ESTIMATION OF EXTREME WIND SPEEDS

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SUMMARY

Extreme wind loads used in design include nominal design wind loads (e.g., the 50-yr wind load) and ultimate wind loads. This paper briefly reviews the relationship between extreme wind loads and extreme wind speeds, assessments of epochal versus 'peak-over-threshold' approaches for estimating extreme non-tornadic winds in areas not subjected to tropical storms, and methods for estimating extremes from short records. Also reviewed are wind direction effects, and the estimation of extreme winds due to tropical cyclones (hurricanes) and tornadoes. We point out uncertainties due to model shortcomings and insufficient data, safety concerns due to current inconsistent uses of reliability concepts, and the implications of these concerns for code writing.

INTRODUCTION

A nominal design wind load is an extreme load with specified probability of being exceeded during a given time interval. In the United States that interval is usually 50 years. For example, for the inland Miami, Florida area, the ASCE Standard 7-93 (1993) specifies a nominal 50-year load based on a specified 50-year nominal design wind speed of 110 mph (49.17 m/s).

A structure or element thereof is expected to withstand loads substantially in excess of a 50- or 100-year wind load without loss of integrity. The wind load beyond which loss of integrity can be expected is referred to as ultimate wind load. The nominal ultimate strength provided for by the designer is based on an assumed ultimate wind load equal to the design wind load times a wind load factor. This statement is valid for the simple case where wind is the dominant load. It needs to be modified if load combinations are considered, but for clarity we refer here only to this case.

The load factor should be selected so that the probability of occurrence of the ultimate load is acceptably small. This probabilistic concept is important from an economic or insurance point of view. To the extent that evacuation or similar measures cannot be counted on to prevent loss of life, it is also important from a safety point of view.

A probabilistic approach has proven helpful in a number of cases, particularly for relative assessments of alternative design provisions, e.g., for mobile homes. However, in most cases the difficulties of obtaining wind load factors by probabilistic methods have proven to be substantial if not prohibitive. For this reason code writers have largely relied on wind load factors implicit in traditional codes and standards. For example, the ASCE Standard 7-93 specifies a wind load factor of 1.3 (e.g., the nominal ultimate wind load for the inland Miami area would correspond to a wind speed of $(1.3)^{1/2}110 \approx 125.4$ mph (56.06 m/s)).

Reliance on traditional code values is sometimes referred to as "calibration against existing practice." Traditional codes were generally adequate for many types of structures, but questions remain on whether safety margins implicit in those codes may be applied to modern structures, which can differ substantially from their predecessors in their materials and design/construction techniques. We discuss later an example involving wind direction effects.

Much effort has been and is being expended in an attempt to develop a practical probabilistic methodology for design. Probabilistic studies aimed at improving estimates of extreme wind loads are part of this effort. In this paper we review the relation between extreme wind loads and extreme wind speeds, and briefly discuss turbulence and wind direction effects on loads that don't entail significant dynamic amplification or aeroelastic effects. We also review the estimation by epochal and 'peaks-over threshold' methods of non-tornadic extreme winds in areas not subjected to tropical storms. To our knowledge this last topic has not yet been the object of a wind engineering state-of-the-art review. Its treatment in this paper is therefore more extensive than for such topics as the estimation of extreme winds from short records or the estimation of extreme winds due to tropical cyclones and tornadoes, that have been covered in some detail elsewhere (e.g., Simiu and Scanlan (1986), ASCE Committee on Wind Effects state-of-the art review (1987), Sill and Sparks (1991), and Marshall (1993), which contain numerous relevant references)

RELATION BETWEEN EXTREME WIND SPEEDS AND EXTREME WIND LOADS

Assume that the wind velocity is known at a particular location and elevation near a structure, where it is unaffected by any obstructions and is therefore indicative of the ambient wind environment. The wind pressure at a point on the building surface, or the wind force on a member, is a function of that wind speed and can be determined from results of wind tunnel or full-scale tests.

Turbulence and Flow Separation Effects.

The wind load on a particular member is obtained by integrating the pressures over the member's tributary area. Since, owing to turbulence and flow separation effects, pressures are time-dependent and imperfectly correlated spatially, with generally unknown correlation, the integration cannot be performed analytically, except for a very few simple cases, and is performed instead by a variety of techniques in wind tunnel or full-scale tests. When the tributary area is small correlation effects are relatively small, and the fluctuating force excursions may be many times larger than the standard deviation of the fluctuations. The magnitude of the force fluctuation to be specified for design purposes is an issue for which no clear and consistent reliability-based solution appears to be available at this time. This issue is complicated oy questions on the extent to which loads measured on small scale models can provide satisfactory indications on the magnitude of their prototype counterparts, particularly if the results of interest involve large fluctuating pressure excursions.

