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Structural Safety 20 (1998) 271–281

STRUCTURAL
SAFETY

Assessment of wind load factors for hurricane-prone regions

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Abstract

We study the issue of whether the wind load factors specified in the ASCE 7–95 Standard for hurricane-prone regions on the one hand and extratropical storm regions on the other are mutually consistent with respect to risk. We consider structures or elements whose design is governed by wind loads and for which wind directionality effects are not significant. We present estimates according to which ASCE 7–95 Standard provisions for wind loads inducing the design strength result in (1) safety levels that are considerably lower for hurricane-prone than for extratropical storm regions, and (2) estimates of mean recurrence intervals of hurricane wind loads inducing the design strength of about 500 y if epistemic uncertainties are neglected, and significantly lower than 500 years otherwise. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: Building technology; Codes and standards; Structural reliability; Wind engineering.

1. Introduction

The ASCE Standard 7–95 [1] specifies design wind loads that are normally associated with estimated 50-yr wind speeds [1, pp. 15, 17, 154]. In addition, the Standard specifies, explicitly or implicitly, wind load factors for extratropical storm and hurricane-prone regions. A first function of the wind load factors is to augment the 50-yr load by accounting for epistemic (knowledge) uncertainties affecting pressure or force coefficients, the terrain exposure coefficient, and the estimate of the 50-yr wind speed. A second function is to ensure that the mean recurrence interval of the wind load inducing the design strength exceeds 50 yr; otherwise, the probability that the design strength will be exceeded during a 50-yr period would be about 2/3 if epistemic uncertainties were negligible and even higher otherwise. Depending on the effective strength reserve this could lead to unacceptably high failure probabilities.

The wind load factor specified in [1] is 1.3, but for hurricane-prone regions this factor is in effect increased via multiplication by $(1.05)^2$. The factor 1.05 is referred to as the hurricane importance factor [1]. Ref. 2 [pp. 114–116] reports results used for the development of the load

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PII: S0167-4730(98)00012-5

factor specified in [1] based on 7 wind speed data sets. None of these sets is typical of hurricane wind climate conditions, and the latter are not considered in [2]. According to [1, p. 152], the justification for the choice of the value 1.05 is that "probability distributions of hurricane-winds and extratropical winds are different (Weibull versus Type I)" however, no quantitative results or references supporting the choice of the value 1.05 are given in [1].

According to extreme value theory, probability distributions of the largest values belong to one of three types: reverse Weibull (Type III), Gumbel (Type I), and Fréchet (Type II), listed here in the order of increasing tail length. The Weibull distribution (as opposed to the reverse Weibull distribution) is an extreme value distribution of the *smallest* values [3]. Also, according to a significant body of published research [4–8], extreme wind speeds are better fitted by reverse Weibull distributions than by Type I distributions. Given (1) these theoretical and statistical results, (2) the apparently obsolete distributional assumptions invoked in [1], (3) the lack of differentiation in Ref. [2] between extratropical and hurricane winds, and (4) the lack of published analyses supporting the choice of the factor 1.05, an assessment of the effective load factors specified in [1] for hurricane-prone regions appears to be in order.

The purpose of this work is to present such an assessment for the relatively simple case where (1) the design of the structure or element is governed by the wind load, the other loads being negligible, and (2) wind directionality effects are not significant. For this case the design strength induced by the wind load is proportional to the wind load factor times the wind load associated with a 50-y wind speed. We also assume that the speed is estimated without considering wind directionality, and that epistemic uncertainties are negligible. The implications of this assumption are discussed below. Our objective is to present an investigation into the question of whether the wind load factor specified in [1] for hurricane-prone regions on the one hand and for extratropical regions on the other are mutually consistent with respect to risk.

