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ULTIMATE WIND LOADS AND DIRECTION EFFECTS IN NON-HURRICANE AND HURRICANE-PRONE REGIONS

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SUMMARY

We use 'peaks over threshold' approach to estimate extreme wind loads calculated by taking into account the directional dependence of both the aerodynamic coefficients and the extreme wind climate. Our interest is focused primarily on ultimate wind loads, that is, loads that are sufficiently large to cause member failure. For non-hurricane regions (1) we comment on issues raised by the fact that directional data published by the National Weather Service are incomplete, and (2) note that, owing to the relatively small sizes of the data samples, results on directional effects for mean recurrence intervals longer than a few hundred years are inconclusive. For hurricane-prone regions we show that, on average, the common practice of disregarding wind directionality effects is conservative for 50-year wind loads. However, according to our results, the degree of conservatism decreases as the mean recurrence interval increases. While individual estimates of speeds with very long mean recurrence intervals are unreliable, statistics based on estimates obtained from large numbers of records can provide useful indications of average trends and suggest that, for mean recurrence intervals associated with ultimate wind loads, the favorable effect of wind directionality tends to be marginal. © 1998 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Two types of method for estimating wind forces are currently in use. The *non-directional* method is one in which the wind forces are calculated by replacing the set of aerodynamic coefficients measured for each wind direction by a single aerodynamic coefficient, equal to the maximum value in this set. We are interested in the conservatism inherent in non-directional calculations, particularly for ultimate wind loads, that is, loads with long mean recurrence intervals which cause structural failures. Unlike the non-directional method, *directional* methods account explicitly for the dependence upon direction of both the wind speeds and the aerodynamic coefficients. A description and assessment of existing directional methods is available in Simiu and Scanlan (1996, p. 308).

In the following sections we review briefly the non-directional method and a directional method appropriate for the estimation of wind loads or linear functions thereof (Simiu and Scanlan, 1996, p. 311; Simiu and Filliben, 1981). Methods for estimating extreme wind speeds

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differ according to whether the site of concern is located in a non-hurricane or a hurricane-prone region (Simiu and Scanlan, pp. 95, 102). We analyze data sets in both types of region. We then present results of our analyses, comment on the results, and present our conclusions.

2. ESTIMATION METHODS

2.1. Directional method

So that the paper be self-contained, we review briefly the directional estimation method proposed in Simiu and Filliben (1981). The method is applicable provided that the wind effects depend on wind speed and direction in the form

$$p(\theta) = (\rho/2)C(\theta)x(\theta)^2 \tag{1}$$

where $\rho =$ air density, $C =$ aerodynamic pressure or force coefficient (or other wind effect coefficient independent of wind speed), $p =$ pressure or force (or other wind effect), $x =$ wind speed, and $\theta =$ wind direction, respectively. The estimation method is based on the analysis of the set of N time series

$$P_j(\theta_j) = C(\theta_i)x_j(\theta_i)^2/\max_i[C(\theta_i)] \tag{2}$$

where $i = 1,2, \ldots, N$ denotes the direction, $j = 1,2, \ldots, M$, M is the number of years or, for hurricane-prone regions, of hurricane events, $\max_i[C(\theta_i)]$ is the largest of the values $C(\theta_i)$, and $\max_i$ denotes the maximum over all is. For non-hurricane regions data are available for a number of directions $N = 8$. For hurricane-prone regions $N = 16$. From these time series we form the single time series

$$P_j = \max_i\{[P_j(\theta_i)]\}. \tag{3a}$$

To within a constant factor, P_j is the largest wind effect in year (or hurricane) j. Rather than analyzing the time series P_j, we analyze the time series of *equivalent wind speeds*

$$x_{\text{eq}} = (P_j)^{1/2} \tag{3b}$$

The analysis yields the extreme values $x_{R\text{eq}}$, where R denotes the mean recurrence interval (MRI). The extreme wind effect for the MRI of interest is

$$P_R = (\rho/2)\{\max_i[C(\theta_i)]\}(x_{R\text{eq}})^2. \tag{4}$$

2.2. Non-directional method

We now discuss the non-directional method, which is used in most codes and standards. First form the time series

$$x_j^{\max} = \max_i[x_j(\theta_i)] \tag{5}$$

of the largest wind speed in year (or hurricane) j, regardless of its direction. Next, from the analysis of this time series, obtain the estimate x_R, that is, the non-directional estimate of the

R-year speed, where R now denotes a nominal MRI. The corresponding non-directional estimate of the wind effect with an R-year nominal MRI is

$$P_{R,\text{nom}} = (\rho/2)\max_i[C(\theta_i)]x_R^2. \tag{6}$$

In other words, $P_{R,\text{nom}}$ is obtained by following exactly the same steps used in the preceding subsection to estimate P_R, except that in equation (2) the factor $C(\theta_i)$ is replaced by the factor $\max_i[C(\theta_i)]$. Each of the terms of the time series $x_j^{\max}$ is equal to or larger than its counterpart in the time series $x_{\text{eq}j}$. Therefore, if the MRI and the nominal MRI have the same value, one might expect $p_R < p_{R,\text{nom}}$; if $p_R = p_{R,\text{nom}}$ the MRI may be expected to be larger than the nominal MRI. This explains the common belief that non-directional estimates of wind effects are conservative from a design viewpoint. However, as is shown subsequently, even if the conservatism can in certain instances by substantial for 50 year loads, it decreases as the MRI increases and can be marginal for loads corresponding to the large MRIs associated with member failure.

