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Aeroelastic Model Test and Field Measurement of 40-m High Lattice Tower

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Abstract

Lattice tower structure is one of the most vulnerable structures under typhoon disasters. Based on the wind engineering research field laboratory of Tongji University near Shanghai Pudong International Airport, the mean wind speeds and wind directions at 10 m height as well as the accelerations at 40 m height of a lattice tower were collected under the influence of Typhoons Neoguri and Nakri in 2014. Then, the acceleration responses and the dynamic characteristics of the lattice tower were analysed. Regarding the 40 m high lattice tower as the prototype, an aeroelastic model, which can precisely simulate the dynamic characteristics of the lattice tower, was made by using the discrete stiffness method. Through wind tunnel test of the aeroelastic model, the fluctuating acceleration responses of the tower were studied and compared with the results of field measurement. The results in the wind tunnel test agree well with the field-measured data, which verifies the accuracy of the aeroelastic model.

Keywords: Lattice tower structure; Aeroelastic model test; Discrete stiffness method; Wind tunnel test; Field measurement.

0 Introduction

Lattice tower structure is a kind of hollow structures, which has sophisticated three-dimensional (along-wind, across-wind and torsional direction) wind-induced vibration mechanisms. Although researchers all over the world have done a lot of work on the wind resistance of lattice tower structures, there is still not an explicit design method at present. The general research methods about the lattice tower are wind tunnel test and numerical simulation, while the field measurement of wind-induced vibration responses of tower structures is relatively rare due to the cost and time involved in such measurement. The existing field measurement studies mainly focus on the near-surface wind characteristics [7] as well as the along-wind loads and responses of lattice structures [2,3]. However, to date, no consistent agreement has been reached among researchers on the across-wind loads, the torsional loads and the response theory. In particular, the existing studies on wind-induced responses of lattice towers under typhoons or other strong wind events are still in a preliminary stage [4,5]. In this paper, the mean wind speeds and wind directions at 10 m height as well as the accelerations at 40 m height of a lattice tower were collected. The acceleration responses and the dynamic characteristics of the lattice tower under Typhoons Neoguri and Nakri were analysed. Through wind tunnel test of the aeroelastic model, the fluctuating acceleration responses of the lattice tower were studied and compared with the results of field measurement.

1 Profile of field laboratory and field measurement

1.1 Introduction of field laboratory and typhoon

A wind engineering research field laboratory has been set up by State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University. It consists of a 40 m high lattice tower and a low-rise building with adjustable roof pitch.

In this paper, two typhoons in 2014 were selected to study. One of them, Typhoon Neoguri, happened on July 4th in the Northwest Pacific Ocean. It was strengthened from tropical storm to super typhoon and then decayed into typhoon on July 9th. The other one, Typhoon Nakri, which happened on July 17th on the sea surface of western Marshall Islands, was strengthened to tropical storm and then decayed into tropical depression on August 3rd.

The time histories of wind speed and wind direction at 10 m height as well as the wind-induced accelerations at 40 m height were collected during the typhoons. The steel-tube lattice tower and the layout of accelerometer are shown in Figure 1.

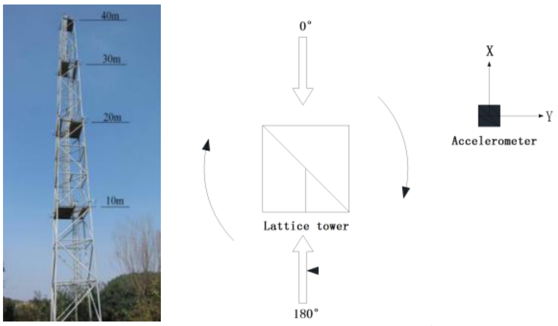


Figure 1. Steel-tube lattice tower and the layout of accelerometer

1.2 Mean wind speed and wind direction of the typhoon

The duration of wind load is specified as 10 minutes in Chinese load code [1], which is taken as the sampling time of the data in this paper. The time histories of wind speed and wind direction of Typhoon Neoguri and Nakri are shown in Figures 2 and 3, respectively.

