The 12th Americas Conference on Wind Engineering (12ACWE)
Seattle, Washington, USA, June 16-20, 2013

Gust durations and effective frontal areas – with applications to codes and standards

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ABSTRACT: This paper discusses the appropriate duration for basic gust wind speeds in wind loading codes and standards. Although various proposed definitions are discussed, the 'moving average' gust duration has been accepted internationally, and is suggested as the appropriate one for use by wind engineers. Various historical definitions or descriptions are discussed and compared with the 'moving average' gust duration that has been more recently accepted internationally by the World Meteorological Organization (WMO) for gust speed recording. By this definition, gust durations for analogue outputs from various anemometers are shown to be generally less than 1 second, even though these were historically described as '3-second gust'. It is shown that a 3-second moving digital average, as suggested for gust reporting by the World Meteorological Organization, has significant attenuation effects on wind spectra at design wind speeds, and is equivalent to the filtering of a structure with a frontal area equivalent to that of a typical tall building in a city centre. Hence, for codes and standards that have adopted the WMO 3-second gust as a basis (such as ASCE 7), it is appropriate that 'gust effect factors' greater than 1.0 should be adopted for small structures, or that another adjustment should be made to correct the design pressures.

KEYWORDS: anemometer, codes, gust, gust factor, peak factor, spectra, standards.

1 INTRODUCTION

Codes and standards for wind loading are currently based on extreme wind speeds with a variety of nominal averaging times. These variations have occurred for a number of reasons, such as the type of recording systems used by meteorological services to record winds, or the type of extreme wind event that dominates designs for wind in a particular jurisdiction.

Many national wind codes and standards are based on a maximum gust wind speed, with a defined gust duration. In those codes and standards that are based on a peak gust wind speed, it is most common to find it stated as a '3-second' gust, or a '2 to 3 second gust', following the descriptions provided historically in, for example, BS CP3: Chapter V: Part 2 (1972) [1], and AS CA34 Part 2, 1971 [2]. A '3-second gust' has been adopted by ASCE 7 [3], since 1995.

Other codes are based on wind speeds averaged over periods such as ten-minutes or one hour. However, even in these cases, the wind speed is effectively converted to a gust speed within the format of the code, before calculating building pressures or forces. Gust factors, being the ratios between the expected maximum gust and the mean value, in an averaging time such as one hour, are therefore important for these conversions. In every case, it is desirable to be precise about the gust duration that has been adopted by a particular design code or standard, so that recorded wind data can be used correctly, or if necessary, corrected. Accurate gust factors and peak factors are also required to enable wind-tunnel data on building pressures to be converted for use in codes and standards.

Harper *et al.* [4] reviewed the available information on gust factors for tropical cyclones, and found a great deal of scatter and inconsistency in these factors in the literature. At least partly, this variation can be attributed to the lack of a clear knowledge of, and method of defining, the gust duration. The latter is the focus of this paper, together with a discussion of the effective frontal area that can be associated with peak gusts of a particular duration.

2 DEFINITIONS OF GUST DURATION

2.1 *Definitions based on anemometer characteristics*

The original methods of stating gust duration were usually based on characteristics of the measuring instrument. For example, in many cases cup anemometers were used, and continue to be used, as the principal wind-measuring instrument by national meteorological agencies. The response characteristics of this instrument can be accurately described by a distance constant, *D*, so that the transfer function for response to turbulence treated as a random function, such as turbulent wind speeds, can be written:

$$|H_1(n)|^2 = \frac{1}{1+\left(\frac{2\pi nD}{\overline{U}}\right)^2} \tag{1}$$

where n is frequency and $\overline{U}$ is the mean wind speed

This instrument responds to a step change in wind speed exponentially so that it reaches 63% of its final value in a time equal to $(D/\overline{U})$. Thus, a natural measure of gust duration as recorded by a cup anemometer is the distance constant divided by the mean wind speed – the 'time constant' of the instrument. Thus a cup anemometer, with a distance constant of 6 metres would have a time constant of 0.2 seconds at a mean wind speed of 30 m/s and 0.3 seconds at 20 m/s.

Miller [5] proposed an alternative effective gust duration, equal to the reciprocal of the half-power frequency of a cup anemometer. From Equation (1) this gives an effective gust time equal to $2\pi\,(D/\overline{U})$ – i.e. more than six times the "time-constant" definition. However, this definition cannot readily be applied to the Dines pressure tube- float anemometer which has two resonant frequencies, and hence two 'half-power' frequencies [6].

