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Gust Factors Applied to Hurricane Winds

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Abstract

An important consideration in the design of structures is their response to extreme winds. This is especially true in regions affected by hurricanes. In this research, gust factors derived from hurricane wind-speed records are compared with those derived by Durst and others from open-scale records obtained in well-developed, extratropical storms. Based on records obtained from four hurricanes and 11 different recording stations, it is concluded that an upward adjustment of the Durst gust factors for the estimation of hurricane gust speeds may be in order. Anomalously high gust factors observed for hurricane winds in inland areas suggest the need for additional study. Also, it is concluded that a reexamination of the statistics of gust factors obtained from extratropical storm data would be useful in clearly identifying the appropriate probability distribution function.

1. Introduction

The design of buildings and other structures must take into consideration the wind-field climatology of the region. Both a structure as a whole and individual elements of that structure have resonance frequencies that respond to winds of varying periods. Long-span bridges, for instance, respond as a whole to changes in wind speed over periods of several minutes. Windows, shutters, and shingles, on the other hand, respond to wind gusts of much shorter duration, commonly less than 5 s. Accurate estimates of statistical maximum sustained wind speeds can be obtained from local climatological data; however, closed-scale wind recorder strip charts do not afford the temporal resolution necessary to directly estimate extreme wind gusts of short duration. Since the load placed on a structure by wind varies as the square of the wind speed, a small error in the estimation of design wind speeds is magnified, and may result in unexpected failure. The problem of wind loading is all the more critical in regions that are prone to tropical storms and hurricanes.

For these reasons it is required that the wind speed averaged over some reference period T be convertible to the probable maximum wind speed averaged over some shorter interval within that period. The usual approach is to define a gust factor, $G(t)$, averaged over several sets of observations, as the ratio of the maximum gust speed of duration t to the corresponding hourly mean speed:

$$G(t) = \frac{1}{N}\sum_{1}^{N} \hat{U}_t / \bar{U}_{3600} . \qquad (1)$$

Two widely used formulations of the gust factor are plotted in Fig. 1. The curve designated as "A" (Cook 1985) yields $G = 1.60$ for the basic conditions of duration $t = 1$ s, height above ground $z = 10$ m, and surface roughness length $z_o = 0.03$ m. Curve "B" is applicable to these same basic conditions and is based on the statistical analyses of wind-speed records carried out by Durst (1960).

Strip-chart records obtained from anemometer sites in the course of several postdisaster investigations of wind damage (Marshall 1984, 1990; Mehta et al. 1983; Sparks 1990; Sparks et al. 1991) provided an opportunity to examine the applicability of conventional gust factors to hurricane winds. The data and models used to establish the gust factor relationships described above are based on observations made in extratropical storms. An important question is whether these same gust factors are equally applicable to extreme winds associated with tropical storms and hurricanes. That is the issue this paper addresses.

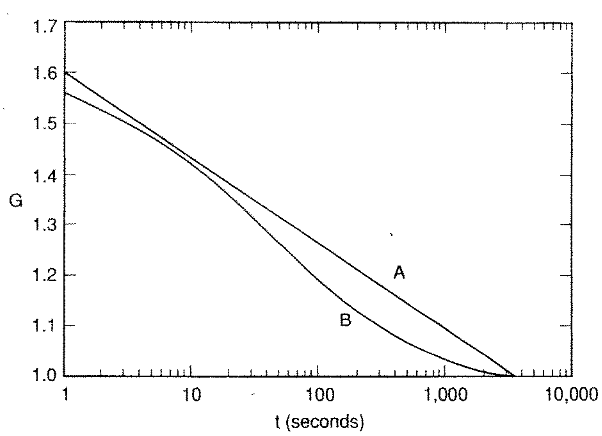

FIG. 1. Gust factors based on hourly mean wind speed ($z = 10$ m, $z_o = 0.03$ m). Curve "A" (Cook 1985) is a simplified representation of gust factors, and is used for structural design in the United Kingdom, while curve "B" (Durst 1960; ASCE 1990) is used in the United States.

TABLE 1. Hurricane wind records used in study.

Recording station	Anemometer height (m)
Hurricane Frederic	
WSO Mobile, Alabama (airport)	6.7
WSO Pensacola, Florida (regional airport)	6.7
Ingalls Shipbuilding, Pascagoula, Mississippi	10.0
Hurricane Alicia	
WSO Alvin, Texas	10.0
NWS Houston, Texas (intercontinental airport)	6.7
Hurricane Elena	
WSO Mobile, Alabama	6.7
Dauphin Island Sea Lab, Alabama	10.0
WSO Pensacola, Florida	6.7
Hurricane Hugo	
NAS Roosevelt Roads, Puerto Rico	7.0
WSFO San Juan, Puerto Rico (international apt.)	6.7
WSO Charleston, South Carolina (airport)	6.7
NWS Columbia, South Carolina	6.7
NWS Charlotte, North Carolina	10.0