Probability distributions of the wind load are functions of epistemic uncertainties with respect to the aerodynamic force coefficient, the oncoming aerodynamic flow characteristics, and the probabilistic estimate of the wind speed. The larger these uncertainties, the longer are the tails of the wind load distributions, that is, the shorter are the estimated mean recurrence intervals of a specified wind load (for an illustration see, e.g., [2]). Estimates of mean recurrence intervals that do not account for epistemic uncertainties are an upper bound for estimates that do. Therefore, if the former estimates—the upper bounds —are unsatisfactory, so, a fortiori, are the latter estimates. In this paper we present, for both extratropical storm regions and hurricane-prone regions, estimates of ratios between wind loads corresponding to various long mean recurrence intervals R on the one hand and the 50-yr wind load on the other. Since all our estimates are conditional upon the epistemic uncertainties being negligible, and since we assume loads other than those induced by wind to be negligible, our estimated load ratios are equal to the squares of the ratios between the R-yr and the 50-yr speeds. According to the results of our analyses, the mean recurrence intervals of hurricane loads inducing the design strength are on average of the order of 500 years, while the corresponding estimates for extratropical storms are roughly two orders of magnitude larger. Since our estimates yield longer mean recurrence intervals than those that would be obtained if the epistemic uncertainties were accounted for, it follows from our results that the load factors inherent in the provisions of the ASCE 7–95 Standard correspond, on average, to mean recurrence intervals of the hurricane wind load inducing the design strength that can be significantly less than 500 yr, as suggested by estimates based on [7] and [2, p. 114].

The paper is organized as follows. Section 2 discusses briefly the sources of data and probabilistic models of the extreme wind speeds. Sections 3 and 4 present results of our analyses for hurricane-prone and extratropical storm regions, respectively. Section 5 presents our conclusions.

2. Sources of data and probabilistic models

The data used in the analyses are described in [4] for extratropical winds and in [7] and [9] for hurricane winds. They are publicly accessible, as indicated in the Appendix A. To the authors' knowledge, the data of [4] are the only publicly available micrometeorologically homogeneous [10, p. 94] sets of extreme wind data that contain extremes other than yearly maxima and are therefore appropriate for "peaks over threshold" analysis. Details on the data are given in Sections 3 and 4.

Several authors have produced alternative sets of hurricane wind speed data. In particular, estimates of 50-yr hurricane wind speeds reported in [12] are, on average, very close to corresponding estimates in [9] (see [11]) and [7]. However, at least for some locations, 2000-yr speeds estimates are higher in [12] than in [7] and [9]. For example, estimated ratios of 2000-yr speeds to 50-yr speeds are, on average, about 1.30 according to [7] and about 1.45 according to [12]. If the data of [7] led to the conclusion that the load factors specified for hurricane-prone regions in [1] are too small, that conclusion would be stronger if the data reported in [12] were used instead.

The issue of the probabilistic modeling of extreme wind speeds also deserves comment. A veritable revolution has occurred in the last two decades in the field of extreme value estimation. In 1980, when [2] was published, extreme value theory was still relying almost exclusively on the work of Gumbel from the 1950's and earlier. Alternative methods were only beginning to be developed and were unknown to most structural reliability researchers. The wind map of the 1971 predecessor of the ASCE 7–95 Standard, which was still being widely used in 1980, was based on the assumption that extreme wind speeds are best fitted by the Type II distribution of the largest values. In 1978 it was determined that the Type I distribution is a more appropriate probabilistic representation of the wind speeds than the Type II distribution [13]. The calculations of [2] were performed using the Type I distribution. "Peaks over threshold" methods are now available that allow the probabilistic modeling of extreme values to be performed much more effectively than was the case in the past [3]. As mentioned in Section 1, such methods have already been applied extensively to extreme wind speed data, and they have yielded the result that reverse Weibull distributions model extreme wind speeds better than the Type I distribution for both extratropical storm and hurricane-prone regions. The statistical analyses of [4] and [7] were based on de Haan's procedure [14]. Results based on maximum likelihood analyses of the data of [9] were found to be very close those based on the de Haan procedure.

