Database-assisted design, standardization, and wind direction effects

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DATABASE-ASSISTED DESIGN, STANDARDIZATION, AND WIND DIRECTION EFFECTS

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ABSTRACT: The writers present a simple methodology, developed for use in design assisted by electronic aerodynamic and climatological databases (for short, database-assisted design), that allows a realistic assessment of wind directionality effects. The methodology is applied to typical low-rise industrial steel frame buildings with a rectangular shape in plan, located in hurricane-prone areas, and results are compared with results obtained by the procedure specified in the ASCE 7-98 Standard, which, for buildings, consists of applying a blanket directionality reduction factor $K_d = 0.85$ to wind effects obtained by disregarding directionality. The results show that, for significant numbers of buildings in hurricane-prone areas, the use of the ASCE procedure can result in the underestimation of wind effects corresponding to strength design. They also show that database-assisted design for wind loads offers the potential for significantly more risk-consistent, safer, and economical design for buildings with both known and unknown orientation.

INTRODUCTION

Wind directionality effects raise design and codification issues that have received increased attention in recent decades. The British Standard BS 6399 Part 2 (1995) and the ASCE 7-98 Standard (1999) are among the standards that make explicit allowance for such effects. In this paper, the writers present a contribution to the wind directionality problem based on a methodology proposed for the development of electronic standard provisions for wind loads (Simiu et al. 1993; Whalen et al. 1998). Following a description of our approach, the writers present results obtained for a typical low-rise industrial building.

The objective of electronic provisions for wind loads is to allow the use in design of large aerodynamic databases containing time series of pressures measured in the wind tunnel at a large number of points on the building surface. If available, climatological databases can also be used. The use of databases is referred to here as database-assisted design and is accepted by the ASCE 7-98 Standard (1999, Section 6.6.2, item 3) as an alternative to the use of wind pressure tables and plots.

The development within the last 100 years of tables and plots for estimating wind pressures was due to: (1) constraints on the amount of information storage inherent in conventional, printed standards; and (2) the limited information processing capabilities inherent in the use of the slide rule, the computational tool predominantly used by structural designers until about three decades ago. Since tables and plots summarize vast amounts of information in a few numbers, they tend to distort the wind loading picture and lead to designs that are not risk-consistent. In contrast, significantly more risk-consistent design for wind loading can be accomplished if time series of pressures measured in the wind tunnel are utilized to the fullest possible extent. The acceptance of database-assisted design by the ASCE 7-98 Standard followed from recognition of this fact.

Database-assisted design for wind loads in hurricane-prone regions is based on: (1) the development of technology for recording and compactly storing simultaneous wind tunnel or full-scale pressure time histories at as many as 1,000 pressure ports over the external and internal surfaces of building models; (2) the development of climatological databases containing large numbers of simulated hurricane wind speed data (see Appendix 2); and (3) computational capabilities allowing the use of pressure and climatological databases for the fast and user-friendly calculation of bending moments, shear forces, and axial forces in wind-resistant structures (Lin and Surry 1997; Whalen and Simiu 1998; Whalen et al. 1998, 2000).

Database-assisted design for wind loading can eliminate a substantial inconsistency inherent in current structural engineering practice as applied, in particular, to low-rise structures. Owing to the use of finite elements or other computationally intensive techniques, structural analysis methods for determining stresses in structures subjected to specified wind loads can in many instances be remarkably accurate—say, to within 5% or less. On the other hand, the wind loads themselves are specified in conventional standards much more crudely: deviations of wind effects based on current standard tables and plots from their values based on wind tunnel or full-scale measurements can be as high as 25 or even 50%. The use of state-of-the-art structural analysis methods in conjunction with conventional wind loading provisions therefore provides the illusion, rather than the substance, of good engineering design; many portions of a building are overdesigned, meaning that material is wasted, while other portions may be underdesigned, meaning that they—and the entire structure—may be exposed to unnecessarily high risk of damage or failure. Therefore, the intent of the ASCE 7-98 Standard—to protect buildings from damage or failure by specifying “minimum loads”—is in many instances not realized. One example, related to the way the ASCE Standard 7-98 accounts for wind directionality, will be discussed in this paper.

The writers note, first, that database-assisted design would be more risk-consistent than design based on conventional standard provisions even if the data recorded in the aerodynamic databases covered no more than the relatively modest number of building configurations and dimensions used in past decades to develop standard tables and plots. However, assembling a comprehensive aerodynamic database is a continual process, and over time an increased database can further enhance this advantage.

