Influence of Surface Roughness Uncertainties on Design of Structures with Open and Suburban Exposures

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Abstract: Following an investigation into the causes of a 40% difference between estimates of structural response to wind by two reputable wind engineering laboratories, the National Institute of Standards and Technology recommended the development of nationally accepted performance standards based on sound technical methods. The development of such standards requires the use of an uncertainty quantification procedure applicable to the response of structures subjected to wind loads. As part of this development, this paper considers the effect of uncertainty in the subjective determinations of the surface roughness lengths at sites with open and suburban exposures. Extensive data developed jointly by the University of Florida, Applied Research Associates, and the National Oceanic and Atmospheric Administration (NOAA)/National Hurricane Center were used in conjunction with analytic and probabilistic tools to quantify the effect of this uncertainty on the estimation of structural response to wind. It was found that neglecting this uncertainty can result in underestimation of the response by as much as 45%. It is recommended that techniques for the objective measurement of surface roughness lengths be used for structural design purposes and that, in the absence of such measurements, the effect of uncertainty in the determination of surface roughness be accounted for in structural design. **DOI: 10.1061/AJRUA6.0001191.**

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Introduction

A landmark Skidmore, Owings & Merrill (SOM) report (SOM 2004) noted the need to develop a procedure for estimating wind load factors commensurate with building-specific uncertainty in the wind loading of structures designed by the wind tunnel method. Due to a modification— implemented in the ASCE 7-10 (ASCE 2010) and 7-16 (ASCE 2016) standards—of the original load and resistance factor design (LRFD) approach, a parallel procedure for estimating wind loads with wind load factors equal to unity and appropriate mean recurrence intervals (MRIs) is called for. Based on the SOM report and motivated by the fact that discrepancies between estimates of wind effects by independent wind engineering laboratories can exceed 40% for both high-rise and low-rise structures (SOM 2004; Fritz et al. 2008; Coffman et al 2010), the National Institute of Standards and Technology issued a recommendation aimed at developing nationally accepted performance standards based on sound technical methods (NIST 2005). The development of such standards requires, among other things, the use of an uncertainty quantification procedure applicable to the response of structures subjected to wind loads. This objective has not yet been achieved due to a lack of sufficient data about uncertainties in the various elements that determine wind loading and to the fact that uncertainty quantification methods for structural engineering applications are still in the developmental stage.

One of the elements that determines wind loading is the surface roughness lengths that characterize the terrain exposures at the meteorological site at which wind speed measurements are typically performed and at the site of the structure of interest. Valuable data developed jointly by the University of Florida, Applied Research Associates, and the National Oceanic and Atmospheric Administration (NOAA)/National Hurricane Center (Masters et al. 2010) concern the significant uncertainties inherent in the subjective estimation of roughness lengths for terrains with open and suburban exposures.

The purpose of this paper is to present an uncertainty quantification procedure aimed at examining the extent to which uncertainty in the determination of surface roughness lengths can affect the estimation of design wind loads on structures of various heights. The paper is organized as follows. Uncertainty in subjectively determined surface roughness lengths is propagated through the calculation of wind speeds with specified MRIs. Next, we consider the extent to which the uncertainty in the subjectively estimated surface roughness lengths, through the estimated wind speeds, affects the estimation of the requisite design wind loads. An example is presented that shows that the failure of current design provisions to adequately account for uncertainty in the subjective determination of surface roughness lengths can result in the underestimation of design wind loading by as much as 45%. Following a set of conclusions, the appendix provides the Python scripts used in this work and a table of notation definitions.

