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Aeroelastic Wind Tunnel Tests for a Memorial Park Sculpture

Joachim Paetzold[1], Peter Bourke[2], Matt Glanville[3]

[1]Cermak Peterka Petersen Pty Ltd (CPP), St Peters, NSW 2044, Australia, jpaetzold@cppwind.com

[2]CPP, pbourke@cppwind.com

[3]CPP, mglanville@cppwind.com

ABSTRACT

CPP conducted wind tunnel tests to investigate the potential for wind induced excitation on cantilever tablets of the Memorial Park sculpture, Abu Dhabi, UAE, which consists of a set of 31 individual tablets arranged in 14 frames. Aeroelastic models of the Memorial Park tablets were constructed at a scale of 1:50 and displacement measurements were taken for a range of wind directions. The measured time series revealed no significant lock-in response and suggested that the resonant response is caused by turbulence buffeting within the design wind speed range. Further testing during an isolated tablet scenario suggests the majority of the local turbulence leading to buffeting response was created by the surrounding tablets. Additional tests using a high-frequency balance showed potential for vortex shedding near the natural frequency for one tablet but beyond the design wind speed.

1. Introduction

CPP was engaged by UAP Australia and Robert Bird Group to investigate the potential for wind induced excitation on cantilever tablets of the Memorial Park sculpture, Abu Dhabi, UAE. The Memorial Park sculpture consists of a set of 31 individual tablets arranged in 14 frames up to 23 m in height, Figure 1 and 2. A desktop analysis was undertaken based on Standards Australia (2011) and ESDU (1972) for the estimation of wind loads on the individual tablets. Additionally, an assessment of the aerodynamic stability of the tablets with regard to excitation due to vortex shedding off the individual tablets was conducted based on the Strouhal number and vortex shedding on flat plates as per Chen and Fand (1999) and Ricohermoso Matty (1979). This assessment indicated that the tall cantilever tablet (Tablet 7) would have some potential for unstable wind excitation. Based on this assessment, amendments were made to the structural design to increase the resonant frequencies of the cantilever tablets and reduce their susceptibility to vortex shedding excitation. CPP was then engaged to undertake wind-tunnel based model tests to further investigate the potential for wind induced excitation of three cantilever tablets. For the sake of brevity detailed results are only presented for Tablets 7 and 24 in this paper.

Fig. 1. 3D render of the Memorial Park sculpture

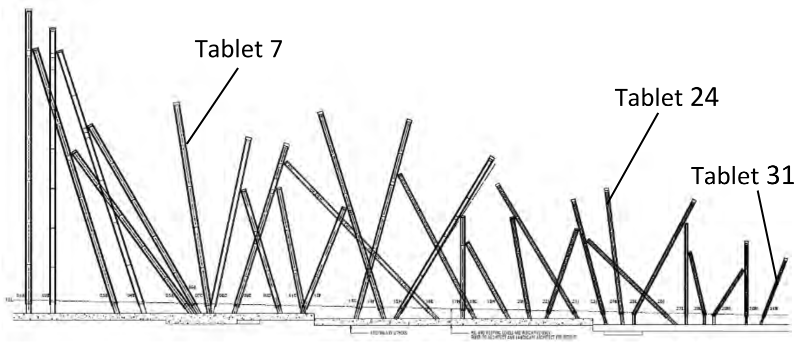

Fig. 2. Elevation of the Memorial Park sculpture indicating the test tablets

2. Methodology

A model of the Memorial Park sculpture was constructed at a scale of 1:50. This scale permitted a reasonable test model size while remaining within wind tunnel blockage limitations. The section length was set to span approximately the width of the test section. A photograph of the model in the wind tunnel is provided in Figure 3. General properties of the model and its construction are provided in Table 1.

Table 1. Wind tunnel model characteristics

General	
Model Geometric Scale:	*1:50*
Velocity Scale:	*1:2*
Reference Height z_{ref}:	*500 mm (25 m at full scale)*
Minimum Test Speed at z_{ref}:	*2 m/s (4 m/s full scale)*
Maximum Test Speed at z_{ref}:	*19 m/s (38 m/s full scale)*
Wind directions	*12 wind directions in 30° increments from 0° (north), plus additional directions depending on individual tablet location in the field.*
Model Fabrication	
Tested tablets:	*Aluminium and high-density foam*
Other tablets:	*Wood*

The models of the tested tablets were calibrated to match the mechanical properties of the full-scale tablets at the correct scale. The primary focus of the model design was to match the scaled first mode natural frequency of the full-scale tablets, as the goal of the study was to determine the potential for wind induced instability. The dimensions and first mode natural frequencies assumed for the test are provided in Table 2. Measurements were in the form of displacement using high resolution non-contact sensors.

