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Cross-Wind Response of Cylindrical Towers with Strakes

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Abstract

The development of Yagan Square (previously referred to as Perth City Square) as a central public place adjacent to the central train and bus stations in Perth includes a "Digital Tower" proposed to the south west of the site. This will be an approximately 60m tall structure supporting a digital mesh signage with an electrical substation at the base. The structure is formed by an inner and outer series of steel CHS 'tendrils' extending up from the substation base. Relatively slender tubular cantilevering structures such as the cantilevering tendrils proposed for the digital tower can be susceptible to unpredictable wind induced dynamic excitation, otherwise known as vortex shedding. A code based dynamic exercise has been completed and indicated that due to the slenderness and random positioning of the tendrils, vortex shedding has the potential to be a problem with regard to fatigue stress and in service deflection. This paper outlines the method used to determine the effectiveness of strakes applied to the outer surfaces of the tendrils to mitigate their cross-wind response.

Introduction

The development of Yagan Square (previously referred to as Perth City Square) is a development of a central public place adjacent to the central train and bus stations in Perth (overlying the newly constructed rail Dive Tunnel and older bored underground rail tunnels). It will consist of a number of architectural structures around a landscaped area sitting within the heritage listed "Horseshoe Bridge". The central public space will be used for retail, food and beverage and special events.

The development includes a "Digital Tower" proposed to the south west of the site, seen to the right in Figure 1 below. This will be an approximately 60m tall structure supporting a digital mesh signage with an electrical substation at the base.

Figure 1 Proposed development, with the Digital Tower on the right

Digital Tower - Structural Form

The structure is formed by an inner and outer series of steel CHS 'tendrils' extending up from the substation base. The inner and outer tendrils are braced to each other via dual ring membersthat are then tied together and positioned up the structure. The top ring is positioned so that the top of each tube is a free cantilever up to a maximum of 20m. Refer to Figure 2 below.

The inner series of steel tendrils are supported on a concrete box which forms the substation structure. This structure as well as the outer layer of CHS tendrils is supported on a continuous circular ground beam on top of piled foundations. The location is set away from the bored tunnels to the south-west, to allow for the required piles.

A series of rod cross-bracing elements form a 4 sided bracing box within the inner ring of tendrils which runs from the sub-station structure to the uppermost support ring, this provides the lateral stability to the structure. Maintenance access to the digital mesh area is provided by access platforms at every 3 meters over the height of the digital mesh with a stair running between each landing.

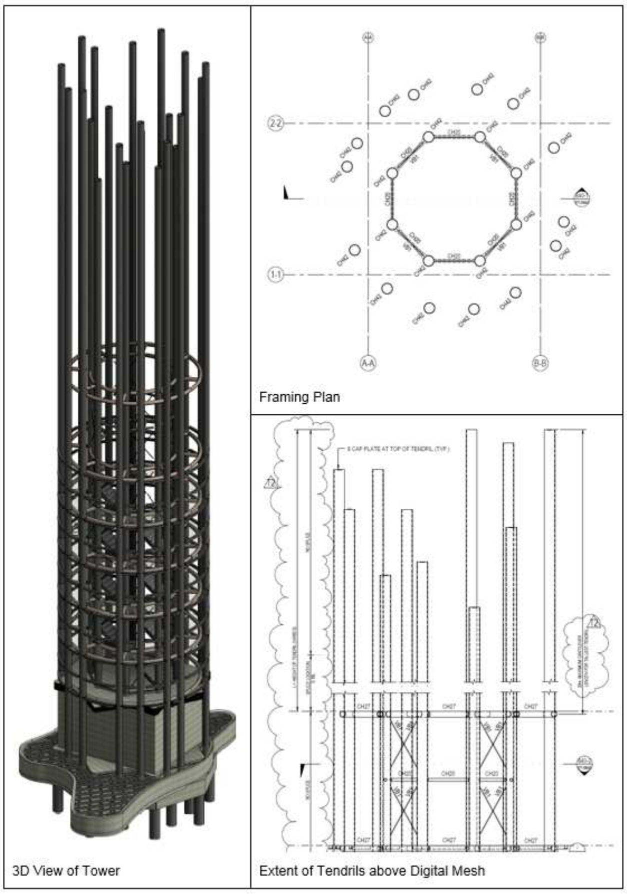

Figure 2 Dimensional drawing in plan and section. Isometric of tower.