Wind Direction Effects.

Pressures (and therefore forces) depend on both wind speed and direction. The dependence is of the form

$$p(\theta)=\tfrac{1}{2}\rho c(\theta)v(\theta)^2 \qquad (1)$$

where ρ, c, p, v and θ denote air density, the aerodynamic coefficient, pressure (or force), wind velocity, and direction, respectively. Two methods have been proposed for obtaining extremes of the vector $p(\theta)$. The first method relies on techniques for estimating the rate of upcrossing by $p(\theta)$ of a limit state $s(\theta)$ (Davenport, 1977). The second method is based on the creation of a set of i ($i=1,2,..,8$ or $i=1,2,..,16$) time series

$$p_j(\theta_i)=\tfrac{1}{2}\rho c(\theta_i)v_j(\theta_i)^2, \qquad j=1,2,..,N \qquad (2)$$

based on a set of i recorded time series $v_j(\theta_i)$, where θ_i are the eight or sixteen directions for which directional wind speeds are measured. From these sets of time series the single time series

$$w_j=\{\max_i[p_j(\theta_i)]\}^{1/2} \qquad (3)$$

is extracted. In Eq. 3 $\max_i$ denotes the maximum over all i's. To within a dimensional constant, w_j may be interpreted as an equivalent wind speed. The time series w_j consists of the largest equivalent wind speeds affecting the structure during the intervals $[t_{j-1}, t_j]$ ($j=1,2,..N$). It is subjected to a statistical analysis and yields the extreme values w, and therefore the extreme pressures (forces) acting on the structure, w^2, for the mean recurrence intervals of interest. For a numerical example, see Simiu and Scanlan (1986). For brevity we refer to the pressures $p=w^2$ as actual extreme pressures.

Extreme Loads Calculated Without Regard for Wind Direction Effects.

Extreme load estimation is simplified if the idealized time series

$$W_j = \tfrac{1}{2}\rho\{\max_i[c(\theta_i)]\ \max_i[v_j(\theta_i)^2]\}^{1/2}, \qquad (4)$$

obtained by ignoring direction effects, is considered in lieu of the time series w_j. For any given mean recurrence interval, depending upon the directional dependence of the aerodynamic coefficient and the wind climate, the extreme values of the variable $P=W^2$ are in general larger — in many instances much larger — than the actual extreme pressures $p=w^2$. We refer here to the pressures P as idealized extreme pressures. Past experience shows that idealized extreme pressures P (based, say, on a 50- or 100-year extreme wind estimated without regard for direction), used in conjunction with a load factor of 1.3, normally result in acceptably small failure probabilities. However, use of the smaller actual extreme pressures p (with a 50- or 100-year mean return period) in conjunction with a load factor of 1.3 will result in higher failure probabilities that could well prove to be unacceptable and cannot be justified by invoking past experience.

This issue has not yet been adequately addressed by standard-writing bodies. For example, the ASCE Standard 7-93 as well as the draft ASCE Standard 7-95 allow nominal wind loads to be estimated on the basis of ad-hoc wind tunnel tests. For many special structures estimates of nominal wind loads based on such tests account for wind direction effects. However, the standard fails to indicate that the use of those estimates in conjunction with the wind load factor specified by the standard generally results in higher failure probabilities than those implicit in the provisions for ordinary structures. In this writer's opinion, which was duly communicated to the ASCE Subcommittee on the ASCE 7-95 Standard, this omission could have serious safety repercussions and deserves careful scrutiny.

A similar failure to address the reliability problem in a consistent fashion led recently to a strong increase in effective safety margins for window glass design, which in the writer's view is largely unwarranted. This issue is discussed in detail by Simiu and Hendrickson (1987).

ESTIMATION OF EXTREME WIND SPEEDS WITHOUT REGARD FOR DIRECTION

To within a constant dimensional factor, the time series W_j is the same as the time series $\max_i[v_j(\theta_i)]=V_j$ $(j=1,2,..,N)$. Extreme idealized wind loads can therefore be obtained from estimates of the extreme variate V inferred from this time series.

The vast majority of structural engineering calculations for wind are based on idealized extreme pressures, rather than actual extreme pressures. This state of affairs is due to: (1) the difficulty of codifying the estimation of actual extreme wind loads for most ordinary structures, (2) the generally inadequate availability of directional aerodynamic and wind climatological data, and (3) computational inconvenience. This last factor carries less weight in the age of personal computers, and it may be that in the near future expert systems with adequate data bases will increasingly allow directional effects to be accounted for in the estimation of wind loads (Simiu et al. 1993). Nevertheless, for the time being, estimating extremes wind speeds without regard for direction remains an important structural engineering problem.

