The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28-September 1, 2016

Effects of Additional Diaphragms on the Wind-Resistant Performance of Power Transmission Tower

*Yunzhu Cai[1], Qiang Xie[2], Songtao Xue[2]

[1) 2)] *School of Civil Engineering, Tongji University, 200092 Shanghai, China*

* *2014caiyunzhu@tongji.edu.cn*

ABSTRACT

By field investigation, it is found that the lower section of transmission tower body is the critical position for insuring tower's integral stability under strong wind. For improving tower's wind-resistant performance, the scheme of adding diaphragms at mid-height of diagonal members in lower tower body was proposed and its static effectiveness was researched by static loading tests. Taking the tower-line system into consideration, this paper explores the scheme's dynamic effectiveness by wind tunnel test and numerical simulation. Two types of tower model are involved in the wind tunnel test: one is with additional diaphragms at lower panels of tower body, the other is without. Test results indicate additional diaphragms can not only promote tower's wind-resistant capacity but also change its dynamic failure mode. Based on ABAQUS platform, numerical calculation shows diaphragms can effectively weaken and change tower's local vibration. For balancing steel dosage, an upgrade scheme for adding diaphragms is introduced. Numerical results indicate the new scheme achieves the unity of low steel consumption, well-controlled local vibration and unaltered stress level for adjacent members.

1. INTRODUCTION

As one component of electric power grid, the power transmission tower line system is widely concerned by researchers and engineers due to its significance to keep power system functioning well and its particularity in term of structure. The transmission tower is one kind of wind-sensitive structures and the situation will become more adverse when transmission wires characterized with strong non-linearity are connected to it and work together under wind. Moreover, with the increase of voltage class and line span, transmission towers become higher and types for conductors are more diverse, which requires more researches and techniques to insure the tower's safety and reliability.

[1)] Graduate Student
[2)] Professor

Due to tough site conditions and technical difficulties about sensors and data collection, field monitoring is not easy and the relevant data are quite precious for research (Momomura 1997, Mayumi 2010). With the continuous improvement of test techniques and theories, wind tunnel test becomes popular in China. By means of the base balance technique, Liang and Zou et al. (2007) studied the lattice towers under three-dimensional dynamic wind load by wind tunnel test; Deng et al. (2013) did a comparative research on wind-induced responses of single tower and tower-line coupling system by wind tunnel test.

Wind disasters to transmission towers are common in China, both in coastal and inland areas, because of the changeable climates and complex landform. The collapse accidents of 500kV transmission tower in inland regions are concerned in the paper. Part of significant accidents are listed. The damage of transmission tower indicates the lower section of tower body are the critical part for insuring tower's ultimate dynamic stability and diaphragms' function of improving tower's wind-resistant capacity is underestimated. Wind tunnel test to the aero-elastic model of a 500kV transmission tower line system is implemented for investigating the tower's wind-resistant performance when setting and not setting additional diaphragms at mid-height of diagonal members in lower tower body. For balancing steel consumption, an upgrade scheme for adding diaphragms is proposed and the tower's local vibration properties before and after retrofit are obtained by numerical simulation.

2. WIND-INDUCED COLLAPSE ACCIDENTS OF 500kV TRANSMISSION TOWER

500kV transmission lines have been the backbone of power grid in China. Their anti-wind capacity is always concerned due to frequently wind disasters to them. In severe cases, some transmission line towers collapse, which causes regional power outage and demands much more time for restoration. Table 1 shows the main collapse accidents of 500kV transmission tower in recent decades in China. In coastal areas, due to typhoon's frequently landing, 500kV lines have mostly been retrofitted with the steel tube tower that owns better wind-resistant performance. In some inland areas, extreme wind occurs occasionally due to the climate and terrain, but many 500kV transmission towers are still the angle-steel tower. This leads to more collapse accidents in inland areas than in coastal areas.

Table 1. Collapse accidents of 500kV transmission tower caused by strong wind

Time	Location	Wind Type	Quantity	Cumulant
1989	Jiangsu Zhenjiang	Downburst	8	8
1992-1993	Hubei	-	7	15
1998	Jiangsu Yangzhou	Downburst	4	19
2000	Jilin	Tornado	10	29
2005	Jiangsu Yutai	Tornado	8	37
2005	Jiangsu Siyang	Downburst	10	47
2007	Henan Kaifeng	Tornado	6	53
2009	Jiangsu Zhenjiang	Severe storm	6	59
2009	Hebei Xingtai	Severe storm	8	67

2014	Guangdong Shanwei	Typhoon	1	68

By field investigation, it was considered that most 500kV angle-steel towers collapsing in wind disasters could be imporved by adding diaphragms to tower body especially in lower sections. From Fig. 1(ab), it was found that instead of tower legs' buckling, the damage occurred among the 2nd to 4th panels above the tower leg and the diagonal memebers in these panels failed completely. For the two failed lines, all the towers were not set with diaphragms at the lower tower body section. The tower in Fig. 1(c) was attacked by tornado and collapsed with 180-degree torsion. The lower section of tower body was destroyed severely while the upper section kept good because of the diaphragms set at the end and top of the section. Different from the towers in Fig. 1(ab), the damage position of the tower in Fig. 1(d) was upper due to the diaphragm set over the second panel above tower leg.

Most 500kV single-circuit towers in inland areas are lack of diaphragms in the lower section of tower body especially at the mid-height of diagonal members of each panel, the survey found. Static research found that the additional diaphragms at mid-height of diagonal members could effectively improve tower's mechanical property (Albermani 2003, Xie 2013). This paper will concentrate on its dynamic effectiveness for the tower by wind tunnel test and numerical simulation, which will be helpful to retrofit the existing towers as well as new ones.