Relatively slender tubular cantilevering structures such as the cantilevering tendrils proposed for the digital tower can be susceptible to unpredictable wind induced dynamic excitation, otherwise known as vortex shedding. A code based dynamic exercise has been completed and indicated that due to the slenderness and random positioning of the tendrils, vortex shedding has the potential to be a problem with regard to fatigue stress and in service deflection.

Background

The alternate shedding of vortices from circular cylinder structures is a well-known phenomenon in fluid mechanics, as shown below in Figure 3. Under certain conditions it can cause severe cross-wind (lateral) oscillations of structures (eg. Chimneys, poles etc) at or near the critical velocity at which the vortex shedding frequency coincides with a natural frequency of the structure.

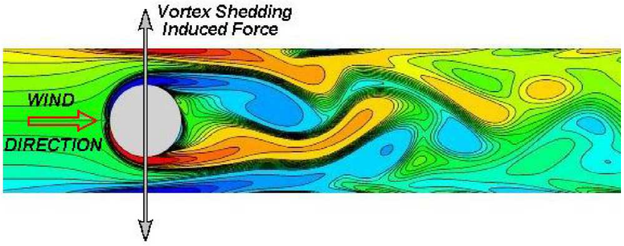

Figure 3 Vortex shedding as a result of flow incident on a cylinder

The character of the vortex shedding forces depends on the Reynolds Number (ratio of inertial to viscous effects):

$$Re = \frac{VD}{\nu}$$

where the velocity is represented by V, cylinder diameter is represented by D, and the kinematic viscosity for air as ν (with $\nu = \mu/\rho$ where ρ is the density of air, and μ is the dynamic viscosity) being a constant dependent on atmospheric conditions.

The various flow regimes for a circular cylinder with a smooth surface finish in smooth (low turbulence) flow are shown in Figure 5. The sharp fall in drag coefficient at a Reynolds number of about $2{\times}10^5$ is caused by a transition to turbulence in the surface boundary layers ahead of the separation points. This causes separation to be delayed to an angular position of about 140° from the front stagnation point, instead of 90°, which is the case for sub-critical Reynolds numbers. This delay in the separation results in a narrowing in the wake and an increased base pressure and a lower drag coefficient. The pressure distributions at sub-critical and super-critical Reynolds numbers are shown in Figure 6. This can be seen in drag and lift coefficients in the sub and super-critical regimes as noted in EN 1991 (2010).

The vortex shedding frequency depends on the Strouhal Number, which is given by (with f_s the vortex shedding frequency):

$$St = \frac{f_s D}{V}$$

The Strouhal Number varies with the Reynolds Number (and surface roughness) as shown in Figure 4, but for much of the range is about 0.2.

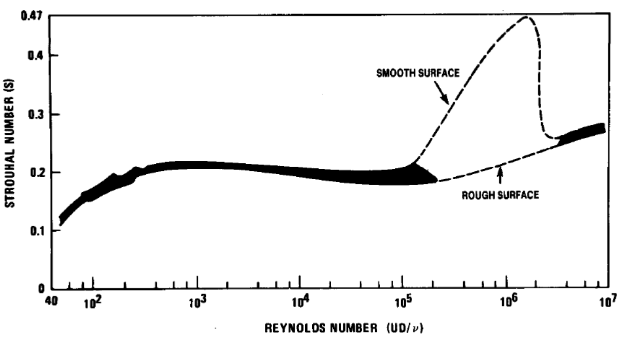

Figure 4 Variation of Strouhal and Reynolds Numbers with surface roughness.

The susceptibility of vibrations depends on the structural damping and the ratio of structural mass to fluid mass. This is expressed by the Scruton Number Sc, which is given by:

$$Sc = \frac{2\delta_s m}{\rho D^2}$$

Where δ_s is the structural damping expressed as the logarithmic decrement (or , $\delta_s = 2\pi\varsigma$, with ς the critical damping ratio),