Assume that, from the analysis of data best fitted by the reverse Weibull distribution, it is concluded that the load factor is too small. The question we are now addressing is whether, for the purpose of assessing load factors, the fitting of Extreme Value Type I distribution to the same data would lead to a similar conclusion. Consider ratios r of R-yr variates X_R to 50-yr variates X_{50} for a random variable X with expectation $E(X) = 1$ and various distributions. Figure 1(a) shows these ratios for a population with Type I distribution as a function of the coefficient of variation of X. Similar plots for populations with reverse Weibull distributions are shown in

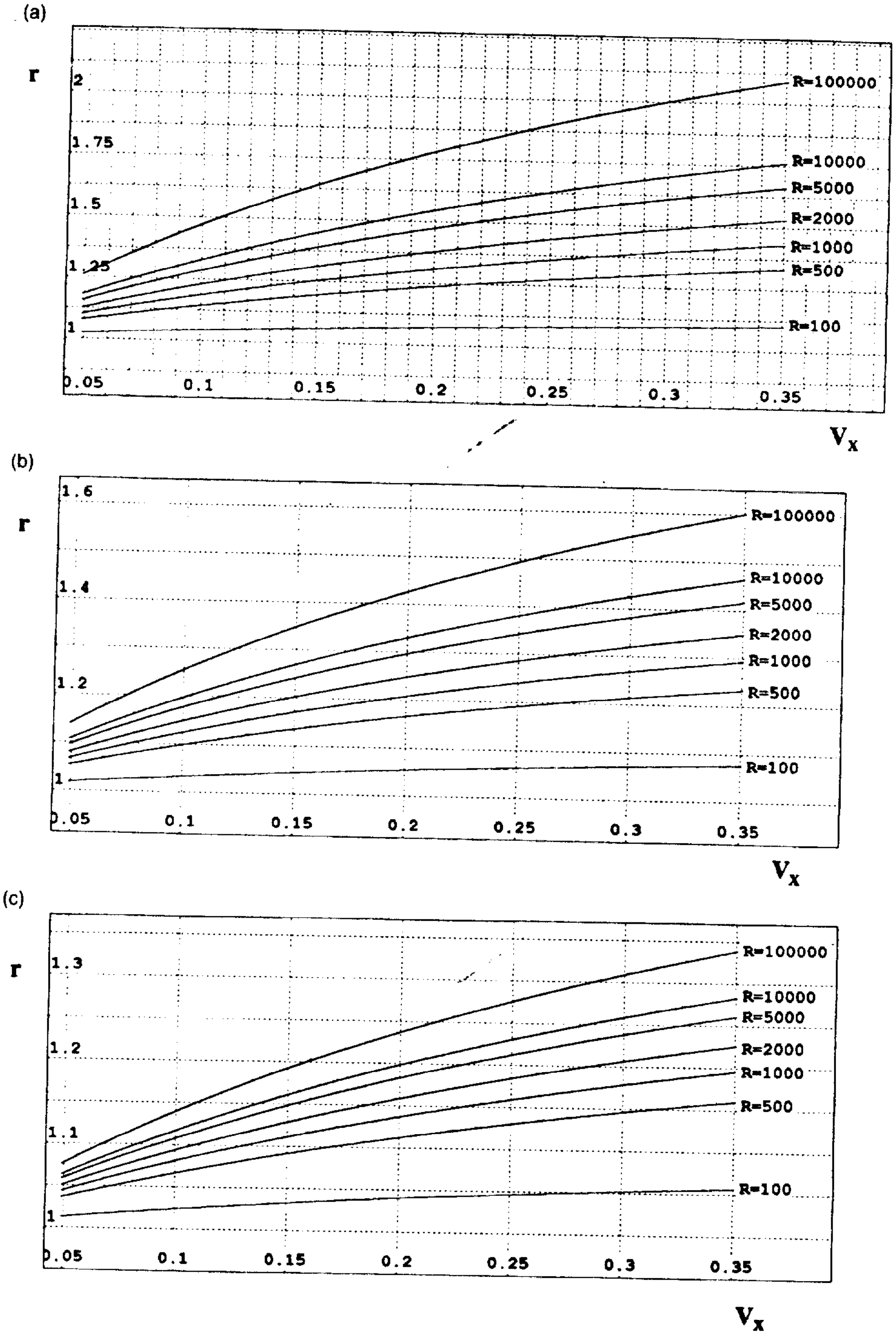


Fig. 1. Ratios r of R-yr variates to 50-yr variates as a function of coefficient of variation V_x of the variate X for (a) variates with Type 1 distribution, (b) variates with reverse Weibull distribution and tail length parameter $c = -0.1$, (c) variates with reverse Weibull distribution and tail length parameter $c = -0.2$.