2. Hurricane wind speeds

The data used in this study were obtained from four separate hurricanes as follows: Hurricane Frederic, along the Gulf coast from Florida to Mississippi in 1979; Hurricane Alicia, on the Texas Gulf coast in 1983; Hurricane Elena, along the Gulf coast from Florida to Mississippi in 1985; and Hurricane Hugo, in the Caribbean and in South Carolina in 1989. Strip-chart records were retrieved from both military and civilian stations within the immediate area of each hurricane's path. The chart speed for these recordings was about 75 mm h^{-1}, meaning that short-duration gusts appeared as spikes in the pen trace. Because of the finite response time of the anemometer and strip-chart recorder, these gusts are associated with averaging times of about 2 s. A number of recording stations were eliminated from this study because the presence of structures or trees near the anemometer site introduced wind-speed anomalies. The list of finalists for use in this study is shown in Table 1. The surface roughness lengths for all recording stations are approximately equivalent to an airport exposure (z_o = 0.03 m), except for Alvin, Texas, which is estimated to be 0.1 m.

To prepare the strip charts for analysis, each record was divided into sequential 10-min segments, and the mean speed, $\bar{U}_{600}$, and peak gust, $\hat{U}_2$, for each segment were compiled. After a preliminary analysis for the actual exposures, the data were adjusted to "standard exposure," that is, z_o = 0.03 m and z = 10 m, using the gust-factor tables prepared by Cook (1985). Typically, these adjustments reduced the measured gust factors by about 2%. Preliminary results from an investigation using open-scale records measured simultaneously at several heights in extratropical cyclone conditions closely corroborate these modifications. Even with these adjustments, however, difficulties exist in the selected datasets. Several of the stations experienced power failures during the height of the storm, producing gaps in the data or ending data collection completely. In some cases, flying debris destroyed the anemometer. The distribution of 10-min segments by station and by mean wind speed is shown in Table 2. In each case, the 10-min mean speeds were at least 5 m s^{-1}. No attempt has been made to classify the data according to station proximity to hurricane track; however, this information is available from the references cited.

Statistical analyses were carried out on all datasets for actual and adjusted exposures without regard to the level of wind speed. To focus on gust factors more

TABLE 2. Distribution of 10-min segments by station and mean speed

Recording station	Number of 10-min segments	$\bar{U}_{600}$ (m s^{-1}) => 10	=> 15	=> 25
Hurricane Frederic				
Mobile	78	78	54	11
Pensacola	78	78	46	0
Ingalls	71	70	53	9
Hurricane Alicia				
Alvin	110	93	43	0
Houston	118	71	34	0
Hurricane Elena				
Mobile	120	83	27	0
Dauphin Island	33	33	22	8
Pensacola	145	72	22	0
Hurricane Hugo				
Roosevelt Roads	78	78	58	16
San Juan	139	73	35	3
Charleston	54	40	26	4
Columbia	85	62	13	0
Charlotte	91	45	5	0
Total	1200	876	438	51