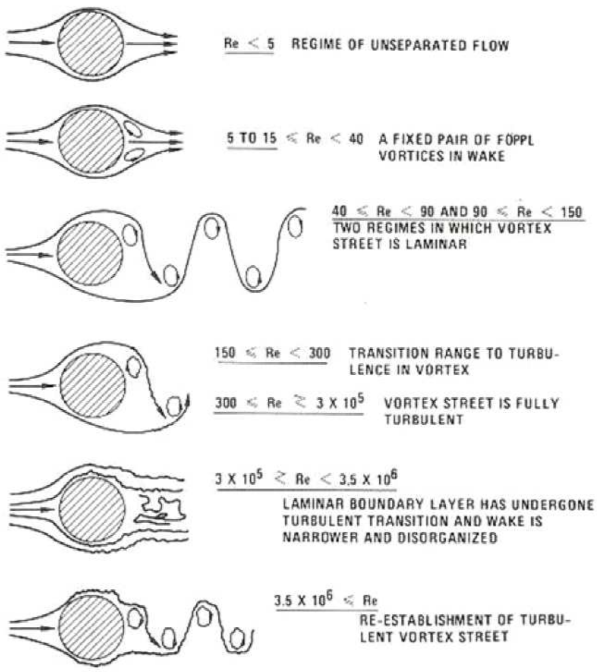

Figure 5 Regimes of fluid flow across a smooth circular cylinders

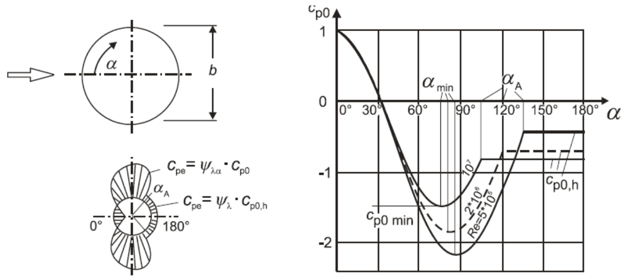

Figure 6 Distribution of mean pressure distribution around a smooth circular cylinder

Code Based Approach

Previously Holmes (1998) reviewed two classes of methods for the calculation of the cross-wind response of structures due to vortex shedding. These approaches have been formalised in EN 1991 (2010) and are outlined below. A comparison of the application of these methods in different international codes is given in Black et al (2009). Both methods rely on the definition of the generalised force on the structure as the integral of the product of the inertia force in the cross-wind direction with the mode shape across the height, h of the structure as detailed in Gaekwad and Mackenzie (2013).

Method 1 : Harmonic Excitation

In this case the inertial force is assumed to be of sinusoidal form, with Ruscheweyh (1988) including the effects of correlation length (this concept is also outlined in Gaekwad and Mackenzie (2013)) to give the ratio of maximum displacement to cylinder diameter (y_{max}/D) as:

$$\frac{y_{max}}{D} = \frac{1}{St^2}\frac{1}{Sc}KK_wC_{lat}$$

With K the mode shape factor, K_w the correlation length factor, and C_{lat} the lateral force coefficient.

Method 2 : Spectral Excitation

This method is similar to that used for high-frequency base-balance tests, also outlined in Gaekwad and Mackenzie (2013), with Holmes (1998) noting that Vickery et al (1983) developed random excitation models over many years.

$$\frac{y_{max}}{D} = \frac{\sigma_y}{D}k_p$$

Where k_p is the peak factor:

$$k_p = \sqrt{2}\left[1 + 1.2\arctan\left(0.75\left(\frac{c}{4\pi K_a}\right)^4\right)\right]$$

and:

$$\frac{\sigma_y}{D} = \frac{1}{St^2}\frac{C_c}{\sqrt{\frac{Sc}{4\pi} - K_a\left(1-\left(\frac{\sigma_y}{Da_L}\right)^2\right)}}\sqrt{\frac{\rho D^2}{m}}\sqrt{\frac{D}{h}}$$

with C_c the aerodynamic constant dependent on the cross-sectional shape, K_a the aerodynamic damping parameter, $a_L$normalised limiting amplitude giving the deflection of structures with very low damping. EN 1991 presents a simplified version of the above equation.

Fatigue

To assess fatigue, EN 1991 also provides an estimate for the number of load cycles, N, caused by vortex excited oscillations which can be compared with

$$N = 2Tf_c\varepsilon_0\left(\frac{V_{crit}}{c}\right)^2 exp\left(-\left(\frac{V_{crit}}{V_0}\right)^2\right)$$

With ε_0 the bandwidth factor describing the band of wind velocities with vortex-induced vibrations, T the life time of the structure (in seconds), V_{crit} the critical wind speed (m/s) for "lock-in" (coincidence of vortex shedding frequency with natural frequency) and V_0 times the modal value of the Weibull probability distribution assumed for the wind velocity (m/s).

