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Dynamic Response Mitigation for Sky Bridge Hong Kong International Airport

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ABSTRACT

Wind tunnel testing of a 200m long Skybridge at Hong Kong International airport was conducted. Aeroelastic dynamic section testing and static section testing was performed using a scaled two-dimensional aeroelastic bridge model. The results of the dynamic section testing conducted in smooth flow demonstrated that an aerodynamic instability occurred at a wind speed similar to the design wind speeds and this instability primarily occurred for vertical motion. There was an associated decrease in the peak factor from values expected for a buffeting response to values consistent with a sinusoidal response. A review of the literature identified that the most likely cause of the instability is 'impinging leading edge vortices'. It was demonstrated through additional testing that the response of the bridge to the vortices can be reduced by increasing the background level of turbulence in the wind tunnel and can be eliminated by making small changes to the existing bridge sunshades.

1. Introduction

The Sky Bridge at Hong Kong International airport is a 200m long airside bridge that links Terminal 1 with the north satellite concourse and will replace the current shuttle bus system. Figure 1 shows a photo of the bridge which is in the final stages of construction.

Figure 1. HKIA Sky Bridge prior to completion

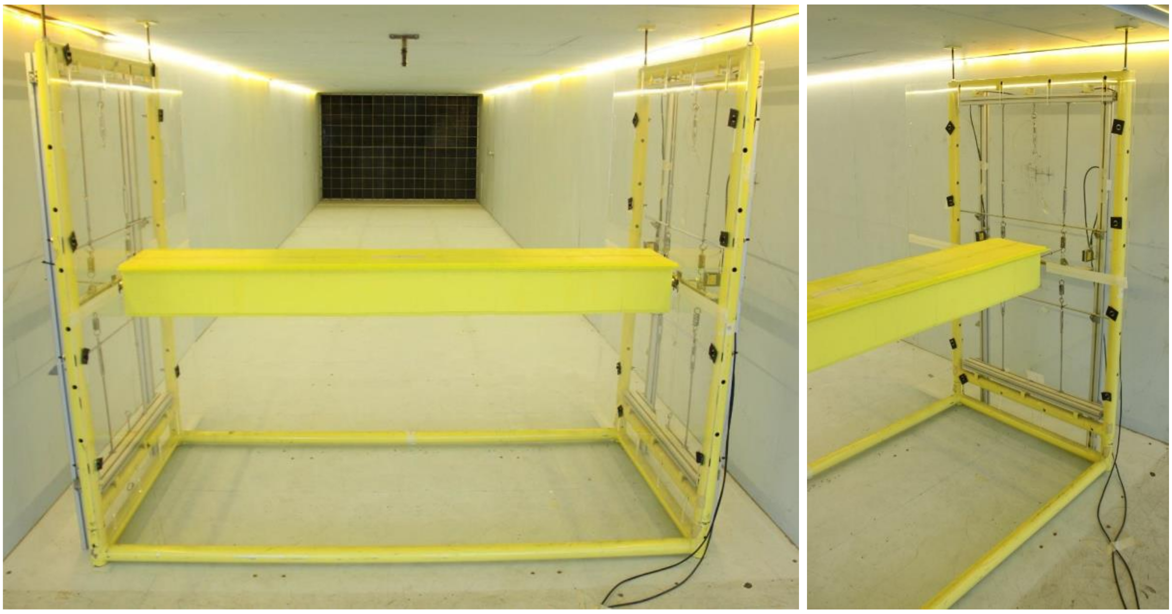
Wind tunnel testing of this bridge was conducted. Two separate section model tests of the bridge were performed to determine the dynamic response of the bridge and measure the static force coefficients. Design loads for the bridge were then calculated for the 120 year design wind speed (Hong Kong Highways Department, 2013). In this paper only the results of the dynamic response wind tunnel tests are discussed.

2. Wind tunnel testing procedure

2.1 Initial Testing in Smooth Flow

A 1 to 70 scale model of the skybridge was constructed and tested (Figure 2). As the profile of the prototype bridge varies along its longitudinal axis, the two-dimensional cross section of the central span of the bridge was modelled. The main body of the bridge is 16m high and has a width/height ratio of ≈1:1.5. There are overhanging horizontal sunshade elements attached to the roof of the bridge. The scale model was mounted on a suspension style dynamic section test setup (Hjorth-Hansen, 1992).