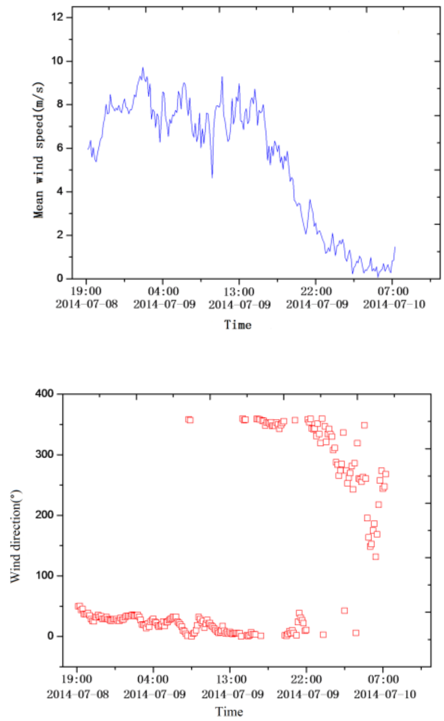


Figure 2. Wind speed and wind direction vs. time of Typhoon Neoguri

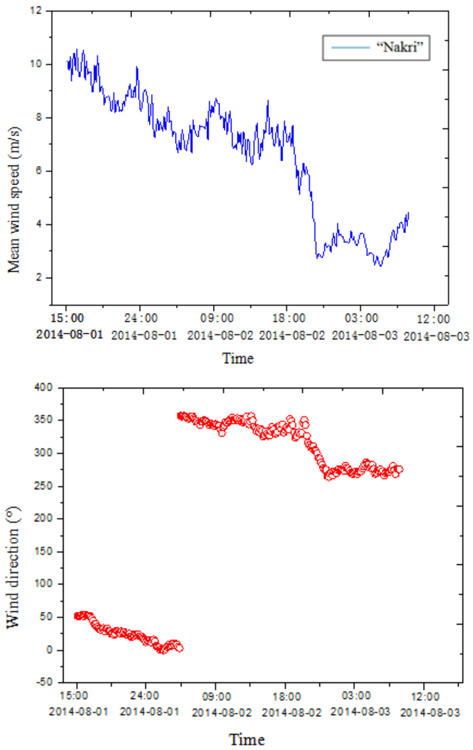
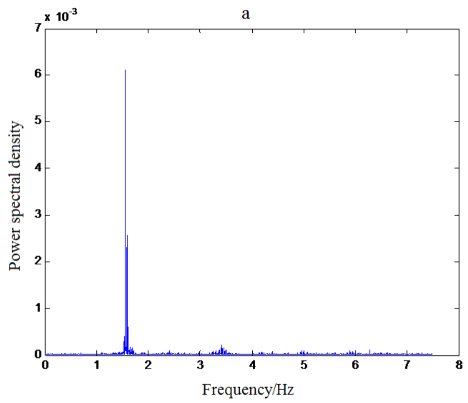


Figure 3. Wind speed and wind direction vs. time of Typhoon Nakri

1.3 Field-measured dynamic characterization of the tower

Figure 4 shows the acceleration power spectral densities of X and Y directions at 40 m height of the tower. It can be seen that under the influence of strong wind, vibrations of the tower depend on the first-order natural frequencies, which in X direction and Y direction are 1.580 Hz and 1.564 Hz, respectively.



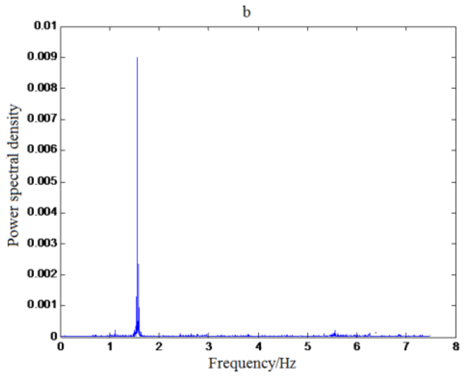


Figure 4. Power spectrum of the (a) X-axial (b) Y-axial acceleration

2 Profile of wind tunnel test

2.1 Design of aeroelastic model

The aeroelastic model is difficult to make, but it has a more precise simulation of the actual wind-induced vibrations of the structure [6]. In the present study, there are mainly two kinds of aeroelastic model design methods: the concentrated stiffness method and the discrete stiffness method. Since the concentrated stiffness method doesn't take into account the twisting effect of the model, the discrete stiffness method was used for the aeroelastic model production in this experiment, which can simulate both geometry and stiffness of the model rods.