(a) Jiangsu Siyang (2005)

(b) Heibei Xingtai (2009)

(c) Jiangsu Yutai (2005)

(d) Hebei Xingtai (2009) left: before collapse, right: after collapse

Fig. 1 Wind-induced collapse accidents of 500kV transmission tower

3. WIND TUNNEL TEST TO AERO-ELASTIC MODEL

3.1 Model Information

The prototype of the tower model is a typical 500kV single-circuit angle-steel tower in inland areas. The transmission line’s geometrical and material information are listed in Table 2.

Table 2. Primary information for the prototype of tower line system

Tower			Conductors			Ground wires	
Total height	Nominal height	Horizontal span	Type	Material	Sag	Material	Sag
48.5m	39m	400m	4-bundled	LHGJT-440	12.97m	GJ-169	11.68m

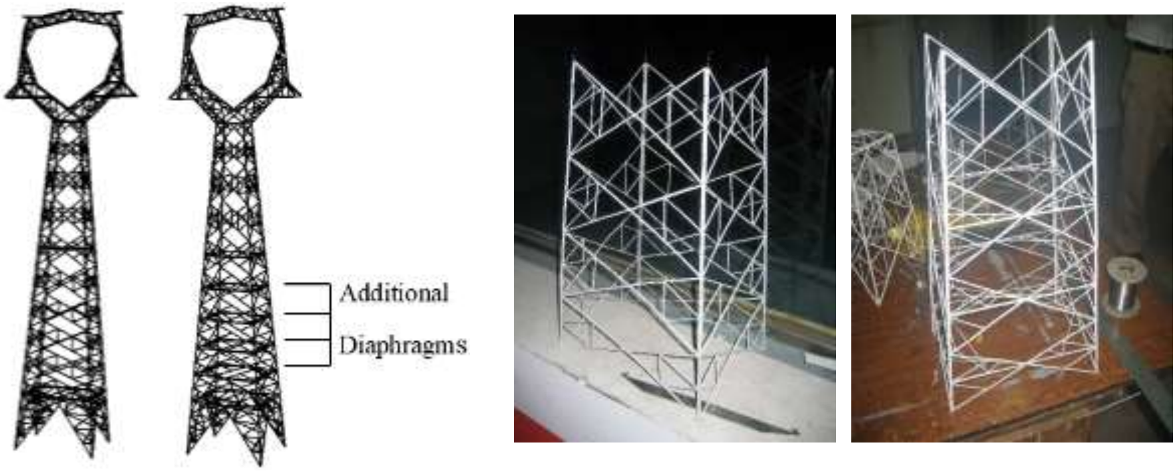
The test was implemented at TJ-3 wind tunnel affiliated to the State Key Laboratory of Civil Engineering Disaster Reduction in Tongji University (Fig. 2). According to the tunnel size, the geometric similarity ratio of tower model was set as 1:30 and that of wires (including conductors and ground wires) was 1:60 with the span correction coefficient of 0.5 (Loredo-Souza 2001). Insulator model’s similarity parameters were same as tower model. All the primary similarity parameters for the tower line model are shown in Table 3. Two types of tower model were involved in the test: one was with additional diaphragms at lower panels of tower body; the other was without (Fig. 3). This paper is concerned with the tower model’s wind-resistant performance before and after adding diaphragms.

Table 3. Primary similarity parameters for tower line model

Geometry				Stiffness		Mass	Freque ncy	Damp ratio	Wind speed
Tower	Span	Wire diameter	Sag	Tower member	Wire				
1:30	1:60	1:15	1:30	1:27,000	1:54,000	1:27,000	5.48:1	1:1	1:5.48

(a) Wind tunnel (b) Tower line model

Fig. 2 Wind tunnel and tower line model



(a) Whole model; left: without diaphragms, right: with diaphragms (b) Section model; left: without diaphragms, right: with diaphragms

Fig. 3 Two types of tower model

3.2 Loading Cases

The wind speed can be controlled ranging from 1.0 m/s to 17.6m/s. In the paper, just the wind direction that perpendicular to transmission line is considered. During the test, the mean wind speed started with 2m/s and increased by 0.5 m/s stepwise until the tower failed. The turbulence intensity was adjusted with fences, wedges and rows of rough blocks in the front of tunnel (Fig. 2a) and conformed to the national regulation about open terrain (GB 50009-2012). The tower line system was the object of loading and two types of tower model were involved during the test. Towers' top responses are concerned in following analysis: the cross-line and along-line displacement; the along-line and cross-line acceleration (Fig. 4).

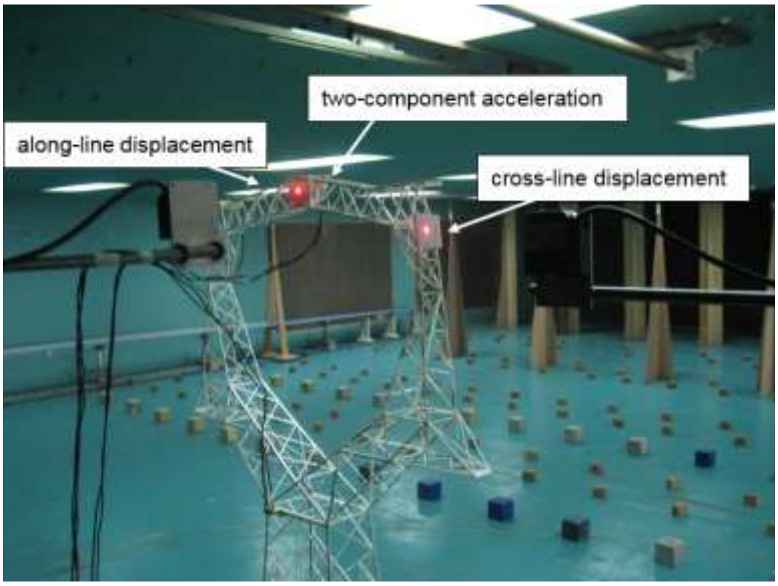


Fig. 4 Response measurement of tower top

3.3 Test Results

3.3.1 Tower Top Responses

Fig. 5 shows the top displacement of the two tower models, with and without additional diaphragms at lower tower body. According to the peak value, tower without additional diaphragms failed under the wind speed of 4.5m/s; the RMS also increased remarkably under this wind speed. While, the ultimate wind-resistant capacity of the tower with diaphragms reached 5.5m/s. When wind speed reached 6m/s, the tower deformed severely and no valid data was traced during test. In addition, Fig. 5 illustrates that though the cross-line displacement is larger than along-line displacement due to cross-line wind action, along-line response is large enough that cannot be ignored during structural analysis. When the wind speed increases to 3m/s, 3.5m/s and 4m/s, it is found the two towers' displacements are close which means additional diaphragms have no apparent effect on tower's integral response when the towers remain safe.