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Uncertainties in Wind Speeds with Specified Mean Recurrence Intervals

Consider the matrix of estimated directional wind speeds at the reference height of a structure's site. An example is shown for illustrative purposes in Eq. (1), in which $i = 1, 2, 3$ indexes storms and $j = 1, 2, 3, 4$ indexes direction, for example, 0°, 90°, 180°, and 270° clockwise from the north

$$U_{ij} = \begin{bmatrix} 34 & \mathbf{45} & 32 & 44 \\ 37 & 39 & 36 & \mathbf{51} \\ 42 & 44 & 35 & \mathbf{46} \end{bmatrix} \tag{1}$$

In this example, the wind speed from the third direction of the second storm event is $U_{i=2j=3} = 36\ \mathrm{m \cdot s^{-1}}$. In Eq. (1), the largest wind speeds in each of the three storm events are indicated in bold type. For structural design purposes it may be assumed that only the largest wind speed occurring in each storm i, $\max_j[U_{ij}]$, is of interest. Those largest speeds form a sample of data of a size equal to the number of storm events being considered; in this example the sample of data is [45, 51, 46]. The wind speed with a specified N-year MRI at the structural site of interest is then estimated by fitting to that sample—which must consist of statistically independent speeds—an appropriate probability distribution with cumulative distribution function $P(U)$. Assuming there are, on average, m storms per year, the wind speed $U(N)$ solves the equation $[P(U)]^m = 1 - 1/N$.

In the example in Eq. (1), uncertainty due to surface roughness length is masked from $U(N)$, because the wind speed in each entry is fixed and associated with a specific roughness length for the terrain at which the observations were recorded. To account for uncertainty in the roughness length at the meteorological station at which the observations were made and at the site of the structure, the approach outlined in the previous paragraph should be repeated for many Monte Carlo samples of matrices of directional wind speeds in which each matrix is a perturbed version of the original. Sources of uncertainty in $U(N)$ to be accounted for by the Monte Carlo algorithm include but are not necessarily restricted to (1) the subjective determination the roughness lengths at the meteorological station and at the structure site, and (2) the finiteness of the size of the measured data sample.

The basic relationships used to propagate uncertainty due to the subjective estimation of roughness lengths are the logarithmic law and the relation between friction velocities in two different roughness regimes. The logarithmic law has the expression

$$U(z, z_0) = 2.5 u_* \ln \frac{z}{z_0} \tag{2}$$

where u_* = friction velocity; z_0 = roughness length; and z = height above ground. For strong winds, Eq. (2) may be assumed to hold up to elevations on the order of 1 km [for details on Eq. (2) see, e.g., Simiu and Yeo 2019, pp. 22–30 and references therein]. The relationship between friction velocities u_{*1} and u_{*2} in different roughness regimes defined by roughness lengths z_{01} and z_{02} is (CEN 2005; Simiu et al. 2007)

$$u_{*1} = \left(\frac{z_{01}}{z_{02}}\right)^{0.071} u_{*2} \tag{3}$$

Data provided by Prof. F. Masters of the University of Florida (see item 9 at www.nist.gov/wind, and Fig. 1) shows that objectively determined roughness length z_0^{obj} can vary greatly for a given subjectively determined roughness length z_0^{subj}; that is, to any subjectively determined surface roughness length there correspond several objective roughness lengths, each characterized by a relative frequency. To clarify the meaning of the term *subjective*, we cite Masters et al. (2010): "Today, many modelers use aerial photographs or land use cover information to assign directionally dependent z_0 values to surface weather observation sites, which are inherently subjective ...." In contrast, objective measurements are obtained from the analysis of historical records available at weather stations using the technique described in Masters et al. (2010). The available data pertain to subjectively determined surface roughness lengths of up to about 0.3 m and are useful for buildings with suburban or open exposures. Fig. 1 shows the distribution of objectively determined roughness lengths for various subjectively determined roughness lengths. In Fig. 1, the histogram at the bottom left shows that approximately 21% of the cases for which the roughness length was subjectively determined to be $z_0^{\mathrm{subj}} = 0.1$ m had objectively determined roughness lengths $z_0^{\mathrm{obj}} < 0.04$ m. There was great variability in objectively determined surface roughness lengths for a given subjectively determined roughness length; however, we noticed that for small subjectively determined roughness lengths, the distribution of objectively determined roughness lengths was concentrated toward small values, but for large subjectively determined roughness lengths, the concentration was less pronounced (i.e., the probability distribution of objectively determined surface roughness lengths had a longer upper tail). This can be seen by comparing the upper left and lower right panels in Fig. 1.

