Shake Table Test for Large Indirect-Air-Cooling Tower Structure of Fire Power Plant—Part I

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SUMMARY:
For understanding the seismic behavior of extra-large scale cooling tower with dimension of 220 meters high and 188 meters in diameter, both of the dynamic nonlinear finite element analysis and shake table tests for a 1:30 (length ratio) model were carried out to simulate the earthquake impacts. In the model design, a new model material simulation method is developed. Specially treated lead sand was used as one of the main aggregates of the model construction mortar. Both of the dynamic NFE analyses for the prototype tower structure and its 1:30 model counterpart were carried out to compare each other in considering of the similitude law. The earthquake resistant capacity of the tower as well as its' critical element of the support leg columns were verified and studied carefully. This paper provides useful reference to the seismic design practice for the extra-large tower structures.

Key words: shake table test, large indirect-air-cooling tower, model structure, prototype structure

1. BACKGROUND

With the rapid demand of the fire power plant, extra-large indirect-air-cooling tower (1000MW) will be selected to be constructed in the high seismic risk areas of China such as mid-north and west-north regions. The dimension of the huge tower structure can reach up to 220 meters high and 188 meters in diameter. It's constructed with X type R/C column supported hyperboloid shell and the X column's length-width ratio can reach up to 1:40. It's really a challenge but very necessary and urgent to know the seismic behavior and design weak points of the huge tower under strong earthquake attacks.

In 2005, S. Sabouri-Ghomi and M.H.K. Kharrazi took a study on the reinforced concrete column supported hyperboloid cooling tower stability assessment for seismic loads. In their study, finite element analyses have been performed to obtain the stress concentration, nonlinear behavior, stability or safety factor of the R_C_ tower due to earthquake loads. Outcomes of their study show that considerable plastic hinges were created in the X shape long columns of the R/C hyperboloid cooling tower due to seismic loads, which resulted in a significant decrease in the stability safety factor. According to W.S. Guo's introduction, R.Harte and U.Montag performed a study on computer simulations and crock-damage evaluation for the durability design of the world-largest cooling tower shell (200m high and 152m span) at Niederaussem power station (1000MW grade). But as we all know, Germany is not located in the seismic region and the Niederaussem power station is not exposed to severe earthquake risk. The study on the 200m high and 152m span cooling tower can't provide useful reference to the seismic design for the world largest 220m high and 188m span cooling tower in China.

This paper studies the seismic behavior of the world-largest R/C hyperboloid cooling towers with very long X shape supporting columns. Both of the dynamic nonlinear finite element analysis and shake table tests for a 1:30 (length ratio) model were carried out to simulate the earthquake impacts. A new model material simulation method is developed to fulfill the goal of shaking table test. Specially treated lead sand is used as one of the main aggregates of the model construction micro–aggregate concrete. Both of the dynamic nonlinear finite element analyses for the prototype tower structure and its 1:30 model counterpart were carried out to compare with each other in considering of the similitude law. The earthquake resistant capacity of the tower as well as its' critical element, the support X-type columns were verified and studied carefully.

2. Length Ratio 1:30 Model Similitude Design

The first step of shaking table test is the proper model design. Generally, the length ratio of the model to the prototype structure should be determined according to the load capacity and dimension of the available shaking table. For the cooling tower, the most difficult issue is the installation of artificial mass to the model structure. In some test cases, the artificial masses have to be hanged out along the shell wall like hanging sacks. It caused a new problem that is the hanging way may change the real dynamic response of the model structure and the test results error due to the stiffness and damping change. For avoiding the problem of the artificial hanging way, the authors develop a new method to solve the mass loss and the hanging problem simultaneously.

