DESIGNING FOR DIRECTIONALITY

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1. INTRODUCTION

Designers who have looked at the possibility of taking wind directionality into account have often seen the very great potential for design optimisation in using different values of design wind speed for different directions. The gains may come about because of

(a) the varying wind speed with direction for a given probability level (risk),

(b) the effect of terrain roughness (and shielding) with direction, and

(c) the variation of the structure's wind sensitivity with direction (effect of dominant openings for example).

All of these factors can be taken into account if a full probability integration is undertaken. For all but major structures this is not a very practicable approach (although it may well become so when the full advantages are perceived). The entire process can be greatly simplified if basic design wind speeds could be given with respect to a range of wind directions and for which terrain effects can be taken into account for each directional sector, rather than having one design wind speed for all directions. The problem is that such an approach can only be made for a situation where the maximum wind loads and/or maximum design wind speeds are confined to relatively narrow bands of wind direction. In which case the major contributors to a given probability of occurrence are confined to a narrow directional band. The opposite extreme of this can be illustrated by an axi-symmetric structure, such as a chimney stack, in a terrain and wind climate where the probability of a given wind speed occurring is the same in all directions; in which case the contribution to a maximum stress level is the same for all directions and each direction shares equally to the total probability of that stress occurring (albeit at different places around the circumference).

A tentative proposal for design wind speeds with direction for the main Australian population centres will be made in this paper, along with two examples of typical applications and one example of an extreme application.

2. A PROPOSAL FOR DIRECTIONAL DESIGN WIND SPEEDS

A proposal for directional design wind speeds has been under test by the author for about three years, with a view to providing such data for use in the Australian Wind Loading Code, AS1170.

This proposal is based simply on the hypothesis that the major contributions to the probability of a given load occurring will mostly be confined to two 45° directional sectors. On this basis Regional Basic Design Wind Speeds can be determined for 45° sectors which have half the probability of occurring as the desired total probability of occurrence.

For example, take the probability distribution of wind speeds for the Perth region, obtained from data evaluated by Melbourne and Dorman, given in Table 1. This probability distribution of 3 second mean maximum gust wind speeds with direction has been obtained from daily maximum gust wind speed records corrected for approach terrain, anemometer position and height, to refer to the 10 m height in open country terrain (i.e. Terrain Category 2, for which, in the log law parlance, the roughness length z_o is 0.020 m).

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For a 50 year return period for all directions the probability level is

$$P_{(>\hat{V})} = \frac{1}{50\ .\ 365} = 55 \times 10^{-6} \qquad \text{. . . . . (1)}$$

giving the Basic Regional Design Wind Speed for Perth for all directions of 40 ms^{-1}, as shown on the right hand side of Table 1.

The proposal is now to select Basic Regional Design Wind Speeds with direction for the 45° sectors which have half the above probability level,

$$\text{i.e. } P_{(>\hat{V}_{45^0})} = 27.5 \times 10^{-6} \qquad \text{. . . . . (2)}$$

A line for this probability level has been drawn through Table 1.

TABLE 1

WIND SPEED PROBABILITY DISTRIBUTION WITH DIRECTION FOR THE PERTH REGION FROM DAILY 3 SECOND MEAN MAXIMUM GUST WIND SPEED RECORDS, CORRECTED TO REFER TO A HEIGHT OF 10 m IN OPEN COUNTRY TERRAIN

(Terrain Category 2, z_o = 0.020 m)

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 1 000000 PERTH COMPOSITE
****************************************************************** RECORDS = 26375,  YEARS = 72.3
TABLE FOR FITTED MODE AND SLOPE:

            MODE =  11.146,  SLOPE =   2.927,  V̂50 =  39.9,  V̂2000 =  50.7
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Wind Speed V ms^{-1}	PROBABILITY > SPEED X 10**6 PER 45 DEGREES NE	E	SE	S	SW	W	NW	N	TOTAL	OVERALL RET PERIOD (YEARS)
10	40437.	371835.	21142.	22887.	173654.	101914.	36180.	4180.	772228.	0.00
11	31161.	317431.	15794.	16268.	143296.	91085.	31798.	3676.	650510.	0.00
12	23689.	251704.	11646.	11437.	116394.	80484.	27668.	3217.	526237.	0.01
13	17721.	188411.	8454.	7928.	92847.	70024.	23731.	2785.	411899.	0.01
14	13024.	134889.	6032.	5407.	72651.	59849.	20013.	2377.	314242.	0.01
15	9405.	93290.	4230.	3628.	55778.	50227.	16584.	1998.	235140.	0.01
16	6678.	62793.	2918.	2395.	42070.	41423.	13512.	1654.	173444.	0.02
17	4670.	41360.	1982.	1558.	31224.	33618.	10839.	1349.	126600.	0.02
18	3221.	26766.	1329.	1000.	22843.	26892.	8572.	1086.	91708.	0.03
19	2194.	17070.	880.	634.	16490.	21235.	6694.	864.	66069.	0.04
20	1478.	10752.	576.	398.	11783.	16576.	5169.	680.	47411.	0.06
21	986.	6701.	373.	247.	8330.	12808.	3951.	529.	33927.	0.08
22	652.	4137.	240.	152.	5837.	9807.	2994.	409.	24229.	0.11
23	428.	2534.	153.	93.	4058.	7448.	2250.	313.	17278.	0.16
24	279.	1541.	97.	56.	2801.	5617.	1679.	239.	12309.	0.22
25	181.	931.	61.	34.	1921.	4209.	1245.	180.	8762.	0.31
26	116.	560.	38.	20.	1311.	3136.	918.	136.	6235.	0.44
27	75.	335.	24.	12.	889.	2324.	674.	102.	4434.	0.62
28	48.	190.	15.	7.	601.	1715.	492.	76.	3153.	0.87
29	30.	118.	9.	4.	405.	1261.	358.	56.	2242.	1.22
30	19.	70.	6.	3.	271.	924.	260.	42.	1593.	1.72
31	12.	41.	3.	1.	181.	675.	188.	31.	1133.	2.42
32	7.609	24.148	2.110	0.873	121.033	491.323	135.299	22.547	804.941	3.40
33	4.780	14.153	1.288	0.511	80.525	356.962	97.301	16.543	572.064	4.79
34	2.996	8.277	0.785	0.298	53.461	258.791	69.826	12.112	406.546	6.74
35	1.875	4.832	0.477	0.174	35.426	187.263	50.014	8.851	288.912	9.48
36	1.171	2.816	0.290	0.101	23.435	135.277	35.764	6.458	205.311	13.34
37	0.730	1.639	0.176	0.059	15.480	97.577	25.535	4.704	145.900	18.78
38	0.455	0.952	0.106	0.034	10.212	70.290	18.208	3.422	103.680	26.42
39	0.283	0.553	0.064	0.020	6.729	50.574	12.968	2.487	73.677	37.19
40	0.176	0.320	0.039	0.011	4.429	36.349	9.226	1.805	52.356	52.33
41	0.109	0.186	0.023	0.007	2.912	26.101	6.558	1.309	37.205	73.64
42	0.068	0.107	0.014	0.004	1.913	18.726	4.657	0.948	26.438	103.63
43	0.042	0.062	0.009	0.002	1.256	13.424	3.305	0.687	18.787	145.83
44	0.026	0.036	0.005	0.001	0.824	9.617	2.344	0.497	13.350	205.22
45	0.016	0.021	0.003	0.001	0.540	6.886	1.661	0.359	9.487	288.79
46	0.010	0.012	0.002	0.000	0.354	4.927	1.176	0.260	6.741	406.40
47	0.006	0.007	0.001	0.000	0.232	3.524	0.833	0.188	4.791	571.91
48	0.004	0.004	0.001	0.000	0.152	2.519	0.589	0.135	3.404	804.82
49	0.002	0.002	0.000	0.000	0.099	1.800	0.417	0.098	2.419	1132.57
50	0.001	0.001	0.000	0.000	0.065	1.286	0.295	0.070	1.719	1593.81
51	0.001	0.001	0.000	0.000	0.042	0.910	0.208	0.051	1.222	2242.89
52	0.001	0.000	0.000	0.000	0.028	0.655	0.147	0.037	0.868	3156.29
53	0.000	0.000	0.000	0.000	0.018	0.468	0.104	0.026	0.617	4441.69
54	0.000	0.000	0.000	0.000	0.012	0.334	0.073	0.019	0.438	6250.54
55	0.000	0.000	0.000	0.000	0.008	0.230	0.052	0.014	0.311	8796.09

The same procedure has been carried out for the major centres of population in Australia, using composite data from a number of anemometers in each region, and the results given in Table 2, with the one modification that no directional wind speed should be greater than the all directions wind speed.