It is necessary to introduce more intricate notation to properly define the necessary equations to propagate uncertainty due to subjectively defined roughness lengths. We describe all notation at first appearance, and it is summarized in the notation list. Let $U_{ij}(z_{\mathrm{open}}, z_{0\,\mathrm{open}\,j}^{\mathrm{obj}})$ $i = 1, 2, \ldots, i_{\max}$; $j = 1, 2, \ldots, j_{\max}$ represent the wind speed from direction j measured at height above the ground z_{open} at the meteorological site during storm i, where the true but unknown roughness length at the meteorological site is $z_{0\,\mathrm{open}\,j}^{\mathrm{obj}}$. Although we cannot know $z_{0\,\mathrm{open}\,j}^{\mathrm{obj}}$, we are able to sample $z_{0\,\mathrm{open}\,j}^{\mathrm{obj}\,r}$ from the distribution of objectively determined roughness lengths for the subjectively determined roughness length $z_{0\,\mathrm{open}\,j}^{\mathrm{subj}}$ (the subscript j indicates that the roughness lengths depend upon direction; the superscript r indicates that $z_{0\,\mathrm{open}\,j}^{\mathrm{obj}\,r}$ is a sample from the distribution of objectively determined roughness lengths corresponding to $z_{0\,\mathrm{open}\,j}^{\mathrm{subj}}$). Analogously, we define $U_{ij}(z_{\mathrm{str}}, z_{0\,\mathrm{str}\,j}^{\mathrm{obj}})$ to be the wind speed from direction j for height z_{str} at the structure for storm i, where $z_{0\,\mathrm{str}\,j}^{\mathrm{obj}}$ is the true but unknown roughness length at the structure site. We are also able to sample $z_{0\,\mathrm{str}\,j}^{\mathrm{obj}\,s}$ from the distribution of objectively determined roughness lengths for the subjectively determined roughness length $z_{0\,\mathrm{str}\,j}^{\mathrm{subj}}$. Similar to r, the superscript s indicates that $z_{0\,\mathrm{str}\,j}^{\mathrm{obj}\,s}$ is a sample from the distribution of objectively determined roughness lengths for the subjectively determined roughness length $z_{0\,\mathrm{str}\,j}^{\mathrm{subj}}$.

We have measurements of $U_{ij}(z_{\mathrm{open}}, z_{0\,\mathrm{open}\,j}^{\mathrm{obj}})$, and the first step in our uncertainty analysis is to derive an equation relating those measurements to $U_{ij}(z_{\mathrm{str}}, z_{0\,\mathrm{str}\,j}^{\mathrm{obj}})$. Using Eq. (2), it follows that for each storm i and direction j

$$u_{*ij\,\mathrm{open}}^{\mathrm{obj}} = \frac{U_{ij}(z_{\mathrm{open}}, z_{0\,\mathrm{open}\,j}^{\mathrm{obj}})}{2.5 \ln \frac{z_{\mathrm{open}}}{z_{0\,\mathrm{open}\,j}^{\mathrm{obj}}}} \quad \mathrm{i} = 1, 2, \ldots i_{\max}; \quad r = 1, 2, \ldots, r_{\max} \tag{4}$$