2.1. Describe of the Prototype Cooling Tower

The huge prototype R/C hyperboloid cooling tower has a total height of 220 m, a span of 188 m in diameter on the foundation, a span of 169 m in diameter at the transition of columns to shell, a span of 107 m at the throat section and a span of 110 m in diameter at the top. The total elevation from the grade for the X shaped column is 28.7 m. The columns have a dimension of 1.6 m by 0.9 m and the thickness does not vary throughout the height. They were built on the concrete supporting piers with the dimension of 4.0m High by 4.0m wide by 3.5m thick. The thickness of the shell varies from 1.7 m close to the columns top end to 0.45 m at an elevation of 38.6 m. From there, it decreases to 0.4 m at the elevation of 165.3 m, and the keep 0.4 m to the elevation of 214.6 m, then it increase to 0.65 m at the top. The cooling tower is built on a ring strip foundation, which is 4.0 m below grade and with a width of 14.0 m and an average height of 2.0 m. A concrete stiffening ring (or transient ring) with a thickness and width of 0.40 m and 1.7 m is built together with the upper tower shell at the top of the X shaped columns. As well, a concrete stiffening ring (or top ring) with a thickness and width of 0.45 m and 1.8 m, respectively, has been built at the top of the cooling tower. Fig. 1 shows the elevation plan of the R/C cooling tower.

The material properties of the cooling tower including the concrete and reinforcement are shown in Table 2.1.

Table 2.1. Material properties of the R/C cooling tower

Material	Yield point (MPa)	Ultimate point (MPa)
Concrete	--	45
Reinforcement	335	445