The estimation of nominal design wind speeds (e.g., wind speeds with, say, a 50-year return period) is in general not unduly sensitive to the choice, within reasonable limits, of the statistical estimation procedure and the distributional form assumed to underlie the data. For example, the method of moments is inferior to the probability plot correlation coefficient (ppcc), but using it, instead of the ppcc, to estimate 50-year wind speeds entails errors of about 3 to 5 percent. Similar errors are inherent in the use of the assumption that a Fréchet distribution with tail length parameter γ=9, rather than a Gumbel distribution, best fits the data. However, if ultimate loads (or load factors) are of interest, the results can be sensitive to the choice of estimation procedure and distribution.

Extreme largest value distributions are, strictly speaking, valid only in the asymptotic limit of large extremes. It is nevertheless reasonable to assume that extreme winds are described probabilistically — at least approximately — by extreme largest value distributions. There are exactly three such distributions. In order of increasing tail lengths, they are the reverse Weibull distribution, the Gumbel distribution, and the Fréchet distribution. (The reverse Weibull and Fréchet are more properly referred to as families of distributions, each distribution being characterized by a particular value of the tail length parameter.) A remarkable feature of the reverse Weibull distribution is its finite upper tail.

The American National Standard A58.1-1972 (a predecessor of the current ASCE Standard 7-1993) was based on the assumption that extreme wind speeds are described by a Fréchet distribution with tail length parameter γ=9. As shown by subsequent studies, it may be confidently assumed that the Gumbel distribution — which is shorter-tailed than the Fréchet distribution with γ=9 — is a better probabilistic model of the extreme speeds (Simiu and Scanlan, 1986). However, even studies based on the Gumbel model result in apparently unrealistically high estimates of failure probabilities (Ellingwood et al., 1980). This may be explained in part by the fact that those studies do not adequately account for wind direction effects. However, an additional explanation may be that the extreme speeds are best fitted not by Gumbel distributions, which have infinite upper tails, but rather by reverse Weibull distributions which — like wind speeds in nature — have finite upper tails.

Recent substantial advances in extreme value theory appear to justify efforts to develop more realistic probabilistic models of extreme wind speeds and, consequently, more realistic wind load factors. This is likely to be true in spite of difficulties such as the limited availability of long-term data, the current insufficiency of comprehensive meteorological models available to the extreme wind analyst, and limitations inherent in statistical procedures. We describe some recent contributions to these efforts.

Classical Extreme Value Theory and 'Peaks over Threshold Methods.'

Classical extreme value theory is based on the analysis of data consisting of the largest value in each of a number of basic comparable sets called epochs (a set consisting, e.g., of a year of record, or of a sample of data of given size; in wind engineering, it has been customary to define epochs by calendar years). For independent, identically-distributed variates with cumulative distribution function F, the distribution of the largest of a set of n values is simply F^n. With proper choice of the constants a_n and b_n, and for reasonable F's, $F^n(a_n + b_n x)$ converges to a limiting distribution, known as the asymptotic distribution. As mentioned earlier, a notable result of the theory is that there exist only three types of asymptotic extreme largest value distributions, known, in order of decreasing tail length, as the Fréchet (or Fisher-Tippett Type II), Gumbel (Type I), and reverse Weibull (Type III) distributions (Lechner et al., 1993· Gross et al., 1994).

In contrast to classical theory, the theory developed in recent years makes it possible to analyze all data exceeding a specified threshold, regardless of whether they are the largest in the respective sets or not. An asymptotic distribution — the Generalized Pareto Distribution (GPD) — has been developed using the fact that exceedances of a sufficiently high threshold are rare events to which the Poisson distribution applies. The expression for the GPD is

$$G(y) = \mathrm{Prob}[Y \le y] = 1-\{[1+(cy/a)]^{-1/c}\} \qquad a>0,\ (1+(cy/a))>0 \qquad (5)$$

Equation 5 can be used to represent the conditional cumulative distribution of the excess $Y = X - u$ of the variate X over the threshold u, given $X > u$ for u sufficiently large (Pickands, 1975). $c>0$, $c=0$ and $c<0$ correspond respectively to Fréchet, Gumbel, and reverse Weibull (right tail-limited) limiting distributions. For $c=0$ the expression between braces is understood in a limiting sense as the exponential $\exp(-y/a)$ (Castillo, 1988, p. 215).