2.3. Extreme value statistical estimation procedure

For information on the 'peaks over threshold' approach to estimating extremes, see Castillo (1988). Our analyses are based on de Haan's estimation procedure, described in some detail in de Haan (1994) (see also Appendix 1 of Simiu and Scanlan, 1996). On account of the form of equations (4) and (6), it is sufficient to compare the estimated values of $X_{R\text{eq}}$ and X_R, rather than the respective wind effects. (In this paper we omit the circumflex used in the statistical literature to denote estimated values.) The performance of the de Haan estimation procedure was compared in Gross *et al.* (1994) with the performance of other estimation procedures and was found to be satisfactory for the purposes of our analyses. In addition, we note that analyses of the hurricane data used in this paper were made by using the de Haan procedure and the maximum likelihood techniques. The differences between the respective estimates were found to be insignificant for practical purposes (Coles, 1996).

3. ANALYSES AND RESULTS FOR NON-HURRICANE REGIONS

3.1. Aerodynamic coefficients and wind speed data

The wind effect coefficients were assumed to have the values shown in Table I.

Table I. Direction-dependent aerodynamic coefficients (after Peterka and Cermak, 1978)

θ_i	N	NE	E	SE	S	SW	W	NW
$C(\theta_i)$	1·1	1·0	0·7	0·9	3·3	1·1	0·6	0·2

The data represent an envelope of absolute values of aerodynamic coefficients obtained for a large number of wind directions for a corner location of a tall building roof (Peterka and Cermak, 1978). Note that, as is commonly the case for corner pressures, for one of the directions the coefficient is much larger than for the others. Seven additional sets of aerodynamic coefficients were used. These were obtained from the set just listed via rotation of the building by 45°, 90°, . . . , 270°, 315°.

The directional wind speed data, which do not include tornado speeds, were taken from Changery *et al.* (1984). They consist of 22 sets of largest annual directional fastest-mile speeds at 10 m above ground in open terrain for eight azimuths, recorded over periods of 19–30 years at stations where hurricanes do not occur. These data were extracted from original National Weather Service records. In addition, for the same stations and periods, annual directional data for the eight azimuths were extracted from published Local Climatological Data (LCD) monthly summaries. All data listed in Changery *et al.* (1984) are fastest-miles in mph. In our calculations the data were converted to fastest-miles in m/s. The data are listed in electronic data files (see Appendix for instructions on accessing the data).

3.2. Effect of 'hidden' values on estimated percentage points

Most of the data from original records coincide with those from the published records. However, for some data this is not the case owing to the 'hidden' values problem. The data in the LCD summaries for the periods we used consist of the largest daily speed and the associated direction. On the date this largest speed occurred, another (lower and therefore unpublished) value from a different direction could have exceeded the published extreme for that direction. Since that value would not appear in the LCD summaries, it is referred to as 'hidden'. We compared directional estimates based on data from original records on the one hand and on the corresponding published data on the other. For example, for Omaha, Nebraska, for 1950, W direction, the 'hidden' value was 27 m/s, while the published value was 21 m/s; in 1953, S direction, the respective data were 25 m/s and 19 m/s; in 1957, SE direction, they were 24 m/s and 17 m/s. We show in Figures 1(a) and (b), respectively, estimates of $x_{R\text{eq}}$ for Omaha based on 1950–1076 data taken from original records (i.e., including the 'hidden' data) and data taken from LCDs (i.e., data from which the 'hidden' data are missing) for the period 1950–1976. For small MRIs the differences between equivalent wind speed estimates based on the two sets are relatively small. It is only for large MRIs that the differences become significant, that is, about 10% or more. Since loads are proportional to the squares of the equivalent wind speeds, this translates into differences of the order of, say 20% or more between the respective load estimates. Similar results were obtained for other stations.

However, the fact that our estimates for low (25–100 year) MRIs did not exhibit significant errors associated with 'hidden' data does not exclude the possibility that such errors do occur in some instances. Given this possibility, consideration may be given to a change in current National Weather Service data publication policy, so that data of interest be no longer 'hidden'. An opportunity for such change exists at this time, as the National Oceanic and Atmospheric Administration is attempting to respond more effectively to the needs of the design professions. In the meantime, for structural engineering purposes, methods of analysis may be used that account for the incompleteness of the directional data published so far by the National Weather Service.