TABLE 2

REGIONAL BASIC DESIGN WIND SPEEDS FOR 45° DIRECTIONAL SECTORS FOR MAJOR CENTRES IN AUSTRALIA (3 second mean maximum gust wind speed in metres/second relating to a 50 year return period)

Wind Direction (45° sectors)	Perth	Adelaide	Brisbane	Sydney	Canberra	Melbourne	Hobart
All Directions	40	42	40	41	40	40	40
NE	29	33	28	32	23	29	21
E	32	33	30	31	26	27	17
SE	27	32	33	38	29	29	27
S	25	32	34	39	28	34	36
SW	36	42	40	37	30	38	36
W	40	41	39	40	37	40	39
NW	37	39	30	37	40	36	40
N	32	36	23	30	32	38	36

(NOTE The values for Brisbane should be treated with caution as these data do not include tropical cyclones. It is assumed that the limit state format of AS1170 will use a risk equivalent to a 20 to 30 year return period for serviceability, which would exclude tropical cyclone data, and the equivalent of a 1000 to 2000 return period for collapse conditions which would include tropical cyclone data.)

3. EXAMPLES OF TYPICAL APPLICATIONS

Consider the peak pressure coefficient, given in Figure 1, measured recently at a tapping point on the roof of a model of a complex low rise structure to be built in the Perth region.

Case A

From Figure 1 the maximum design pressure occurs for $C_{\check{p}} = -5.9$ in the west sector for which the Basic Regional Design Wind Speed proposed in Table 2 is 40 ms^{-1}. The building is in Terrain Category 2 conditions and the height is 20 m, and the pressure coefficient is based on mean wind speed. Using the Deaves and Harris wind model

$$\bar{V}_{\substack{20,W\\Cat2}} = 0.66\ \hat{V}_{\substack{10,W\\Cat2}}$$

$$= 0.66\ .\ 40 = 26.4\ ms^{-1}$$

This then gives a design pressure based on directional design wind speed data of

$$\check{p} = -5.9\ .\ 0.6\ .\ 26.4^2 = -2470\ Pa$$

Case B

If the building had been rotated through about 110° such that the maximum peak pressure coefficient occurred in the south sector, we would have two possibilities for the maximum design pressure

$$C_{\check{p}_{south}} = -5.9$$

$$C_{\check{p}_{west}} = -3.4$$

From Table 2 and the Deaves and Harris wind model.

$$\bar{V}_{\substack{20,S\\Cat2}} = 0.66 \cdot 32 = 21.1 \text{ ms}^{-1}$$

$$\bar{V}_{\substack{20,W\\Cat2}} = 0.66 \cdot 40 = 26.4 \text{ ms}^{-1}$$

and the resulting design pressures are

$$\check{p}_S = -5.9 \cdot 0.6 \cdot 21.1^2 = -1580 \text{ Pa}$$

$$\check{p}_W = -3.4 \cdot 0.6 \cdot 26.4^2 = -1420 \text{ Pa} \quad .$$

In which event the design pressure becomes -1580 Pa, compared with -2470 Pa for the most unfavourable orientation.