2.2 *The moving average definition*

The moving-average definition of maximum gusts was proposed by Beljaars for international use, on behalf of the World Meteorological Organization (WMO) in 1987, ([7], [8]), and was introduced at the time of the adoption of computer controlled automatic weather stations, and digital processing of anemometer data.

In the frequency domain, the transfer function for a simple moving average 'filter' can be written as:

$$|H_2(n)|^2 = \left(\frac{\sin(n\pi\tau)}{n\pi\tau}\right)^2 \tag{2}$$

where τ is the moving average time.

Beljaars originally suggested a value of τ of 2 to 5 seconds, obtained by digital filtering, as being an appropriate for national meteorological services to record maximum gusts on a consistent basis around the world. In fact, a value of τ equal to 3 seconds appears to have been widely adopted – i.e. a digital moving average extending for 3 seconds is commonly applied to sampled data from automatic weather stations. Note that, when τ is equal to 3 seconds, the right-hand-side of Eqn. (2) takes a value of zero for n equal to (1/3) Hertz, and the half-power point is approximately 0.15 Hertz, frequencies that are well within the energy-containing range of atmospheric turbulence, and that are significant for wind pressures on structures.

The use of a true 3-second moving average, as described above, is potentially a source of confusion and error, as this definition of a '3-second gust' gives lower values than those previously recorded by all anemometer types in use; it is also not equivalent to the peak gusts used historically in many wind codes and standards, and can be up to 20% lower. However, in the digital age, it seems appropriate to adopt a common moving-average definition of gust duration, as has been done by ISO 4354 [9] and ESDU Data Item 83045 [10], as well as the WMO.

As noted above, recorded gust data from analogue instrumentation systems in the pre-digital era was simply a function of the anemometer response. In those cases, equivalence with the moving average definition can be obtained by matching peak factors and/or gust factors, by the use of random process theory with a defined spectrum of turbulence.

By matching the response to turbulence of various anemometer types, equivalent gust durations, τ_{equiv}, for analogue response of various anemometers as a function of mean wind speed can be obtained as shown in Table 1. For the cup anemometers, the transfer function given by Eq. (1) was used. Transfer functions for the Dines pressure-tube types obtained experimentally, and given by Miller *et al.* [6], were used to derive equivalent moving average times in Table 1.

Table 1. Equivalent moving averaging times for various anemometers

Anemometer	**$\bar{U}$ (m/s)**	**τ_{equiv} (sec)**
cup (D = 6 m)	25	0.5
cup (D = 6 m)	40	0.3
cup (D = 13 m)	25	0.9
cup (D = 13 m)	40	0.6
Dines	25	0.5
Dines (high-speed version)	40	0.3

Table 1 shows that anemometer gust data recorded in the pre-digital era generally had equivalent averaging times of less than 1 second – and usually significantly lower than the 3 seconds commonly assumed.

3 EFFECT OF MOVING-AVERAGE FILTERS ON WIND SPECTRA

The effect of moving average filters can be illustrated by applying the filter transfer function (Eq. (2)) to a typical spectral density of wind turbulence. This has been done in Figures 1 and 2, with the averaging time, τ, equal to 3 seconds and 0.2 seconds, respectively. The spectral density chosen was the von Karman form given in Eq. (3), with the integral length scale, L_u, of 85 metres (as recommended in the current Australian/New Zealand Standard [11] for a height of 10 metres).

$$\frac{n.S_u(n)}{\sigma_u{}^2} = \frac{4\left(\frac{nL_u}{\bar{U}}\right)}{\left[1+70.8\left(\frac{nL_u}{\bar{U}}\right)^2\right]^{5/6}} \tag{3}$$

The hourly mean wind speed $\bar{U}$ for both Figures 1 and 2 was selected as 30 m/s, ($L_u/\bar{U}$ = 2.8)

From Figure 1, it is clear that the effect of a moving-average filter with the value of τ equal to 3 seconds on the high frequency end of the wind spectrum is severe. However, a moving average with an averaging time of 0.2 seconds (Figure 2) is much less severe. These filtering effects are reflected in the peak factors and gust factors discussed in Section 4.