Table 2. Tablet properties

	Full-scale			*Model scale*		
	Tablet 7	*Tablet 24*	*Tablet 31*	*Tablet 7*	*Tablet 24*	*Tablet 31*
Height from footing	*16.71 m*	*10.83 m*	*5.15 m*	*334 mm*	*217 mm*	*103 mm*
Width	*3 m*	*2.5 m*	*2 m*	*60 mm*	*50 mm*	*40 mm*
Thickness	*0.45 m*	*0.315 m*	*0.24 m*	*9 mm*	*6.3 mm*	*4.8 mm*
1st mode natural frequency	*2.07 Hz*	*2.4 Hz*	*3.76 Hz*	*49 Hz*	*58 Hz*	*94 Hz*

The level of structural damping that will exist in the finished tablets cannot be accurately predicted during design but is assumed to be in the order of 0.2 to 0.5% of critical damping, which is in line with the damping of the model scale tablets, which was measured as 0.19% for tablet 7, 0.12% for tablet 24, and 0.28% for tablet 31.

The gust design wind speed of 45 m/s as provided by UAP corresponds to a mean reference wind speed of approximately 32 m/s as per the American Standard ASCE 7. The tested velocity range of up to a mean wind speed of 38 m/s (full-scale) hence exceeds the design wind speed for the location of the sculpture..

In addition to the testing of the full sculpture, the three test tablets were also tested individually in an isolated scenario without any of the surrounding tablets present.

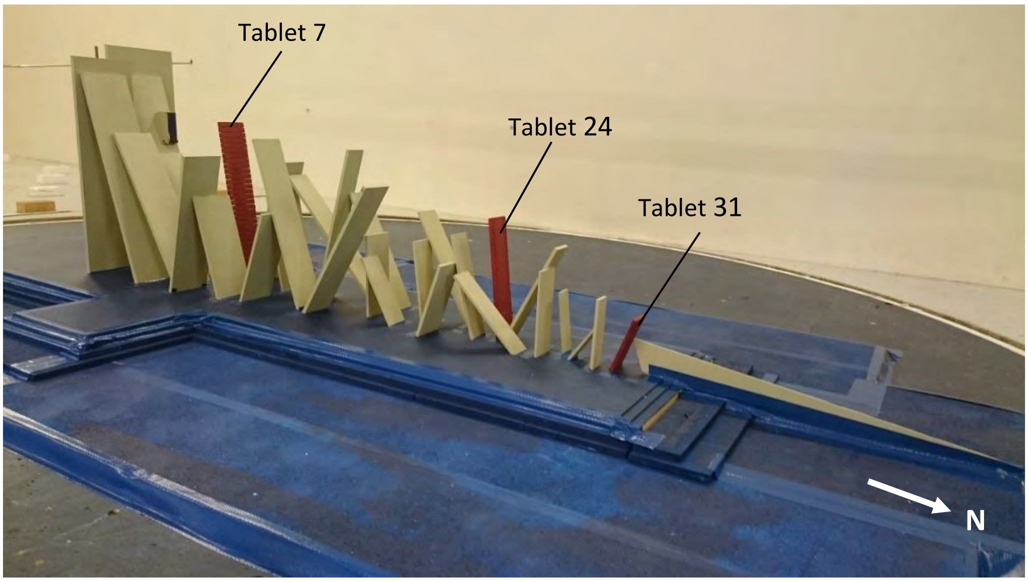

Fig. 3. Wind tunnel model viewed from the north-east

Free vibration decay tests from initial displacement were performed both with and without wind and at various wind speeds to estimate the aerodynamic damping of the structure under various conditions.

Results are presented as Aerodynamic and Total Damping Ratios, ζ, which is defined as the ratio of the measured damping level to critical damping level for the system,

$$\zeta = c/c_{crit} \quad (1)$$

Where c is the coefficient of damping for the system and c_{crit} is the critical damping coefficient. In this study damping ratios were obtained using the Logarithmic Decrement method. Damping Ratios are plotted with respect to Reduced Velocity defined by,

$$RV = U/fD \quad (2)$$

Where U is the mean test wind speed, f is the resonant frequency in the direction of interest and D is the width of the tablet.

Additional wind tunnel tests were performed with a rigid model and a high-frequency balance technique for Tablet 7 to analyse the vortex shedding frequencies that the tablet is exposed to. For these tests the tablet was mounted on a high-frequency balance and tested at constant velocity at 36 wind directions at 10° increments from 0° (north). During the test, sample time series of the moment components Mx, My, and Mz were sampled at 400 Hz. The aerodynamic model/balance system had fundamental natural frequencies of approximately 80 Hz and well above the model scale first mode frequencies. A spectral analysis of the data was performed to identify the frequency composition of the wind loads that the model is exposed to in longitudinal, lateral, and torsional directions.