Second, database-assisted design allows the structural characteristics of the structure (e.g., its influence lines) to be taken into account when calculating wind effects. This is not possible in design based on conventional standard provisions, such as those of the ASCE 7 Standard, since the latter were developed on the basis of generic, “hard-wired” structural in-
puts designed to cover a large number of different structural parameters and types. In addition to being in many cases unrealistic, such “hard-wired” inputs may be a barrier to the development of innovative designs, that is, designs that would result in, e.g., more advantageous bending moment distributions.

Third, conventional standards specify, for all frames, the loading that affects the most unfavorably loaded frame and do not account for the effect of the distance between frames upon the fluctuating part of the load. In contrast, database-assisted design automatically accounts in a realistic fashion for the loading affecting each individual frame, including the dependence of the fluctuating part of the load on distance between frames. Depending upon the degree of load redistribution among frames, knowledge of the actual wind effects on each frame may offer the potential for additional economies in design, especially if automated design and fabrication methods are used.

In this paper, the writers focus on database-assisted design as applied to the directionality issue and show that it can account for wind direction more realistically than is the case for design based on conventional standards. For buildings, the ASCE 7-98 Standard does not differentiate between directional effects on cladding or components, on the one hand, and main wind-load resisting systems, on the other, even though the dependence of the wind load upon direction may be drastically different in the two cases. The ASCE 7-98 tables and plots cannot be used to take advantage of building orientations that are favorable with respect to the directional wind climate. They do not take into account (1) the dependence of wind directionality reduction factors upon the mean recurrence interval of the wind load [Simiu and Heckert (1998); see also Appendix I]; (2) the directional aerodynamic properties of the specific type of building being designed; and (3) the directional wind climate at the location of interest. Database-assisted design for wind loads can account for each of these three factors.

The writers present typical results of calculations of bending moments at various cross sections of frames of a common type of industrial building, first by disregarding and then by accounting for wind directionality effects. The results confirm that wind directionality effects depend upon the mean recurrence interval of the wind load, a dependence that is not considered in the ASCE 7-98 Standard. They also help to assess the adequacy of the value of the directionality reduction factor $K_d = 0.85$ specified for buildings by the ASCE 7-98 provisions (pp. 24, 25, 60, 115). The writers’ estimates do not reflect sampling errors in the estimation of extreme wind speeds—due either to the relatively short length of the historical record on which climatological parameter estimates are based, or to the limited number of simulated hurricanes used in this work. Those errors constitute a separate issue dealt with in detail by Minciarelli et al. (2000). However, they do not affect the basic conclusions of our work, which would be the same even if they had been based on “true” wind speeds corresponding to various mean recurrence intervals or on larger number of simulated hurricanes. The fact that the writers obtained similar results for tens of stations is an indication to this effect.

The choice of the factor $K_d = 0.85$ is justified in the ASCE 7-98 Commentary by reference to Ellingwood et al. (1980). However, Ellingwood et al. mention this value in a tentative manner (p. 115), with no supporting material concerning its technical basis, no indication of primary or secondary sources, and no apparent intent to ascribe to it any definitive status. A tentative justification for a similar value was suggested by Davenport (1977), which is based upon statistics of winds unrelated to extremes. The writers believe that the database-assisted approach offers a useful approach for the assessment of the choice of the factor $K_d = 0.85$ in the ASCE 7 Standard and for the clear separation of directionality effects from other effects that this factor may have been intended to reflect.

**COMPUTATION METHODOLOGY**

The writers’ methodology makes use of records of measurements made on a 1/200 scale model of a typical rectangular building with overall dimensions $30.48 \times 60.96$ m, 6.096 m eave height, and a two-slope roof with slopes 1/24. The measured data consist of time series of the fluctuating pressures sampled at 400 Hz for a duration of 60 s, corresponding to about 1 h in the prototype and recorded at about 500 pressure taps distributed over the entire building envelope. Pressure records are available for each of 37 directions, i.e., $0^\circ$ (coinciding with the direction of the long axis of the building), $5^\circ$, $10^\circ$, $\ldots$, $180^\circ$ (Lin and Surry 1997; Whalen et al. 1998).