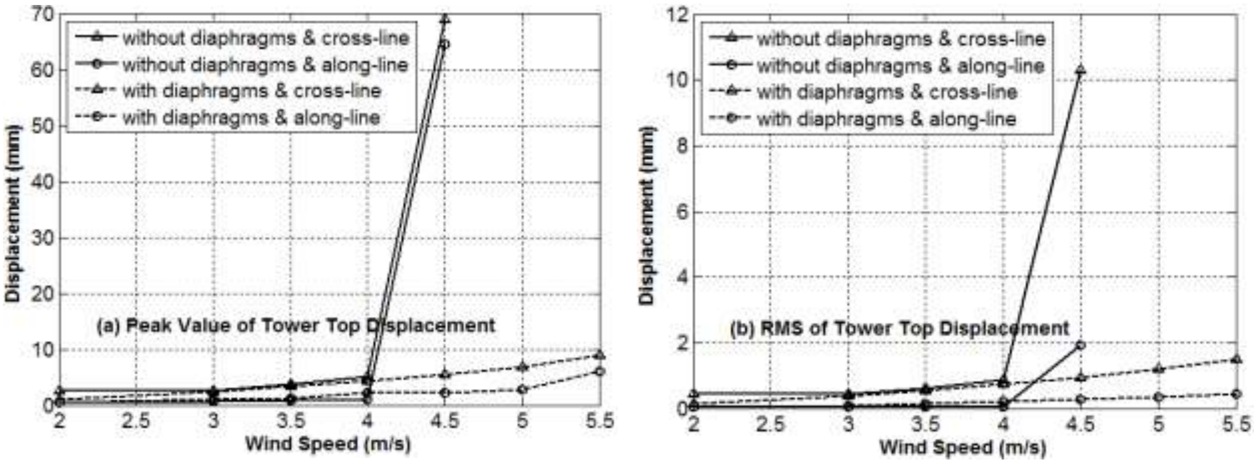


Figure 5 Top displacement of tower with and without additional diaphragms

In order to investigate the two towers' vibration property, the PSD of top displacement and acceleration is involved (Fig. 6-9). Before wind loading, the tower line system's natural vibration properties were tested (Table 4). The tower in Table 4 is without additional diaphragms.

Table 4 Tested natural vibration property of tower line model

Parameter	Tower with wires					wires			
	Cross-line		Along-line		Torsion	In plane		Out of plane	
	first	second	first	second		first	second	first	second
Frequency (Hz)	1.82	4.31	0.63	1.20	1.24	0.29	0.42	0.15	0.29
Damping ratios (%)	4.3	6.3	3.7	4.0	6.8	0.83	0.53	1.19	0.83

Fig. 6 shows that the two towers' cross-line vibration is similar and accordant with the wind field. But with the wind speed going up, the two towers' low-frequency vibration becomes obvious (Fig. 6d). Turning to the cross-line acceleration PSD (Fig. 7), it can be apparently known that except from the forced vibration, the two towers vibrate mainly based on their cross-line first-order mode. The cross-line first-order frequency of the tower with additional diaphragms is slightly larger than that of the tower without additional diaphragms. Moreover, the low-frequency vibration near 0.7Hz becomes strong with the growing wind speed especially for the tower without diaphragms. This vibration is induced by the wire's vibration. Therefore, it can be considered that as the wind speed increasing, tower's vibration is influenced more by wires and this influence is larger to the tower without additional diaphragms.