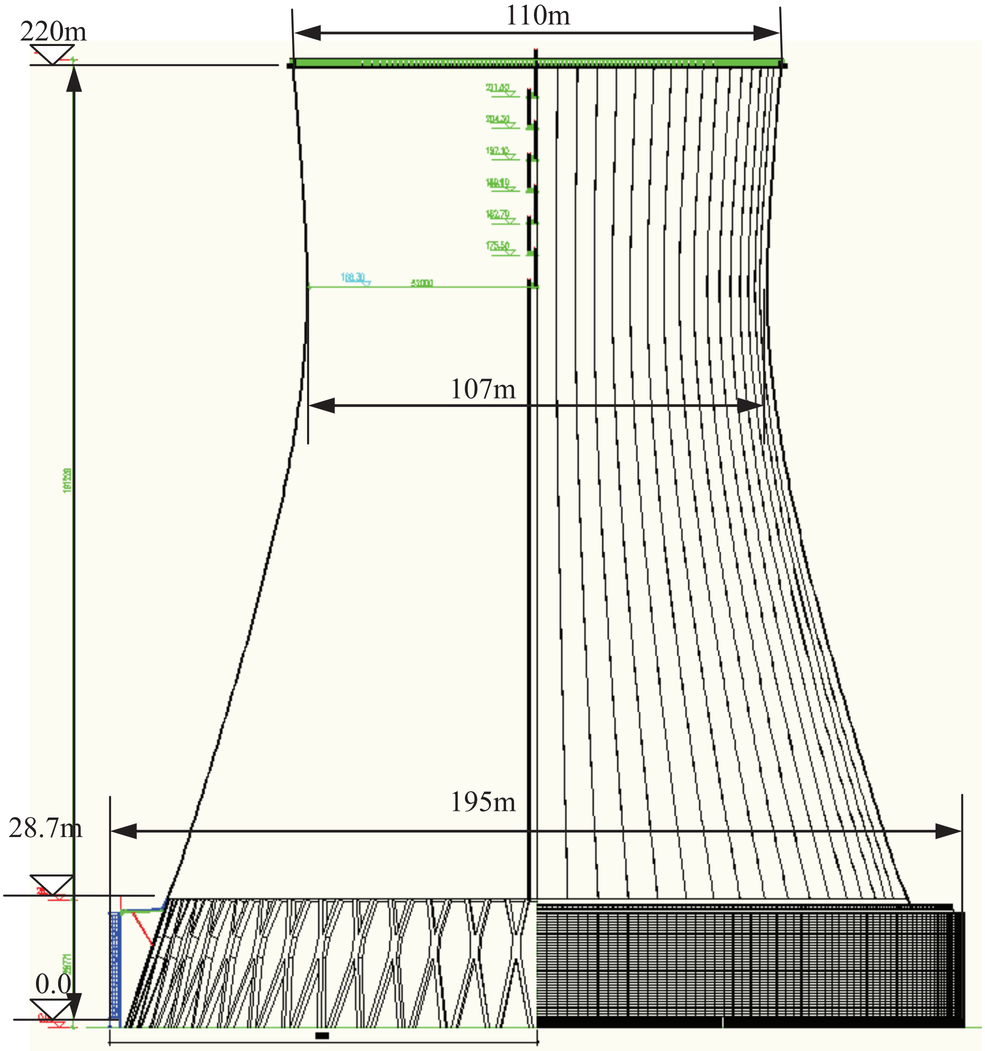


Figure 1. Elevation of the prototype cooling tower

2.2. Design and Construction of the Model Structure with Length Ratio 1:30

All structural elements including the X shaped supporting columns, tower shell and the column supporting piers are scale down to 1:30 of the prototype tower in geometric dimension. The vital corresponding dimensions are shown in table 2.2. As in known, in the dynamic shaking table test for small ratio model structures, due to the dimension scale down, the mass missing will cause significant inertial force loss and bring inevitable error to the test results. For compensating of the mass loss, artificial mass usually has to be used in the test. However, due to the special shape and structure of the hyperboloid shell tower, it's difficult to add the artificial mass on the model's shell during the dynamic earthquake simulation test. For solving this problem, in design and construction of the tower model, a kind of specially treated lead sand was used as one of the main aggregates of the model micro-concrete. The micro-concrete's equivalent mass density reaches up to about 6700Kg/m^3 by mixing with the lead sand, almost 3 times of the common micro-concrete's mass density. The similar design for reinforcements in all structural elements is controlled by the reinforcement ratio. As result, the number of reinforcement bars is decreased significantly for considering of the construction convenience. For example, the longitudinal reinforcement bars number in X shaped column decreases from the prototype $60\Phi36$ to the model $2\Phi6+2\Phi2$. Correspondingly, in the dimensional analysis of the similitude law for dynamic test, the equivalent density ratio, length ratio as well as the efficient elastic modulus ratio can be set as the basic variables, and other variables such as acceleration, frequency and time etc. could be derived from the dynamics formulation easily, shown in table 2.3.

Table 2.2. Dimension scaling of the cooling tower structure

No.	Critical index	Dimension of the structure	
		Prototype tower	1:30 model tower
1	Overall height	220m	7333mm
2	Diameter at throat level	107 m	3567mm
3	Diameter at the foundation top	188 m	6267mm
4	Sealing structure edge	195 m	6500mm
5	Height at the top of X shaped column	28.7 m	957mm
6	Max./Min. thickness of the tower shell	1700mm/400mm	57mm/13mm
7	Height of the column supporting pier	4000mm	133mm
8	Thickness of the ring foundation	2000mm	67mm
9	Absolute overall height	226m	7533mm

Table 2.3. Similitude relationship used in dynamic test and finite element analysis for model structure

Physical parameters	Similitude ratio		
	Lower excitation	Medium excitation	Large excitation
Length	l_r	l_r	l_r
Equivalent modulus	E_{r0}	$E_{r1}=\frac{E_{r0}f_1^2}{f_0^2}$	$E_{ri}=\frac{E_{r0}f_i^2}{f_0^2}$
Density	ρ_r	ρ_r	ρ_r
Stress	$\sigma_r=E_{r0}$	$\sigma_r=E_{r1}$	$\sigma_r=E_{ri}$

Time	$t_r = l_r (\frac{E_{r0}}{\rho_r})^{-0.5}$	$t_r = l_r (\frac{E_{r1}}{\rho_r})^{-0.5}$	$t_r = l_r (\frac{E_{ri}}{\rho_r})^{-0.5}$
Deformation	$r_r = l_r$	$r_r = l_r$	$r_r = l_r$
Velocity	$\upsilon_r = (\frac{E_{r0}}{\rho_r})^{0.5}$	$\upsilon_r = (\frac{E_{r1}}{\rho_r})^{0.5}$	$\upsilon_r = (\frac{E_{ri}}{\rho_r})^{0.5}$
Acceleration	$a_r = \frac{E_{r0}}{l_r \rho_r}$	$a_r = \frac{E_{r1}}{l_r \rho_r}$	$a_r = \frac{E_{ri}}{l_r \rho_r}$
Frequency	$\omega_r = l_r^{-1} (\frac{E_{r0}}{\rho_r})^{0.5}$	$\omega_r = l_r^{-1} (\frac{E_{r1}}{\rho_r})^{0.5}$	$\omega_r = l_r^{-1} (\frac{E_{ri}}{\rho_r})^{0.5}$