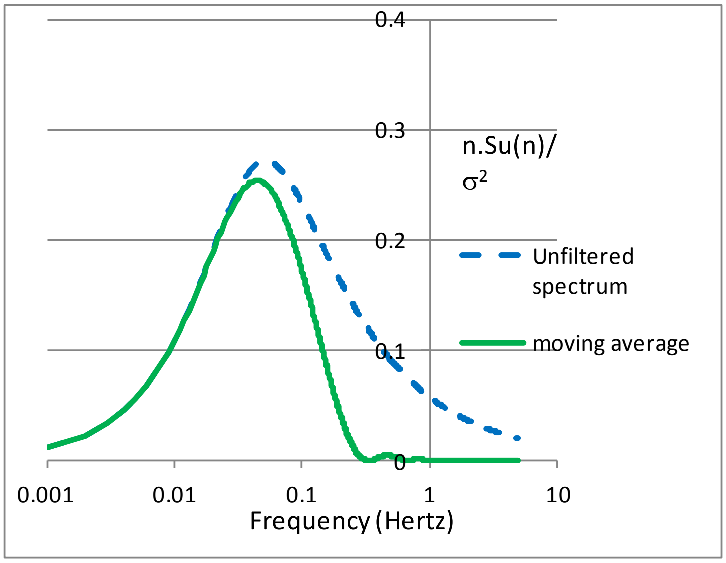

Figure 1. Effect of moving average filter with an averaging time, τ, of 3 seconds on the wind spectrum at a typical design wind speed.

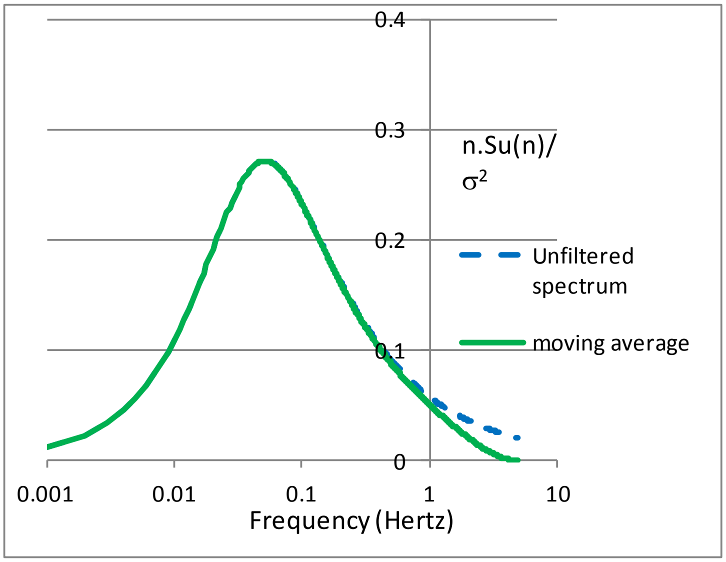

Figure 2. As for Fig. 1 but with the averaging time, τ, equal to 0.2 seconds

4 EFFECTIVE AVERAGING AREAS

An important consideration in defining a maximum gust duration for a wind code or standard, is the effective frontal area over which a gust can be considered to act. Using an expression for aerodynamic admittance proposed by Vickery [12] and given in Eq. (4), and a moving average filter, effective, or equivalent, frontal areas for a 3-second gust can be derived by matching the calculated expected peak factors, for a range of mean wind speeds. This process results in a relationship between equivalent frontal area and (hourly) mean wind speed shown in Figure 3.

$$|H(n)|^2 = \frac{1}{\left[1+\left(\frac{2n\sqrt{A}}{\bar{U}}\right)^{4/3}\right]^2} \qquad (4)$$