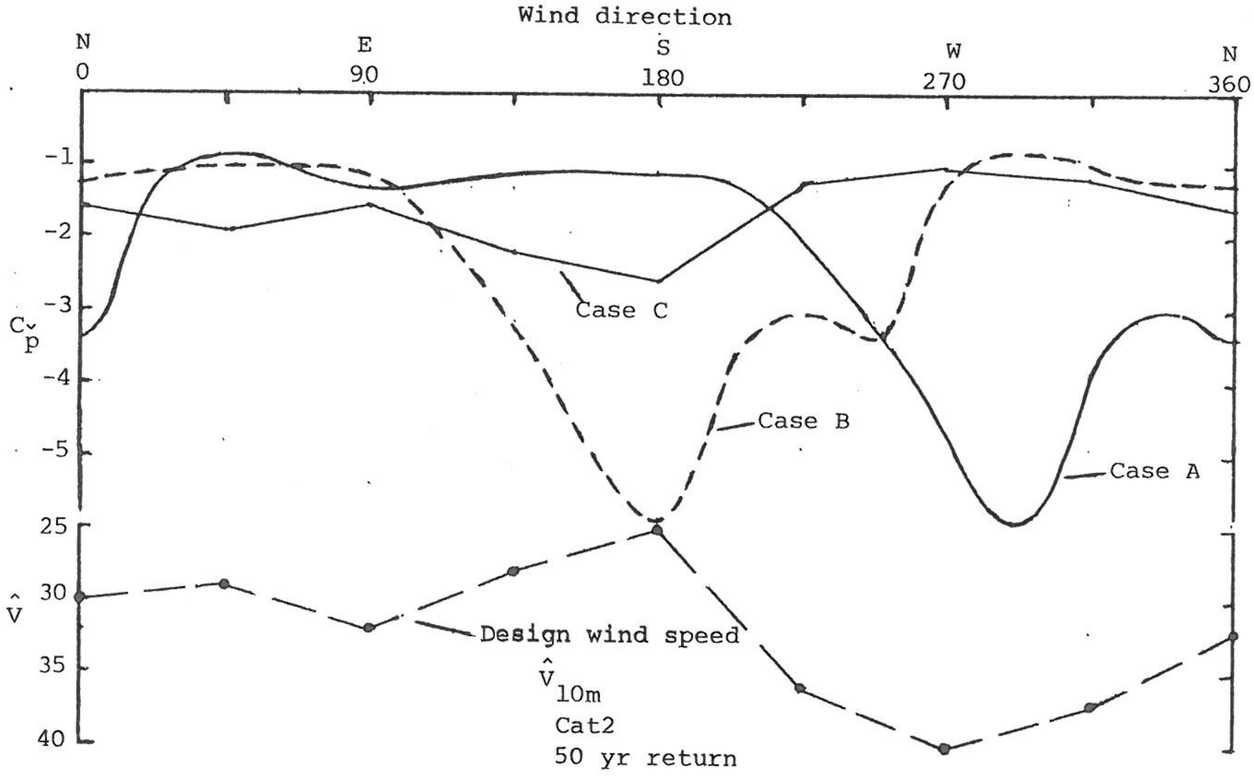

Figure 1 Basic regional design wind speed with direction for Perth from Table 1, and peak pressure coefficients with direction for the three case studies.

The full integration of the peak pressure coefficients in Figure 1, with the wind speed probability distribution in Table 1, has been been tabulated in the Appendices. The steps in the integration are as follows:

(i) The maximum negative pressure coefficients and hence maximum negative pressures per sector are listed as a function of the reference wind speed, i.e. mean wind speed at 20 m in Terrain Category 2 in Cases A and B.

(ii) This relationship is inverted to give the reference windspeed as a function of pressure.

(iii) The reference wind speed is converted to the wind speed used in the probability distribution of wind speeds, in this case 3 second mean maximum gust wind speed at 10 m in Terrain Category 2. The relationship used here is from the Deaves and Harris wind model

$$\bar{V}_{\substack{20m\\Cat2}} = 0.66\ \hat{V}_{\substack{10m\\Cat2}}$$

(iv) A table of pressures versus wind direction sectors is drawn up and $\hat{V}_{\substack{10m\\Cat2}}$ is calculated for a given pressure.

(v) The probability of exceedance $P_{(>\hat{v})}$ is then obtained from the wind speed probability distribution, Table 1 in this example.

(vi) Finally, the total probability of exceedance for each pressure is added up.