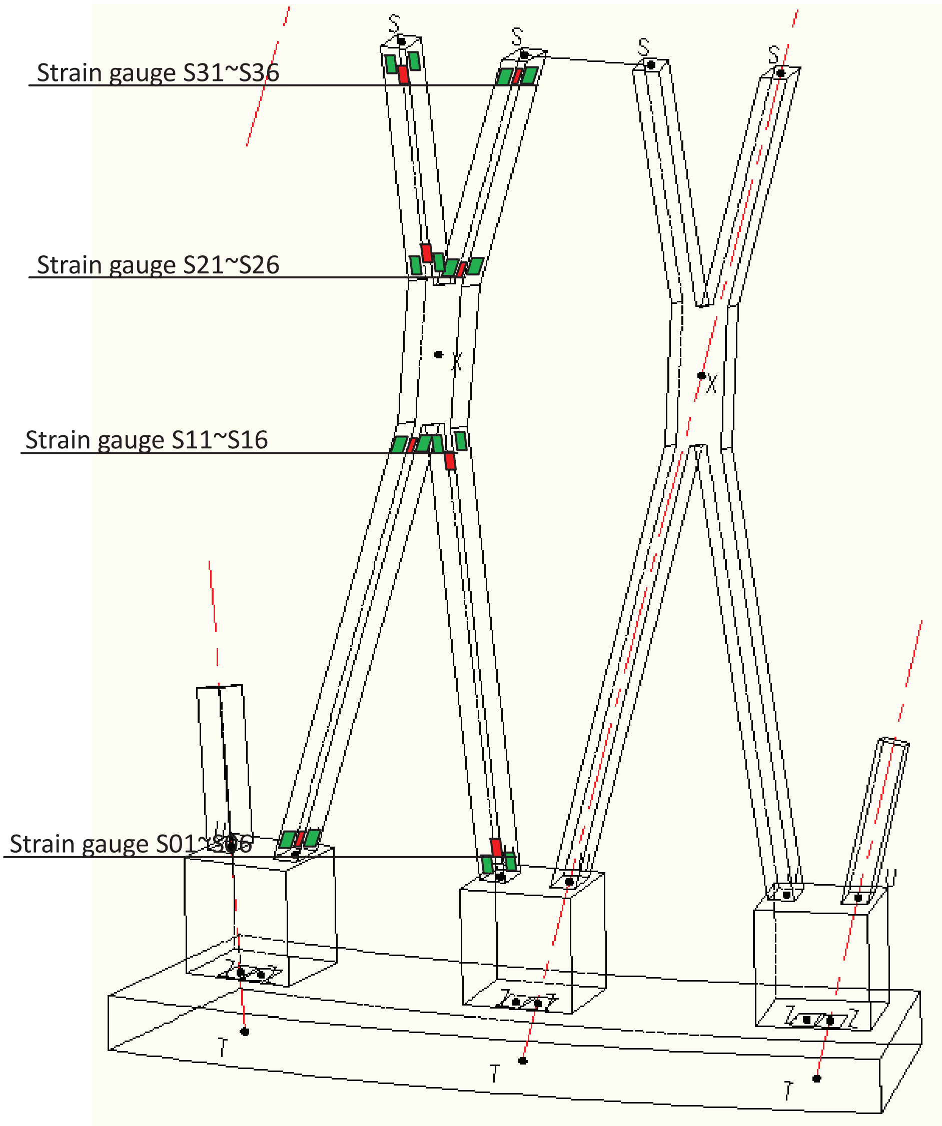


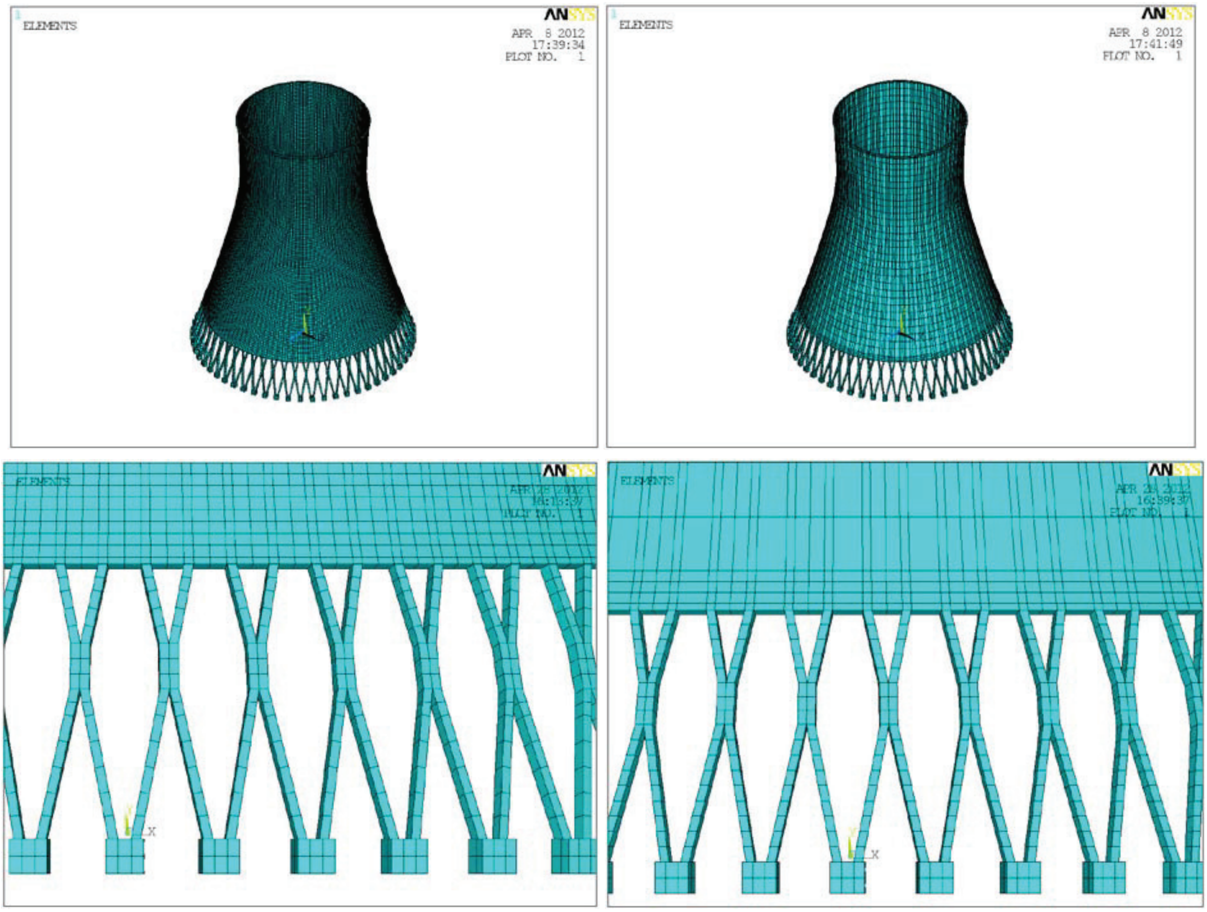
Figure 2. X shaped column and the supporting piers, ring foundation

Figure 3. Construction of the 1:30 model cooling tower structure to be tested on shaking table

3. □inite □lement □nalyses for □oth of the Prototype and 1:30 Model Tower

Due to the fact of there is no accurate nonlinear similitude law available for dynamic test and the uncertainty of most laboratory tests, the results obtained from the shaking table test only can be used qualitatively and very difficult to be used directly to compare with the prototype structure design and analysis quantitatively. Therefore, for establishing the relative accurate quantitative relationship for the linear and nonlinear dynamic response between the prototype and the model structure, it's very necessary to do the nonlinear dynamic analysis for both of the prototype structure and its' dimension scale-down model counterpart simultaneously. It's expected to through the comparison of the results between the numerical analyses and the shaking table test, verify and enhance the reliability of the nonlinear analyses for the 1:30 model structure, and then compare with the analytical results for the prototype structure, transfer the dynamic test results for the 1:30 model to the prototype structure quantitatively.