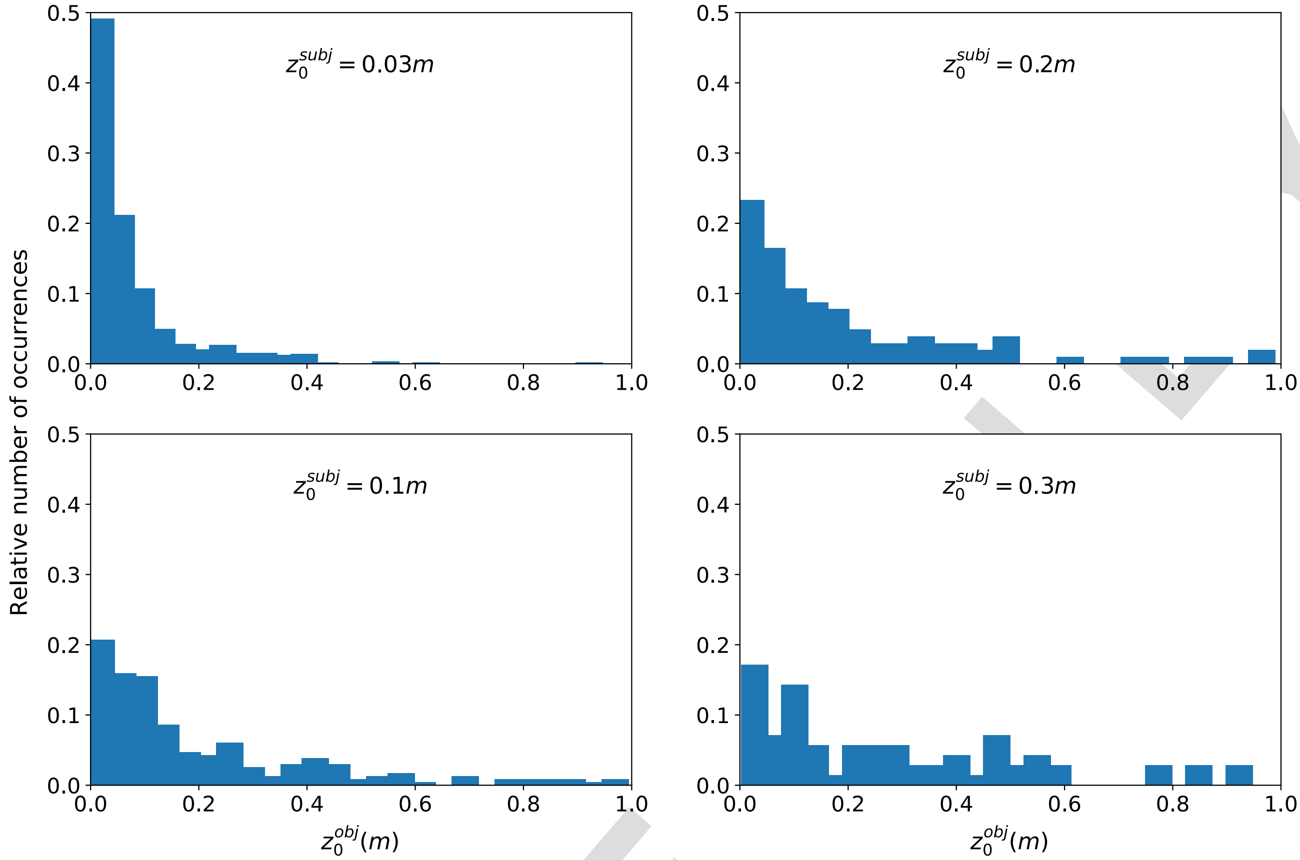

Fig. 1. Histograms showing the distribution of objectively determined roughness lengths for various subjectively determined roughness lengths. For example, it follows from the histogram at the bottom left of the figure that approximately 21% of the cases for which the roughness length was subjectively determined to be $z_0^{\rm subj} = 0.1$ m had objectively determined roughness lengths $z_0^{\rm obj} < 0.04$ m.