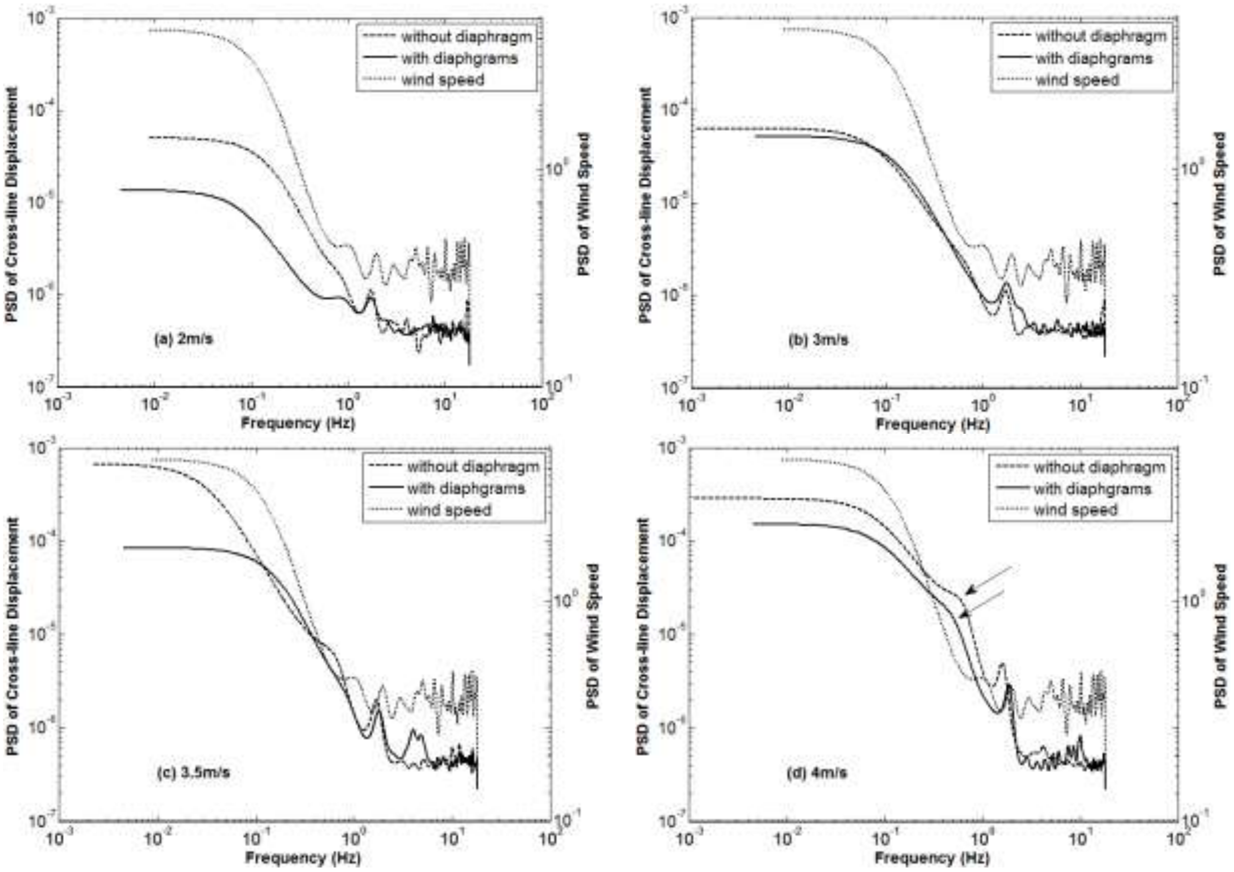
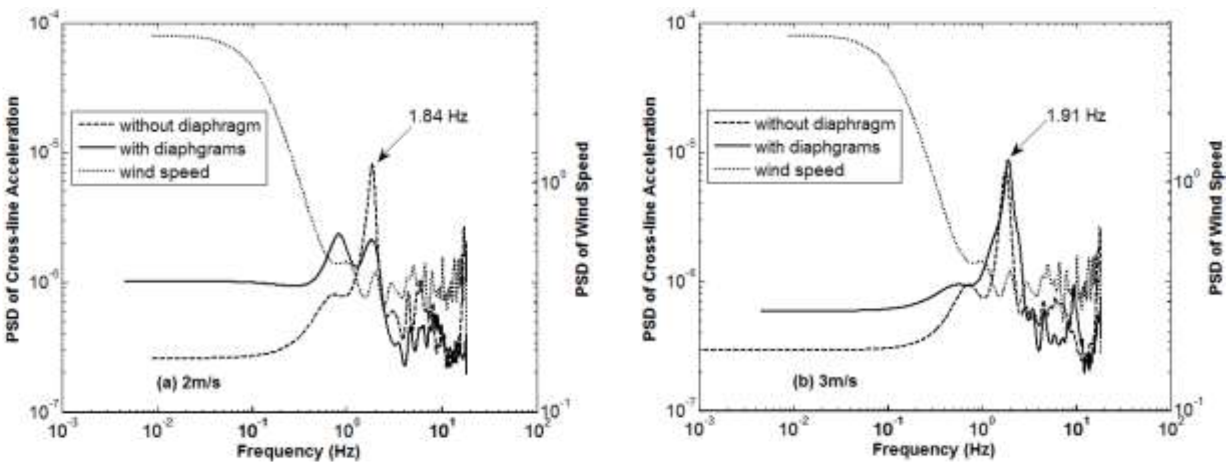


Fig. 6 PSD of cross-line displacement on tower top



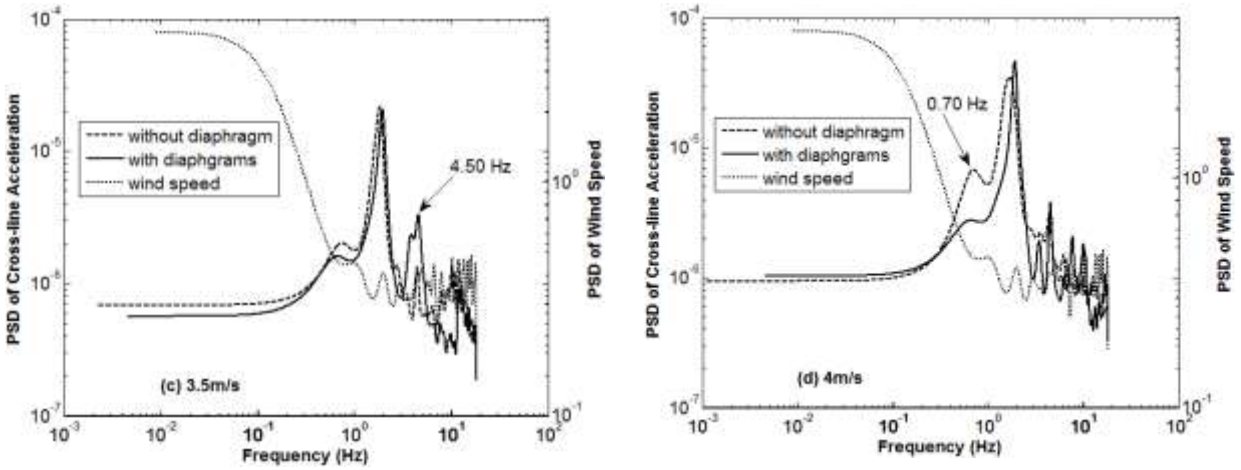
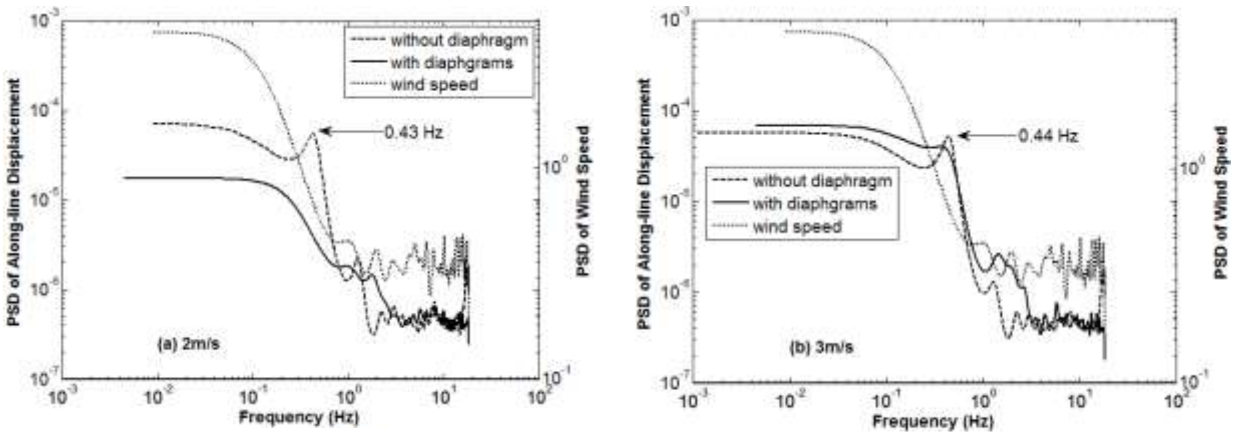