The aeroelastic model should meet the requirements of several similarity ratios including stiffness similarity ratio, geometric similarity ratio, Strouhal number similarity ratio, mass similarity ratio and damping similarity ratio. Values of these similarity ratios are shown in Table 1.

The main steps to produce the aeroelastic model are shown as follows: (1) Calculate the axial tension and compression stiffness (EA) of each prototype rod to derive the stiffness of the model rods according to the theoretical similarity ratios. Solid round rods are used for the production because tube rods are difficult to manufacture, and ABS plastic is used as the materials to simulate the actual stiffness of the prototype rods. (2) Wrap the "no stiffness" foam paper around each model rod to make sure they are similar to prototype rods in shape, which makes the aeroelastic model to satisfy the similarity ratios of stiffness and shape. (3) After the main body of the model is finished, adjust the total mass of the model using lead blocks until the mass similarity ratio is satisfied. At the same time, make the natural frequencies of X and Y directions of the model to satisfy the frequency similarity ratio by adjusting mass of the leads at different heights of the model.

The natural frequency of the model was obtained by knocking test. The test results shown in Table 2 indicate that the model meets the requirements of the similarity ratios mentioned above.

Similar parameter	Geometric similarity ratio	Mass similarity ratio	Stiffness similarity ratio	Frequency similarity ratio	Wind speed ratio
Value	1:25	1:15625	1:15625	5:1	1:5

Table 1. Similarity ratios of the aeroelastic model

	Frequency			Mass		
Direction	Prototype value	Expected value	Model value	Prototype value	Expected value	Model value
X-axis	1.603	8.013	8.057	10180kg	651.52g	651.84g
Y-axis	1.590	7.950	7.996			

Table 2. Results of model knocking test

2.2 Conditions of wind tunnel test

Wind tunnel test of the aeroelastic model was carried in the TJ-3 Boundary Layer Wind Tunnel of Tongji University. Since the tower is close to the seaside, the wind profile is simulated as Exposure A according to Chinese code. The turbulence intensities equal to 10% and 20% at 10 m above the ground are selected to analyse their influence on the responses of the lattice tower. The test wind speeds were selected as 2, 3, 4, 5, 6, 7, 8, 9, and 10 m/s respectively, and the wind directions are shown in Figure 5(b). Four three-directional accelerometers, which can simultaneously record the acceleration time histories in X, Y and Z directions were installed on the model at the heights equivalent to 10, 20, 30 and 40 meters of the prototype tower, respectively. The lattice tower model is shown in Figure 5(a).

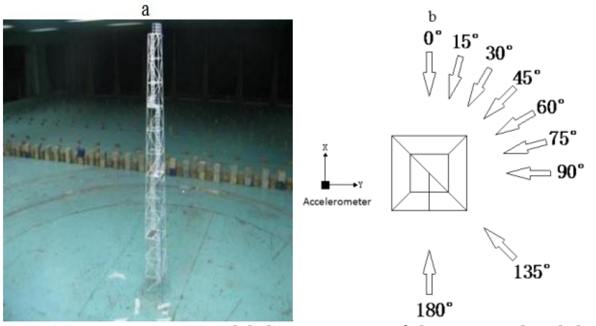


Figure 5. (a) Lattice tower model (b) Directions of the test wind and the accelerometer

3 Analysis of wind tunnel test result

3.1 Characterization of RMS acceleration vs. wind speed

Figures 6(a)-(d) show the relationship between the RMS acceleration of the aeroelastic model and the test wind speed with 10% turbulence intensity in wind directions of 0°, 45°, 90° and 180°, respectively.

In Figure 6, one can see that the difference of RMS acceleration between X and Y directions is small no matter which wind direction is when the test wind speed is 2~6 m/s, which means that the vibration responses in X and Y directions are highly coupled at low wind speed. When the test wind speed is 6 m/s or higher, there will be a relatively significant difference on the acceleration responses between X and Y directions because of their different natural frequencies. The acceleration responses of Y-axis, whose first-order natural frequency is lower, are larger than that of X-axis, which indicates that the direction of lattice structure with a lower first-order natural frequency dominates the structural vibration process. Comparing the acceleration responses in 0° direction to that in 180° wind directions, it can be found that the acceleration responses of both X and Y directions in 0° wind direction are greater than that in 180° wind direction, which may be attributed to the different locations of stairs in 0° and 180° wind directions.