where $u_{*ij\,\rm open}^{\rm obj}$ = friction velocity for storm i from direction j at the meteorological site. Eqs. (2) and (3) yield

$$u_{*ij\,str}^{\rm obj} = \left(\frac{z_{0\,\rm str\,\mathit{j}}^{\rm obj}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}\right)^{0.071} u_{*ij\,\rm open}^{\rm obj} \tag{5}$$

$$U_{ij}(z_{\rm str}, z_{0\,\rm str\,\mathit{j}}^{\rm obj}) = 2.5 \quad u_{*ij\,\rm str}^{\rm obj} \ln\frac{z_{\rm str}}{z_{0\,\rm str\,\mathit{j}}^{\rm obj}} \tag{6a}$$

$$= 2.5 \ln\frac{z_{\rm str}}{z_{0\,\rm str\,\mathit{j}}^{\rm obj}} \left(\frac{z_{0\,\rm str\,\mathit{j}}^{\rm obj}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}\right)^{0.071} \quad u_{*ij\,\rm open}^{\rm obj} \tag{6b}$$

$$= 2.5 \left(\frac{z_{0\,\rm str\,\mathit{j}}^{\rm obj}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}\right)^{0.071} \quad \ln\frac{z_{\rm str}}{z_{0\,\rm str\,\mathit{j}}^{\rm obj}} \frac{U_{ij}(z_{\rm open}, z_{0\,\rm open\,\mathit{j}}^{\rm obj})}{2.5\ln\frac{z_{\rm open}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}} \tag{6c}$$

$$U_{ij}(z_{\rm str}, z_{0\,\rm str\,\mathit{j}}^{\rm obj}) = a_j \quad U_{ij}(z_{\rm open}, z_{0\,\rm open\,\mathit{j}}^{\rm obj}) \tag{7a}$$

$$a_j = \left(\frac{z_{0\,\rm str\,\mathit{j}}^{\rm obj}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}\right)^{0.071} \frac{\ln\frac{z_{\rm str}}{z_{0\,\rm str\,\mathit{j}}^{\rm obj}}}{\ln\frac{z_{\rm open}}{z_{0\,\rm open\,\mathit{j}}^{\rm obj}}} \tag{7b}$$

The parameter a_j reflects the amount by which wind speeds in open terrain at elevation $z_{\rm open}$ are modified as functions of the objective surface roughnesses $z_{0\,\rm open\,\mathit{j}}^{\rm obj}$ and $z_{0\,\rm str\,\mathit{j}}^{\rm obj}$ and measurement heights $z_{\rm open}$ and $z_{\rm str}$. It may also be used to perturb the measured wind speeds at the meteorological site to be able to account for uncertainty in the subjectively determined roughness lengths in a Monte Carlo analysis. A Monte Carlo sample, $a_{j\,rs}$, of a_j may be obtained using $z_{0\,\rm open\,\mathit{j}}^{\rm obj\,\mathit{r}}$ and $z_{0\,\rm str\,\mathit{j}}^{\rm obj\,\mathit{s}}$ sampled from the distributions of objectively determined roughness lengths given the subjectively determined roughness lengths $z_{0\,\rm open\,\mathit{j}}^{\rm subj}$ and $z_{0\,\rm str\,\mathit{j}}^{\rm subj}$, respectively. Fig. 2 is a graphic representation of Eq. (7*b*) that shows the isocontours of a_j as functions of $z_{0\,\rm open\,\mathit{j}}^{\rm obj}$ and $z_{0\,\rm str\,\mathit{j}}^{\rm obj}$ for $z_{\rm str} = 10$ m and 120 m and $z_{\rm open} = 10$ m. The darker (lighter) areas of Fig. 2 show the degree to which, given $z_{0\,\rm open}^{\rm obj}$, $z_{0\,\rm str}^{\rm obj}$, and $z_{\rm str}$, the speeds at the open site are reduced (amplified) at the structure site.