The peaks over threshold approach reflected in Eq. 5 can extend the size of the sample being analyzed. Consider, for example, two successive years in which the respective largest wind speeds were 30 m/s and 45 m/s, and assume that in the second year winds with speeds of 31 m/s, 37 m/s, 41 m/s and 44 m/s were also recorded, at dates separated by sufficiently long intervals (i.e., longer than a week, say) to view the data as independent. For the purposes of threshold theory the two years would supply six data points. The classical theory would make use of only two data points. In fact it may be argued that, by choosing a somewhat lower threshold, the number of data points used to estimate the parameters of the GPD could be considerably larger than six in our example.

Description of CME, Pickands and Dekkers-Einmahl-De Haan Methods.

Several methods have been proposed for estimating GPD parameters: the Conditional Mean Exceedance method (CME), the Pickands method, and the Dekkers-Einmahl-de Haan method (or, for brevity, the de Haan method).

Conditional Mean Exceedance (CME) Method. The CME (or mean residual life — MRL — as it it usually termed in biometric or reliability contexts) is the expectation of the amount by which a value exceeds a threshold u, conditional on that threshold being attained. If the exceedance data are fitted by the GPD model and $c < 1$, $u > 0$, and $a+uc > 0$, then the CME plot (i.e., CME vs. u) should follow a line with intercept $a/(1-c)$ and slope $c/(1-c)$ (Davisson and Smith, 1990). The linearity of the CME plot can thus be used as an indicator of the appropriateness of the GPD model, and both c and a can be estimated from the CME plot.

Pickands Method. Following Pickands' (1975) notation, let $X_{(1)} \geq \ldots \geq X_{(n)}$ denote the order statistics (ordered sample values) of a sample of size n. For s = 1, 2, .., [n/4] ([] denoting largest integer part of), one computes $F_s(x)$, the empirical estimate of the exceedance CDF

$$F(x;s) = \text{Prob}(X-X_{(4s)} < x \mid X > X_{(4s)}) \quad (6)$$

and $G_s(x)$, the Generalized Pareto distribution, with a and c estimated by

$$\hat{c} = \frac{\log((X_{(s)} - X_{(2s)})/(X_{(2s)} - X_{(4s)}))}{\log(2)} \quad (7)$$

$$\hat{a} = \frac{\hat{c}(X_{(2s)} - X_{(4s)})}{2^{\hat{c}} - 1} \quad (8)$$

One takes for Pickands estimators of c and a those values which minimize (for $1 < s < [n/4]$) the maximum distance between the empirical exceedance CDF and the GPD model.

Following a critique of an earlier implementation of the Pickands method (Pickands, 1975, Castillo, 1988), an alternative implementation was developed (Lechner et al., 1991),.which entailed the following steps: (1) choose as threshold u an order statistic of the sample; (2) compute the empirical exceedance CDF for the data above u; (3) nonlinear least-squares fit the GPD model for the parameters c and a; (4) plot the resulting c estimates against u for each order statistic. If the plot of $\hat{c}$ is stable around some horizontal level for most of the order statistic thresholds plotted, then the plot is presumptive evidence for the GPD model being applicable and can be used to yield numerical estimates of c; the distribution is Weibull, Fréchet or Gumbel according as c is negative, positive, or fluctuates around zero. The approach just described was suggested by Bingham (1990).

De Haan Method. Recent work by de Haan (1994) and coworkers provides a moment-based estimator which, like Pickands' estimator, is asymptotically unbiased for the true tail parameter and, in addition, is asymptotically normal. We now describe this estimator, using the order-statistic notation introduced above.

Let n denote the total number of data and k the number of data above the threshold u. (Note that u is then the (k+1)-th highest data point.) Compute, for r=1 and r=2, the quantities

$$M_n^{(r)} = \frac{1}{k} \sum_{i=0}^{k-1} [\log X_{n-i,n} - \log X_{n-k,n}]^r \tag{9}$$

where $X_{n-i,n}$ denotes the (i+1)-th highest value in the set (Note that $X_{n-k,n}=u$.) The estimators of a and c are then

$$\hat{a} = u M_n^{(1)}/\rho_1 \qquad (\rho_1=1 \text{ for } \hat{c}\geq 0;\ \rho_1=1/(1-\hat{c}) \text{ for } \hat{c}<0) \tag{10a}$$

$$\hat{c} = M_n^{(1)} + 1 - \frac{1}{2(1 - (M_n^{(1)})^2/M_n^{(2)})} \tag{10b}$$

The standard deviation of the asymptotically normal estimator of $\hat{c}$ is

$$\text{s.d.}(\hat{c}) = [(1+\hat{c}^2)/k]^{1/2} \qquad \hat{c}\geq 0 \tag{11a}$$

$$\text{s.d.}(\hat{c}) = \{1/k[(1-\hat{c})^2(1-2\hat{c})(4-8(1-2\hat{c})/(1-3\hat{c})+(5-11\hat{c})(1-2\hat{c})/(1-3\hat{c})/(1-4\hat{c}))]\}^{1/2} \qquad \hat{c}<0 \tag{11b}$$

Estimation of Variates with Specified Mean Recurrence Intervals.