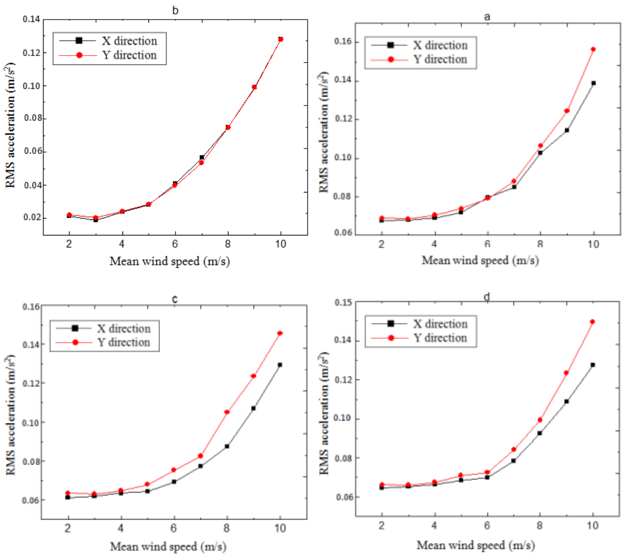


Figure 6. RMS acceleration in X and Y directions vs. mean wind speed in (a) 0° (b) 45° (c) 90° (d) 180° wind directions

3.2 Characterization of RMS acceleration vs. wind direction

Since the RMS accelerations in X and Y directions have distinct difference at relatively high wind speed, two test cases (designated herein as Case One and Case Two) associated with the RMS accelerations at top of the tower were selected to study in detail. The Case One is 10 m/s wind speed with 10% turbulence intensity, and the Case Two is 8 m/s wind speed with 20% turbulence intensity. The results of two cases are shown in Figure 7. It can be seen that the wind directions with the maxmum acceleration response in X and Y directions differ under two kinds of turbulence intensities. In Case One, the maxmum acceleration of Y direction appears in 15° wind direction while the maxmum acceleration of X direction happens in 75° direction. In Case Two, the maxmum acceleration of Y direction appears in 30° wind direction while the maxmum acceleration of X direction happens in 75° direction. Figure 7 also shows that the change of RMS accelerations in Y direction is more significant than that in X direction. The reason is that Y direction of the tower, which has a lower first-order natural frequency, is more sensitive to the variation of wind direction.

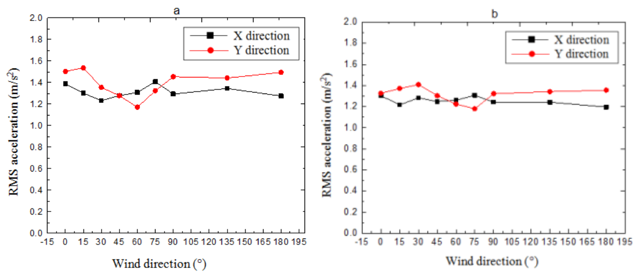
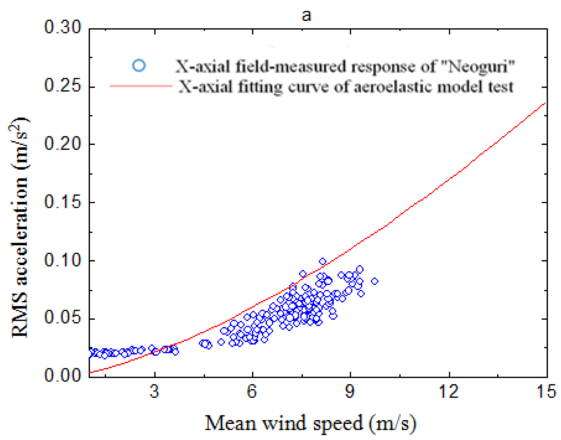


Figure 7. RMS acceleration at top of the tower vs. wind direction (a) in wind field with 10% turbulence intensity at 10m/s wind speed and (b) in wind field with 20% turbulence intensity at 8m/s wind speed