To propagate uncertainty from both the subjectively estimated roughness lengths and from sampling variability, we start with a Monte Carlo sample of each $U_{ij}(z_{\rm str}, z_{0\rm str\,\mathit{j}}^{\rm obj}) = a_{j\,rs} U_{ij}(z_{\rm open}, z_{0\,\rm open\,\mathit{j}}^{\rm obj})$ (which corresponds to the wind direction j for each storm i). We consider the Monte Carlo sample of the maximum speed in each storm i

$$U_{i\,\rm str}^{\rm obj\,\mathit{rs}} = \max_j (a_{j\,rs} U_{ij}(z_{\rm open}, z_{0\,\rm open\,\mathit{j}}^{\rm obj})) \tag{8}$$

On the left-hand side of Eq. (8), for convenience, the explicit dependence on $z_{\rm str}$, $z_{0\,\rm str\,\mathit{j}}^{\rm obj}$, and $z_{0\,\rm open\,\mathit{j}}^{\rm obj}$ is suppressed. To account for finite sampling variability, a nonparametric bootstrap resampling step, that is, sampling $U_{i\,\rm str}^{\rm obj\,\mathit{rs}}$ with replacement over the storm

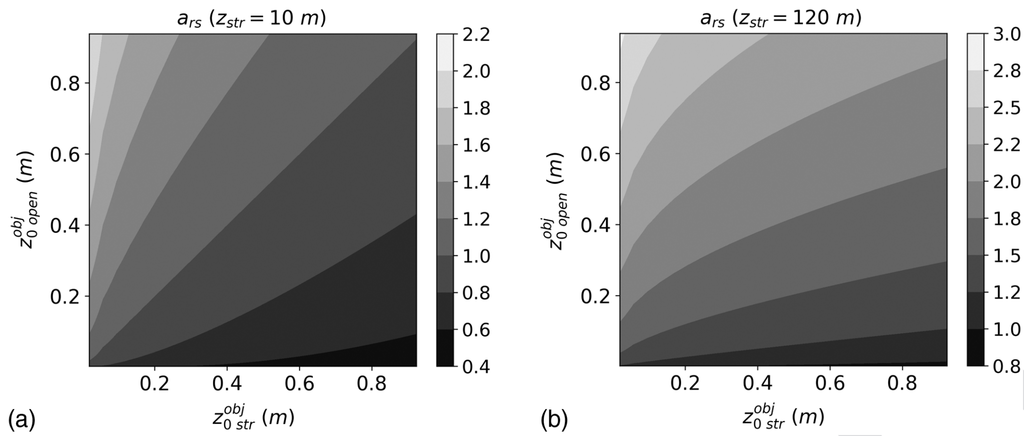

Fig. 2. Isocontours of a_{rs} for $z_{\mathrm{str}} = 10$ m and 120 m and $z_{\mathrm{open}} = 10$ m.

index i, is then performed (Efron and Tibshirani 1994). This gives a bootstrap sample of maximum wind speeds $U_{i^*\mathrm{str}}^{\mathrm{obj}\,rs}$ for the same number of storms as in the original sample. The index i^* differentiates between storm i and the bootstrap sample of storm i. The collection of wind speeds $U_{i^*\mathrm{str}}^{\mathrm{obj}\,rs}$ will likely contain some duplicate values because of resampling with replacement. This is a necessary phenomenon in the bootstrap approach to accounting for sampling variability. The Gumbel (type I) probability distribution is then fitted to the collection of $U_{i^*\mathrm{str}}^{\mathrm{obj}\,rs}$ by maximum likelihood. Taking the estimated Gumbel distribution function as P in the equation $\{P[U_{\mathrm{str}}^{\mathrm{obj}\,rs}(N)]\}^m = 1 - 1/N$, assuming m storms per year, and solving for $U_{\mathrm{str}}^{\mathrm{obj}\,rs}(N)$, produces one Monte Carlo replicate of the wind effect of interest. This entire procedure is repeated n_{MC} times to yield n_{MC} values of the wind effect of interest, the distribution of which accounts for both finite sampling variability (via the nonparametric bootstrap) and uncertainty in the subjectively estimated roughness lengths. The mean and standard deviation of that distribution are of particular interest in the following section.

The number of simulation replications n_{MC} should be large enough that the result of the simulation, that is, the distribution of the wind effect of interest, is stable. The stability of the distribution should be checked by conducting the simulation twice and comparing the two resulting distributions. If the distributions match sufficiently well, the number of simulation replications n_{MC} is sufficient; if not, it should be increased. It might be determined, for instance, from the two simulations that the two means and standard deviations differ by less than 1%. Our simulations employed these ideas.