The density and Scruton number of the model was matched to the prototype. The ratio between the first mode vertical and torsional natural frequencies was maintained between the model and the prototype bridge. The prototype bridge had a low density which resulted in a low Scruton number of ≈ 3 for the base damping case.



(a) (b)

Figure 2. Sky Bridge during testing in smooth flow (a) Full model (b) Suspension Rig

For the initial wind tunnel tests measurements were conducted in the following condition:

- smooth flow (less than 1% turbulence intensity)
- 12 wind speeds (up to 97m/s full scale)
- 11 angles of attack
- three levels of damping at a zero degrees angle of attack.

Smooth flow testing was used to analyse the susceptibility of the bridge section design to aerodynamic instabilities and vortex-induced-vibrations over a range of expected wind speeds (Holmes, 2015). Smooth flow testing is conducted as these effects maybe masked by the natural turbulent which occurs in the atmospheric boundary layer.

2.2 Testing in atmospheric boundary layer conditions (Turbulent flow)

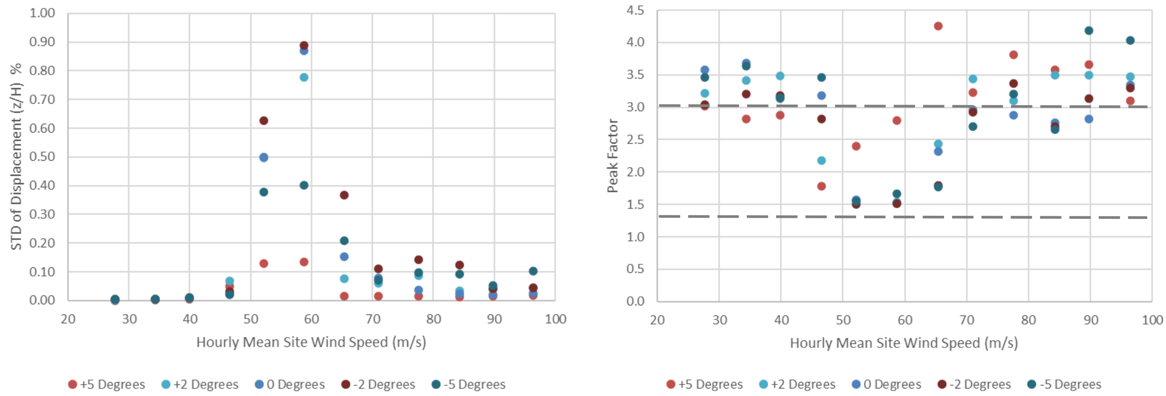
Following analysis of the smooth flow dynamic section test results, testing was also performed in turbulence flow. To match the full-scale turbulence in the wind tunnel, a partial turbulence matching methodology was used (Dyrbye and Hanson, 1999). Using this method, the longitudinal spectral density normalised by the mean wind speed squared measured in the wind tunnel is compared with the full-scale spectra estimated using the Von-Karman Harris Spectral model (ESDU 85020, 2001). The wind tunnel conditions were then assumed to match the full-scale spectra which they completely envelope. For this enveloping to occur typically the wind tunnel turbulence is less than the full-scale turbulence. For these tests the atmospheric boundary layer conditions were based on the Code of Practice on Wind Effect in Hong Kong (2004)

3. Results and Discussion

3.1 Initial tests

The results of the dynamic testing in smooth flow showed an instability. A vibration was found to occur primarily in the vertical motion of the bridge section but not in the rotational motion. This vibration is shown by a distinct discontinuity in the response curve response, starting at ≈45m/s (just below the design wind speed) and continuing until ≈65m/s (Figure 3a).