Mitigation Methods

EN 1991-1-4:2005+A1:2010 includes the following commentary; *The vortex-induced amplitudes may be reduced by means of aerodynamic devices (only under special conditions, e.g. Scruton numbers larger than 8) or damping devices supplied to the structure. The drag coefficient cf for a structure with circular cross section and aerodynamic devices based on the basic diameter b, may increase up to a value of 1.4.*

Robinson and Hamilton (1992) describe methods of suppressing vortex excitation:

- Changes in member properties and structural detailing : Increases in the natural frequency, stiffness or damping, either singly or in combination, will generally reduce the oscillation amplitude;
- Aerodynamic spoilers : These are intended to reduce the amplitude of response of disrupting the fluid processes involved in vortex formation. The interaction affects the shedding mechanism primarily by interfering with the wake and reducing span wise coherence.

There has been much work on suppression of vortex induced oscillations by the likes of Zdrakovich (1981) and Wong and Kokkalis (1982) considering helical and axial strakes. Gartshore et al (1979) considered the effects of smooth and turbulent flow on the effectiveness of strakes, defined by the term, R (ratio of the maximum RMS deflection of a cylinder relative to a cylinder without spoilers in turbulent flow), shown in Figure 7. The cross-wind response is reduced by a factor of upto 20 in turbulent flow, as opposed to 100 in smooth flow.

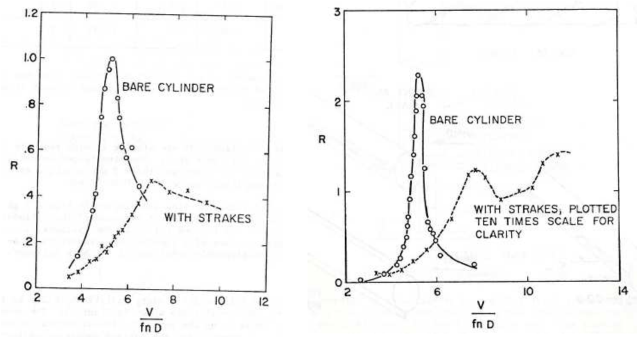

Figure 7 Effectiveness of strakes in smooth and turbulent flow

Digital Tower Assessment

Initial work carried out by Aurecon's structural engineering team used EN1991 (2010) to assess the fatigue life of the cylinders. EN 1991 also includes an amplification factor on the cross-wind response for bundled cylinders, as shown in Figure 8. Based on the physical characteristics of the towers, the risk of failure in fatigue was identified and options considered to reduce the cross-wind response. The use of axial strakes was preferred (with tuned mass dampers an additional future option if required), with the suggested arrangement shown in Figure 9.

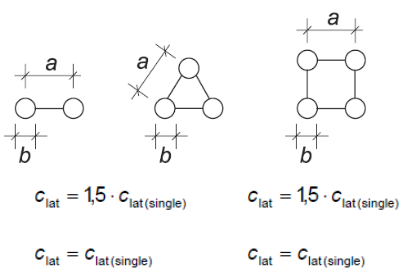

Figure 8 Amplification factors for bundles cylinders.

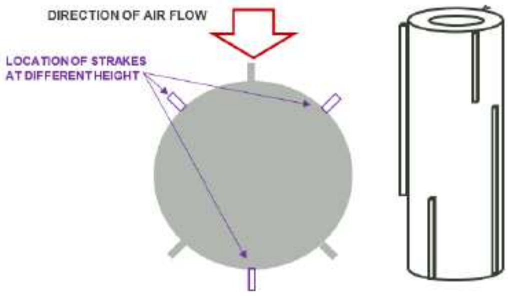

Figure 9 Proposed mitigation method

The effectiveness of strakes was assessed in a wind tunnel on a scale model of the cylinders by firstly determining the surface roughness required to generate vortex streets similar to that at full scale at sub and super critical Reynolds Numbers. The variance (Root-Mean-Square, RMS, amplitude of lift coefficients in the time domain or Power Spectral Density (PSD) of the lift coefficient in the frequency domain) in the lift coefficient was measured using the most relevant surface roughness, with and without strakes. As part of this work, an analytical study was carried out to determine the properties required of the scale model tube to ensure structural modes of the tube would not occur. Surface roughness was modified to ensure Reynolds Number effects were properly modelled at reduced scale.

