15th Australasian Wind Engineering Society Workshop
Sydney, Australia
23-24 February 2012

Estimates of extreme gust wind speeds from failed road-signs

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Abstract

Cantilevered highway road-signs (Windicators) are used for estimating the gust wind speeds when conducting structural damage assessments following windstorms. The upper and lower bounds of wind speeds are calculated by estimating the plastic moment capacity of upright and bent post(s), respectively, and the drag force applied on the road-sign.

This paper describes the theoretical background and summarizes experiments and results obtained from tests conducted following recent damage investigations. The analysis also shows that a typical $1m^2$ road-sign will closely measure the gust wind speed as defined by its revised definition in AS/NZS1170.2 (2011).

Introduction

The wind load standard AS/NZS 1170.2 (2011) and its predecessors have defined the basic gust wind speed as being the 2 to 3 sec gust occurring within 1 hr. These design wind speeds are based on a statistical analysis of uncorrected gusts from the Dines anemometers located at Bureau of Meteorology sites. The Bureau had replaced the Dines instruments with 3-cup anemometers by about the mid 1990s and incorporated a 3sec moving average filter based on a WMO specification by Beljaars (1987). The response characteristics of the Dines and 3-cup anemometers measured in a project for the Department of Climate Change & Energy Efficiency (DCCEE) (2011) found an apparent average overshoot in the Dines relative to the 3-cup of 7-13% for the low-speed type and 12-21% for the high-speed type. This study carried out for the DCCEE and shown in Miller *et al* (2011) found that the first natural mode of the standard low-speed Dines anemometer, and the high-speed type used in the cyclonic regions, have periods of about 2 and 3 sec respectively, but the effective averaging times were much shorter than these – of the order of 0.2 seconds. As the design data in AS/NZS 1170.2 have historically been based on the uncorrected gusts from Dines anemometers, it can be asserted that the basis of the Standard is a gust with an averaging time of about 0.2s. The report also gives correction factors based on these ratios, which are also dependent on the approach wind speed and turbulence intensity.

A reliable assessment of the gust wind speed is also important when assessing post windstorm structural performance of buildings. In many cases, an official operational weather station will not be located in the path of the windstorm, or sufficient numbers of wind speed measuring devices may not be available.

The analysis of wind loads on simple structures such as road signs, subsequently called 'Windicators', was undertaken following Cyclone Tracy (Halpern Glick 1975). Damage surveys reported after cyclones Larry by Henderson *et al.* (2006) and Yasi by Boughton *et al.* (2011) have relied heavily on the response of cantilevered road-signs for estimating the gust wind speeds and the overall wind field. These 'Windicators' give an estimate of upper (U) and lower (L) bounds of peak gust wind speeds at different locations in the study area. Upright sign-posts give an upper bound to the wind speed as they resisted the wind loads, whilst bent posts give a lower bound to wind speed as they failed during the event. These road-signs are generally flat plates that are attached to one or two cantilevered posts. The wind loads acting on these plates can be determined, and wind speeds estimated with confidence based on force coefficients for rectangular flat plates that are well established as shown by Hoerner (1965) reporting measurements by Flachsbart (1932) and Holmes *et al.* (2006).

This paper presents an analysis of typical road signs to fluctuating wind pressures and relates its response to gust wind speeds specified for structural design in AS/NZS 1170.2.

Theoretical Analysis

The peak net wind load (F_N) across the road-sign shown in Figure 1, is given by Equation 1.

$$F_N = \tfrac{1}{2}\rho \hat{U}_h^{\,2}.C_N.A \qquad (1)$$

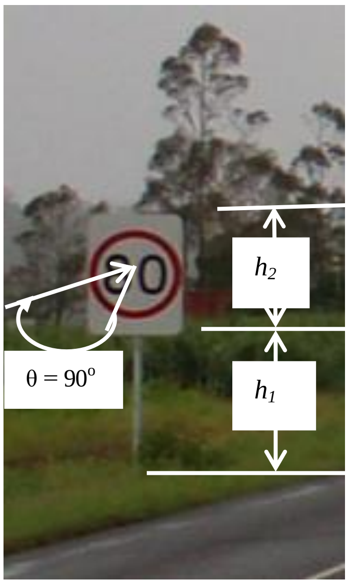

Figure 1. Typical Road Sign

Here, C_N is the normal force coefficient, A is the area of the plate (i.e. road-sign), ρ is the density of air, $\hat{U}_h$ is the gust velocity at the centroid (i.e. $l = h_1 + 0.5h_2$) of the plate. The resulting maximum (i.e. base) bending moment M_{max} on the post(s) is given by Equation (2), where the lever-arm, l is the distance between the base and centroid of the plate. As shown by Holmes *et al.* (2006) in Figure 2, C_N is constant (~1.2) for θ = 40° to 140° and θ = 220° to 320°.