Note that Figure 1 contains estimates of speeds with MRIs of up to 100,000 years. Sampling errors increase as the MRI increases. Therefore, in view of the small size of the observed wind speed data samples, sampling errors inherent in individual wind speed estimates with very large MRIs can be too large for individual estimates to be useful. To show this we consider the simple expression (based on the method of moments) for the sampling errors in the estimation of

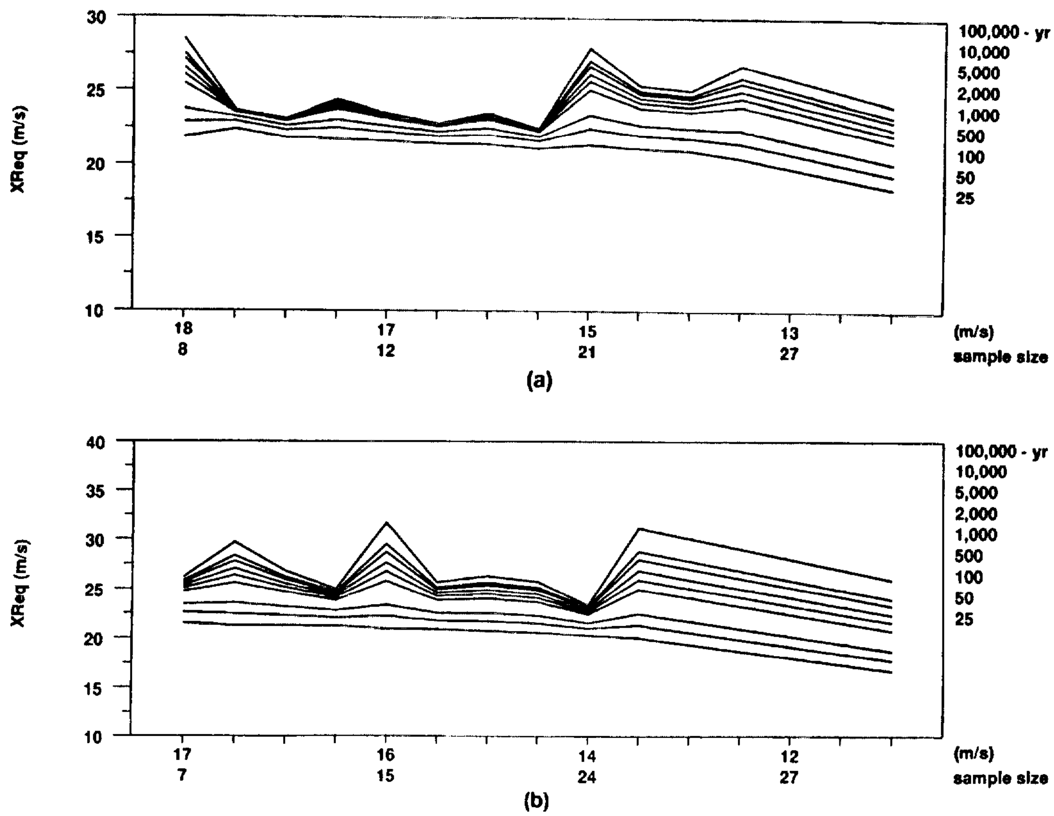

Figure 1. Estimates $x_{R_{eq}}$ with 25 year (bottom curve) to 100,000 year (top curve) MRIs based on (a) original record and (b) on published record, Omaha, Nebraska (1950–1976)

extremes, available for the case of the Type I Extreme Value distribution (Simiu and Scanlan, 1996, p. 98):

$$SD(x_R) = 0{\cdot}78[1{\cdot}64 + 1{\cdot}46(\ln R - 0{\cdot}577) + 1{\cdot}1(\ln R - 0{\cdot}577)^2]^{1/2} s/n^{1/2} \tag{7}$$

where SD denotes sampling error, X_R is the estimate of the variate with an R-year MRI, s is the standard deviation of the extreme value sample, and n is the sample size. Assuming a typical value $s = 3$ m/s (corresponding to a typical sample mean $X = 15$ m/s) (Changery *et al.*, 1984), and a sample size $n = 25$, equation (7) yields $SD(x_{50}) = 2{\cdot}0$ m/s and $SD(x_{100,000}) = 5{\cdot}7$ m/s. The estimates of x_R based on the method of moments are given by the expression (Simiu and Scanlan, 1996, p. 97):

$$x_R = X + 0{\cdot}78(\ln R - 0{\cdot}572)s \tag{8}$$

From equation (8), $x_{50} = 22{\cdot}8$ m/s and $x_{100,000} = 40{\cdot}6$ m/s. 95% confidence intervals for the 50 year and 100,000 year speeds are {18·8 m/s, 26·8 m/s} and {30·2 m/s, 51·0 m/s}, respectively. If we divide these values by x_{50} and $x_{100,000}$, respectively, the intervals are {0·82, 1·18} for the 50 year speed and {0·74, 1·26} for the 100,000 year speed. The corresponding interval for the ratios $[x_{100,000} \pm 2SD(x_{100,000})]/[x_{50} \pm 2SD(x_{50})]$ is {1·61, 1·90} or, if we divide these values by the ratio $x_{100,000}/x_{50} = 1{\cdot}78$, the interval is {0·90, 1·07}. This typical example shows that, for large MRIs, 95% confidence intervals of the estimated wind speeds can be quite wide. It is therefore emphasized once more that, for large MRIs, individual estimates are generally unreliable. On the other hand, for ratios of estimated wind speeds with higher MRIs to 50 year speeds, if a large number of records are examined, appropriate statistics can provide useful indications on average trends, as will be seen in the section on estimates for hurricane-prone regions.