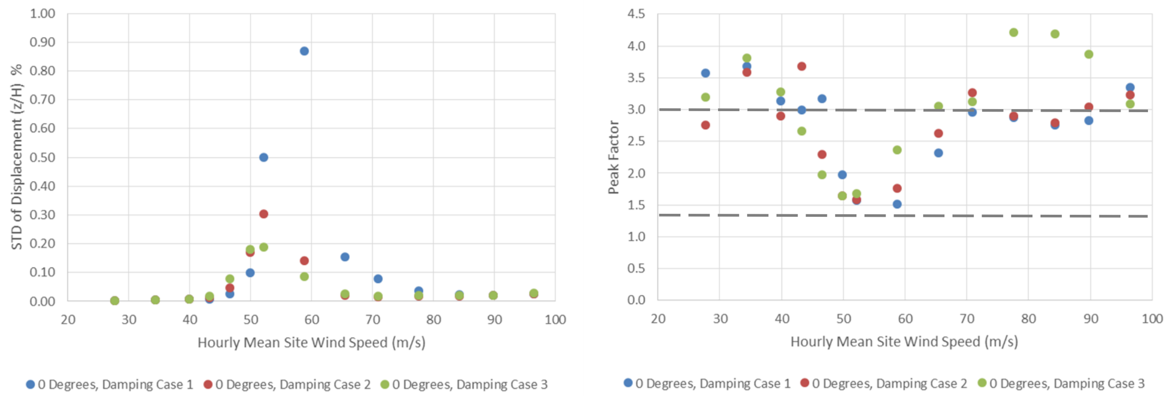
There is also a decrease in the observed peak factor (peak response divided by standard deviation response) from between 3 and 4 to ≈1.5 (Figure 3b). The decrease occurs between 47m/s and 65m/s, and is most clear between 52m/s and 59m/s. The reduction in the peak factor from a typical value for turbulent buffeting of ≈3.5 to a value closer to the ideal sinusoidal value of ≈1.4 as an indicator of the presence of a forced vibration and an aerodynamic instability.



(a) (b)

Figure 3. Vertical Motion in Smooth Flow for 11 angles of attach (a) Normalised Standard Deviation of Displacement (b) Peak Factor

Testing was conducted for three damping ratios (percentage of critical): Case 1, 0.5%; Case 2, 0.7% and Case 3, 1.1%. Note the onset velocity of the instability did not vary although there was a decrease in response (Figure 4).



(a) (b)

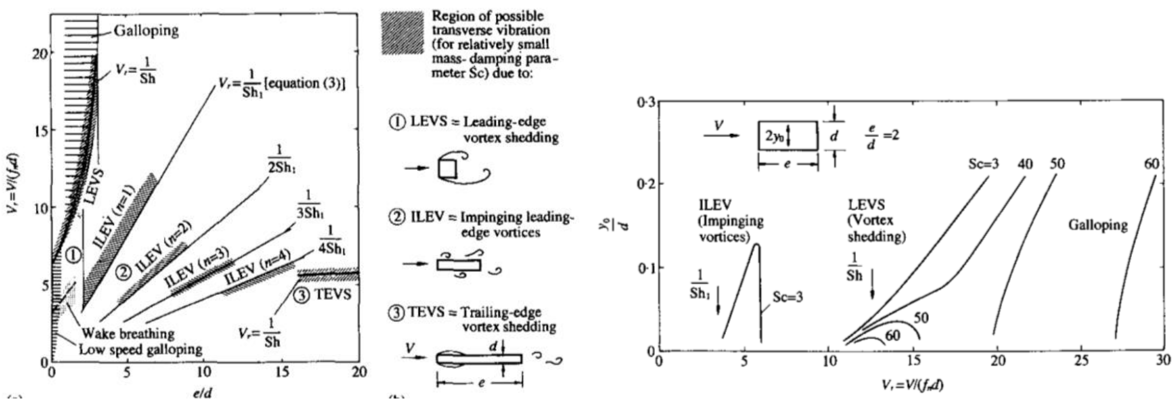
Figure 4. Vertical Motion in Smooth Flow for 0 degrees angle of attack and three damping ratios (a) Normalised Standard Deviation of Displacement (b) Peak Factor

3.2 Flow Mechanism

Figure 5 reproduces two stability diagrams from Naudascher and Wang (1993) for lightly damped rectangular prisms which have been used to analysis and identify the observed response. The spectra of the lift force from the static tests were also examined for a range of wind speeds and the Strouhal number for this shape estimated to be 0.13 or a reduced velocity of 7.5.

The vibration first occurs at a reduced velocity of ≈2 which is well below the critical velocity for leading edge vortex shedding vortex induced vibration based on the dimensions of the whole bridge section. However, it is close to that for impinging leading edge vortices. The response is similar to that for impinging leading edge vortices shown in Figure 5b for a Scruton number of 3. As the onset velocity did not vary for the three damping ratios tested this indicates that the instability mechanism is not sensitive to Scruton number, which is the case for impinging leading edge vortices.