For wind engineering purposes the estimates of the wind speeds corresponding to various mean recurrence intervals are of interest. We give expressions that allow the estimation from the GPD of the value of the variate corresponding to any percentage point $1 - 1/(\lambda R)$, where λ is the mean crossing rate of the threshold u per year (i.e., the average number of data points above the threshold u per year), and R is the mean recurrence interval in years. Set

$$\text{Prob}(Y < y) = 1 - 1/(\lambda R) \tag{12}$$

From Eqs. 5 and 12, we have

$$1 - [1 + cy/a]^{-1/c} = 1 - 1/(\lambda R) \tag{13}$$

Therefore

$$y = -a[1 - (\lambda R)^c]/c \tag{13}$$

The value being sought is

$$x_R = y + u \tag{14}$$

where u is the threshold used in the estimation of c and a.

Relations Between Distribution Parameters and Expected Value and Standard Deviation.

Relations between distribution parameters and the expectation E(X) and the standard deviation s(X) for the Gumbel and reverse Weibull distribution are given below. (Subscripts G and W refer to the Gumbel and reverse Weibull distributions, $F_G(x)$ and $F_W(x)$, respectively.)

$$F_G(x) = \exp\{-\exp[-(x-\mu_G)/\sigma_G]\} \tag{15}$$

$$F_W(x) = \exp\{-[(\mu_W - x)/\sigma_W]^\gamma\}, \quad x < \mu_W \tag{16}$$

$$\sigma_G = (6^{1/2}/\pi)s(X) \tag{17}$$

$$\mu_G = E(X) - 0.57722\sigma_G \tag{18}$$

$$E[(X-\mu_W)/\sigma_W] = -\Gamma(1 + 1/\gamma) \tag{19}$$

$$s[(X-\mu_W)/\sigma_W] = \{\Gamma(1+2/\gamma)-[\Gamma(1+1/\gamma)]^2\}^{1/2} \tag{20}$$

where Γ is the gamma function (Johnson and Kotz, 1972). For the GPD,

$$E(X) = a/(1-c) \tag{21}$$

$$s(X) = a/\{(1-c)(1-2c)^{1/2}\} \tag{22}$$

(Hosking and Wallis, 1987).

Results of Monte Carlo Simulations.

Preliminary Monte Carlo studies reported by Gross et al. (1994) led to the following tentative conclusions:

Comparison of Estimation Methods. The CME and the de Haan methods are competitive. Both methods are superior to the Pickands method. The de Haan method gives better estimates than the CME method for extremes with large mean recurrence intervals. Note, however, that the de Haan method as described in Gross et al. (1994) was based on the de Haan estimator of the parameter c (Eq. 10b), and on an estimator of the parameter a less precise than Eq. 10b. For this reason it is reasonable to expect that the de Haan method that makes use of both Eqs. 10a and 10b performs better than the CME method.

Optimal Crossing Rate. A high threshold reduces the bias since it conforms best with the asymptotic assumption on which the GPD distribution is based; however, because it results in a small number of data, it increases the sampling error. It appears that, with no significant error, an approximately optimal threshold corresponds to a mean exceedance rate of 5/yr to 15/yr.

(We note here a typographical error in Gross et al. (1994): in Table 5 the population value for c should be −0.275, instead of −0.5 — cf. p. 142, line 6 of Gross et al. (1994).)

Results of Extreme Wind Speed Analyses.

Results of analyses performed on sets of about 20 to 45 yearly maximum wind speeds recorded at various U.S. sites were reported by Lechner et al. (1992). About one hundred data samples of size 20 to 45 years recorded at stations not affected by hurricanes were analyzed by the CME procedure. For more than two-thirds of the samples the c values estimated by the modified Pickands method were negative. The same data were recently analyzed by Simiu and Heckert (1995) by using the de Haan method. These analyses confirmed the results of Lechner et al (1992). However, because the number of data available in these samples is small, especially for large thresholds, the confidence bands for the estimates tend to be relatively wide.

Analyses were also done for 48 sets of daily data records with lengths 15 to 24 years. As explained in Gross et al. (1995), the number of data in the sets was reduced by a factor of four to decrease the effect of correlation due to wind speeds recorded in the same storm. Results based on de Haan's method (Eq. 10a) — as opposed to the more inconclusive results based on the CME method reported by Gross et al. (1995) — showed an unmistakable tendency of the estimated values of c to be negative Simiu and Heckert, 1995). These results are significant. They provide evidence that extreme value statistics reflect the physical fact that wind speeds are bounded. However, it appears that dependable quantitative information for use in structural reliability estimates and the development of wind load factors for building standards would require larger data sets than are presently available. We note that, using a different approach, Kanda (1994) also showed that extreme winds are best fitted by distributions with limited tails. See also Walshaw (1994).