3.3. Comparison of estimates by the directional and non-directional methods for various MRIs

We attempted to effect such comparisons by using our directional data based on the complete original records (i.e., the records without 'hidden' values). However, owing to large sampling errors we feel it would be imprudent to use our results as a basis for assessing directionality effects, except for relatively small MRIs. To illustrate this point some representative results are shown in Figures 2 and 3. For Portland, Oregon, and the set of eight aerodynamic coefficients listed earlier, Figures 2(a) and (c) show, as functions of threshold (in m/s), the tail length parameters of the best fitting extreme value distributions and their 95% confidence bounds. (The larger the parameter c, the longer the distribution tail is.) Figures 2(b) and (d) show the estimates

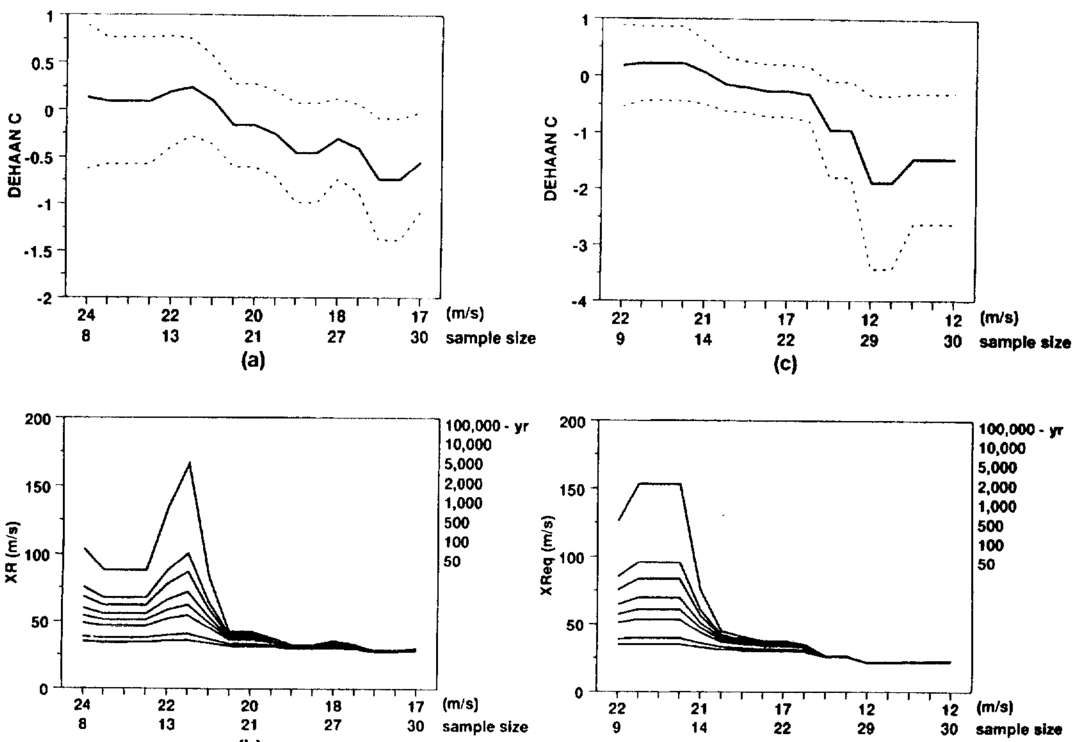

Figure 2. Estimates of: (a), (c) tail length parameter c and 95% confidence bands corresponding to (b) and (d), respectively; (b) speeds x_R with 50 year (bottom curve) to 100,000 year (top curve) nominal MRIs; (d) speeds $x_{R_{eq}}$ with 50–100,000 year MRIs, for largest pressure coefficient $C(\theta_i) = 3{\cdot}3$ in S direction (Portland, Oregon, 1950–1979)