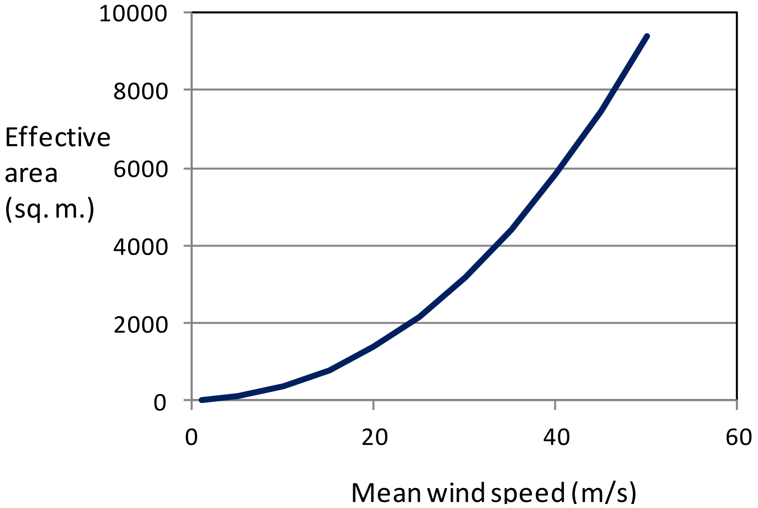

Figure 3. Equivalent frontal area for a 3-second gust

At a mean wind speed of 30 m/s, a 3-second gust has an equivalent frontal area of 3200 square metres – equivalent to that for a tall building 100 metres tall and 32 metres wide. Thus a code based on a 3-second gust with quasi-steady shape factors, should include extra factors to *increase* the effective pressure, when applied to small buildings with smaller frontal areas. Furthermore the ‘gust effect factor’ (or ‘dynamic response factor’) used to estimate dynamic response for tall structures should be adjusted to allow for the ‘built-in’ correlation effects associated with a 3-second gust.

On the other hand, a similar analysis for a gust duration of 0.2 seconds (Figure 4) shows that, at 30 m/s, it has an equivalent frontal area of about 16 square metres – equivalent to that of a small shed or house. This gust duration results in a simpler quasi-steady code format, and has recently been redefined as such for the Australian/New Zealand Standard, AS/NZS 1170.2:2011 [11], (Holmes and Ginger, [13]).

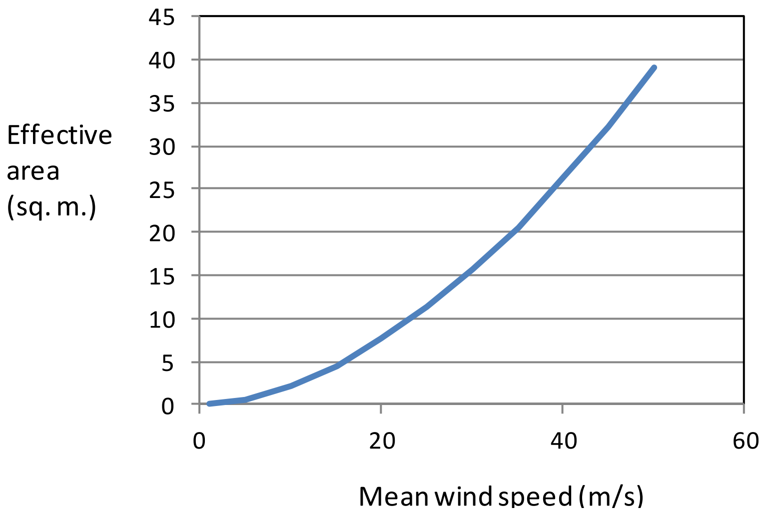

Figure 4. Equivalent frontal area for a 0.2-second gust

5 PEAK FACTORS AND GUST FACTORS

5.1 *Theoretical derivations based on random process theory*

For the conversion of wind tunnel data on building pressures, based on mean wind speeds, for use in codes or standards based on gust speeds, gust factors are required. In general, gust factors are a function of mean wind speeds and turbulence intensity as well as peak factors. The dependence on turbulence intensity means that gust factors vary with the height above ground and terrain. Peak factors are insensitive to the siting however.

For calculation of the gust factors associated with the various gust durations, random process theory can be applied using the transfer function of Eq. (2) with the wind spectrum of Eq. (3). Similar approaches were previously adopted by Davenport [14] and Greenway [15].

The cycling rate or 'average frequency', *ν*, of the filtered process can be calculated as follows:

$$\nu = \left\{ \frac{\int_0^\infty n^2 . S_u(n) . |H(n)|^2 dn}{\int_0^\infty S_u(n) . |H(n)|^2 dn} \right\}^{1/2} \tag{5}$$

The expected peak factor, *g*, can then be calculated using the well-known formula for Gaussian random processes of Davenport [16]:

$$g = \sqrt{2\, log_e\, \nu T} + \frac{0.577}{\sqrt{2\, log_e\, \nu T}} \tag{6}$$

where *T* is the sample time.

Finally, the expected gust factor *G*, is given by:

$$G = \frac{\hat{U}}{\bar{U}} = \frac{\bar{U} + \sigma_u}{\bar{U}} = 1 + g\, I_u \tag{7}$$

where σ_u is the standard deviation of the turbulent wind fluctuations, and I_u is the longitudinal turbulence intensity (= $\sigma_u/\bar{U}$).