In addition, the methodology makes use of (1) the largest 1 min hurricane wind speeds at 10 m above ground in open terrain near the coastline, for each of the 16 azimuths in each of 999 simulated hurricanes (Batts et al. 1979); and (2) mean hurricane arrival rates estimated from historical records. This climatological database is recorded in National Institute of Standards and Technology public electronic files for each of about 50 locations on the Gulf and Atlantic Coasts (see Appendix II). To the writers’ knowledge, no other publicly accessible files of simulated hurricane wind speeds are available. As shown by Heckert et al. (1998) and in Simiu and Scanlan (1996, p. 117), differences between estimates of hurricane coastline wind speeds by Batts et al. (1979) on the one hand and, e.g., Vickery and Twisdale (1995) on the other are in most cases small. Note that the use of 1 min wind speeds is due to historical reasons, but such use has no effect on the basic results, since whenever necessary the 1 min data can be transformed to 1 h (or 3 s, or fastest-mile) data by employing standard micrometeorological procedures.

The wind-force resisting structure consists of steel frames hinged at the column bases and placed at 7.62 m between centers. A schematic elevation of a typical frame is shown in Fig. 1. A plan view of the building and the locations of the

![FIG. 1. Schematic View of Typical Frame, with Designation of Cross Sections](image)

![FIG. 2. Plan View of Frames, with Designation of Frames](image)
frames are shown in Fig. 2. The frames were designed by G. Harris of CECO Building Systems using standard Metal Buildings Manufacturers Association (MBMA) software (Whalen et al. 1998).

The data are processed by the program WiLDE (Whalen et al. 2000), designed for routine office use. The program calculates fluctuating time histories and peaks of moments, shear forces, and axial forces at any desired number of cross sections in any of the frames of buildings of the type just described.

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TABLE 1. 50-year and 500-year Moments (kN-m) Estimated by Accounting for (Columns 1–16) and Not Accounting for (Column 17) Wind Directionality, and Directional Reduction Factor $K_d$ (Column 18)

Calculations in Which Wind Directionality Is Taken into Account

The automated calculation sequence proceeds as follows. First, directional influence factors for bending moments are calculated. These consist, for each frame, of bending moments at various cross sections, induced by wind with a 1 m/s speed at 10 m above ground in open terrain, blowing from directions defined by $0, 5, 10, \ldots, 360^\circ$ angles. Following the calculation of the directional influence factors, the program calculates...
bending moments induced by each of the 16 directional wind speeds in each of the 999 hurricanes. For each hurricane and for each of these 16 directions, these bending moments are proportional to the respective largest directional influence factor in the half-octant corresponding to the direction of interest, times the square of the wind speed blowing in that hurricane from that direction. (A higher resolution may be used but is not necessary for the purpose of estimating moments in frames.) For example, the moment \( M_{ij}(\theta, n) \) induced at the cross section \( i \) of frame \( j \) by the wind speed \( V(\theta, n) \) blowing from direction \( \theta \) in hurricane \( n \) is

\[
M_{ij}(\theta, n) = V(\theta, n)m_{ij}(\theta)
\]

where \( m_{ij}(\theta) \) = moment influence directional factor. For each hurricane, one of the 16 directional speeds produces the maximum bending moment at the cross section being considered. In this manner, 999 largest bending moments at each cross section and for each frame are obtained. The rate of arrival of hurricanes at the assumed building locations being \( \eta/\text{year} \), it follows that the \( m \)th highest of the 999 calculated bending moments is an estimator of the moment with a \([999/(\eta \eta)]\)-year mean recurrence interval. For example, if, as is the case near Miami, the rate of arrival of hurricanes at the site of concern is 0.5/year, the 4th highest moment and the 40th highest moments are estimators of the moments with a 500-year and a 50-year mean recurrence interval, respectively. Calculations were performed for each of 16 distinct building orientations, i.e., for the cases where the long building axis is in the N, NNE, NE, . . . , NNW direction.

**Calculations That Do Not Take Wind Directionality into Account**

The calculation sequence proceeds as follows. Instead of multiplying, for each hurricane, the 16 directional influence factors by the squares of the respective directional speeds, the program multiplies the largest of the 16 directional influence factors by the square of the largest wind speed in that hurricane, regardless of that speed’s direction. Thus, 999 bending moments are obtained. The \( m \)th highest bending moment is an estimator of the bending moment with a nominal \([999/(\eta \eta)]\)-year mean recurrence interval, calculated by disregarding the effect of wind directionality. It is emphasized that the nominal mean recurrence interval differs from the actual mean recurrence interval estimated by considering the wind loading phenomenon in a physically realistic fashion, that is, by taking into account correctly the effect of wind directionality.