In this work, it was assumed that the Gumbel distribution provides a reasonable fit to the Monte Carlo samples of the maximum wind speeds (maximum over storm) $U_{i\,\mathrm{str}}^{\mathrm{obj}\,rs}$; further, maximum likelihood estimation was used to estimate the parameters of the Gumbel distribution. The latter estimation could be replaced by other techniques. Examples include method of moments estimation (e.g., Simiu and Yeo 2019, p. 63) or best linear unbiased estimation (Lieblein 1974). The Gumbel distribution could also be replaced by the generalized extreme value distribution or a peaks-over-threshold model [e.g. as used in Duthinh et al. (2017)]. These last two modifications could be important if the $U_{i\,\mathrm{str}}^{\mathrm{obj}\,rs}$ values are not fitted well by a Gumbel distribution.

To recapitulate, the Monte Carlo procedure used herein can be described by the following steps:

1. Perturb a matrix of directional wind speeds by multiplication by $a_{j\,rs}$, where $a_{j\,rs}$ translates open terrain information into information at the structure site [Eq. (7)] and depends upon the Monte Carlo sampled objective roughness lengths at both locations, $z_{0\,\mathrm{open}\,j}^{\mathrm{obj}\,r}$ and $z_{0\,\mathrm{str}\,j}^{\mathrm{obj}\,s}$.
2. For each storm in the matrix of directional wind speeds, take the maximum over direction [Eq. (8)].
3. Take a statistical bootstrap sample (resample with replacement) of those maxima.
4. Fit a Gumbel distribution to the statistical bootstrap sample and use it to estimate the wind effect of interest.
5. Repeat Steps 1 through 4 many times, each time with a different sample of $a_{j\,rs}$ and statistical bootstrap sample.

Python code for carrying out this procedure is presented in the appendix, and data that can be used to construct an empirical approximation for the probability distributions representing uncertainty in $z_{0\,\mathrm{open}\,j}^{\mathrm{subj}}$ and $z_{0\,\mathrm{str}\,j}^{\mathrm{subj}}$ are available at www.nist.gov/wind.

Wind Load Factors and Design Wind Effects

The design peak wind effect with an N-year MRI, $p_{\mathrm{pk\,des}}(z_{\mathrm{str}}, N)$, is based on empirical structural reliability considerations and defined by the expression

$$p_{\mathrm{pk\,des}}(z_{\mathrm{str}}, N) = E[p_{\mathrm{pk}}(z_{\mathrm{str}}, N)]\{1 + \beta\,\mathrm{COV}[p_{\mathrm{pk}}(z_{\mathrm{str}}, N)]\} \quad (9)$$

where E and COV = mean and coefficient of variation, respectively. The expression between the brackets is called the wind load factor and is denoted by $\gamma_w(N)$, that is

$$\gamma_w(N) = 1 + \beta\mathrm{COV}[p_{\mathrm{pk}}(z_{\mathrm{str}}, N)] \quad (10)$$

The safety index β is determined by calibration against past practice, a process based on engineering judgment in which decisions are made by consensus among experienced professionals. For wind effects on typical structures the approximate value $\beta = 2.0$ was judged to be acceptable (see Ellingwood et al. 1980, pp. 5–6).