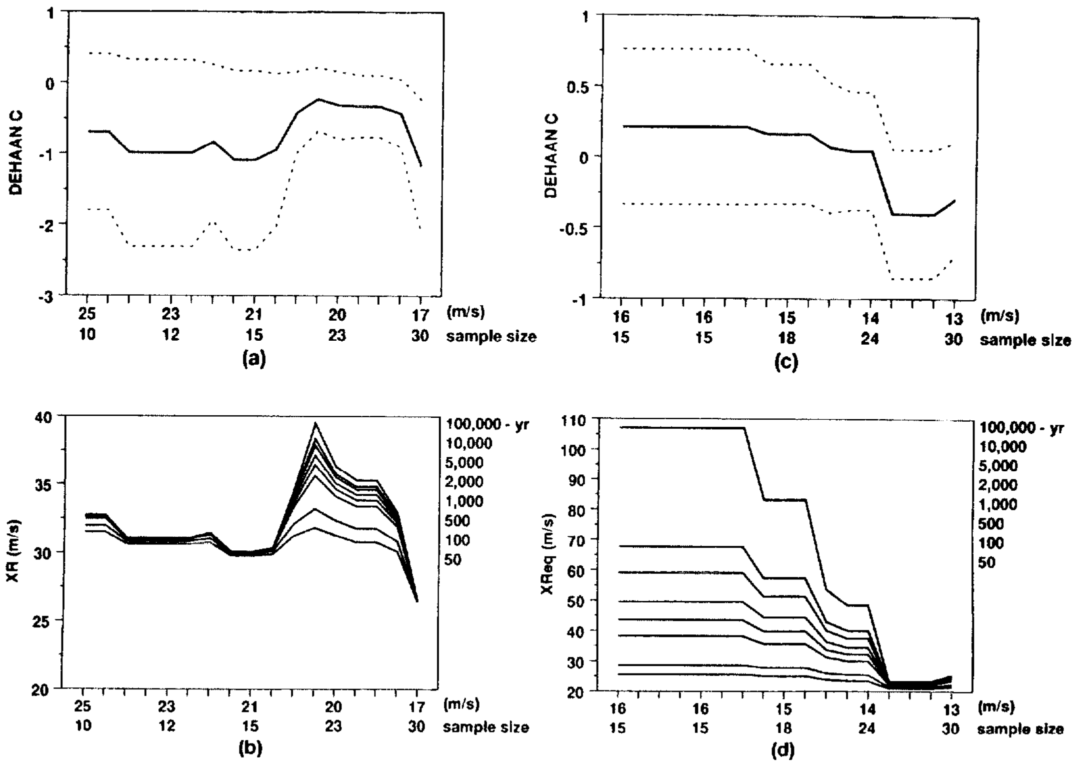

Figure 3. Estimates of: (a), (c) tail length parameter c and 95% confidence bands corresponding to (b) and (d), respectively; (b) speeds x_R with 50 year (bottom curve) to 100,000 year (top curve) nominal MRIs; (d) speeds $x_{R\mathrm{eq}}$ with 50–100,000 year MRIs, for largest pressure coefficient $C(\theta_i) = 3{\cdot}3$ in S direction (Madison, Wisconsin, 1950–1979)

x_R and $x_{R\mathrm{eq}}$, respectively. For the type of graphs of Figure 2, a roughly horizontal portion is judged to correspond to a reasonable approximate estimate of the variate of concern see (Castillo, 1988 or Simiu and Heckert, 1996). Similar results are shown in Figure 3 for Madison, Wisconsin. As a first step toward attempting to obtain more reliable estimates, data sets should be obtained from existing records for longer periods than those covered by the sets of Changery *et al.* (1984). In addition, the sets should include all speeds in excess of specified thresholds, rather than just the largest annual directional speeds.

4. ANALYSES AND RESULTS FOR HURRICANE-PRONE REGIONS

4.1. Hurricane wind speed data and aerodynamic data

The directional hurricane wind speed data were obtained by simulation (Batts *et al.*, 1980; Heckert *et al.*, 1998), are available in electronic files for 16 azimuths for 55 mileposts along the Gulf and Atlantic coasts (for milepost definition see Simiu and Scanlan, 1996, Ch. 3), and may be accessed as indicated in the Appendix. The data stored electronically represent nominal fastest-minute speeds in knots. The nominal fastest-minute speeds were obtained from the hourly speeds via multiplication by a factor of approximately 1·24 (Batts *et al.*, 1980). To transform the data

Table II. Direction-dependent aerodynamic coefficients (after Peterka and Cermak, 1978)

	θ_i	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Set 1	$C(\theta_i)$	1·1	1·0	0·5	0·6	0·7	0·6	0·5	0·9	1·8	**3·3**	1·1	0·6	0·1	0·2	0·2	0·8
Set 2	$C(\theta_i)$	0·9	0·8	0·5	0·4	1·2	0·7	0·6	0·5	0·5	0·6	0·6	0·9	**1·4**	0·8	0·8	0·4

into hourly mean speeds we multiplied the data stored electronically by the factor [0·447 m/s/mph × 1·15 mph/nmi × (1/1·24)]. The sample sizes are 999 hurricanes per milepost.

For this case we considered two sets of aerodynamic (wind effect) coefficients, shown in Table II. Set 1 corresponds to a roof corner location. Set 2 corresponds to a location at the approximate center of a facade. Note that the ratios between the largest aerodynamic coefficient (shown in bold type) and the other coefficients are on average much smaller for set 2 than for set 1.

From each of these two sets, seven additional sets of aerodynamic coefficients were used, which were obtained from those listed above table via rotation of the building by 45°, 90°, ..., 270°, 315°.