Fig. 1(b) and (c) for tail length parameters $c = -0.1$ and $c = -0.2$, respectively. For large R the ratios are significantly larger for the Type I distribution than for the reverse Weibull distributions, and they decrease as $|c|$ increases. [The results of Fig. 1(a)-(c) are based on Eqs. A1.39-A1.41 and A1.65 of [10].] From the results of Fig. 1 it follows that fitting a Type I distribution to the data—that is, assuming the distribution has a longer tail than indicated by the analyses—would lead to the conclusion that the load factor should be increased even more than was found necessary by using the reverse Weibull distribution.

3. Conditional wind load factors corresponding to various mean recurrence intervals—hurricane-prone regions

The conditional load factor corresponding to a mean recurrence intreval R is defined as the ratio of the wind load with a mean recurrence interval of R years to the wind load with a 50-yr mean recurrence interval (1) under the assumption that the wind load W is given by the expression $W = CX^2$, where C is a specified constant and X denotes the wind speed, and (2) conditional on C and X being unaffected by epistemic errors. The regions of interest in this section are the coastal regions of the Gulf of Mexico and the Atlantic Ocean. Data for this study were obtained via simulation of hurricane winds based upon probabilistic models of the climatological parameters that influence hurricane structure. The data represent fastest 1 min hurricane wind speeds in knots at 10 m above ground over open terrain at 55 equidistant locations. They are available as maximum wind speeds within each of sixteen half octants for each of 999 simulated hurricane events. (As indicated earlier, we analyzed data sets consisting of the fastest speed in each hurricane event regardless of direction.) The estimated mean annual rate of occurrence of hurricanes at each location is also included in the data set. See the Appendix A for information on obtaining these data via anonymous file transfer.

Analysis of the data was performed by programs that implement the de Haan version of the "peaks over threshold" method for estimating extreme value parameters. (These programs are also accessible, as shown in the Appendix A.) From the estimated parameters we obtained estimates of wind speeds having mean recurrence intervals R in years. Under the asumption that a reverse Weibull distribution is valid, the probability of no exceedance of a threshold speed is

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

where a and c are the location and the tail length parameter, respectively. Eq. (1) 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. To obtain the estimate of the wind speed, let λ represent the mean crossing rate of the threshold u per year. We can then take

$$\mathrm{Prob}[Y(u) < y] = 1 - 1/[\lambda(u)R] \qquad (2)$$

as an estimate of the probability of no exceedances. Using Eq. (1),

$$y(u) = -a(u)1 - [\lambda(u)R]^{c(u)}\}/c(u). \qquad (3)$$

Recalling the definition of $y(u)$, we get

$$X_R(u) = y(u) + u \tag{4}$$

as the estimated wind speed having a mean recurrence interval of R years for the threshold u. The wind speed with an infinite mean recurrence interval, that is, the limiting upper wind speed as defined by the reverse Weibull distribution, is denoted by X_∞. Using Eq. (1) and setting $G(y) = 1$, we obtain

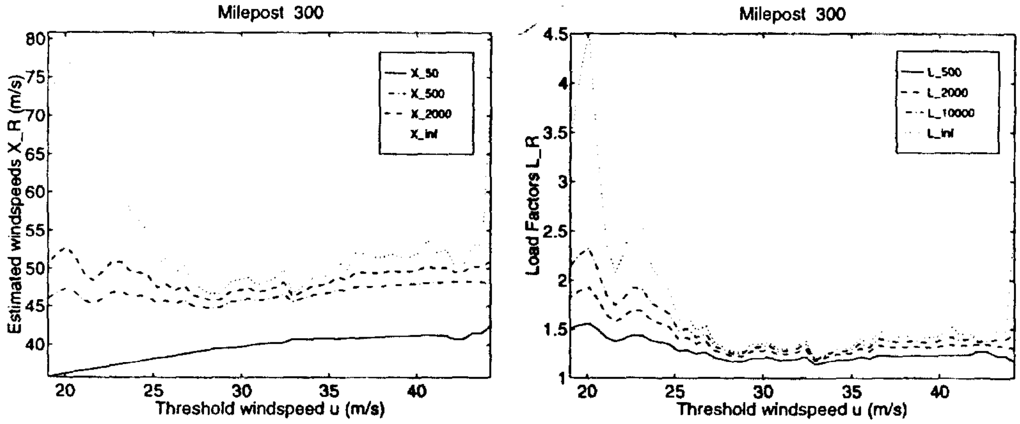
$$X_\infty = u - a/c. \tag{5}$$

The wind load factor specified in the ASCE Standard 7–95 is a measure of the ratio of the wind load inducing the design strength to the wind load based upon the 50-yr wind speed X_{50}, times the square of the importance factor F. We form an estimate of the conditional wind load factor as