The probability of exceedance has been found to follow a Weibull distribution, i.e. in this case of the form

$$\ell n\left(-\ell n\ P_{(>\bar{p})}\right) = f\ (\ell n\ p)$$

The probability of exceedance of a given pressure level has been plotted in Figure 2, along with the return periods (refer Equ. 1)

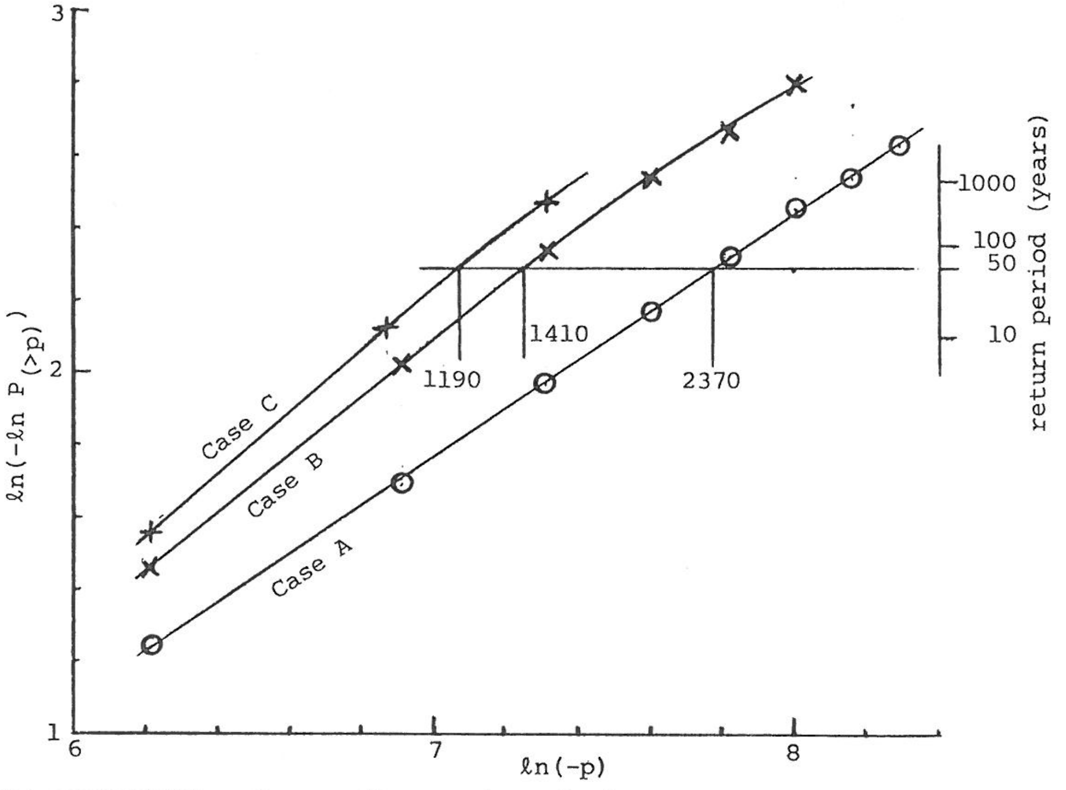

Figure 1 The probability of exceeding a given design pressure for Cases A,B and C

Comparing design pressures for the 50 year return period obtained from the full integration (Figure 2) and the simple design wind speed with direction gives

	Full integration	Using directional design wind speed
Case A	-2370 Pa	-2470 Pa
Case B	-1410 Pa	-1580 Pa

It can be seen in Case A that the use of the directional design wind speed, as proposed, has resulted in only slightly conservative design pressures because the maximum pressure coefficient and strongest wind directions were coincident. For Case B, use of the directional design wind speed, as proposed, has resulted in a more conservative design pressure; in particular, note that whilst the south direction gave the design pressure because of the conservatively selected criterion for design wind speed, in fact, in the full integration the west sector is seen to dominate and the estimate given by the design wind speed for the west sector was the better estimate.

It should also be noted that had the integration been carried out for smaller directional sectors, the design pressure would have reduced for a given probability level. This is easy to see in Case A, because when $C_p = -5.9$ occurred on the boundary between two 45° sectors it was used (conservatively) as the maximum occurring in both west and north west sectors, and if narrower directional sectors, such as 16 by $22\,{}^1\!/_2\,°$, had been used, the $C_p = -5.9°$ would have occurred for 45° instead of 90°.

4. EXAMPLE OF AN EXTREME APPLICATION

The extreme application is obviously a case where the design load calculated using the directional design wind speeds is the same for all directions. On the basis on which the proposed directional design speeds were determined (i.e. at half the probability for each 45° sector) the total probability of this design load occurring would, for a full integration, show up to be four times the probability of the original total probability used to determine the directional design wind speeds. In this case the probability level used was for a 50 year return period, i.e. $P_{(>V)} = 55 \times 10^{-6}$ and the true probability level for the case hypothesised would be 220×10^{-6} which would be equivalent to a quarter the return period, i.e. $12\,{}^1\!/_2$ years.