Fig. 7 PSD of cross-line acceleration on tower top

Fig. 8 and Fig. 9 show the PSD of along-line displacement and acceleration on tower top. Compared with cross-line vibration, tower's along-line vibration is more sensitive to wires' vibration. The vibration near 0.42Hz illustrates the second in-plane vibration of wires is one of significant extra excitation for tower's along-line vibration and this frequency increases with the growing wind speed (Fig. 8). From acceleration PSD (Fig. 9), it is demonstrated that with the wind speed increasing, the high-frequency vibration is more complex. Instead of the tower's along-line first-order vibration (0.63Hz), the vibration frequency that close to tower's along-line second-order vibration and torsion is identified. Because of lacking the information of crosswind field and vibration data about wires, it is hard to evaluate the ingredients of high-frequency along-line vibration of towers.



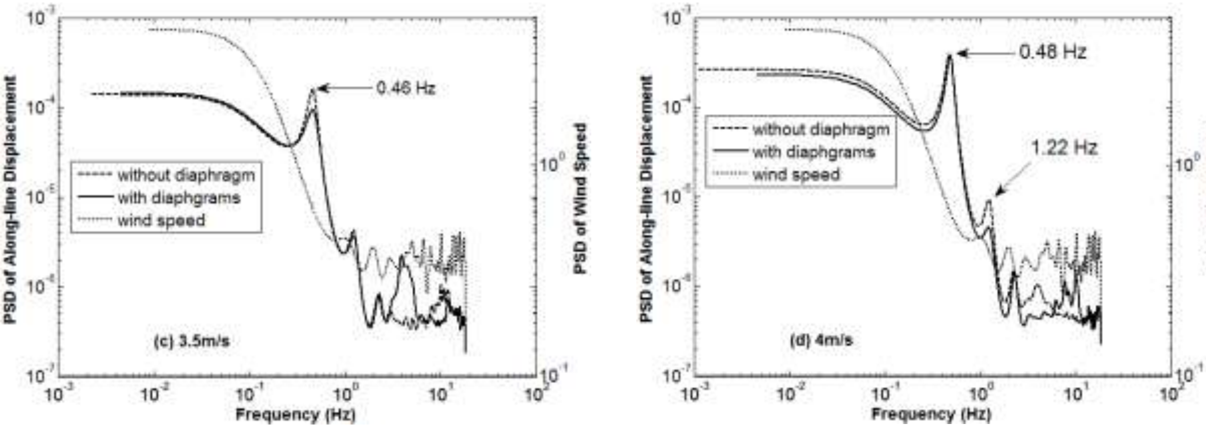


Fig. 8 PSD of along-line displacement on tower top

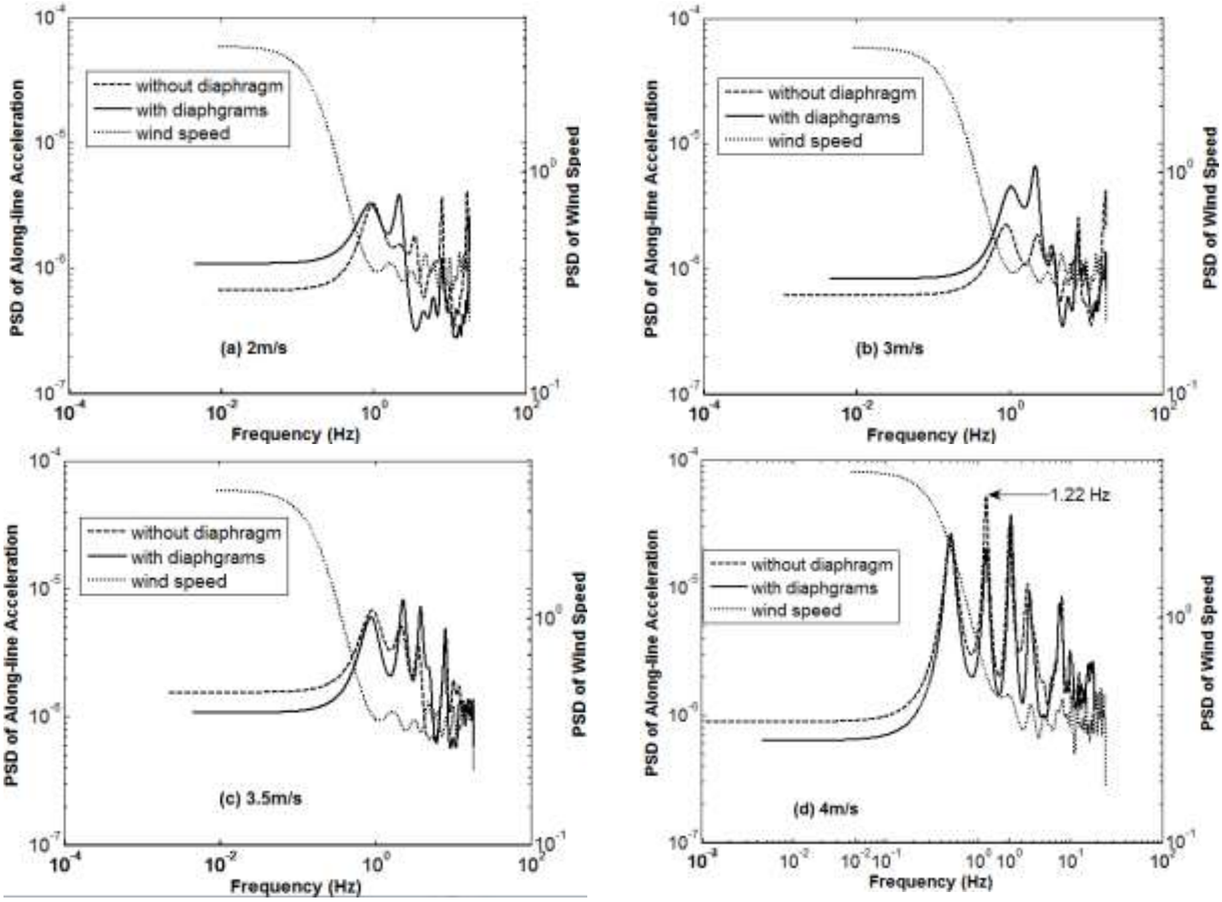


Fig. 9 PSD of along-line acceleration on tower top

According to above test results, it is indicated that adding diaphragms can improve tower's ultimate bearing capacity but have no obvious effect on tower's integral vibration property. With the wind speed going up, the influence of wires' vibration becomes strong for both towers and the influence is more apparent for the tower without additional diaphragms. Comparing the cross-line vibration with along-line vibration under the wind direction of perpendicular to transmission line, it is found that though along-line vibration is relatively weak, it is more complex and easy to be effected by wires.