To perform the seismic response analyses for both of the prototype and its' 1:30 model tower, two softwares were used in the study. The first applied software is the commercial software ANSYS Version 14.0. The modal analyses, dead load analyses as well as the linear analyses for the earthquake spectrum response of the both structures were carried out. The LS-DYNA version 14.0 was used to perform the dynamic nonlinear analysis for both of the prototype and model tower structure under strong earthquake excitations (will be presented in the conference together with the shaking table test results). The structural members including column supporting piers, X shaped columns, tower shell were all modeled with solid elements, as shown in fig.4. The reinforcement ratio at different height is taken into account in the column meshing scheme for both of the prototype and model structure. The difference is in the finite element meshing for the tower shell. That is for the prototype tower, the meshing size for the shell is controlled by the height of construction template each layer (1.3m high, totally 150 layers), but for the 1:30 model structure, for enhancing the calculating speed effectively, most upper shell is meshed with 1/6 of the height of the corresponding prototype elements except for the shell close to the columns top (4 layers), with 1/30 of the size of the prototype elements. The freedom coupling was used to make sure the effective connection between the X shaped columns and their supporting piers.



a) Prototype tower b) 1:30 Model tower

Figure 4. Finite element meshing for the prototype tower and its' 1:30 model structure

3.1. Comparison of the Modal □nalysis □etween Prototype and □ts□1:30 Model Tower

For understanding the dynamic characteristics of the cooling tower structure, the modal analyses were carried out for both of the prototype tower and its' 1:30 model structure respectively. Although there are some difference for the element meshing between the prototype and its' scale-down model, from fig.5 and table 3.1, it can be seen that the vibration mode is quite similar with each other. As example, only the first 3 modes and the 31st mode were listed in fig.5 for comparison.

Table 3.1. Comparison of the modal analyses results for prototype tower and its' 1:30 model