3. Analysis and Results

Aerodynamic damping

Free vibration decay tests were utilised to obtain the structural and aerodynamic damping of the model tablets under still and various wind conditions. To assess the total damping, the models were given an initial displacement in the longitudinal direction and the free oscillation decay behaviour was measured and used to calculate the total damping ratio. The level of total damping is shown for Tablets 7 and 24 for a range of reduced velocities in Figure 4. Apart from data scatter there is a clear increase in total damping with increasing non-dimensional wind speed. Within the displacement range measured structural damping was found to remain constant. Hence, for all tests carried out positive aerodynamic damping was obtained and generally an increasing trend was observed with increasing reduced velocity. Reasonable data for the aerodynamic damping could be extracted from the measurements for full scale wind speeds up to 20 m/s. The maximum aerodynamic damping ratio measured was approximately 0.6% of critical damping.

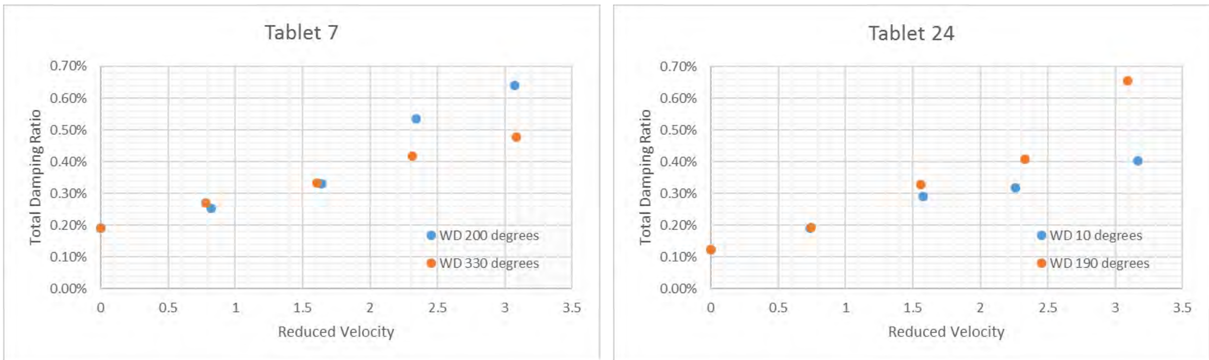

Fig. 4. Total damping ratios with increasing reduced wind speed for Tablets 7 and 24.

Free wind response

To investigate the tablets in regard to dynamic excitation mechanisms, the displacement response to varying wind speeds was measured. No initial displacement or perturbation was induced for these tests. Positive deflections are defined towards the southern end of the field, negative deflections are towards the north. The deflections are measured perpendicular to the tablet surface.

The maximum measured tip displacement (mean plus peak dynamic converted to full scale) over all wind speeds (4-38 m/s at full scale) and directions tested was:

- 206 mm for Tablet 7
- 149 mm for Tablet 24

It is highlighted that the measured peak displacements are primarily caused by the dynamic response. The highest mean deflections, for any given direction and wind speed combination, are determined as:

- -28 mm and +20 mm for Tablet 7.
- -26 mm and +24 mm for Tablet 24.

While peak deflections are caused by dynamic resonant response behavior, no significant excitation or lock-in response was observed for these cases. The time series rather suggests the measured displacements to be primarily resonant response caused by turbulence buffeting. The tests were conducted with a turbulence intensity of about 65-70% of that defined in the relevant standard (2011). Higher turbulence intensity may increase the buffeting response. However, the reduced response behaviour observed during an isolated tablet scenario suggests the majority of the local turbulence leading to buffeting response was created by the surrounding tablets. During all tests no unstable behaviour or lock-in of the displacement response was observed for any of the three tablets. Mass damping calculations suggest lock in behavior is unlikely at serviceability wind speeds.

Further isolated tests of Tablet 7 without the surrounding tablets resulted in lower displacement responses than the test cases in the tablet field. This suggests that the measured response is not caused by dynamic excitation of the tablet due to vortex shedding or a motion induced instability, but rather by the turbulent nature of the approach flow in combination with the turbulence generated by the surrounding tablets.

Figure 5 shows the maximum deflections for each wind speed setting of Tablets 7 and 24. A general increase in the peak deflections with rising velocity is observed. The scatter in these results can be partly explained by the fact that these data represent instantaneous peak measurements.