3.3.2 Tower's Failure

The damages of the two towers under ultimate wind speed were recorded in the test. The two failures are quite different from each other. For the tower without additional diaphragms, its integral bend is mainly caused by tower body's lower section; almost all the slender diagonal members in lower section fail with out of plane buckling; post members in lower section suffer from serious buckling failure in whole (Fig. 10). After adding diaphragms, the tower's integral bend is primarily induced by upper section; some upper diagonal members at pressure side lose the out of plane stability; there is also local buckling for tower legs and lower post members (Fig. 11).

In addition, the failure moment of the tower without diaphragms was captured by video, which demonstrated that when wind speed increased to 4.5m/s, lower diagonal members at pressure side were subjected to instantaneous out of plane vibration several times before failing. Then the tower failed overall with suddenly buckling of post members in lower section.

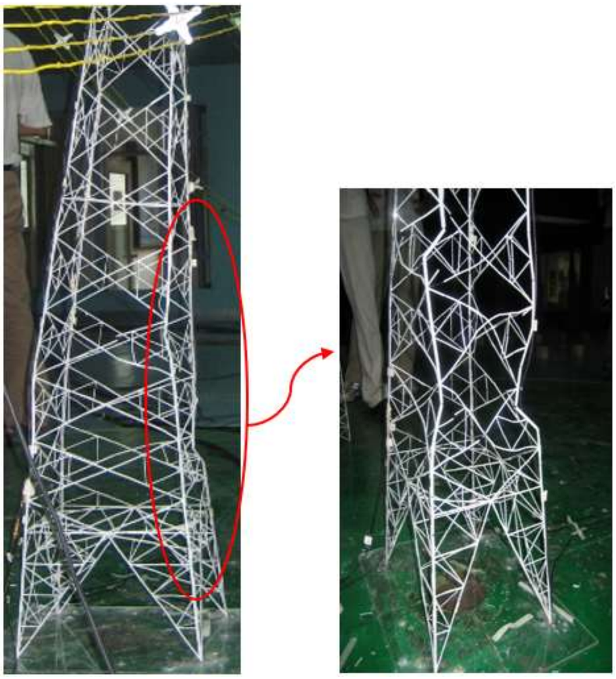


Fig. 10 Failure of the tower without additional diaphragms

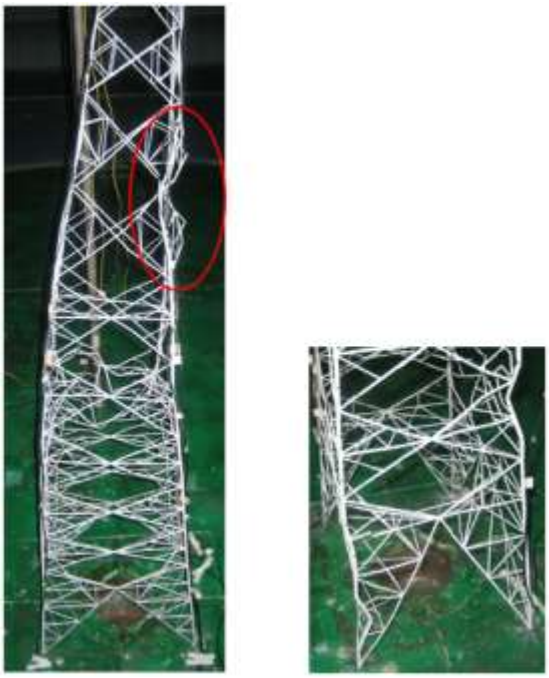


Fig. 11 Failure of the tower with additional diaphragms

4. UPGRADE SCHEME FOR ADDING DIAPHRAGMS

In order to balance the steel dosage, an upgrade scheme for arranging additional diaphragms is proposed for above 500kV transmission tower. Four groups of diagonal brace are reduced to two and diaphragms are added at the mid-height of diagonal members (Fig. 12). By calculation, the steel consumption that before and after retrofit is 1112kg and 1060kg respectively.