Whilst this is helpful to see how non-conservative such an extreme case might be, it is also helpful to see what it would mean in terms of design pressure. The peak pressure coefficient distribution for this case for the Perth directional design wind speeds, which will be designated Case C, is also given in Figure 1. Here a peak pressure coefficient of -1.0, based on $\hat{V}_{\substack{10m\\Cat2}}$ for simplicity, has been used for the west wind direction giving a design pressure of 960 Pa for all wind directions. The full integration with the Perth probability distribution is given in Appendix C.

Again, comparing design pressures for the 50 year return period obtained from the full integration (Figure 2) and the simple design wind speed with direction gives

	Full integration	Using directional design wind speed
Case C	1190 Pa	960 Pa

In this extreme case the use of the simple directional design wind speed approach, as proposed, would have underestimated the true design pressure by 20%.

5. CONCLUSIONS

A proposal for the determination of Basic Regional Design Wind Speeds with Wind Direction has been made, and, for example, values evaluated for a 50 year return period for seven major population centres in Australia. Three cases have been evaluated to facilitate comparison between the design loads (pressures) determined from the full integration and from use of the simple directional design wind speed.

It is concluded from these (and other) studies that use of the simple directional design wind speeds, as proposed, will lead to design estimates being up to about 10% conservative for most cases, but that in the most extreme case could lead to about a 20% underestimate.

Even with the conservative approach proposed here there are considerable gains to be had in terms of design optimisation from using different values of design wind speed for different directions. However, it is the author's belief that there is a strong case for using directional design wind speeds for 16 directions and altering the hypothesis on which this current proposal is made, to the hypothesis that major contributions to the probability of a given load occurring will mostly be confined to two 22 ½ ° directional sectors. If such a move were made designers would need to understand what they are using, so that they could recognise cases where significant load contributions could come from more than two 22 ½ ° sectors and modify the method accordingly.

APPENDIX A

Calculation for Design Case A

	$C_{\check{p}}$	p (-ve)	$\bar{V}_{20m\,Cat2}$	$\hat{V}_{10m\,Cat2}$
N	-3.40	2.04 $\bar{V}^2$	0.70 $\sqrt{p}$	1.06 $\sqrt{p}$
NE	-1.0	0.6	1.29	1.96
E	-1.3	0.78	1.13	1.72
SE	-1.3	0.78	1.13	1.72
S	-1.1	0.66	1.23	1.87
SW	-3.1	1.86	0.73	1.11
W	-5.9	3.54	0.53	0.81
NW	-5.9	3.54	0.53	0.81

Wind Direction / pressure (Pa)		500	1000	1500	2000	2500	3000	3500	4000
N	$\hat{V}_{10m\,Cat2}$	23.7	33.5	41.1	47.4				
	$P(>\hat{V})$	250	15	0	0				
NE	$\hat{V}_{10m\,Cat2}$	43.8	62.0						
	$P(>\hat{V})$	0	0						
E	$\hat{V}_{10m\,Cat2}$	38.5	54.4						
	$P(>\hat{V})$	0	0						
SE	$\hat{V}_{10m\,Cat2}$	38.5	54.4						
	$P(>\hat{V})$	0	0						
S	$\hat{V}_{10m\,Cat2}$	41.8	59.1						
	$P(>\hat{V})$	0	0						
SW	$\hat{V}_{10m\,Cat2}$	24.8	35.1	43.0	49.6				
	$P(>\hat{V})$	2000	30	1	0				
W	$\hat{V}_{10m\,Cat2}$	18.1	25.6	31.4	36.2	40.5	44.4	47.9	51.2
	$P(<\hat{V})$	26000	3500	580	125	31	7.2	2.6	0.85
NW	$\hat{V}_{10m\,Cat2}$	18.1	25.6	31.4	36.2	40.5	44.4	47.9	51.2
	$P(>\hat{V})$	8000	1000	170	35	7	2.5	0.6	0.19
Total $P(>\hat{p})$		0.036	0.0045	0.00075	0.00016	0.000038	0.0000097	0.0000032	0.0000010