3.3 Comparison of RMS accelerations in wind tunnel test with those in field measurement

Figures 8 and 9 show the comparisons of acceleration responses versus mean wind speeds in field measurement to those in aeroelastic model test, which indicates that the two kinds of results agree well and the RMS acceleration increases with the increase of wind speed. When the wind speeds are more than 3 m/s, the test values are a bit larger than the field-measured values. While when the wind speeds are less than 3 m/s, the test values are slightly smaller than the field-measured values. This phenomenon may be attributed to the following reasons: (1) the Reynolds number of wind tunnel test cannot be simulated exactly the same as that of field measurement; (2) the near-surface wind characteristics of field measurement and wind tunnel test have some differences; (3) the actual ambient noise will have an impact on the results of field measurement.



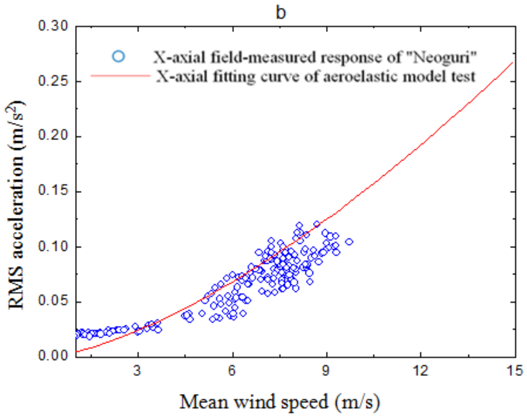


Figure 8. Acceleration responses vs. mean wind speed in field measurement under Typhoon Neoguri and in aeroelastic test: (a) X-axis and (b) Y-axis

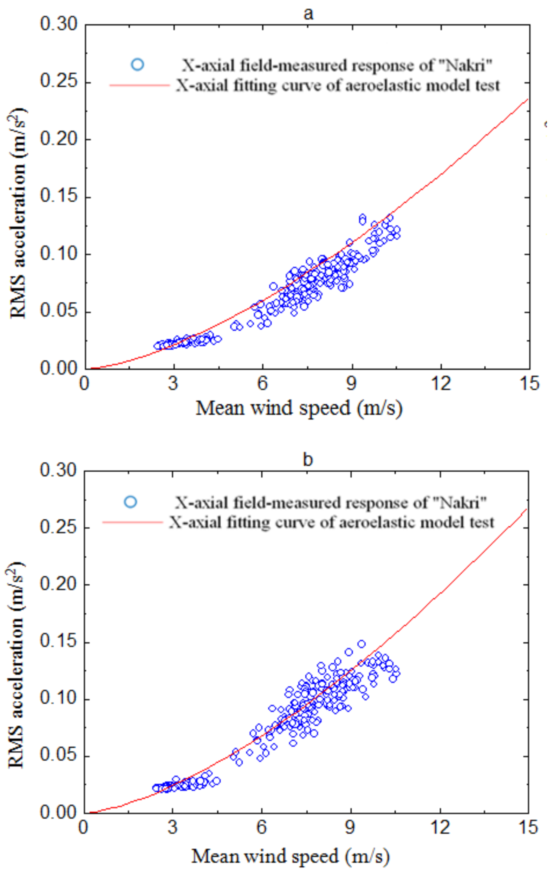


Figure 9. Acceleration responses vs. mean wind speed in field measurement under Typhoon Nakri and in aeroelastic test: (a) X-axis and (b) Y-axis

4 Conclusions

Based on the field-measured data of 40 m high lattice tower in the wind engineering research field laboratory of Tongji University and the aeroelastic model results in wind tunnel test, the following conclusions can be obtained:

(1) Comparing the data of field measurement and the results of wind tunnel test, the two kinds of results agree well, which means the aeroelastic model can precisely simulate the dynamic characteristics of the prototype lattice tower by using the discrete stiffness method.

(2) The values of accelerations of the tower in X and Y directions are close at low wind speed, while those of Y-axis are larger than those of X-axis at high wind speed, which indicates that the vibration modes of the lattice tower in X and Y directions are highly coupled at low wind speed, while the responses of Y-axis with a lower first-order natural frequency dominate the structural vibration process when the wind speed is relatively high.

5 Acknowledgements

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6 References

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