$$M_{max} = F_N.l = (\tfrac{1}{2}\rho\hat{U}_h^{\,2}.C_N.A)l \qquad (2)$$

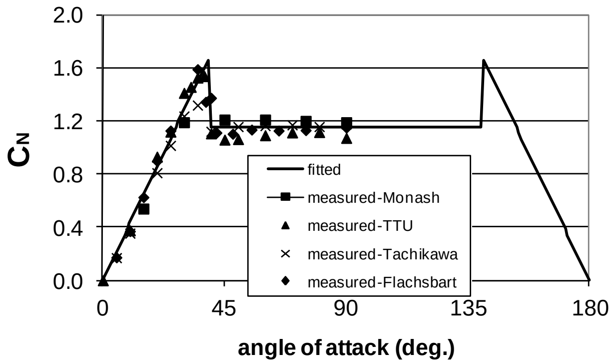

Figure 2. Normal force coefficient for a flat plate versus approach angle, θ from Holmes et al (2006)

The plastic moment capacity of the post(s) M_p is given by Equation (3), where f_y is the yield strength of the material and s is the plastic section modulus.

$$f_y = M_p / s \;;\; M_p = f_y.s \qquad (3)$$

A plastic hinge in the post(s) is created when the peak bending moment generated by the wind load exceeds the plastic moment capacity M_p of the post(s), as shown in Equation (4). The failure wind speed at height, h is then determined from Equation (5).

$$M_{max} \geq M_p \;;\; (\tfrac{1}{2}\rho\hat{U}_h^{\,2}.C_N.A)l \geq f_y s \qquad (4)$$

$$\hat{U}_h \geq \sqrt{f_y s / [(\tfrac{1}{2}\rho.C_N.A).l\,]} \qquad (5)$$

Random Process Theory

The performance of a Windicator will be influenced by the response of the plate and cantilevered post(s) supporting the road-sign. Random process theory can be used to predict the gust factors for wind measured by a Windicator in a turbulent wind of known intensity and spectral density. A similar approach was used to predict the wind gust factors recorded by 3-cup and Dines anemometers in the DCCEE report (2011). The spectral density of the wind turbulence was modelled using the von Karman form, which, in non-dimensional terms, can be written as shown in Equation (6).

$$\frac{n.S_u(n)}{\sigma_u^{\,2}} = \frac{4\left(\dfrac{n\ell_u}{\bar{U}}\right)}{\left[1 + 70.8\left(\dfrac{n\ell_u}{\bar{U}}\right)^2\right]^{5/6}} \qquad (6)$$

where l_u is an integral length scale, and σ_u is the standard deviation of turbulence which can be obtained from the intensity of turbulence and the mean wind speed (i.e. $\sigma_u = I_u \times \bar{U}$).

The dynamic response of windicator can be incorporated by multiplying the spectral density by a transfer function $|H(n)|^2$. In this case, the transfer function can be represented by:

$$|H(n)|^2 = |H_1(n)|^2.|H_2(n)|^2 \qquad (7)$$

Based on many experiments, Vickery (1968) derived the transfer function for a plate; $|H_1(n)|^2 = \dfrac{1}{\left[1 + \left(\dfrac{2n\sqrt{A}}{\bar{U}}\right)^{4/3}\right]^2}$, and