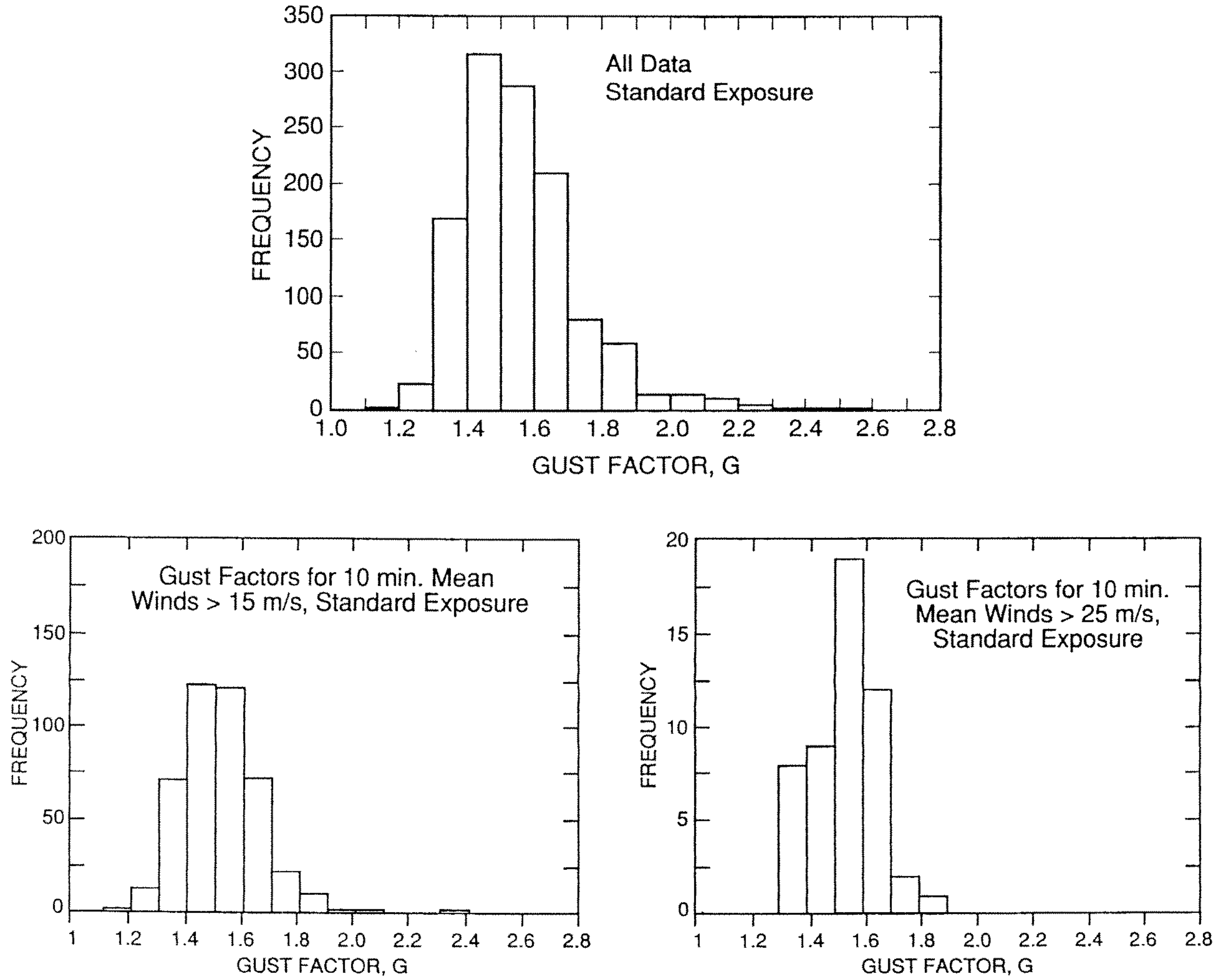

FIG. 2. Histograms of gust factors based on 10-min means, and adjusted to standard exposure. (a) all data; (b) data including wind speeds above 15 m s^{-1}; (c) data including wind speeds above 25 m s^{-1}.

directly influenced by the highest wind speeds, two additional sets of analyses were run after having discarded values of the 10-min mean speed that were under 15 and 25 m s^{-1}, respectively. A mean gust factor and standard deviation, weighted to account for station sample size, were calculated for each analysis and the results are summarized in Table 3. Histograms of gust factors, based on 10-min means and adjusted to standard exposure, are plotted in Fig. 2.

TABLE 3. Results of analysis.

Dataset	Number of 10-min segments	Mean gust factor G[1]	Standard deviation
All data Actual exposure	1200	1.587	0.151
All data Standard exposure	1200	1.556	0.148
$\bar{U}_{600}$ **=> 15 m s^{-1}** Standard exposure	438	1.517	0.108
$\bar{U}_{600}$ **=> 25 m s^{-1}** Standard exposure	51	1.536	0.090

[1] $G = \hat{U}_2/\bar{U}_{600}$

3. Durst's analysis

The next step of the investigation was to compare the computed gust factors with those determined by Durst using data that had been obtained with Dines recorders at Cardington, England. A major obstacle to such a comparison was the difference in averaging times for the reference wind speeds. The analyses reported by Durst involved departures from 10-min

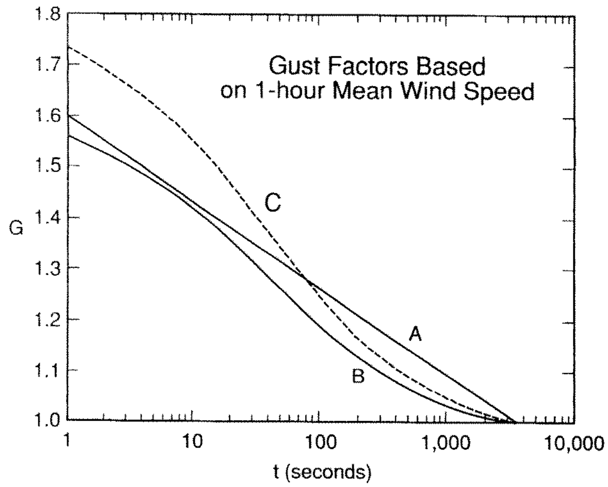

FIG. 3. A comparison of the Cook gust-factor curve (labeled as curve "A") and the Durst curve (curve "B") with a hypothesized curve for hurricane winds (curve "C").

mean speeds as well as from 1 h mean speeds, with the reported gust factors being referenced to 1-h means. The hurricane data, on the other hand, were analyzed on the basis of 10-min mean wind speeds and the corresponding 2-s maximum gust. This difficulty was resolved by transforming the Durst gust-factor relation into one based on the 10-min mean. To understand this transformation, it is necessary to describe briefly the statistical methods employed by Durst in arriving at his gust factors.