The instability is also similar to that shown in Mannini *et al.* (2016) who investigated a 1:1.5 aspect ratio rectangular prism for various Scruton numbers. They found that there was an instability starting at ≈25% of the critical velocity for sections with low Scruton numbers, which is a similar onset point to the present study.



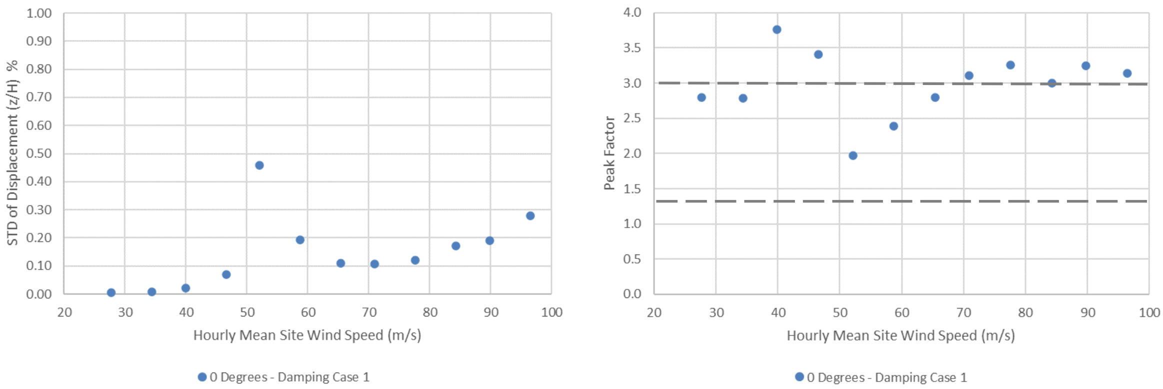
(a) (b)

Figure 5. Figures 2 and 3 from Naudascher and Wang (1993) (a) Flow induced vibration description (b) response diagram

3.3 Turbulent Flow

The results of the dynamic testing in turbulent flow are shown in Figure 6. Background turbulence which is present in atmospheric boundary layer flow is known to suppress the formation of vortex induced vibrations. As vortex induced vibrations generated by an impinging leading-edge vortices (ILEV) mechanism were identified in the previous smooth flow tests, turbulent flow testing was used to analyse the sensitivity of the formation of impinging leading edge vortices to turbulence.

By comparing Figure 6 to Figure 3 it can be seen that the vortex induced vibrations are still present. However, the response of the bridge to the vortices has reduced in magnitude as well as the range of wind speeds over which the vibrations occur. The instability is now concentrated at 52m/s. The observed peak factor has reduced from to ≈3 to ≈1.9 (Figure 6b. The smaller reduction in peak factor compared with the smooth flow case indicates that the response has not fully transitioned from a buffeting response into a sinusoidal response. These results indicate that the higher levels of turbulence partially suppress the mechanism creating the vibration. An increase in the vertical response due to buffeting is also seen at the higher wind speeds.



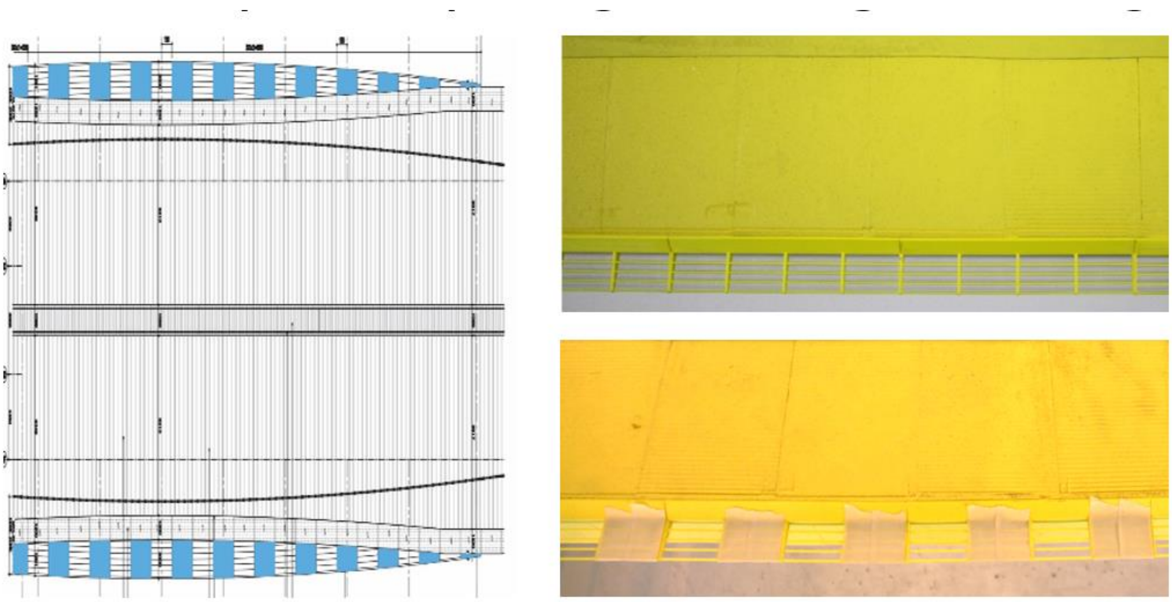
(a) (b)

