

4.1 Aerostatic analysis

In this analysis, the 3-D FE model of the bridge was established in commercial software to investigate the non-uniform and transient effects on the aerostatic behavior of the bridge. The main span was discretized into 184 beam elements which could well model the non-uniform wind distribution along the span. This FE model has been validated by comparing its modal properties with the results from other researcher's report. The natural frequencies and mode shapes of first 20 modes show good agreement with the study by Chen et al. (2002).

Figure 6 shows the aerostatic coefficients of bridge deck, where the C_L , C_D and C_M are measured experimentally in the wind tunnel tests (Chen et al., 2002) and C_W are obtained by CFD simulation. By comparing with the steady state coefficients of a flat plate under 90° (Taira et al., 2007), the CFD simulations show good agreement with the order of the magnitude of the experimental results. This indicates the CFD results have good fidelity for the aeroelastic analysis in this study.

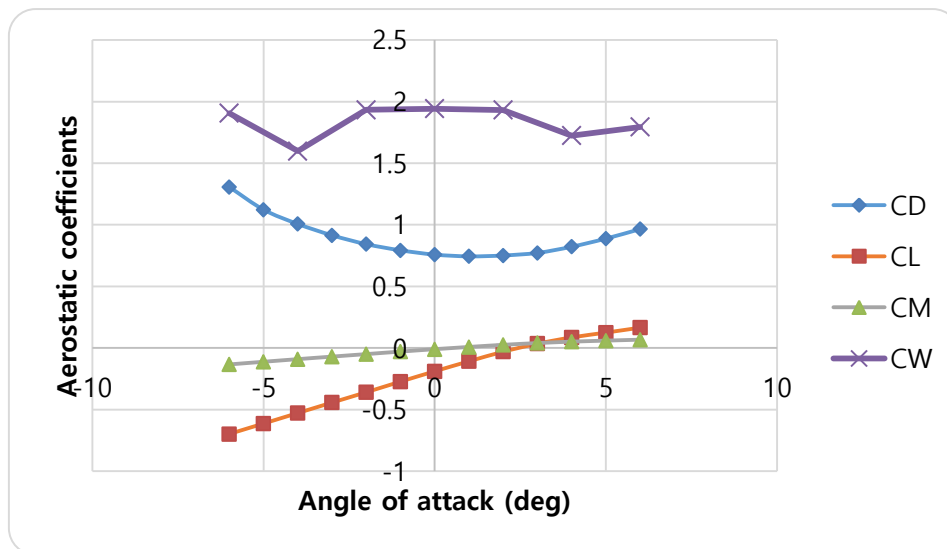


Figure 6. Aerostatic coefficients of bridge deck

Based on the FE model and aerostatic parameters of this example bridge, the aerostatic analysis could be processed following the procedures illustrated in section 2.1. The comparison of the maximum values of bridge deck vertical displacements at various spanwise locations between the tornado case and the equivalent synoptic case are plotted in **Figure 7**. **Figure 8** displays the comparison of the time history of the bridge deck vertical displacements at center of main span between this two cases. It can be noted from these results that, the tornado effects on the long-span bridge aerostatic behavior show intensively localized feature with relatively short duration. In addition, the vertical displacements under the tornado event have larger magnitude compared with synoptic wind case. This is mainly due to the intensive vertical wind velocity.