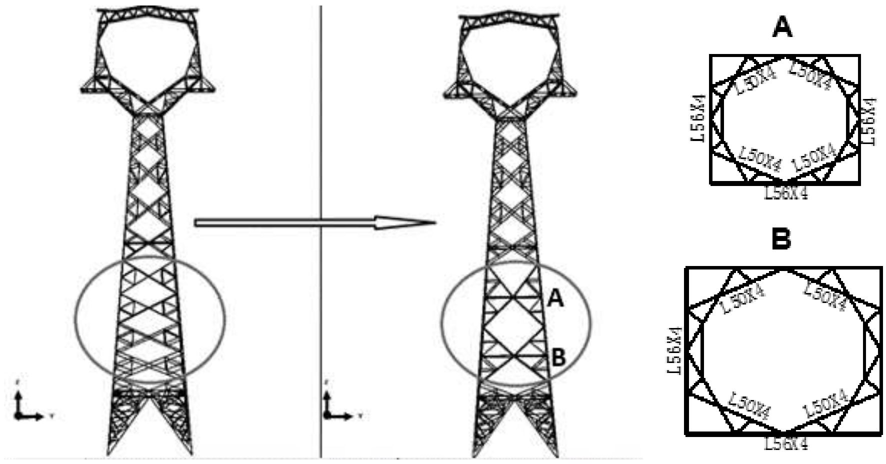


Fig. 12 Original tower and retrofitted tower

For investigating the dynamic performance of the tower after retrofit, the wind-induced vibration of original and retrofitted tower line systems is simulated using ABAQUS (Fig. 13). The tower is modelled with B31 element; the wire and insulator are modelled with truss element. The wind field used in numerical calculation is generated according to the field monitoring data in Jiangsu region. The Stochastic wind field model consists of three ingredients, Fourier amplitude spectrum, phase spectrum and phase-delay spectrum, which are used to describe the information of amplitude, phase and spatial correlation of wind speed respectively(Yan 2011).

Modal analysis for single tower finds that before retrofit the tower's local mode comes to the third order (Fig. 14), which indicates the diagonal members in lower section of the tower body are the weak members under dynamic action. When retrofitted, the integral torsion becomes the third mode and the local deformation weakens in following modes. During dynamic calculation, the aero-elastic effect between the wind and wire is considered by means of UAMP user subroutine. Such effect is generally viewed as a problem of aerodynamic damping. Here, it is viewed as an issue of wind force (Eq. 1).

$$\begin{aligned} M\ddot{X}_{t+\Delta t} + C\dot{X}_{t+\Delta t} + F^{r}_{t+\Delta t} &= F^{w}_{t+\Delta t} + F^{G} \\ F^{w}_{t+\Delta t} &= \frac{1}{2}\rho C_D A\left(\bar{U} + U_{t+\Delta t} - \dot{X}_t\right)^2 \end{aligned} \tag{1}$$

$F^{w}_{t+\Delta t}$ is the wind load vector; $\bar{U}$ and $U_{t+\Delta t}$ are the mean and fluctuating wind speed; $\dot{X}_t$ is the structural velocity response.