$$F^2 L_R = (X_R/X_{50})^2. \tag{6}$$

As specified on p. 152 in the Commentary on ASCE Standard 7–95 [1], $F = 1.05$ for hurricane winds. L_∞ is defined by Eq. (6) with X_∞ replacing X_R.

In Fig. 2 we show plots of the estimated wind speeds X_R and estimated factors L_R vs threshold speed u for various values of R for simulated hurricanes at Milepost 300, a location near Matagorda Bay, Texas. Wind speeds in all figures are fastest-minute wind speeds at 10 m above ground in open terrain. Both L_R and X_R display a great deal of variability for low thresholds ($u < 25$ m/s, roughly). We note that inherent in the reverse Weibull model is the assumption that the thresholds u correspond to high wind speeds. Strong violations of this assumption may lead to poor distribution parameters estimates. Also, both X_R and L_R display variability for high thresholds ($u > 43$ m/s, approximately). This is due to the relatively small sizes of the samples of wind speed data (fewer than 30 data points, on average) exceeding these



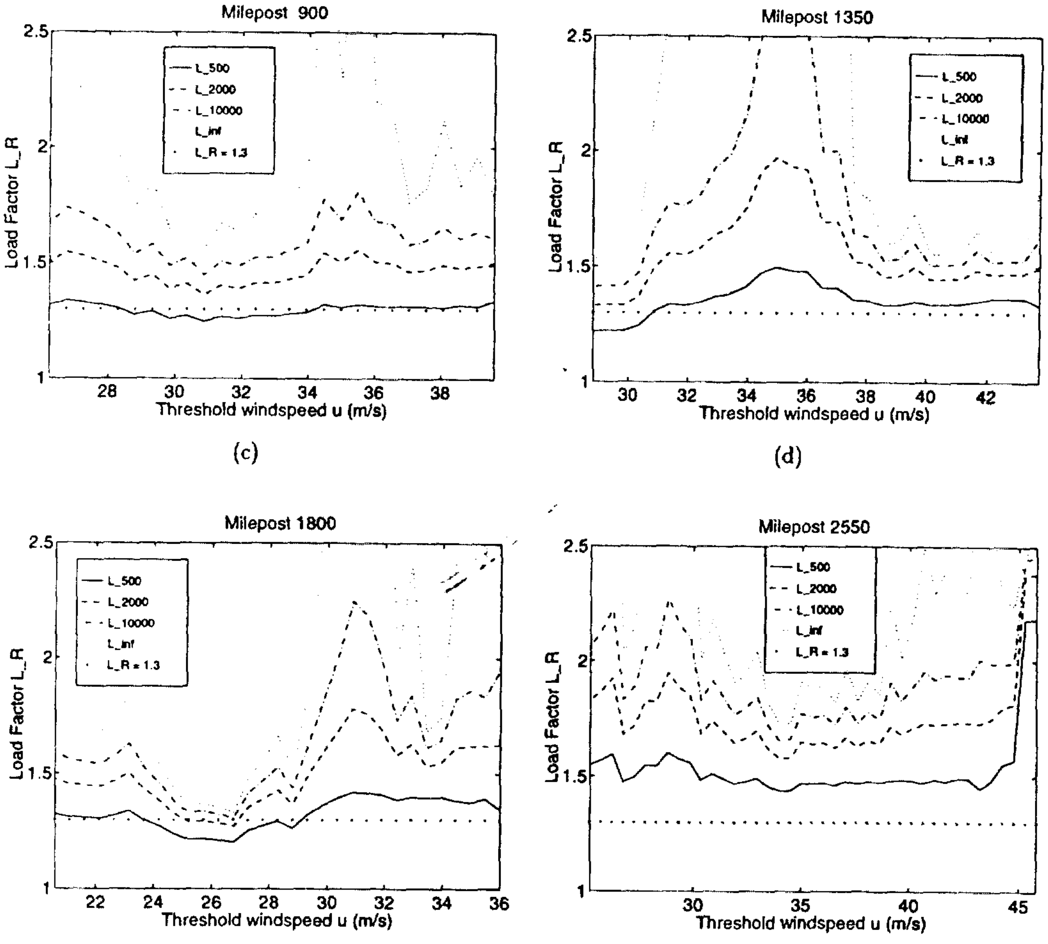
(a) (b)