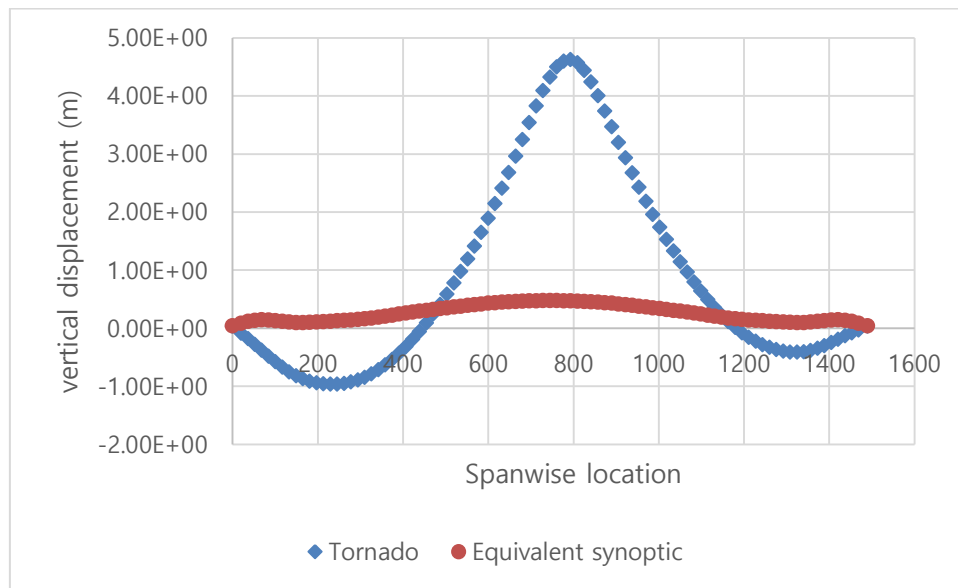


Figure 7. Comparison of maximum values of bridge deck vertical displacements at various spanwise locations at time=68.1 s

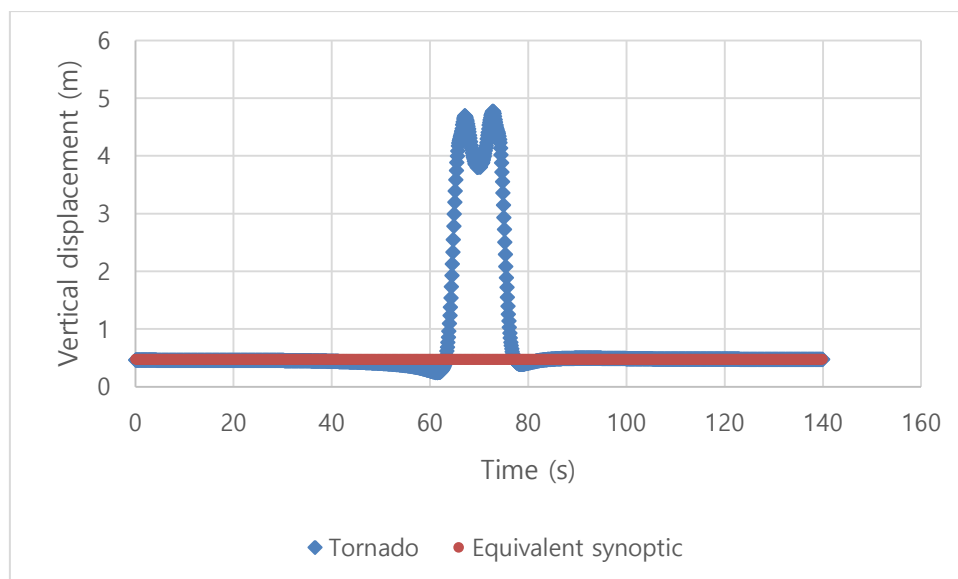


Figure 8. Comparison of the bridge deck vertical displacements time history at center of main span

4.2 Aeroelastic analysis

A unit-length of bridge deck section is utilized to investigate the effects of the transient feature of tornado event on the aeroelastic instability. Based on the flutter derivatives of this example bridge deck experimentally measured in the wind tunnel (Chen et al., 2002), the aeroelastic unit-step response function can be identified using the “semi-inverse” approach (Scanlan et al., 1974). According to the framework illustrated in section 2.2, the 2-D indicial response functions under the tornado event with a time-varying mean wind speed can be extended from the 1-D cases. The four

fundamental 2-D aeroelastic indicial response functions are plotted in **Figure 9**. The bridge response is then calculated using the step-by-step time integration method.