Sequential mean wind speeds $\bar{U}_t$ were obtained from open-scale anemometer records for averaging times ranging from 10 min to 0.5 s. According to Durst, for each averaging time t, the frequencies of departures from the mean, $\bar{U}_t$-$\bar{U}_{3600}$, were found to be consistent with a Gaussian distribution. Standard deviations of $(\bar{U}_t-\bar{U}_{3600})/\bar{U}_{3600}$, denoted here as SD(1 h, t), were calculated, and values of the standardized normal deviate SU associated with 1 − t/3600 were determined. Durst then obtained the gust factors, which he defined as G = 1 + [SU][SD(1 h, t)]. Values of SD(1 h, t) and the associated gust factors are summarized in Table 4.

TABLE 4. Summary of Durst's analysis and computed gust factors for various averaging times referenced to the hourly mean speed.

t(s)[1]	SD(1 h, t)[2]	t/3600	SU[3]	G[4]
600	0.065	0.167	0.9	1.06
60	0.115	0.017	2.1	1.24
30	0.132	0.0085	2.4	1.32
20	0.140	0.0056	2.55	1.56
10	0.150	0.0028	2.8	1.42
5	0.159	0.0014	3.0	1.48
0.5	0.165	0.00014	3.6	1.59

[1] t = gust duration in seconds
[2] SD = standard deviation of departures from hourly mean speed
[3] SU = number of units, standardized normal distribution
[4] G = gust factor referenced to hourly mean speed

Note that the gust factors in Table 4 are the basis for curve "B" in Fig. 1. From interpolation, SD(1 h, 2 s) = 0.162 and, since 1 − 2/3600 = 0.99944, the number of standard units associated with the estimated maximum 2-s gust is 3.26. Thus, from Durst's analysis, the gust factor for t = 2 s referenced to the hourly mean speed is G(1 h, 2 s) = 1 + (3.26)(0.162) = 1.53.

Standard deviations of gusts with respect to a 10-min mean wind speed, SD(10 min, t), were calculated using the relationship (translation theorem)

$$[\mathrm{SD}(10\ \mathrm{min}, t)]^2 = [\mathrm{SD}(1\ \mathrm{h}, t)]^2 - [\mathrm{SD}(1\ \mathrm{h}, 10\ \mathrm{min})]^2 \qquad (2)$$

from which one obtains SD(10 min, 2 s) = 0.148. For a 2-s gust and a 10-min mean wind speed, 1 − 2/600 = 0.99667 and the number of standard units to the estimated maximum 2-s gust is 2.71. The corresponding gust factor is G(10 min, 2 s) = 1 + (2.71)(0.148) = 1.40.

4. Comparison of gust factors

From Table 3, the mean 2-s gust factor based on the 10-min mean speed in hurricane winds is seen to be about 1.55, as compared to the corresponding Durst value of 1.40. In fact, more than 80% of the observed gust factors for hurricane winds were found to be larger than 1.40, as can be seen from the histogram plotted in Fig. 2. Transformation of the hurricane gust factor of 1.55 to an equivalent hourly mean reference wind speed is not straightforward. First, the standard deviations obtained from the hurricane datasets are based on the maximum gust within the 10-min interval, rather than on the 300 sequential 2-s means within that interval. Second, the stationary hourly mean does not have a physical counterpart in hurricane winds, particularly in and near the eyewall where the gust speeds are of greatest interest. One approach is to determine an "equivalent" standard deviation SD(10 min, 2 s) = (1.55 − 1)/2.71 = 0.203 for hurricane winds. Using Eq. (2) with Durst's value for SD(1 h, 10 min) = 0.065, one obtains SD (1 h, 2 s) =

0.213 and the corresponding gust factor is G(1 h, 2 s) = 1 + (3.26)(0.213) = 1.69. Curve "B" in Fig. 3 is the Durst plot, while curve "C" is a hypothesized hurricane gust-factor curve based on this research.

5. Conclusions

The results of this investigation seem to support an upward adjustment of the Durst gust factors for the estimation of gust speeds from mean wind speeds in hurricanes. There is no question that additional data are needed, especially in the eyewall region and under rainbands, where turbulence from convective processes may be significant. Inland areas may warrant a separate study; for example, data from NWS Charlotte, adjusted to standard exposure, show an anomalously high average gust factor of 1.78. But at present there are no corroborative datasets available. Finally, it would be useful to reexamine the statistics of gust factors obtained from open-scale records of wind speeds in extratropical storms to clearly identify the appropriate probability distribution function.

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