Figure 6. Turbulence Flow Results for Vertical Motion for 0 degrees angle of attach only (a) Displacement (b) Peak Factor

3.4 Changes to Leading Edge Sunshade

The bridge design includes open lattice style horizontal sunshade elements extending from the roof of the bridge. As the instability mechanism identified is related to the generation of vortices from the leading edge of the bridge an alteration to the geometry of the leading edge was trialed to disturb the formation of these vortices.

The proposed solution was to in-fill every second sunshade bay with an impermeable panel (Figure 7). This solution could be implemented using clear panels or paneling matching the roof of the bridge. They could be attached to the existing sunshade supports.

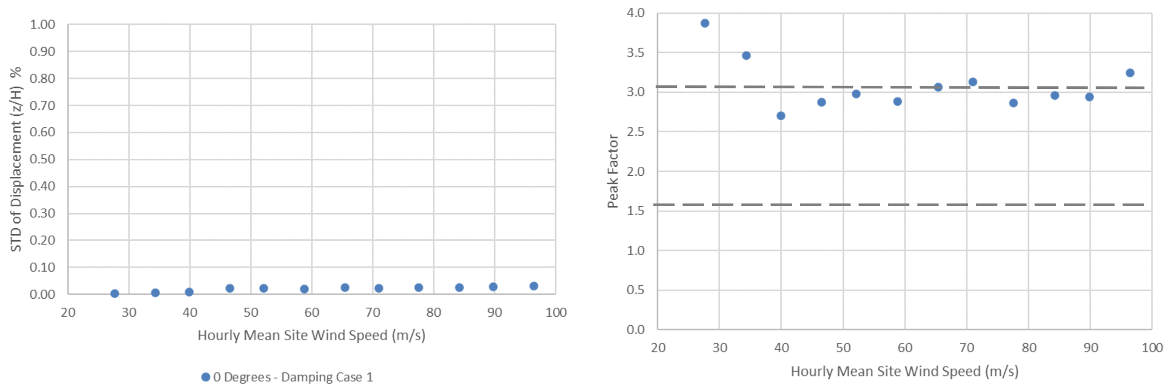


(a) (b)

Figure 7. Sunshade Modification (a) Drawing (b) without modifications (top) and with modifications (bottom)

By comparing the results presented in Figure 8 to Figure 3 the testing shows that the effect of the vortex induced vibration is almost completely removed. The standard deviation is less than 5% of the original design and the peak response is less than 10% of the original design. Importantly, Figure 8b shows that the peak factor has not decreased below 3, indicating that the response has not transitioned from a buffeting response into a sinusoidal response.

These results demonstrate the instability can be mitigated using a modified sunshade design.



(a) (b)

Figure 8. Sunshade in Smooth Flow Results for Vertical Motion (a) Displacement (b) Peak Factor

4. Conclusions

The results of the wind tunnel test demonstrate that under smooth flow conditions there is a dynamic instability that occurs at a wind speed similar to the design wind speeds. This instability is most likely generated by impinging leading edge vortices and is enhanced by the bridge's low Scruton Number.

The response of the prototype bridge to this instability will be reduced compared to the smooth flow results due to the natural turbulence present in the atmospheric boundary layer. The instability can be further reduced to the point of being almost eliminated by making additions to the sunshade elements.

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