For example, for a 45° rotation, for the N, NNE, NE ..., NW, NNW directions, the aerodynamic coefficients for set 1 are 0·2, 0·8, 1·1, ..., 0·1, 0·2.

4.2. Comparisons of estimates by the directional and non-directional methods for various MRIs

Because the data samples have larger sizes than for the non-hurricane region records, it is possible to attempt comparisons between directional estimates $x_{R\mathrm{eq}}$ for MRIs of 50, 2000, 10,000 and 100,000 years on the one hand, and non-directional estimates x_R for nominal MRIs of 50, 2000, 10,000 and 100,000 years, on the other. As an example, for milepost 250, located on the coastline near Corpus Christi, Texas, Figure 4 shows the mean and the maximum wind speeds for each of the 16 azimuths (minima are in many instances zero for certain directions and were not accounted for in calculating means). For set 1 of aerodynamic coefficients listed earlier, Figures 5(a) and (c) show estimated tail length parameters c of the best fitting extreme value distributions, and their 95% confidence bounds, for x_R and $x_{R\mathrm{eq}}$, respectively. Figures 5(b) and (d) show estimates x_R and $x_{R\mathrm{eq}}$, respectively, as functions of threshold. From Figures 5(b) and (d) we estimate, roughly, $x_{50} \approx 34$ m/s, $x_{50\mathrm{eq}} \approx 20$ m/s and $x_{100,000} < 43$ m/s, and $x_{100,000\mathrm{eq}} > 50$ m/s. Note that, for the milepost being considered, while the estimates of the 50 year speeds vary slowly as a function of threshold, for the 100,000 year speeds the variability is large. Therefore, we emphasize again that individual estimates for long MRIs are unreliable. However, as noted earlier, statistics of such estimates obtained from a large number of cases can provide useful indications of average trends. Overall, conditional on the errors in the estimation of the climatological parameters used in the simulations being small, the estimates of the equivalent speeds are more useful than those based on our non-hurricane wind speed records.

Table III. Mean and standard deviation of ratios r_R

	r_{50}	r_{2000}	$r_{10,000}$	$r_{100,000}$
Mean	0·71 (0·82)	0·85 (0·88)	0·90 (0·90)	0·96 (0·95)
Standard deviation	0·12 (0·04)	0·11 (0·05)	0·12 (0·09)	0·18 (0·10)

Note: Values not between parentheses (between parentheses) correspond to aerodynamic coefficients set 1 (set 2).

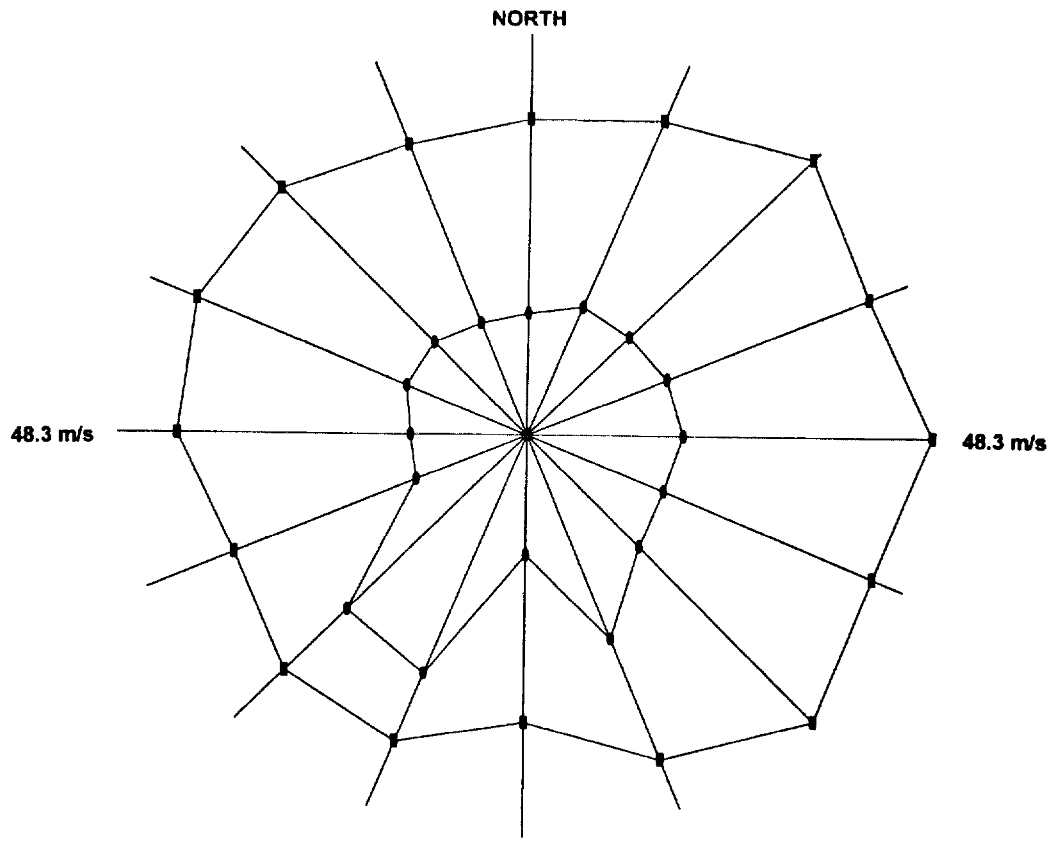

Figure 4. Directional mean and maximum hurricane mean hourly wind speeds, milepost 250