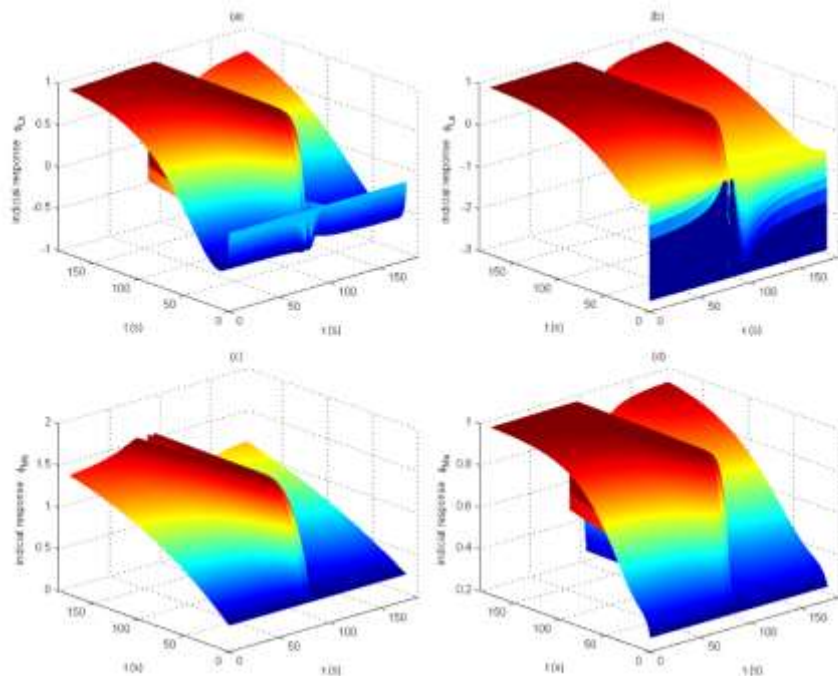


Figure 9. 2-D aeroelastic indicial response function under tornado wind

The investigation of the aeroelastic instability under synoptic wind event was conducted firstly. It should be noted that, the 1-D indicial response function where the bridge is subject to the synoptic wind event with a constant mean wind speed for all τ is a special case of the 2-D indicial response function. The time history of the vertical and torsional motion-induced responses under the onset flutter critical velocity $U_{cr} = 57.2 \text{ m/s}$ are depicted in **Figure 10**, which shows good agreement with the wind tunnel test result as $U_{cr} = 58.1 \text{ m/s}$. This indicates that the employed analysis approach has good fidelity for non-synoptic aeroelastic analysis.

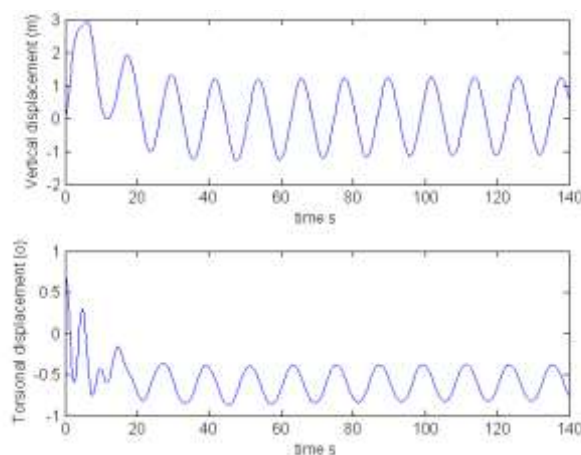


Figure 10. Motion-induced responses at flutter critical speed

Figure 11 shows the calculated motion-induced responses based on the current analysis framework subject to the tornado wind event. As shown in the figure, as the mean wind speed approaches to a high magnitude, the response will increase abruptly to a large value, but will not diverge. The phenomenon indicates that, although the instantaneous wind speed is larger than the critical flutter wind speed, the aeroelastic instability cannot occur under tornado wind event which presents transient feature. This mainly attributes to the lack of the build-up time for structure to sustain a high level of response. The build-up time decreases with the increase of the the structure damping ratio and frequency (Chen, 2014). In other words, the long-span bridges, which have lower frequency and damping ratio, have longer build-up time for the aeroelastic instability. Therefore, it is necessary that the extreme wind events have enough long duration to initiate the aeroelastic instability of the long-span bridge.