Fig. 2. Representative plots of X_R and L_R versus u for Milepost 300, near Matagorda Bay, Texas.

thresholds. Between these two bounding cases, the values of L_R and X_R are fairly constant, although fluctuation clearly exists.

Graphs of estimated factors vs threshold speed for four additional locations in hurricane-prone regions are provided in Fig. 3. These graphs are representative of the results found for all the mileposts, see [15] for a full report. For the previously mentioned reasons, no results have been shown for thresholds having more than 300 exceedances or fewer than 30 exceedances. Also, estimated factors L_R larger than 2.5 are not shown. For comparison, we have included in these plots a dotted line at $L_R = 1.3$, representing the value of the nominal wind load factor from [1].

The graphs of Fig. 3 show noticeable variability in the load factors as a function of threshold, especially for the high recurrence intervals $R = 10{,}000$ years and $R = \infty$. However, certain trends are discernable. For example, the factor L_{500}, shown as a solid line in the graphs, is close to or higher than 1.3 for most mileposts. Examination of the full set of graphs leads to the same conclusion, although certain mileposts do show values of L_{500} below 1.3. This result is in agreement



(c) (d)

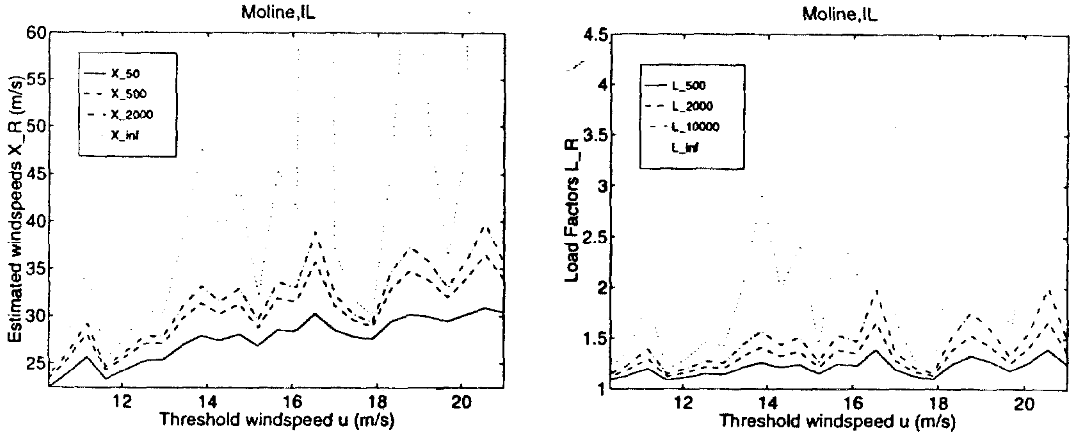
(e) (f)

Fig. 3. Plots of L_R versus u for four mileposts in hurricane-prone regions.

with the conclusions of [7], according to which the load factor standard value corresponds to hurricane winds with relatively short mean recurrence intervals. These recurrence intervals would be smaller if epistemic uncertainties were not assumed to be vanishingly small, as was done in our calculations.