Peak factors have been calculated from Equations (3), (5) and (6), and are shown in a non-dimensional format in Figure 5.

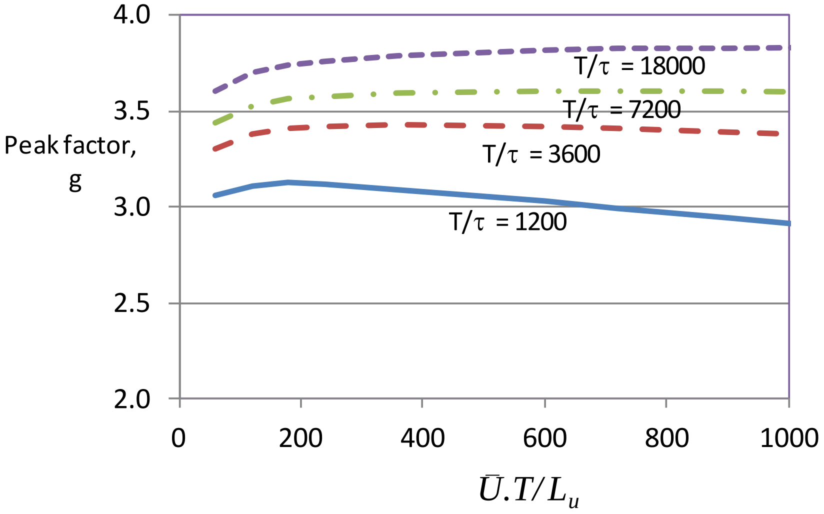

Figure 5. Expected peak factors for various moving average filters (T = sample time; τ = moving average time; $\bar{U}$ = mean wind speed; L_u = turbulence length scale)

Thus, for T= 3600 secs (1 hour.), L_u = 100 m, τ = 3 secs, and $\bar{U}$ =20 m/s, T/τ = 1200 and $\bar{U}.T/L_u$ = 720. For these values, Figure 5 gives g = 3.0. This value of peak factor agrees with the value for 3-second gusts based a 1-hour sample time given in ESDU 83045 [10] and ISO 4354 [9].

Other values of expected peak factors for various values of τ and T are summarized in Table 2 (for $\bar{U}$ = 20 m/s and L_u = 100 m).

Table 2. Expected peak factors for various τ and T

Averaging time, τ (secs.)	Sample time, T (secs.)	T/τ	$\bar{U}.T/L_u$	g
3	3600	1200	720	3.0
3	600	200	120	2.5
1	3600	3600	720	3.4
1	600	600	120	2.9
0.2	3600	18000	720	3.8
0.2	600	3000	120	3.3

It will be noted from Fig. 5 that for low values of T/τ , the peak factor becomes more sensitive to $\overline{U}.T/L_u$ – i.e. to the mean wind speed, $\overline{U}$. For high values of T/τ - i.e. for shorter gust durations, τ, the peak factor is nearly constant with varying mean wind speed.

Note also that the turbulence intensity, I_u, to which the peak factors in Table 2 should be applied is based the true *unfiltered* standard deviation, σ_u, not the filtered value σ_u'. Figure 1 shows that the area under the spectral density is significantly reduced when a 3-second moving average filter is applied – hence in that case σ_u' would be much less than σ_u.

Use of the peak factors in Table 2 gives gust factors of 1.60 and 1.76 for the expected ratios of maximum 3-second and 0.2 second gust, respectively, to the hourly mean, in open country terrain (Exposure C in ASCE 7) at 10m height, assuming a turbulence intensity of 0.20. For open water exposures (Exposure D), the corresponding values are 1.45 and 1.57.

The dependency of gust factors on turbulence intensity is illustrated in Figure 6.

