21	4922	0.14
	X085Y100	4305	0.13	5716	0.17

Lanzhou	X100Y085	2460	0.07	2280	0.07
	X085Y100	2118	0.06	2421	0.07
Taft	X100Y085	4779	0.14	4113	0.12
	X085Y100	4113	0.12	4263	0.13

Besides, the analysis data indicate that stress of some members is larger than the design value of load-carrying capacity of members, which means the members have developed into plastic stage. The nonlinear behavior of these members led to the re-distribution of internal forces of the whole structure as well as the appearance of some plastic hinges. In order to investigate the developing process of the structural members from elastic to plastic under rare earthquake and find out the weak points of the structure, this paper took the El_centro wave record as an example to evaluate the seismic behavior of the tower.

Figure 2 and Figure 3 show the distribution of the plastic hinges which are formed under rare earthquake load. The possible weak points firstly appear at the connecting of observation decks and the top truss for supporting antennas, then near the link of the main body and the lateral trusses have several weak degrees. All in all, the seismic resistant performance of this structure against rare earthquake is good and only a few points need to be paid more attention. However, plastic deformation of these weak points still satisfies the requirement of allowable value which is 1/50 for the drift angle value.

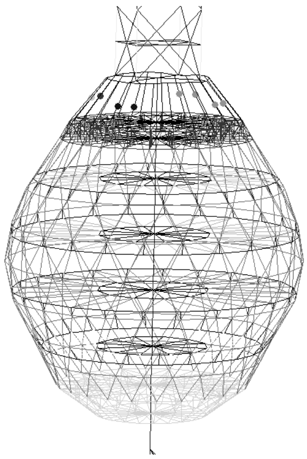


Figure 2 Plastic hinges distribution at the connecting of observation decks and the top truss for supporting antennas(the round spots represent the location of the plastic hinges)

Figure 3 Plastic hinges distribution at the connecting of the main body and the lateral trusses

4. OVERALL EVALUATION OF THE SEISMIC RESISTANT PERFORMANCE

This paper presented a study on the seismic resistant performance of the Linyi TV tower against conventional earthquake and rare earthquake. Based on the analytical results, some conclusions can be summarized as following:

(1) The structural system, members' dimension as well as design details of the Linyi tower satisfy the requirements of the seismic design.

(2) Under conventional earthquake, the maximum values of displacement and drift angle are less than the allowable values. Moreover, the members of the structure have a low stress level under load fundamental combination with the earthquake action as the main load.

(3) Nonlinear time-history analytical results indicate that the structure has great load-carrying capacity and less deformation against rare earthquake. Therefore, the seismic resistant design can meet the requirement that the whole structure will not collapse under rare earthquake.

Although Linyi TV tower has some characteristics such as significant height, great flexibility as well as the complex and unsymmetrical structure type, the structure design will not be dominated by the earthquake action because of the low deadweight of steel structure. However, the designers should pay more attention to some weak points of the structure such as the locations of the plastic hinges against rare earthquake.

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