$|H_2(n)|^2 = \dfrac{1}{\left[\left(1 - \left(\dfrac{n}{n_0}\right)^2\right)^2 + 4\xi^2\left(\dfrac{n}{n_0}\right)^2\right]}$ accounts for the additional effect of the cantilevered post(s). Here the first natural frequency, $n_0 = \dfrac{3.52}{2\pi}\sqrt{\dfrac{EI}{ml^3}}$ and ξ is the damping coefficient of the post(s). A typical 60.3mm (OD) 2.3mm thick 2m tall CHS steel post has a mass (m) of about 6.6 kg and $I = 0.177 \times 10^{-6}$ m^4 and a Youngs modulus E = 200 GPa, giving a natural frequency, n_0, of about 14.5Hz, well outside the wind velocity fluctuations. The dynamic response of road signs to atmospheric turbulence was investigated by Simpson (1975). The natural frequency and damping at low amplitudes were found to depend closely on the support conditions for the post. Once a post starts to fail and plastic deformation occurs in the steel, the damping increases dramatically. Best (1976) investigated the combination of dynamic response and plastic deformation for a structure representative of a road sign, and found that the two effects tended to cancel each other out. Best (1976) concluded that static calculations of road sign failures could be used to estimate peak gusts within 10%, although no averaging time was stated. Hence, $|H_2(n)|^2$ has been taken as 1.0 for the range of excitation frequencies, n considered here.

The cycling rate or 'average frequency', υ, of the filtered process can be calculated from Equation (8). The expected peak factor can then be calculated using the well-known formula for Gaussian processes of Davenport (1964) given in Equation (9), where γ is Euler's Constant (0.5772), and T is the sample time for which the expected peak is to be determined.

$$\upsilon = \left[\int_0^\infty n^2 . S_u(n) |H(n)|^2 dn \Big/ \int_0^\infty S_u(n) |H(n)|^2 dn \right]^{1/2} \quad (8)$$

$$g = \sqrt{2\ln(\upsilon T)} + \frac{\gamma}{\sqrt{2\ln(\upsilon T)}} \quad (9)$$

The gust factor is obtained from, $G = 1 + g\sigma_{u,f} / \overline{U}$, where $\sigma_{u,f}$ is the standard deviation of the filtered process given by,

$$\sigma_{u,f} = \left[\int_0^\infty S_u(n) |H(n)|^2 dn \right]^{1/2} \quad (10)$$

Experimental Testing, Analysis and Results

Many upright and bent road-signs were examined during damage surveys after cyclones 'Larry' and 'Yasi', and several of these were selected as providing the most reliable wind speed information. The dimensions of the plate, the height and number of posts and their sectional dimensions (i.e. inner/outer diameters and thickness) were measured in the field. The plastic moment capacities of typical Grade G350 steel posts used by the Queensland Dept of Main Roads were calculated for two yield strength values using Equation (3), and presented in Table 1.

Table 1: Calculated Moment Capacities for typical posts

Outside Diameter (OD) (mm)	Thick -ness (mm)	Plastic Modulus, *s* 10^3 x mm^3	Plastic Moment Capacity, M_p (kNm)	
			f_y 350MPa	f_y 420MPa
60.3	2.9	9.56	3.35	4.02
76.1	3.2	17.02	5.96	7.15
88.9	3.2	23.51	8.23	9.88
101.6	3.2	31.00	10.85	13.02

Selected posts were dismantled and sample lengths of these posts were subjected to third point bending tests in the laboratory, at James Cook University, as shown in Figure 3. The measured plastic moment capacities were compared with data given in Table 1, and used to calculate the yield strengths.

Figure 3. Third Point Bending Test

Table 2 gives the plastic moment capacities measured on four samples from two common sizes of road-sign posts. The 60.3 mm (OD) 2.3 mm thick posts have plastic moment capacity of about 2.8 kNm and a yield strength of about 360 MPa. For two 76.1 mm (OD) pipes with a thickness of 3.2 mm, the measured moment capacities increased to 7.48 and 7.75 kNm, with calculated yield strengths of 440 and 455 MPa, respectively.

Table 2. Measured properties of posts

Outside Diameter (OD) (mm)	Thick-ness (mm)	Plastic Modulus, *s* 10^3 x mm^3	Measured Moment Capacity, M_p (kNm)	Calc Yield Strength, f_y (MPa)
60.3	2.3	7.74	2.84	367
60.3	2.3	7.74	2.72	351
76.1	3.2	17.02	7.48	440
76.1	3.2	17.02	7.75	455

The spectral density of the approach turbulent flow as modified by a 1 m^2 plate for approach mean wind speeds of 20 and 40 m/s are shown in Figures 4 and 5, respectively. It can be seen that the 1 m^2 plate modified spectra (i.e. that associated with the new definition in AS/NZS 1170.2) moves to the right (increasing frequencies with increasing wind speed along with the underlying wind spectrum. This shows that the Windicator road signs provide a reliable measure of the gust wind speed that is required to bend the cantilevered post(s). As these road signs are generally 2 to 3 m tall an empirical terrain height multiplier is used to estimate the wind speed at 10m in standard terrain category 2 conditions.