Mode	Frequency of the 1:30 model tower (Hz)	Frequency of the 1:30 model tower (Hz)	Similitude ratio
1	10.01911	0.648679	15.445412
3	10.62728	0.689223	15.419225
5	10.66332	0.700281	15.227199
7	11.58211	0.765836	15.123478
9	14.09556	0.928196	15.185974
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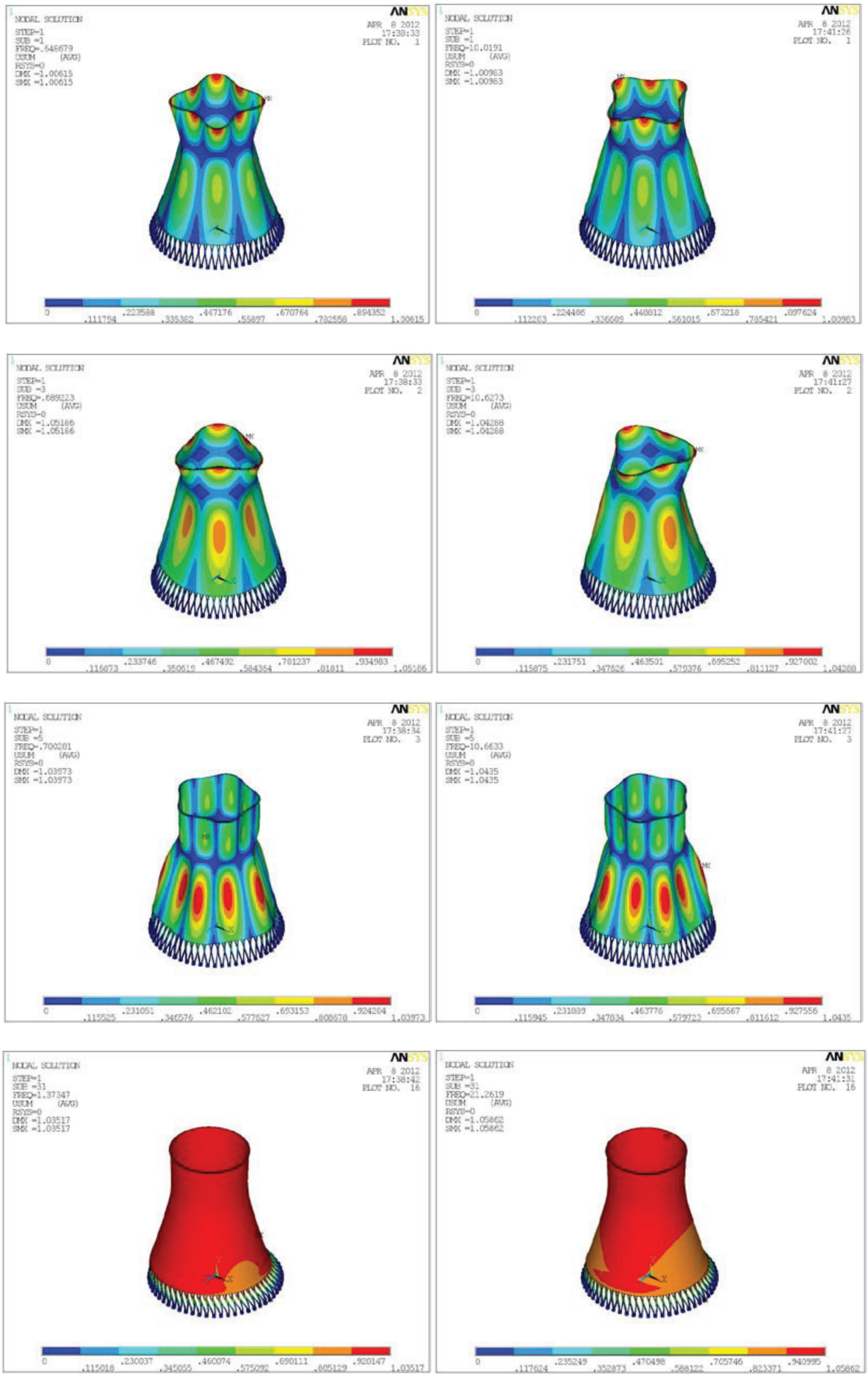
31	21.26193	1.373466	15.480494