4. Conditional wind load factors corresponding to various mean recurrence intervals—extra-tropical regions

We now turn to the estimation of wind load factors for areas of the United States in which tropical storms are not expected to occur. We use as our source of data the records of the largest daily wind speeds collected at 44 US weather stations not subjected to hurricane winds. Each set contains approximately 20 years worth of daily fastest mile wind data. We again used the de Haan estimation method, and the analysis proceeded largely as described in the previous section, with one additional step. In order to reduce possible correlations among the data due to a single storm producing strong winds for more than one day, the records were broken into intervals of eight days, and maximum speeds in each interval were identified. If maxima of adjacent intervals (denoted by I_1 and I_2) were found to be less than four days apart, the following procedure was used. Let I_1 contain the smaller of the two maxima. This maximum was replaced by the highest value in I_1 separated from the maximum in I_2 by four days or more. This procedure ensured that all data in the set were at least four days apart. The interval of four days was chosen because it represents a reasonable maximum duration of a strong windstorm. Analyses with interval lengths of four days and separation times of two days were performed and were found to produce no significant differences in the results. Previous studies [4] have shown that this procedure, while reducing the total number of data points used in the estimation process, tends to remove more low wind speeds from consideration than high ones. Thus, the resulting data set is more representative of extreme winds.

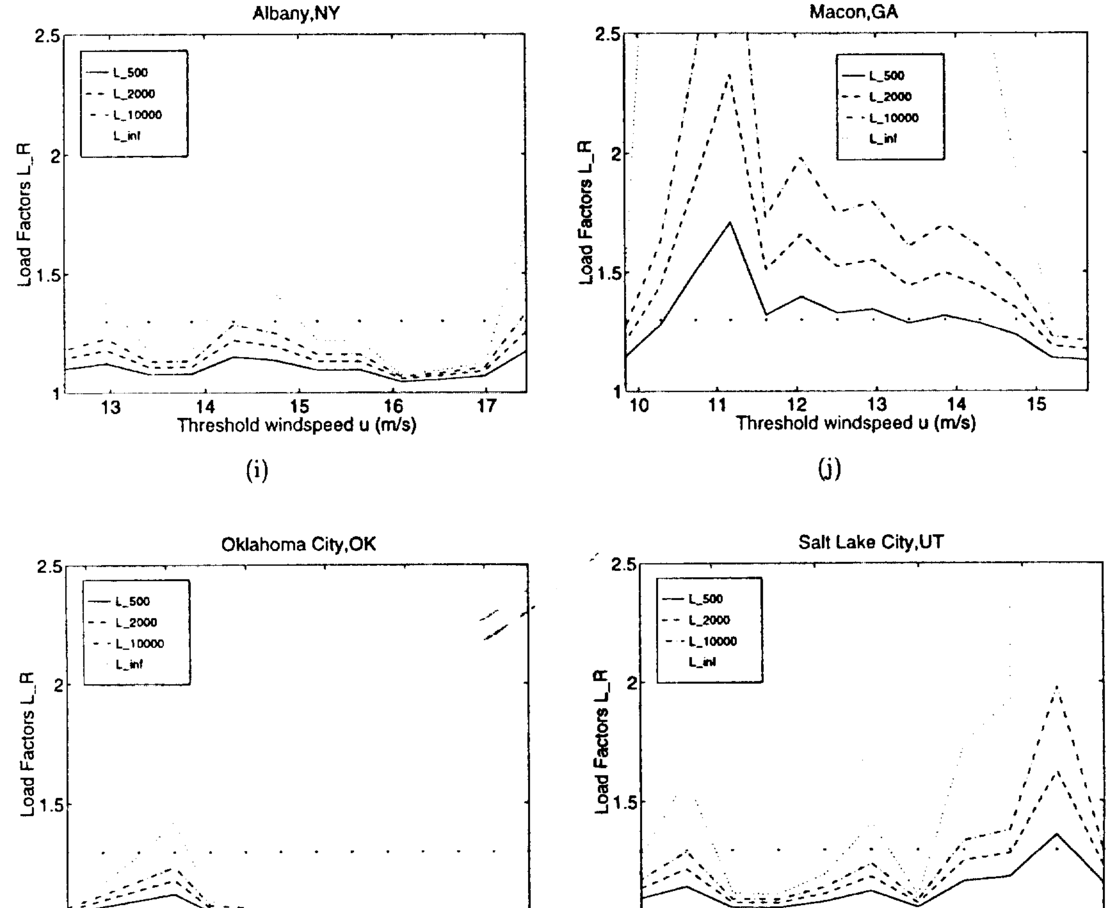


(g)

(h)

Fig. 4. Representative plots of X_R and L_R versus u for Moline, Illinois.