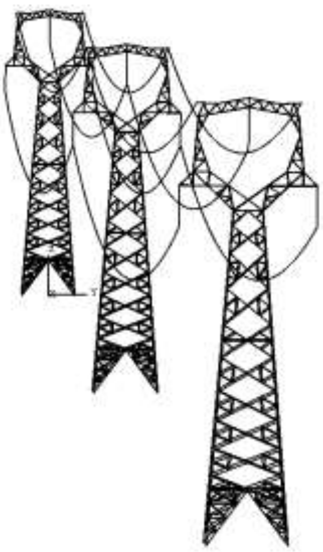


Fig. 13 Tower line system model

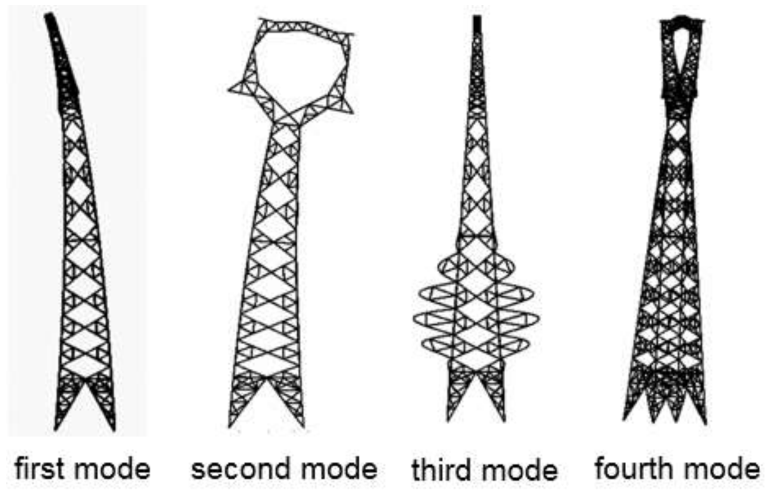
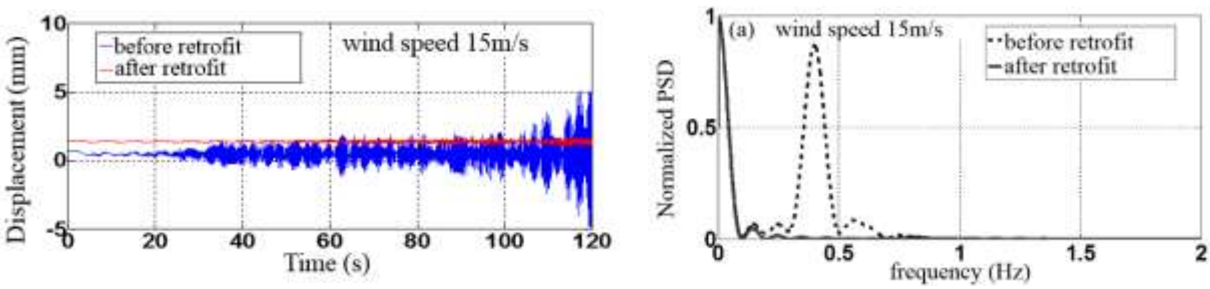
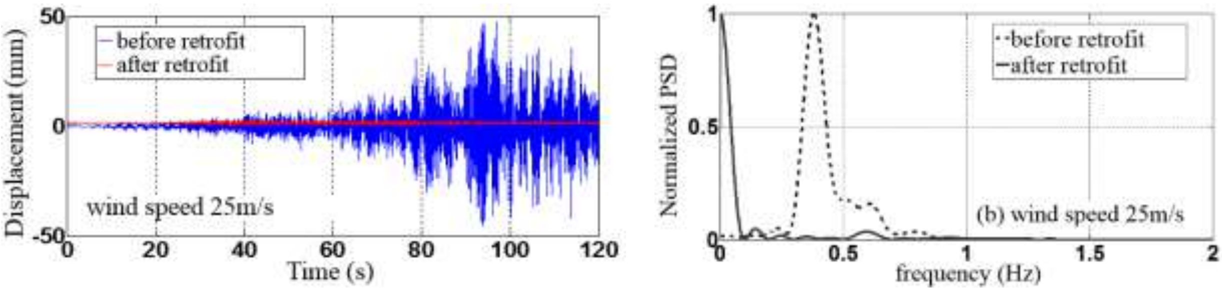


Fig. 14 Natural vibration modes for single tower before retrofit

For investigating the diaphragms' function of controlling tower's local vibration, lower diagonal members' out of plane vibration is traced during calculation. From time-history results, it is shown that diaphragms can obviously limit diagonal members' out of plane vibration; frequency-domain results reveal that before retrofit, the diagonal member's out of plane vibration is mainly influenced by wires with the main vibration frequency of 0.4Hz; after retrofit, its vibration is just induced by wind field (Fig. 15).



(a) wind speed 15m/s



(b) wind speed 25m/s

Fig. 15 Out of plane displacement at mid-height of lower diagonal members for the tower before and after retrofit

However, there is another concern that whether such upgrading will amplify other members' dynamic responses or not. Therefore, the maximum stress and average dynamic stress of post and diagonal members near retrofitted positions are checked. By comparison, the retrofit does not lead to the increase of adjacent members' stress level.

5. CONCLUSION

Above research supports following conclusions:
(1) The lower section of tower body is the vulnerable part to resist wind and diaphragm's function of strengthening tower's dynamic wind-resistant capacity is underestimated for many 500kV transmission towers in inland areas in China.
(2) According to wind tunnel test results, the additional diaphragms at lower tower body can help enhance tower's ultimate bearing capacity under wind action and improve tower's failure modes. Though the vibration properties of towers with and without diaphragms are similar, the tower without diaphragms is easier to be influenced by the wire's vibration.
(3) By upgrading the arrangement of additional diaphragms, the out of plane vibration properties of diagonal members at lower tower body can be changed: the vibration is weakened remarkably and controlled by wind action instead of wires. Besides, the retrofit can achieve the unity of less steel consumption, well-controlled local vibration and unaltered stress level for adjacent tower members.

REFERENCE

Albermani F., Mahendran M., Kitipornchai S. (2004), "Upgrading of transmission towers using a diaphragm bracing system", *ENG STRUCT,* 26(6), 735-744.
Deng H.Z., Si R.J., Hu X.Y., et al. (2013), "Wind Tunnel Study on Wind-Induced Vibration Responses of a UHV Transmission Tower-Line System", *ADV STRUCT ENG*, 16(7): 1175-1185.
GB 50009-2012, *Load Code for the Design of Building Structures*, Beijing, China Building Industry Press. (in Chinese)

Liang S.H., Zou L.H., Zhao L., et al. (2007), "The Investigation of 3-D Dynamic Wind Loads on Lattice Towers by Wind Tunnel Test", *ACTA AERODYNAMIC SINCA*, 25(3): 311-318, 329. (in Chinese)

Loredo-Souza A.M., Davenport A.G. (2001), "A Novel Approach for Wind Tunnel Modeling of Transmission Lines", *J WIND ENG IND AEROD*, 89 (11-12): 1017–1029.

Mayumi Takeuchi, Junji Maeda, Nobuyuki Ishida (2010), "Aerodynamic Damping Properties of Two Transmission Towers Estimated by Combining Several Identification Methods", *J WIND ENG IND AEROD*, 98: 872-880.

Momomura Y., Marukawa H. (1997), "Full-scale Measurements of Wind-induced Vibration of a Transmission Line System in a Mountainous Area", *J WIND ENG IND AEROD*, 72: 241-252.

Xie Qiang, Sun Li. (2013), "Experimental study on the mechanical behavior and failure mechanism of a latticed steel transmission tower", *J STRUCT ENG, ASCE,* 139(6), 1009-1018.

Yan Qi, Li Jie. (2011), "Evolutionary-phase-spectrum based simulation of fluctuating wind speed", *Journal of Vibration and Shock*, 30(9), 163-168. (in Chinese)