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.

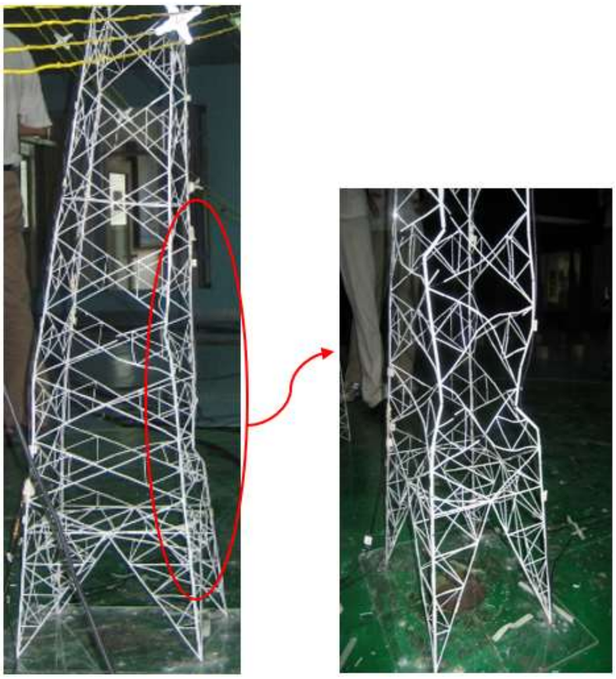


Fig. 10 Failure of the tower without additional diaphragms

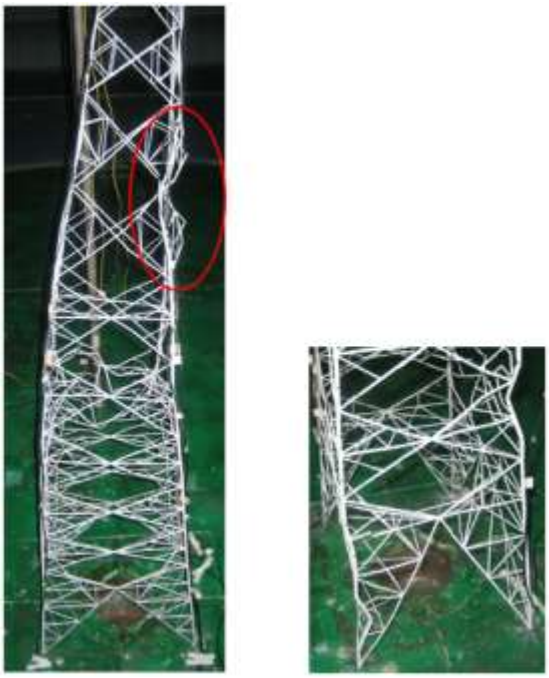


Fig. 11 Failure of the tower with additional diaphragms

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.

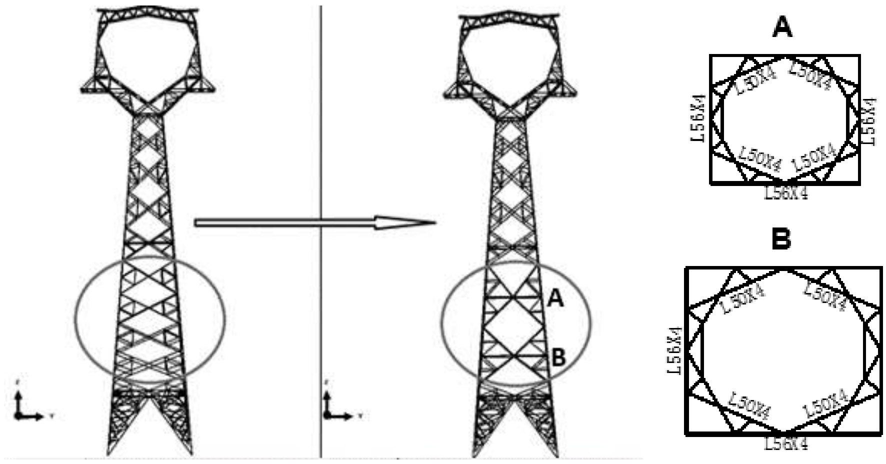


Fig. 12 Original tower and retrofitted tower

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).

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

$F^{w}_{t+\Delta t}$ 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.