**RESULTS**

Typical results are shown in Table 1 for a coastal location near Miami, FL. The results pertain to three frames (frames 1, 2, and 5; see Fig. 2) and to six cross sections of those frames (Fig. 1). The results consist of wind-induced moments with nominal 50-year and 500-year mean recurrence intervals estimated by disregarding wind directionality effects (column 17 of Table 1), and wind-induced moments with 50-year and 500-year mean recurrence intervals estimated by taking wind directionality effects into account for buildings whose axis parallel to the long dimension is oriented in the NNE, NE, . . . , NW, and N direction (columns 1–16).

As an example, we consider cross section 2 (the column cross section at the column knee) of frame 1. The directional influence coefficient for moments at this cross section is shown in Fig. 3, and the estimated wind speeds with a 50-year and 500-year mean recurrence interval are shown in Fig. 4. (For some directions the winds induced by most, though not all, hurricanes are zero, owing to the directions at the site of interest of the velocities associated with the respective vortex flows; for example, if a hurricane with a northwestward translation velocity hits a site located on the hurricane translation axis, the velocity into the southeast direction will be zero. For those directions, the estimated 50-year wind speed—which, as was shown earlier, corresponds in our case to the 40th highest speed in a set of 999 wind speeds—will be zero, but the estimated 500-year speed will not be zero; see Fig. 4. This would also be true if a set of size larger than 999 were used.) For none of the 16 building orientations does the moment with a 50-year mean recurrence interval (columns 1–16) exceed 86% of the moment estimated without accounting for wind directionality (column 17). Therefore, in this case a 0.85 directionality reduction factor adequately reflects the wind directionality effect.

Let us now consider the estimated 500-year moments. The 500-year moment calculated without considering wind directionality effects is 333 kN-m. The use of the 0.85 factor specified by the ASCE 7-98 Standard to obtain the value corresponding to strength design yields 283 kN-m. The 283 kN moment is exceeded for buildings with SSE, S, SSW, SW, WSW, W, NWW, and N orientation. Therefore, according to the results of Table 1, the use of the ASCE 7-98 blanket di-
CONCLUSIONS

From the results presented in this paper, the writers conclude the following:

1. Database-assisted design makes it possible to account for wind direction in a manner that yields more risk-consistent designs than can be achieved by using conventional standard provisions for wind loads. This is the case for buildings whose orientation is not known at the time of their design and is true to an even greater extent for buildings with known orientation.

2. For buildings with either known or unknown orientation, database-assisted design provisions allow the option of differentiated designs of distinct frames within a building.

3. The use of the blanket wind direction reduction factor \( K_d = 0.85 \) specified for buildings in the ASCE 7-98 Standard may result, for as many as 10 or even 15% of the buildings designed in accordance with the standard, in the significant underestimation of wind effects corresponding to strength design. Since a similar wind reduction factor is implicit in earlier versions of the ASCE 7 Standard, the same statement holds for buildings designed in accordance with those versions. It may be argued that the term “wind directionality factor” applied to the 0.85 reduction factor in the ASCE 7-98 Standard is a misnomer, and that this factor in fact makes allowance for other, nonspecified effects. The writers believe our analysis will allow a separation of those other effects, if they exist, leading to more realistic standard provisions.

APPENDIX I. DEPENDENCE OF DIRECTIONALITY REDUCTION FACTOR ON MEAN RECURRENCE INTERVAL OF WIND SPEEDS

To understand qualitatively the dependence of the wind directionality reduction factor upon mean recurrence interval, consider the simple case of pressure at a point and assume that the wind climate is defined by extreme yearly wind speeds blowing from \( N \) directions. The pressures depend on wind speed and direction in the form

\[
p(\theta) = (\rho/2)C(\theta)x(\theta)^2
\]

where \( \rho \) is air density; \( C \) is aerodynamic pressure or force coefficient (or other wind effect coefficient independent of wind speed); \( p \) is pressure or force (or other wind effect); \( x \) is maximum yearly wind speed; and \( \theta \) is wind direction, respectively. We may base our estimates of extreme wind effects on the \( N \) directional time series

\[
P_i(\theta_j) = C(\theta_j)x_i(\theta_j)^2 \max\{C(\theta_j]\}
\]

where \( i = 1, 2, \ldots, N \) denotes the wind direction; \( j = 1, 2, \ldots, M; M = \text{number of years of record; } \max[C(\theta_j)] \text{ is the maximum of all } \theta \text{ for a specific time series of equivalent wind speeds} \]

\[
x_{eq,i} = P_i^{1/2}
\]