Sampling Errors in Estimation of Extreme Wind Speeds.

Estimates of sampling errors are available under the assumption that the extreme annual wind speeds have a Gumbel distribution — see Simiu and Scanlan (1986, p. 87). Based on that assumption, the standard deviation of the sampling errors was estimated to be about 5 to 10 percent of the wind speeds obtained from an approximately 30-year long sample of maximum yearly data. Sampling errors so estimated are acceptable approximations for use in reliability calculations.

Gust Wind Speeds versus Fastest Mile Speeds.

Peterka (1992) reported results of extreme wind analyses based on peak gust, as opposed to fastest-mile, records, and used a technique to reduce variability due to sampling error by combining stations with short records into "superstations" with long records. The acceptability of this technique is a function of the degree of mutual dependence of the storm occurrences at the various stations being consolidated.

ESTIMATES OF EXTREME WIND SPEEDS FROM SHORT RECORDS

A procedure for estimating extreme wind speeds without regard for direction at locations where long-term data are not available was reported by Simiu et al. (1982) and Grigoriu (1984). The method, whose applicability was tested for 36 U.S. stations and a total of 67 three-year records, makes it possible to infer the approximate probabilistic behavior of extreme winds from data consisting of the largest monthly wind speeds recorded over a period of three years or longer. Estimators of the wind speed with an N-year mean recurrence interval and of the corresponding standard deviation of the sampling errors are given in Simiu and Scanlan (1986, p. 91).

Inferences concerning the probabilistic model of the extreme wind climate have also been attempted from data consisting of largest daily or largest hourly wind speeds by the authors just quoted and by Gusella (1991). Using such data raises two questions. First, what is the effect on the analysis of the mutual correlation among daily or hourly data? According to an estimate by Grigoriu (1982) that effect is tolerably small. Second, what is the effect of basing the inferences on data that are overwhelmingly representative of weak winds having little in common metorologically with the extreme winds of interest? According to preliminary results by Gross et al. (1995), weak winds may be viewed as noise obscuring the process of interest, rather than providing useful information on wind extremes.

ESTIMATES OF HURRICANE/TROPICAL CYCLONE WIND SPEEDS

In tropical-cyclone-prone regions the winds of interest to the structural engineer are primarily those associated with hurricanes (strong tropical cyclones). Statistical analyses of hurricane winds would therefore be necessary. However, the number of hurricane wind speed data at any one location is in most cases small. The confidence limits for predictions based on hurricane wind speed data at one location would, in general, be uncceptably wide.

For this reason estimates of hurricane wind speeds at a site are obtained indirectly from statistical information on the climatological characteristics of hurricanes, used in conjunction with a physical model of the hurricane wind field. Such a model allows the estimation of maximum wind speeds induced at any given location by a hurricane for which the following climatological characteristics are specified:

-- difference between atmospheric pressures at the center and the periphery of the storm
-- radius of maximum wind speeds

-- speed of storm motion
-- coordinate of crossing point along the coast or on a line normal to the coast.

The probability distribution of the hurricane wind speeds is then estimated as follows:

(1) A region is defined such that hurricanes occurring outside that region have a negligible effect at the site of concern. (In the United States such a region includes 750 km of coastline, say, and a 450 km segment over the ocean, normal to the coast.)

(2) The climatological characteristics of the hurricane, including the frequency of hurricane occurrences in this region, are modeled probabilistically from statistical data obtained in the region under consideration.

(3) The values of the climatological characteristics for a number, n, of hurricanes are obtained by Monte Carlo simulation from these probabilistic models.

(4) The maximum wind speeds, v_i, $(i=1,2,..,n)$ induced by each of these hurricanes at the location of concern are calculated on the basis of the climatological characteristics thus obtained and of the physical model of the hurricane wind field, including a model for the decay of the storm as it travels over land. Thus, a set of n hurricane wind speeds is calculated, which is consistent with the statistical data on climatological characteristics of hurricanes in the region of interest.

(5) A statistical estimation procedure is applied to the calculated hurricane wind speeds in order to estimate the probability distribution of the hurricane wind speeds at the location being considered.