APPENDIX B

Calculations for Design Case B

	$C_{\check{p}}$	p (-ve)	$\bar{V}_{\substack{20m \\ Cat2}}$	$\hat{V}_{\substack{10m \\ Cat2}}$
N	-1.3	0.78 $\bar{V}^2$	1.13 $\sqrt{p}$	1.87 $\sqrt{p}$
NE	-1.1	0.66	1.23	1.87
E	-2.0	1.20	0.91	1.38
SE	-4.8	2.88	0.59	0.89
S	-5.9	3.54	0.53	0.81
SW	-3.9	2.34	0.65	0.99
W	-3.4	2.04	0.70	1.06
NW	-1.3	0.78	1.13	1.87

Wind Direction	pressure (Pa)	500	1000	1500	2000	2500	3000	3500	4000
N	$\hat{V}_{\substack{10m \\ Cat2}}$	42	59						
	$P(>\hat{V})$	1	0						
NE	$\hat{V}_{\substack{10m \\ Cat2}}$	42	59						
	$P(>\hat{V})$	0	0						
E	$\hat{V}_{\substack{10m \\ Cat2}}$	31	43.6	53					
	$P(>\hat{V})$	40	0.05	0					
SE	$\hat{V}_{\substack{10m \\ Cat2}}$	19.9	28.1	34.5	39.8	44.5	49		
	$P(>\hat{V})$	600	14	0.6	0.04	0.004	0		
S	$\hat{V}_{\substack{10m \\ Cat2}}$	18.1	26	31.4	36.2	40.5	44	48	
	$P(>\hat{V})$	950	28	0.9	0.09	0.009	0.001	0	
SW	$\hat{V}_{\substack{10m \\ Cat2}}$	22.1	31.1	38.3	44	50	54	58	
	$P(>\hat{V})$	5600	70	9	0.8	0.065	0.012	0	
W	$\hat{V}_{\substack{10m \\ Cat2}}$	23.7	33.5	41	47.4	53	58		
	$P(<\hat{V})$	6100	310	19	3.1	0.47	0.06		
NW	$\hat{V}_{\substack{10m \\ Cat2}}$	42	59						
	$P(>\hat{V})$	5	0						
Total $P(>\hat{p})$		0.0133	0.00052	0.000030	0.0000040	0.00000054	0.0000097	0.0000032	0.0000010

APPENDIX C

Calculations for Design Case C

	$\hat{V}_{10m\,Cat2}$	$C_{\check{p}}$	Design pressure	$\hat{V}_{10m\,Cat2}$
NE	29	1.902	960	0.936 $\sqrt{p}$
E	32	1.563	960	1.033
SE	27	2.195	960	0.871
S	25	2.560	960	0.807
SW	36	1.235	960	1.162
W	40	1.000	960	1.291
NW	37	1.169	960	1.194
N	32	1.563	960	1.033

Wind Direction \ pressure (Pa)		500	960	1500
NE	$\hat{V}_{10m\,Cat2}$	20.9	29	36.3
	$P(>\hat{V})$	1000×10^{-6}	27.5×10^{-6}	1.0×10^{-6}
E	$\hat{V}_{10m\,Cat2}$	23.1	32	40
	$P(>\hat{V})$	2300	27.5	0.3
SE	$\hat{V}_{10m\,Cat2}$	19.5	27	33.7
	$P(>\hat{V})$	700	27.5	0.9
S	$\hat{V}_{10m\,Cat2}$	18.0	25	31.3
	$P(>\hat{V})$	1000	27.5	0.9
SW	$\hat{V}_{10m\,Cat2}$	26	36	45
	$P(>\hat{V})$	1300	27.5	0.6
W	$\hat{V}_{10m\,Cat2}$	28.9	40	50
	$P(>\hat{V})$	1300	27.5	1.3
NW	$\hat{V}_{10m\,Cat2}$	26.7	37	46.2
	$P(<\hat{V})$	900	27.5	1.1
N	$\hat{V}_{10m\,Cat2}$	23.1	32	40
	$P(>\hat{V})$	300	27.5	1.8
Total $P(>\hat{p})$		0.0088	0.000220	0.0000079