In Fig. 4 we show representative plots of the estimated wind speeds X_R and wind load factors L_R for data from Moline, Illinois, based on 15 yr of daily wind speeds. Note that L_R is still defined by Eq. (6) for extratropical regions, but the importance factor F is now set to 1.00 in accordance with [1], so that L_R is the conditional wind load factor. As was true for the results of the previous section, we note a downward trend for the estimated variates with lower thresholds, which we ascribe to bias associated with the inclusion of relatively weak winds. For this reason, and to reduce sampling errors due to small sample sizes associated with very high thresholds, we have plotted in Fig. 5 results only for thresholds having between 30 and 450 data points. Once again, we note that there is significant variability both among the plots and within a given plot. We may, however, state that the conditional load factor L_{500} tends to be considerably lower than was the case for hurricane-prone regions. When considering the results for all stations [15], we find this conclusion is indeed true for a significant majority of the sites. A comparison of the



(i) (j)

(k) (l)

Fig. 5. Plots of L_R versus u for four locations in extratropical regions.

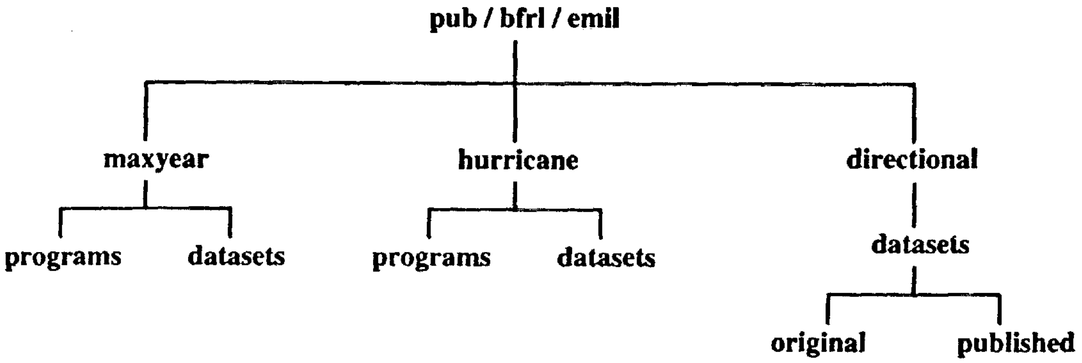


Fig. 6. Directory structure of the FTP site.

graphs of Figs 3 and 5 also suggests that the tails of the load factor distributions are considerably shorter for stations in extratropical regions than in hurricane-prone regions.

5. Conclusions

In this paper we considered structures whose design is governed by wind loading and for which wind directionality effects are negligible. We reported statistical estimates of ratios of wind loads with various long mean recurrence intervals to loads with a 50-yr mean recurrence interval. All estimates were performed by assuming that epistemic uncertainties are negligible. According to these estimates, mean recurrence intervals of the wind loads inducing design strengths obtained in accordance with the ASCE 7–95 Standard are considerably longer for structures in extratropical storm regions than for structures subjected to hurricane winds; in the latter case the estimated recurrence intervals are about 500 years if epistemic uncertainties are neglected, and can be significantly lower otherwise.

Because (1) safety levels inherent in the provisions of [1] for loads induced by hurricane winds on the one hand and extratropical winds on the other are mutually inconsistent with respect to risk, and (2) for hurricane-prone regions safety levels appear to be inadequate, future research that takes into account epistemic uncertainties is needed on the probabilistic description of wind loads in both hurricane-prone and extratropical storm regions.

Acknowledgements

The research of the first author was performed during his tenure in the NIST/NRC Postdoctoral Research Associateship Program at NIST. The participation of the second author was supported partially by the National Science Foundation (Grant No. CMS-9411642). The authors would like to thank Mr. Alan Heckert of NIST for his assistance with the data sets and programs used in this study. They would also like to thank Dr. E. Schechter for his helpful cooperation and the preparation of Fig. 1.

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Appendix. Instructions for accessing data sets and computer programs.

Electronically stored data and program files are structured as shown in Fig. 6. Note that the directories have README files with details on the contents of the directory. This information can be accessed via anonymous FTP at ftp://ftp.nist.gov; the files are located under the directory pub/bfrl/emil.