Note in Figure 5 that the 50 year estimates are significantly smaller for x_{Req} than for x_R. A similar example, for milepost 600, is given in Simiu and Heckert (1997). However, in many cases, including the case of Figure 5, this is not true for estimates with large MRIs. We list in Table III sample statistics of the 55 milepost estimates of $r_R = x_{Req}/x_R$.

We stress again that these values are based on the very approximate estimates made possible for large MRIs by plots similar to those of Figures 5(b) and (d). Note that, for both sets of aerodynamic coefficients, for very large MRIs the estimated ratios are, on average, close to unity, although owing to statistical variability individual estimates can be larger than unity, as is clearly the case in Figure 5.

To understand these results qualitatively, consider the simple example of the time series $x_j(\theta_i)(i = 1,2; j = 1,2,3)$: $x_j(\theta_1) = \{52,41,47\}$, and $x_j(\theta_2) = \{48,46,39\}$. Let us assume $C(\theta_1) = 0{\cdot}5$ $C(\theta_2) = 1$. By equation (3), the time series of the equivalent wind speeds x_{eqj} is then identical to the time series $x_j(\theta_2)$. Its mean and standard deviation are 44·33 and 4·33, respectively. On the other hand, using equation (5), we obtain the time series $x_j^{max} = \{52,46,47\}$, with mean and standard deviation 48·33 > 44·33 and 3·21 < 4·33, respectively. From the fact that the mean is larger and the standard deviation is smaller for the time series x_j^{max} than for the time series x_{eqj},

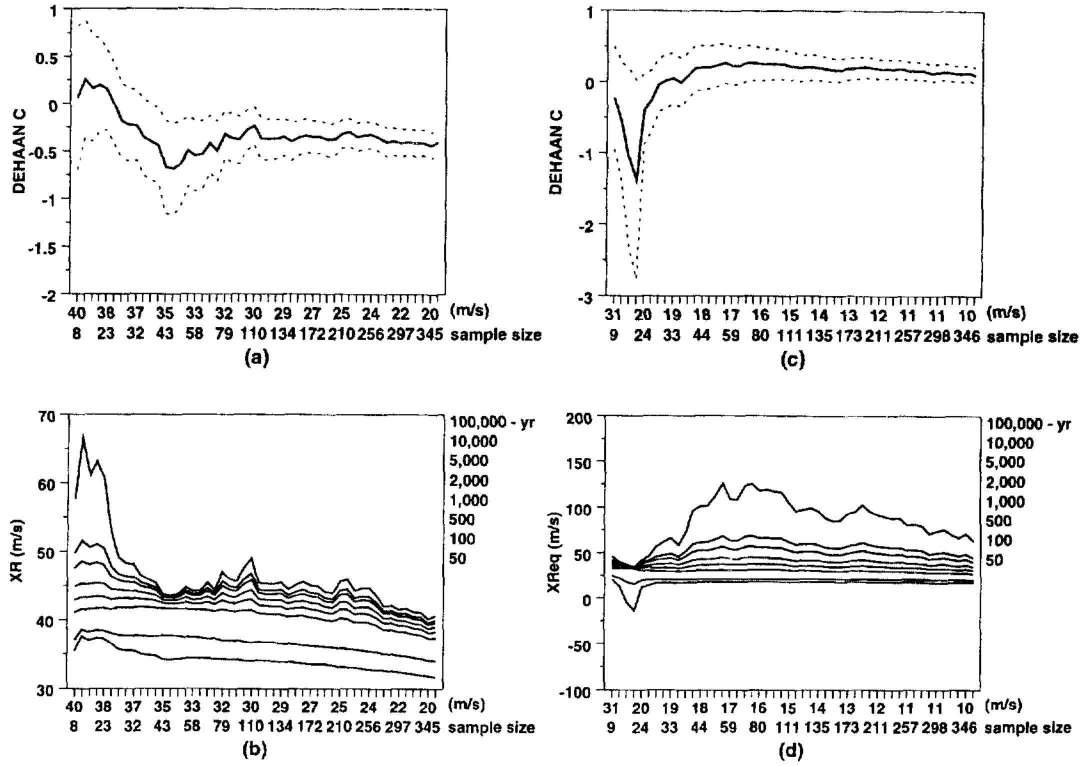

Figure 5. Estimates of: (a), (b) tail length parameter c and 95% confidence bands corresponding to (c) and (d), respectively; (c) speeds x_R with 50 year (bottom curve) to 100,000 year (top curve) nominal MRIs; (d) speeds $x_{R\mathrm{eq}}$ with 50–100,000 year MRIs, for largest pressure coefficient $C(\theta_i) = 3{\cdot}3$ in SSW direction (Milepost 250)

and from typical expressions of percentage points as functions of population means and standard deviations, it follows in many situations that, for very short MRIs, x_R can be significantly larger than $x_{R\mathrm{eq}}$, while for very long MRIs this is not longer the case.