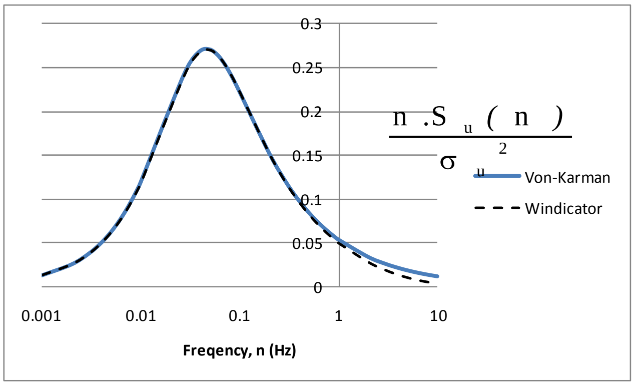

Figure 4. Approach wind velocity spectral density and spectral density as "filtered" by a 1m^2 plate; $\overline{U}$ = 20 m/s

Using the random process methodology, the expected cycling rate, peak factors and gust factors for wind speeds recorded by a 1 m^2 plate windicator, were calculated for the following values: $\overline{U}$ = 20 m/s; I_u = 0.25; ℓ_u = 63 m; T = 600 s are given in Table 3. The value of ℓ_u of 63 m is derived from Equation 6.2(3) in Australian Standard AS/NZS1170.2 (2011), for a height of 3 metres. Table 3 shows that the 1 m^2 plate windicator gives a gust factor G = 1.87 at 3 m in terrain category 2 conditions (based on truncating the integration in Equations (8) and (10) at 5 Hertz. The equivalent G for a 0.2-second moving average gust is 1.84.

Table 3. Calculated response parameters of 1 m^2 plate windicator

Cycling rate, υ (Hz)	0.504 *
Std deviation, $\sigma_{u\,f}$(m/s)	4.90*
Peak factor, g	3.55
Gust factor, G	1.87

- integration carried out up to 5 Hertz

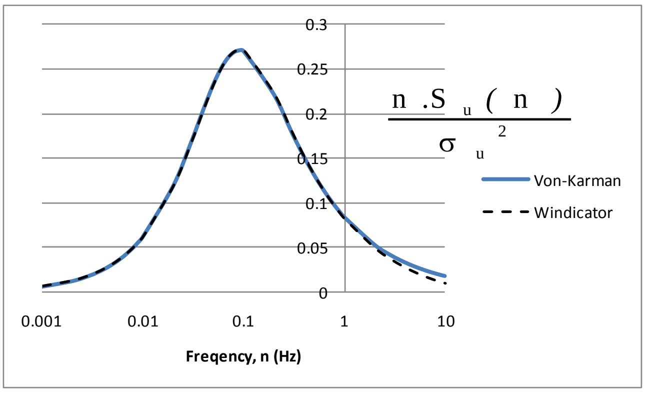

Figure 5. Approach wind velocity spectral density and spectral density as "filtered" by a 1m^2 plate; $\bar{U}$ = 40 m/s

Discussion and Conclusions

Cantilevered highway road-signs (windicators) can be used in damage investigation assessments to provide a reliable estimate of upper and lower limit unfiltered gust wind speeds. These estimates are based on the peak wind load acting on the plate attached to typical 2 to 3 m tall post(s). The analysis requires measurements of the dimensions of the plate and post(s) and an estimation of the material properties of the post(s).

Experimental data have shown that the normal force coefficient, C_N on flat plates is essentially a constant value of 1.2, for winds approaching from any direction within ± 50° from a line normal to the plate on either side, giving a total effective coverage of 200 degrees. In addition, random process theory has shown that the 1 m^2 flat plate responds to gust velocity fluctuations such that the gust wind speed recorded is representative of a 0.2 second gust, as it will shortly be re-defined in AS/NZS 1170.2.

In the future, it is planned to study Windicators further, by subjecting a series of posts to simulated dynamic loading, and by assessing their response ranging from elastic to the formation of a plastic hinge at the base.

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