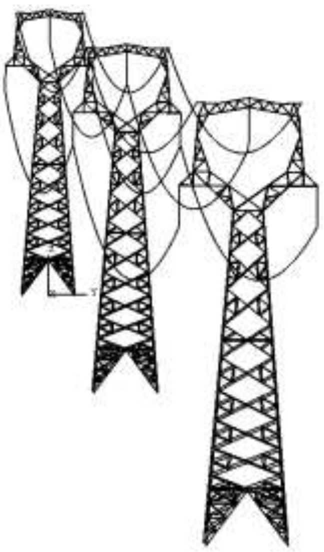


Fig. 13 Tower line system model

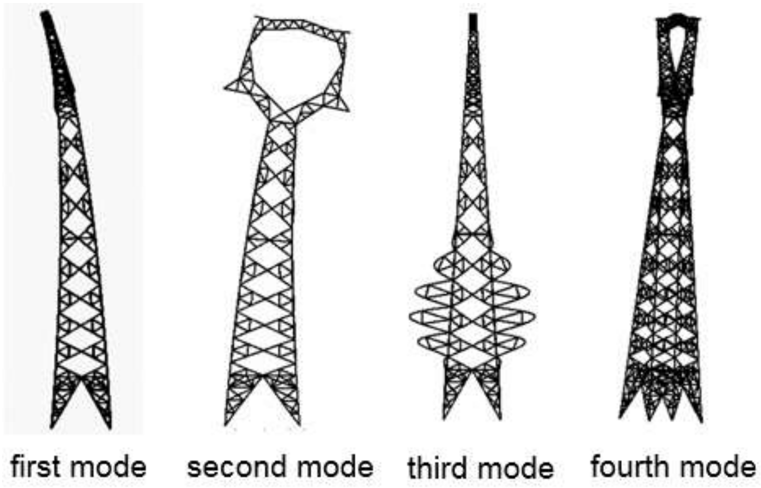
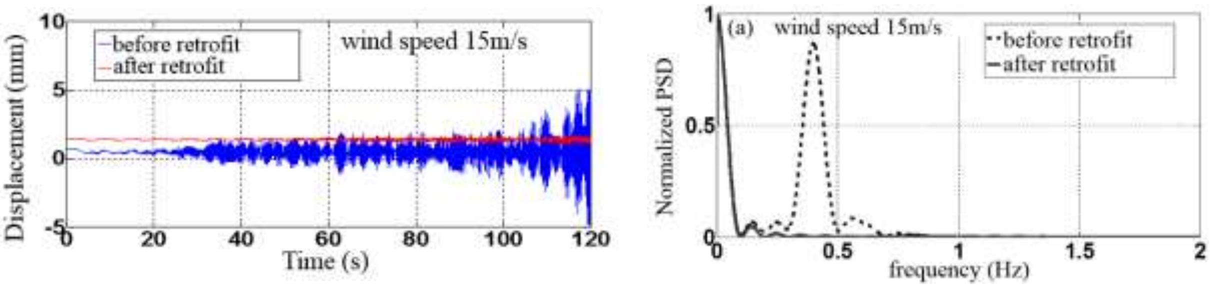
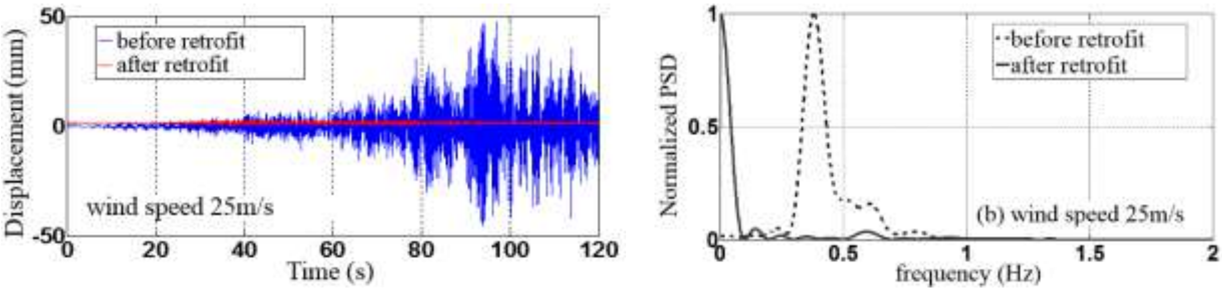


Fig. 14 Natural vibration modes for single tower before retrofit

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.

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