Designs are governed by loads with large MRIs, rather than by the 50 year loads. Therefore, our results appear to indicate that, contrary to common belief, ultimate loads obtained by the non-directional method (i.e., from the time series $x_j^{\max}$) may be only marginally conservative. It would be of interest in this context to perform studies on penultimate distributions, as opposed to asymptotic extreme value distributions, and to attempt the development of practical criteria for ascertaining whether the use of asymptotic extreme value distributions is warranted for various types of wind speed data sets.

4.3. MRIs of ultimate wind loads

In accordance with ASCE (1993), for hurricane-prone regions near the coastline, wind loads inducing the design strength are defined as the loads with a 50 year nominal MRI multiplied by an effective wind load factor ($1{\cdot}3 \times 1{\cdot}05^2$). The MRIs of those loads were found to be, on average, of the order of 500 years (see Whalen (1996)). For Figure 5 (milepost 250), the nominal MRI and the MRI of the ultimate wind load are estimated as follows. The speed inducing the design strength is $(1{\cdot}05)(1{\cdot}3)^{1/2}x_{50} \approx 1{\cdot}2 \times 34$ m/s = 40·8 m/s. From Figure 5(b), the nominal MRI of that speed is about 300 years (see also Simiu and Heckert, 1997). From Figure 5(d), the MRI of the 40·8 m/s speed (and, therefore, the MRI of the ultimate wind load) is about 3000 years.

Similar estimates were made for 55 mileposts with eight distinct building orientations at each milepost. It was found that estimated MRIs were larger than nominal MRIs by a factor of about 3–15. A rough estimate of the average MRI for these 55 × 8 situations is 3500 years. However, as was the case for milepost 250, MRIs considerably smaller than 3500 years can occur in some cases. We note that these estimates are conditional on the uncertainties pertaining to the estimation of the aerodynamic, micrometeorological, and climatological parameters that determine the wind loads being small. Unconditional estimates would lead to smaller estimates of the MRIs. The small estimated MRIs of the wind loads inducing the design strength may explain, at least in part, the large losses caused by many hurricane events. In light of these results it appears that the standard specification of wind load factors in hurricane-prone regions needs to be reassessed and revised. Efforts to this effect are currently being pursued by the ASCE 7 Standard Committee.

5. SUMMARY AND CONCLUSIONS

In this paper we presented estimates of wind loads which take into account the dependence of direction of both the aerodynamic coefficients and the extreme wind climate. Estimates were based on time series of the square root of the largest annual wind load for non-hurricane regions, and of square root of the largest load induced by each simulated storm for hurricane-prone regions. The times series were analyzed by the 'peaks over threshold' approach for the estimation of extremes. For any given load, the nominal mean recurrence interval (nominal MRI) was estimated for that load by ignoring the variation of the aerodynamic coefficients and the extreme wind climate with direction. The mean recurrence interval (MRI, without the qualifier 'nominal') was estimated for that same load by accounting for that variation.

For non-hurricane regions results pertaining to ultimate loads were not conclusive owing to the relatively small size of the available samples. An improvement can be attempted by obtaining from longer records than those used in this paper directional wind speed data exceeding specified thresholds, rather than largest annual directional data, as was done in the present work. We noted that directional data sets extracted from Local Climatological Data (LCD) summaries published by the National Weather Service are incomplete owing to the omission of so-called 'hidden' directional values. By comparing load estimates based on such sets on the one hand, and on complete sets on the other, we fond that for very long mean recurrence intervals differences between the respective estimates of the wind forces can be as high as 20%. Such errors can be reduced by performing analyses of incomplete sets based on methods that take the incompleteness into account.

For hurricane-prone regions our results confirm the well-known result that loads with a relatively short MRI (50 years, say) are generally smaller than loads whose nominal MRI is equal to that MRI. However, according to our results this is not necessarily true for large MRIs, that is, contrary to common belief, method for estimating extreme wind loads that do not take directionality into account may be only marginally conservative from a structural engineering point of view.

We also found that, for hurricane-prone regions near the coastline, MRIs of loads inducing the design strength, as specified by the 1993 ASCE 7 Standard, vary between less than 1000 years to more than 10,000 years, the average being, roughly 3500 years. This suggests that the 1993 ASCE

7 Standard provisions for hurricane-prone regions may result in unsafe designs in need of revision. This suggestion becomes even stronger if it is recalled that our estimates are conditional on uncertainties pertaining to various relevant parameters (e.g., the terrain roughness parameter) being small. Unconditional mean recurrence intervals of the wind loads inducing the design strength can therefore be expected to be even lower than those we estimated.

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