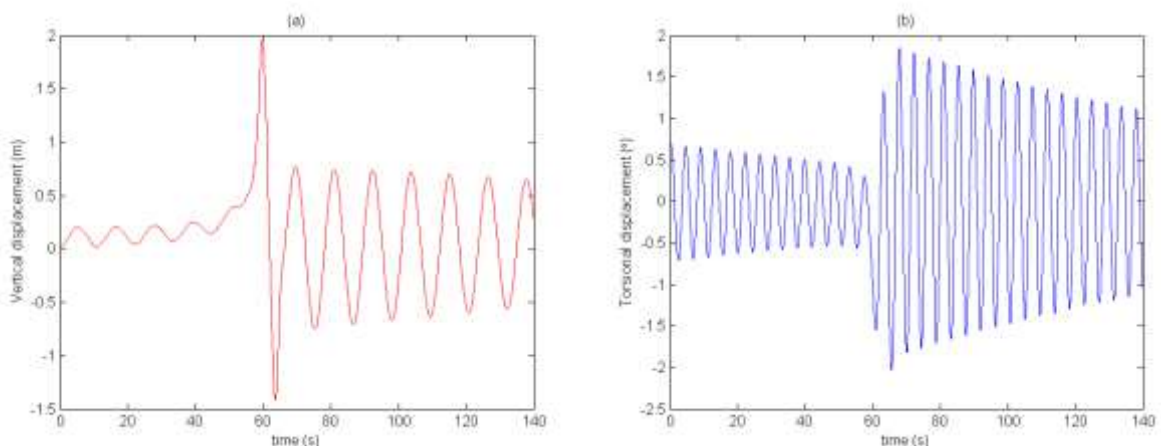


Figure 11. Motion-induced responses using 2-D indicial response function under tornado wind event

5. CONCLUDING REMARKS

The nonlinear aerostatic analysis based on the quasi-steady model and aeroelastic analysis based on the 2-D indicial response function are presented in this study to highlight the effects of transient nature, non-uniformity and intensive vertical wind velocity under tornado winds. The refined finite element model is used to model the structure for better capturing the non-uniform effects. CFD simulation is conducted to account for the significant vertical wind effects on bluff-body aerodynamics. A typical long-span suspension bridge is utilized as a numerical example to emphasize the tornado induced effects on structure performance. The results based on the numerical examples show that: 1) the non-uniform and localized nature has intensive impact on the long-span structure; 2) due to the intensive vertical wind velocity, the vertical displacement is significantly larger compared to the equivalent synoptic wind event; 3) the transient nature could significantly modify the bridge aerodynamics which can be represented by the 2-D indicial response function; and 4) there is no aeroelastic instability occurred under tornado wind event which may be due to the lack of the build-up time for the structure. The relation between the extreme wind impact duration on the structure and the build-up time is an interesting topic that needs to be investigated in the future study.

REFERENCES

- Chen, 2014. Analysis of multimode coupled buffeting response of long-span bridges to nonstationary winds with force parameters from stationary wind. *Journal of Structural Engineering* 141, 04014131.
- Chen, Guo, Z., Zhou, Z., Ma, R. and Wang, D., 2002. Study of Aerodynamic Performance of Runyang Bridge. Technical Report WT200218.
- Hao, J. and Wu, T., 2016. Non-synoptic wind-induced effects on linear bluff-body aerodynamics. *Proceedings of 8th International Colloquium on Bluff-Body Aerodynamics and its Application (BBAAVIII)*, Boston.
- Kuo, H., 1971. Axisymmetric flows in the boundary layer of a maintained vortex. *Journal of the Atmospheric sciences* 28, 20-41.
- Sarpkaya, T. and Garrison, C., 1963. Vortex formation and resistance in unsteady flow. *Journal of Applied Mechanics* 30, 16-24.
- Scanlan, R., Budlong, K. and Béliveau, J., 1974. Indicial aerodynamic functions for bridge decks. *Journal of Sanitary Engineering Division* 100.
- Taira, K., Dickson, W.B., Colonius, T., Dickinson, M.H. and Rowley, C.W., 2007. Unsteadiness in flow over a flat plate at angle-of-attack at low Reynolds numbers. *AIAA Paper* 710, 2007.
- Tamura, Y., 2009. Wind induced damage to buildings and disaster risk reduction. *Proceedings of the APCWE-VII*, Taipei, Taiwan.
- Wang, H., Li, A., Hu, R. and Li, J., 2010. Accurate stress analysis on steel box girder of long span suspension bridges based on multi-scale submodeling method. *Advances in Structural Engineering* 13, 727-740.
- Wen, Y.-K. and Chu, S.-L., 1973. Tornado risks and design wind speed. *Journal of the Structural Division* 99, 2409-2421.
- Zhang, Z., Chen, Z., Hua, X., Li, C. and Ge, Y.J., 2010. Investigation of turbulence effects on torsional divergence of long-span bridges by using dynamic finite-element method. *Journal of Bridge Engineering* 15, 639-652.