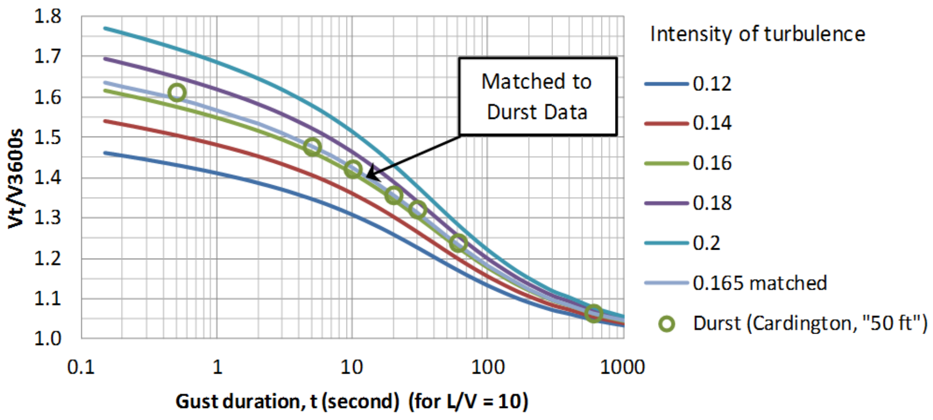

Figure 6. Gust factors as a function of turbulence intensity for $L_u/\overline{U}$ = 10,

The gust factor curves in Fig. 6 are similar to those recommended in Harper *et al.* ([4], Fig. 4.2) for ‘off-water’, off-sea’ and ‘at-sea’ winds, with turbulence intensities of 0.20, 0.15 and 0.10, respectively. The Harper *et al.* curves were derived from ESDU 83045 [10].

5.2 *Experimental values of gust factor – the Durst ‘curve’*

A gust factor curve attributed to Durst [17] has been provided in the Commentary to ASCE 7 for several editions. In fact that curve is not directly taken from the original Durst paper from 1960, but has apparently been plotted from tabular data given in the paper. The data was derived from measurements from the late 1920s from the airship port at Cardington, U.K., at a height of 50 feet (about 15 metres), not at the standard height of 10 metres. Also those data were not direct measurements of gust factors, but the latter can be inferred using the assumption of a Gaussian probability distribution.

Comparison with theoretically derived gust factors in Figure 6, shows that the Durst curve is consistent with a turbulence intensity of 0.165 – a reasonable value for a height of 15 metres above the open terrain of Cardington. However, this value of turbulence intensity is lower than the value of 0.20 specified for 10 metres height in open terrain (Exposure C) in ASCE 7.

6 APPLICATION TO ASCE 7

A gust basis for ASCE 7 was adopted in the 1995 edition and described as a '3-second' gust. Since the WMO definition was well established by the mid 1990s, it can probably be assumed that the moving-average definition was intended. However, gust data analyzed for the non-hurricane regions of the U.S. by Peterka and Shahid [18] were primarily analogue (i.e pre-ASOS) data from cup and propeller anemometers. As discussed in Section 2.2, this data probably had an equivalent gust duration of 1 second or less, rather than 3 seconds. However, more recent ASOS data was digitized with either 5 or 3 seconds moving average filters.

As discussed earlier in this paper, the effective frontal area associated with a 3-second gust is about that of a tall building (i.e. about 3200 m^2 at a mean wind speed of 30 m/s). Hence for application, using the quasi-steady principle (in which mean or pseudo-mean pressure coefficients are used with the gust wind speed), to smaller buildings such as houses or industrial sheds, requires a gust effect factor somewhat *greater* than unity. In contrast, the default gust effect factor for small buildings is currently 0.85. A discussion of the gust effect factor for tall buildings is given by Holmes [19].

7 CONCLUSIONS

A moving-average definition of gust duration has been adopted universally by meteorological agencies, with a 3-second average being the most common gust quoted by these agencies. However, this paper has shown that the filtering effect of a 3-second moving average truncates a large part of the turbulent wind spectrum at typical design wind speeds, and the equivalent spatial filter has a frontal area about that of a large tall building (i.e. 3200 m^2 at a mean wind speed of 30 m/s). Hence, if this gust duration is used as a basis of a loading code or standard, it is clear that a 'gust effect' factor greater than 1.0 should be applied for small buildings.

A shorter gust duration leads to a simpler code format, and the Australia/New Zealand Standard has re-defined its gust as one with a 0.2 second duration, (the previous description of previous Dines anemometer gust data as having a 3-second duration was found to be incorrect based on the moving average definition). However, unless the meteorological agencies can be persuaded to record gusts with this shorter duration, correction factors must be applied to the '3-second' gusts currently recorded when used in the Standard.

8 ACKNOWLEDGEMENTS

Collaborations on the gust duration issue with several others, including John Ginger of James Cook University Australia, and Craig Miller of the University of Western Ontario, Canada are gratefully acknowledged by the authors, as also is input from Jon Peterka of CPP Inc., on the gust data used for the wind speed maps in ASCE 7.

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