The procedure just oulined was first developed by Russell (1971), and was applied with various modifications by, among others, Batts et al. (1980a) and Georgiou et al. (1983), whose respective estimates for the Gulf coast and the East coast of the United States are compared in Simiu and Scanlan (1986). Recent work by Vickery and Twisdale (1994) was aimed at improving certain aspects of the estimates by Batts et al. (1980), and resulted in lower estimates of hurricane wind speeds inland. Models of the ratio between peak gusts and sustained winds in hurricanes used by Batts et al. (1980) were based on data for extratropical storms. Improved models based on hurricane wind speed data have been proposed by Krayer and Marshall (1992). The issue of sampling errors in the estimation of hurricane wind speeds was examined by means of Monte Carlo simulations (Batts et al., 1980b), which showed that the standard deviation of the errors was typically 5 to 10 percent of the estimated speeds. A computer program for estimating direction effects in hurricanes is described in Hendrickson and Simiu (1986).

of hurricanes Hugo and Andrew are the object of studies by Sill and Sparks (1991), Reinhold et al. (1993), and Marshall (1993). The latter study reviews in detail, and contains recommendations for the improvement of, wind load provisions for manufactured home construction.

TORNADO WINDS

The approach to the estimation of hurricane winds discussed in the preceding section could be described, roughly, as the monitoring of a billiard game played by nature with balls in the form of hurricanes having complex physical and probabilistic characteristics, against various targets such as towns. A similar approach is used for tornado winds.

Let A_0 be some large reference area, and let n be the estimated number of tornado occurrences per year in area A_0. The estimated probability that a tornado will strike a particular location within A_0 in any one year is asssumed to be $P(H) = n\ a/A_0$, where a = estimated mean area of individual tornado path. The probability that a tornado with maximum wind speeds higher than some specified value V_0 will strike a location in any one year can be written as $P(H,V_0) = P(V_0)P(H)$, where $P(V_0)$ is the probability that the maximum wind speed is at least V_0, given that a tornado has occurred. The estimation of $P(H,V_0)$ relies on relatively few and uncertain data — inferred mostly from observations of damage — on tornado occurrences, path areas, and wind speeds, and on largely subjective extrapolations from these data to small probability levels. According to estimates presented by Markee et al. (1974), maximum tornado wind speeds corresponding to a probability $P(H,V_0) = 10^{-7}$ in any one year vary between 400 mph (179 m/s) in Oklahoma and Nebraska to 240 mph (107 m/s) in Northern California and Oregon. More refined estimates have subsequently been proposed (see Simiu and Scanlan (1986) for a summary of codified estimated tornado winds, pressure drops and pressure drop rates in the United States, and information on estimated tornado-borne missile speeds, and for additional references).

REFERENCES

American Society of Civil Engineers (1987), **Wind Loading and Wind-Induced Structural Response**, A state-of-the-art report prepared by the Committee on Wind Effects.

ASCE 7-93 (1993), **Minimum Design Loads for Buildings and Other Structures**, American Society of Civil Engineers, New York.

Batts, M.E., Russell, L.R., and Simiu, E. (1980), "Hurricane Wind Speeds in the United States," **Journal of the Structural Div., ASCE**, 106, 2001-2015.

Batts, M.E., Simiu, E. and Cordes, M.R., (1980), "Sampling Errors in Estimation of Extreme Hurricane Winds," **Journal of the Structural Division, ASCE**, 106, 2111-2115.

Bingham, N.H., "Discussion of the Paper by Davisson and Smith,"