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

\[
p_n = (\rho/2)\max[C(\theta_j)](x_{eq,i})^2
\]

where \( \rho \) is air density; \( C \) is aerodynamic pressure or force coefficient (or other wind effect coefficient independent of wind speed); \( p \) is pressure or force (or other wind effect); \( x \) is maximum yearly wind speed; and \( \theta \) is wind direction, respectively. From the fact that the mean is larger and the standard deviation \( 48.33 > 44.33 \) and \( 3.215 < 4.726 \), respectively, from the analysis of this time series, obtain the estimate \( x_{eq,i} \), that is, the nondirectional estimate of the \( R \)-yr wind speed, where \( R \) now denotes a nominal MRI. The corresponding nondirectional estimate of the wind effect with an \( R \)-yr nominal MRI is

\[
p_n = (\rho/2)\max[C(\theta_j)]x_{eq,i}^2
\]

In other words, \( p_{n,\text{nom}} \) is obtained by following exactly the same steps used when accounting for wind directionality to estimate \( p_n \), except that in \( R \), the factor \( C(\theta) \) is replaced by the factor \( \max[C(\theta)] \). Each of the terms of the time series \( x_{eq,i} \) is equal to or larger than its counterpart in the time series \( x_{eq,i} \). Therefore, if the MRI and the nominal MRI have the same value, one might expect \( p_n < p_{n,\text{nom}} \).

We now consider, as a deliberately simple illustration, the wind speed time series \( x(\theta) \) for \( i = 1, 2, j = 1, 2, 3, 4 \): \( x(\theta) = \{52, 41, 47\} \), and \( x(\theta) = \{48, 46, 39\} \). Let us assume that the directional pressure coefficients are \( C(\theta) = 0.5 \) and \( C(\theta) = 1 \). Given these values of \( C(\theta) \), it follows from (3) that the time series of the equivalent wind speeds \( x_{eq,i} \) is identical to the time series \( x(\theta) \). Its mean and standard deviation are \( 44.33 \) and \( 4.726 \), respectively. On the other hand, using (5), we obtain the time series \( x_{eq,i} \) for \( x_{eq,i} \), with mean and standard deviation \( 48.33 > 44.33 \) and \( 3.215 < 4.726 \), respectively. From the fact that the mean is larger and the standard deviation is smaller for the time series \( x_{eq,i} \), and from typical expressions of percentage points as functions of population means and standard deviations, it follows that, for very short MRIs, \( x \) can be significantly larger than \( x_{eq,i} \), while for very long MRIs this is no longer the case. Since designs are governed by loads with large MRIs, rather than by the 50-yr loads, this result indicates that ultimate loads...
obtained by the nondirectional method (i.e., from the time series \( x^{(m)} \)) may be only marginally conservative. We note, however, that, as indicated by tens of computer runs, for long mean recurrence intervals the directional reduction factor, while being on average larger than 0.85, is less than unity, typically 0.95 or so.

The example presented in this Appendix was deliberately simple, but the reader can consider actual directional sets, either for hurricane or nonhurricane winds, that can be accessed as indicated in Appendix 2.

APPENDIX II. INSTRUCTIONS FOR ACCESSING COMPUTER PROGRAMS AND WIND SPEED DATA FILES

If you are using the Microsoft Windows FTP program, use the following commands:

First, create a new folder called ASCE-7 or a name of your choice.

You should create subdirectories named “maxyear,” “directional,” and “hurricane.”

You will also need subdirectories below each of these named “programs” and “datasets.”

This can be done from the Window Explorer program.

Click the START button on the task bar.

Click once on the RUN menu option.

Enter the command: ftp ftp.nist.gov

Click once on the RUN menu option.

You will also need subdirectories below each of these named “programs” and “datasets.”

Each directory contains a readme file, programs, and data sets.

For example, to access the readme file for the hurricane directory set the default to the hurricane directory:

ftp> cd hurricane (Do not use a “/” here because you only want to go to the next lower directory.)

ftp> dir (You should be able to see the subdirectories “maxyear,” “directional,” and “hurricane.”)

You may choose to save the readme files to a different name, such as: get readme hurricane.txt.

To download the programs and data sets you should either use the full path names or set the default directories for the local and remote computers to the corresponding directories.

The command to move multiple files between “default” directories is:

ftp> mget *

Other FTP programs for Windows offer dual directory displays for the local and remote systems, with click and drag capabilities for downloading both individual files and entire folders (directories). Anyone not familiar with command line FTP programs may find this process to be easier with one of these programs.

REFERENCES