The base tube was mounted on a high frequency base balance or load cell which enabled lateral, longitudinal (and vertical) forces and moments about each axis to be measured in time. An upper tube was used to reduce end effects and simulate worst case excitation. Cable stays were used to support the tube and maintain vertical alignment at high wind speeds. Wind speeds varied from 0 to just under 40m/s (the maximum velocity of the wind tunnel). The base tube was rotated 90 degrees to consider the effects of strakes impacting affecting flow on one side of the tube only. Refer to Figure 10 below.

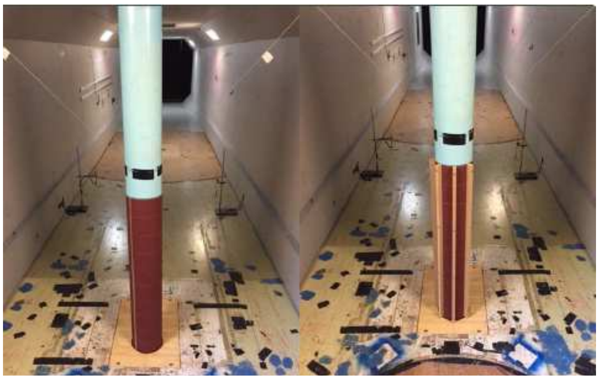

Figure 10 Wind tunnel setup

The introduction of strakes to the cylinder had a dramatic reduction in fluctuating lift coefficients, in the order of 70% at sub-critical Reynolds Numbers. This was achieved despite the strakes being apparent to the incoming flow on one side of the cylinder only. At super-critical Reynolds Numbers, the strakes had limited impact given the flow was already disturbed and the vortex street was turbulent in nature and therefore less intense.

An interesting issue encountered during testing was a pronounced differential lift force on one side of the cylinder during the transition from sub to super critical Reynolds Numbers. This was recently demonstrated and investigated by van Hinsberg et al as shown below in Figure 11, with each flow regime achieved by varying the ambient pressure within the wind tunnel (and therefore kinematic viscosity) as opposed to surface roughness.

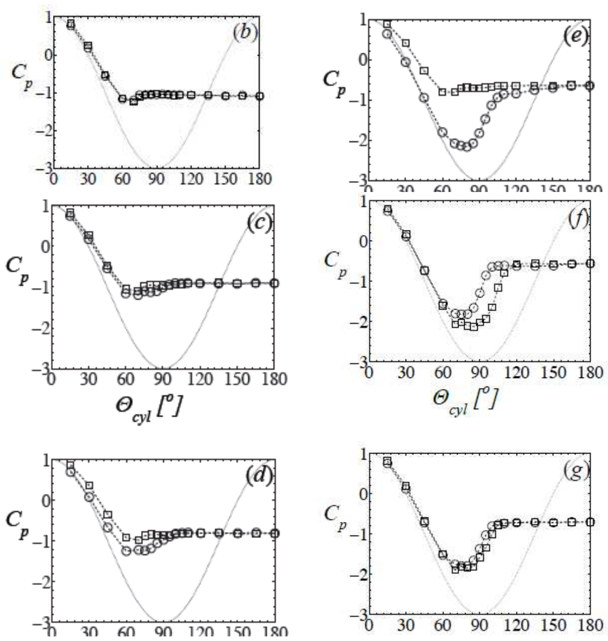

Figure 11 Mean circumferential pressure coefficient distribution at mid-span. ○: Lower half-cylinder ($0° \leq \theta_{cyl} \leq 180°$); □: Upper half-cylinder ($0° \leq \theta_{cyl} \leq 180°$); (c) to (f) are in the critical regime, while (b) is subcritical and (g) is supercritical.

Conclusions

This paper has investigated the application of axial strakes to minimise cross-wind excitation of cylindrical towers that form part of the "Digital Tower" at Yagan Square in Perth. It was found that in the sub-critical regime, the introduction of strakes significantly reduced the cross-wind response for both smooth and turbulent flow, reducing fatigue effects, while in the super-critical regime they had limited effect.

Acknowledgments

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