Journal of the Royal Statistical Society , series B, 52, p. 431.
Castillo, E. (1988), **Extreme Value Theory in Engineering**, Academic Press, New York.
Davenport, A.G. (1977), "The Prediction of Risk Under Wind Loading," **Proceedings 2nd Intern. Conf. on Stroctural Safety and Reliability**, Munich, 511-538.
Davisson, A.C., and Smith, R.L. (1990), "Models of Exceedances Over High Thresholds," **Journal of the Royal Statistical Society**, Series B, 52, pp. 339-442.
De Haan, L. (1994), "Extreme Value Statistics," **Extreme Value Theory and Applications**, Galambos, J., Lechner, J. and Simiu, E., (eds.), Kluwer, Boston.
Ellingwood, B.R. et al. (1980), **Development of a Probability-Based Load Criterion for American National Standard A58**, NBS Special Publication 577, National Bureau of Standards, Washington, DC.
Georgiou, P.N., Davenport, A.G. and Vickery, B.J. (1983), "Design Wind Speeds in Regions Dominated by Tropical Cyclones," Journal **of Wind Engineering and Ind. Aerodynamics**, 13, 139-152.
Grigoriu, M. (1982), "Estimates of Design Winds from Short Records," **Journal of the Structural Div., ASCE**, 108, 1034-1048.
Grigoriu, M. (1984), "Estimation of Extreme Winds from Short Records," **Journal of Structural Engineering**, 110, 1467-1484.
Gross, J., Heckert, A., Lechner, J. and Simiu, E. (1994), "Novel Extreme Value Estimation Procedures: Application to Extreme Wind Data," **Extreme Value Theory and Applications**, Galambos, J., Lechner, J. and Simiu, E., (eds.), Kluwer, Boston.
Gross, J., Simiu, E., Heckert, N.A. and Lechner, J.A. (1995), "A Study of Optimal Extreme Wind Estimation Procedures," **Proceedings, Ninth International Wind Engineering Conference**, New Delhi.
Gusella, V. (1991), "Estimation of Extreme Wind Speeds from Short-term Records," **Journal of Structural Engineering**, 117, 375-390.
Hendrickson, E.M. and Simiu, E. (1986), **Directional Hurricane Wind Effects**, NBSIR 86-3317, National Bureau of Standards, Gaithersburg, MD.
Hosking, J.R.M. and Wallis, J.R. (1987), "Parameter and Quantile Estimation for the Generalized Pareto Distribution," **Technometrics**, 29, pp. 339-349.
Kanda, J. (1994), "Application of an Empirical Extreme Value Distribution to Load Models," **J. Res. Natl. Inst. Stand. Technol.**, 99, 413-420.
Krayer, W.J. and Marshall, R.D. (1992), "Gust Factors Applied to Hurricane Winds," **Bulletin of the American Meteorological Society**, 73, 613-617.
Lechner, J.A., Leigh, S.D., and Simiu, E. (1991), "Recent Approaches to Extreme Value Estimation with Application to Extreme Wind Speeds..," **Journal of Wind Engineering and Industrial Aerodynamics**, 41-44, 509-519.
Lechner, J.A., Simiu, E. and Heckert, N.A. (1993), 'Assessment of 'Peaks over Threshold' Methods for Estimating Extreme Value Distribution Tails," **Structural Safety**, 12, 305-314.
Markee, E.H., Beckerley, J.G., and Sanders, K.E. (1974), **Technical Basis for Interim Regional Tornado Criteria**, WASH 1300, U.S. Atomic Energy Commission, Washington, DC.

Marshall, R.D. (1993), **Wind Load Provisions of the Manufactured Home Construction and Safety Standards -- A Review and Recommendations for Improvement**, NISTIR 5189, NationalInstitute of Standards and Technology, Gaithersburg, MD.

Peterka, J.A. (1992), "Improved Extreme Wind Prediction for the United States," **Journal of Wind Engineering and Industrial Aerodynamics**, 41-44, 533-541.

Pickands, J. (1975), "Statistical Inference Using Order Statistics," **Annals of Statistics**, 3, 119-131.

Reinhold, T.A., Sill, B.L., Vickery, P.J., and Powell, M., (1993), Wind Speeds in Hurricane Andrew: Myths and Reality, Conference **Proceedings, The 7th U.S. National Conference on Wind Engineering**, Vol. 2, (G.C. Hart, ed.), University of California at Los Angeles.

Russell, L.R. (1971), "Probability Distributions for Hurricane Effects," **Journal of Waterways, Harbors, and Coastal Engineering Division**, 97, 139-154.

Sill, B.L.and Sparks, P.R. (eds.) (1991), **Hurricane Hugo One Year Later**, American Society of Civil Engineers, New York, N.Y.

Simiu, E., Filliben, J.J. and Shaver, J.R. (1982), "Short-term Records and Extreme Wind Speeds," **Journal of the Structural Division, ASCE**, 108, 2571-2577.

Simiu, E., and Scanlan, R.H. (1986), **Wind Effects on Structures**, Second Edition, Wiley-Interscience, New York.

Simiu, E., and Hendrickson, E. (1987), "Design Criteria for Glass Cladding Subjected to Wind Loads," J. Str. Eng., 113, 1199-1203.

Simiu, E., Garrett, J.H., and Reed, K.A. (1993), "Development of Computer-based Models of Standards and Attendant Knowledge-base and Procedural Systems," in **Structural Engineering in Natural Hazards Mitigation**, ASCE Struct. Congr., Irvine, CA., 841-946.

Simiu, E., and Heckert, N.A. (1995), **Extreme Wind Distribution Tails**, Building and Fire Research Laboratory, National Institute of Standards and Technology (in preparation).

Vickery, P.J. and Twisdale, L.A. (1994), "Windfield and Filling Models for Hurricane Windspeed Predictions," submitted to Journal of Structural Engineering.

Walshaw, D. (1994), "Getting the most from your extreme wind data: a step-by-step guide," J. Res. Natl. Inst. Stand. Technol., 99, 399-412.