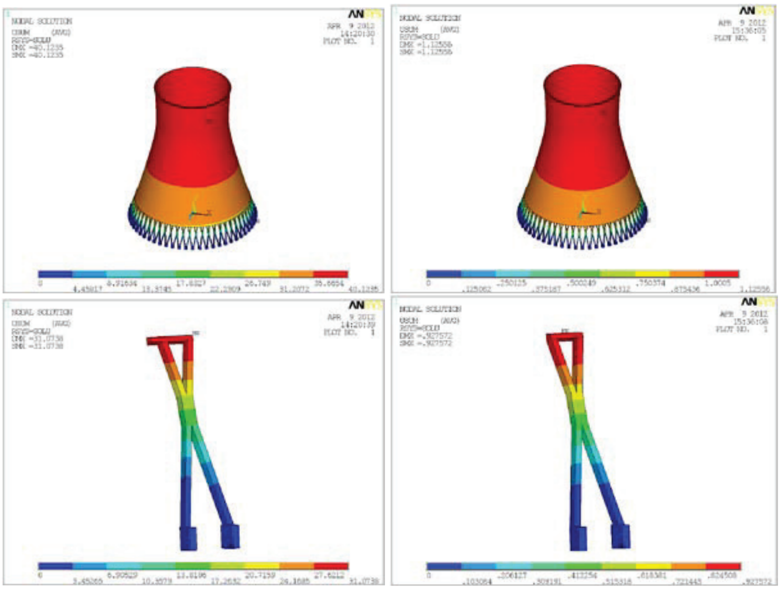


a) Prototype tower b) 1:30 Model tower

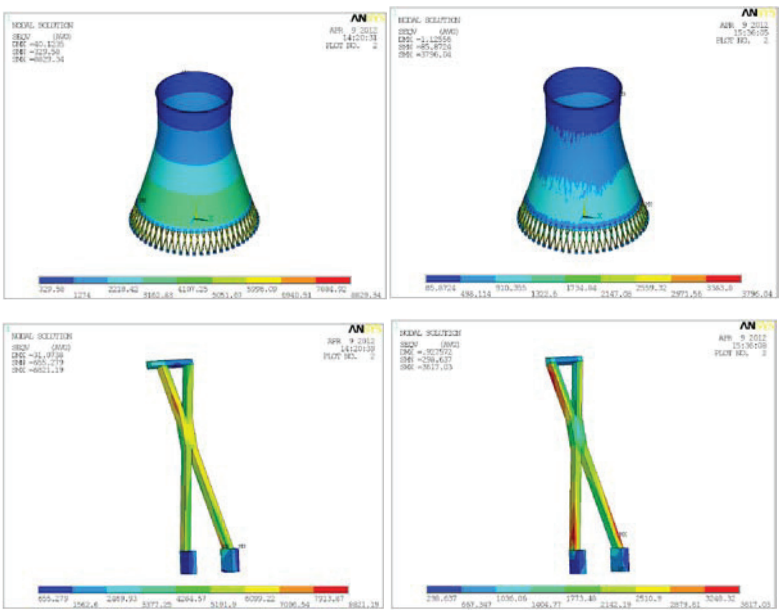
Figure 5. Comparison of part vibration modes of the prototype tower and its' 1:30 model structure

3.2. Response Spectrum □nalysis for the Prototype and □ts□1:30 Model Tower

For estimating the overall seismic capacity of the cooling tower, the first step should be check the results of the response spectrum analysis (RSA) under the seismic design intensity 8 in Chinese earthquake intensity scale. For considering the most disadvantage case, this paper chooses the most disadvantage site class IV (soft soil with shear velocity no larger than 150m/sec., with prominent period 0.65sec, which is almost the same with the first vibration mode's natural period 0.65sec of the prototype tower.) as one of the conditions to determine the input spectrum. In the RSA the dead load (weight) is also taken into account. For comparing, the analytical results for deformation and stress for both of the prototype and its' 1:30 model are abstracted in the fig.6 and table 3.2~3.3., respectively.



Equivalent deformation contour



Equivalent Von-Mises stress contour

a) Prototype tower b) 1:30 Model tower

Figure 6. Comparison of the RSA results for prototype and its' 1:30 model structure

Table 3.2. Maximum deformation response (response spectrum + dead load)（mm）

Load case	Prototype	1:30 model	Solution ratio	Design ratio	Solution/design ratio
Dead load only	17.3483	0.077027	0.00444	0.033333	0.133201
Horizontal RS	78.9246	2.47151	0.031315	0.033333	0.939446
Vertical RS	5.92809	0.168633	0.028446	0.033333	0.853394
Standard EQ. RS	27.6923	0.866988	0.031308	0.033333	0.939238
Dead load plus RS	40.1235	1.12556	0.028052	0.033333	0.841572

Table 3.2. Maximum Von-Mises stress response (response spectrum + dead load)（N/mm^2）

Load case	Prototype	1:30 model	Solution ratio	Design ratio	Solution/design ratio
Dead load only	6921.01	475.816	0.06875	0.537	0.128025
Horizontal RS	17130.1	8479.2	0.494988	0.537	0.921766
Vertical RS	1589.83	749.591	0.471491	0.537	0.87801
Standard EQ. RS	6017.37	2978.31	0.494952	0.537	0.921699
Dead load plus RS	8829.34	3796.04	0.429935	0.537	0.800623

CONCLUDING REMARKS

In summary, due to the papers limitation, this paper here only provides basic research activities and preliminary results for both of the prototype cooling tower and its' 1:30 model very briefly. The preliminary study shows that there huge of analytical and test researches should be carried out for understanding the accurate earthquake response of the extra-huge cooling tower. The results for both of the nonlinear dynamic analysis and the shaking table test as well as the comparison analyses will be reported in the following papers and in the oral presentation of the 15WCEE.

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