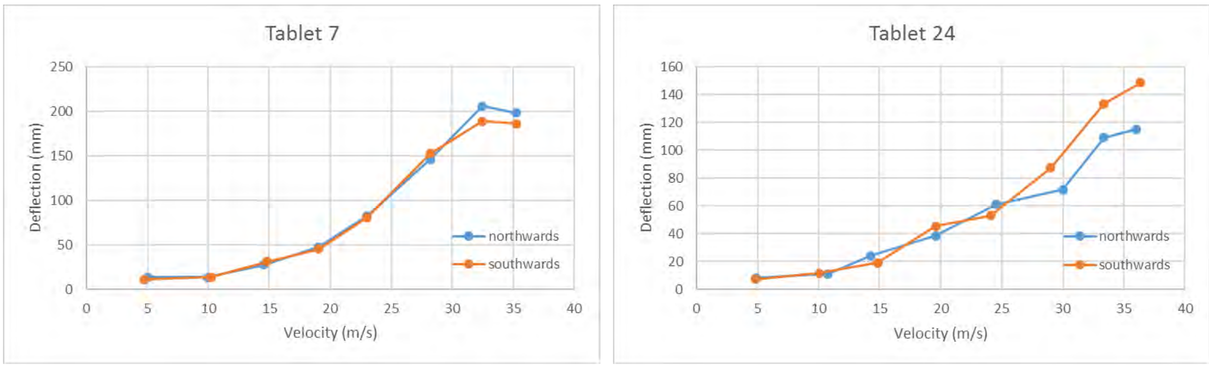

Fig. 5. Maximum deflections as a function of the wind speed for Tablets 7 and 24.

<u>High-frequency balance tests</u>

The spectral analysis of the high-frequency balance tests for Tablet 7 showed a significant spectral hump for winds from the south-east quadrant around the full scale mean design wind speed (32 m/s) at a frequency between 1.5 Hz and 1.6 Hz indicating the presence of regular vortex shedding for these cases. Figure 6 shows the power spectrum for a wind direction of 120° at full scale equivalent mean wind speed of 32 m/s. The spectral hump was observed for wind directions between 100° and 140° only. No other wind direction showed a similar response.

A higher mean wind speed will cause an increase of this vortex shedding frequency, so a mean wind speed of approximately 40 m/s will cause the tablet to be exposed to wind load fluctuations close to its first mode natural frequency with the risk for wind induced instability. The conditions at which the vortex shedding frequency coincides with the natural frequency of the tablet are beyond the design wind speed, however, it was recommended that the natural frequency of this tablet not be below the current value of 2.07 Hz. Also the torsional load shows a distinct peak at the same frequency, however, the torsional mode natural frequency is significantly higher than the one for longitudinal bending. Therefore, the conditions for the vortex shedding frequency coinciding with the torsional mode natural frequency will occur at even higher mean wind speeds, well beyond the design wind speed.

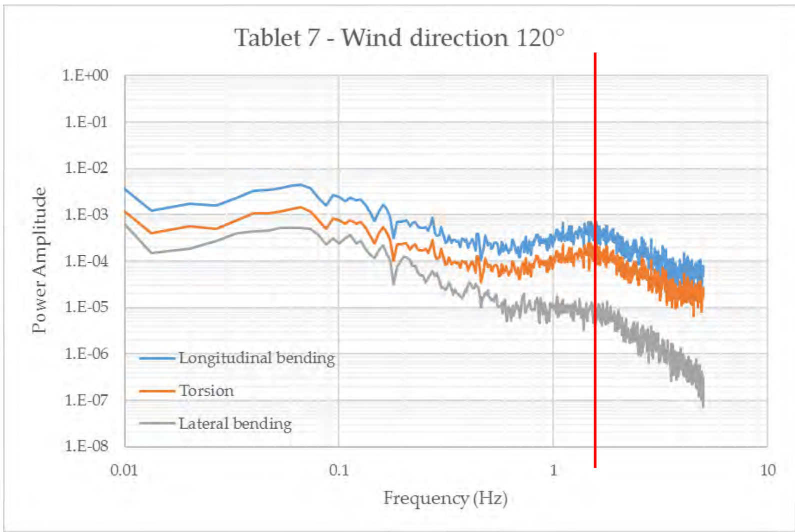

Fig. 6. Spectral analysis of the loads measured for Tablet 7 at a wind direction of 120°.

4. Conclusions

Aeroelastic wind tunnel testing has been conducted to assess the susceptibility of the proposed cantilever tablets of the Memorial Park sculpture Abu Dhabi, UAE, to wind induced excitation.

Free vibration decay tests on the model showed positive aerodynamic damping and a general increasing trend of damping with increasing wind speed. The maximum aerodynamic damping ratio measured was approximately 0.6% of critical damping.

No significant excitation due to vortex shedding from any of the tested tablets was detected at any of the design wind speeds tested. Results suggest the majority of the local turbulence leading to buffeting response was created by the surrounding tablets.

References

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