Two versions of Eqs. (9) and (10) are now considered. In the first version, the expressions $p_{\mathrm{pk\,des}}$ and p_{pk} are replaced by $p_{\mathrm{pk\,des}}^{\mathrm{std}}$ and $p_{\mathrm{pk}}^{\mathrm{std}}$, respectively. The superscript "std" indicates that the expressions for the mean and coefficient of variation of the peak design wind effect are taken to have the following forms:

$$E[p_{\mathrm{pk}}^{\mathrm{std}}(z_{\mathrm{str}}, N)] \approx cE[K_z]E[K_d]E[G(\theta_m)]E[C_{p,\mathrm{pk}}(\theta_m)]\{E[U_{\mathrm{open}}^{\mathrm{subj}}(N)]\}^2 \quad (11)$$

$$\mathrm{COV}[p_{\mathrm{pk}}^{\mathrm{std}}(z_{\mathrm{str}}, N)] \approx \{\mathrm{COV}^2(Kz) + \mathrm{COV}^2(K_d) + \mathrm{COV}^2[G(\theta_m)] + \mathrm{COV}^2[Cp, \mathrm{pk}(\theta m)] + 4\mathrm{COV}^2[U_{\mathrm{open}}^{\mathrm{subj}}(N)]\}^{1/2} \quad (12)$$

$$K_z = \left[\frac{U_{\mathrm{str}}^{\mathrm{subj}}(N)}{U_{\mathrm{open}}^{\mathrm{subj}}(N)}\right]^2 \quad (13)$$

These forms are similar to those proposed for standardization purposes by Ellingwood et al. (1980). The factor c is a constant that depends upon the type of wind effect, and θ_m denotes the aerodynamically most unfavorable direction. Ellingwood et al. (1980) proposed $\mathrm{COV}(K_z)$ approximately equal to 0.16, $\mathrm{COV}[C_{p,\mathrm{pk}}(\theta_m)]$ approximately equal to 0.12, where $C_{p,\mathrm{pk}}(\theta_m)$ denotes peak pressure coefficient, and $\mathrm{COV}[G(\theta_m)]$ approximately equal to 0.11, where $G(\theta_m)$ denotes the dynamic response factor. It may be assumed that $\mathrm{COV}(K_d)$ is approximately equal to 0.05, where K_d denotes the directionality reduction factor that accounts for the fact that the direction θ_m and the direction of the largest directional wind speeds typically do not coincide [see Habte et al. (2015)]. No explicit allowance for K_d was made in Ellingwood et al. (1980), although its effect appears to have been accounted for implicitly. According to extensive data available in Simiu et al. (1979), for nonhurricane regions it may be assumed conservatively that $\mathrm{COV}[U_{\mathrm{open}}^{\mathrm{subj}}(N)]$ is approximately equal to 0.10 to 0.12, due predominantly to sampling errors. Using these values, Eqs. (12) and (13) yield $\mathrm{COV}[p_{\mathrm{pk}}^{\mathrm{std}}(z_{\mathrm{str}}, N)]$ approximately equal to 0.31 to 0.33. By Eq. (10), with $\beta = 2$, $\gamma_{w\,\mathrm{std}} = 1.62$ to 1.66. The ASCE 7-05 (ASCE 2005) standard adopts the value $\gamma_{w\,\mathrm{std}} = 1.6$.

In the second version of Eqs. (9) and (10), the expressions $p_{\mathrm{pk\,des}}$ and p_{pk} are replaced by $p_{\mathrm{pk\,des}}^{\mathrm{obj}}$ and p_{pk}^{obj}, respectively. The superscript "obj" indicates that uncertainties of the terrain roughness lengths are accounted for by using data similar to those of Masters et al. (2010). The following expressions are used for the estimation of the expectation $E[p_{\mathrm{pk}}^{\mathrm{obj}}(z\mathrm{str}, N)]$ and the coefficient of variation $\mathrm{COV}[p_{\mathrm{pk}}^{\mathrm{obj}}(z_{\mathrm{str}}, N)]$:

$$E[p_{\mathrm{pk}}^{\mathrm{obj}}(z_{\mathrm{str}}, N)] \approx cE[K_d]E[G(\theta_m)]E[C_{p,\mathrm{pk}}(\theta_m)][E[U_{\mathrm{str}}^{\mathrm{obj}}(N)]]^2 \quad (14)$$

$$\mathrm{COV}[p_{\mathrm{pk}}^{\mathrm{obj}}(z_{\mathrm{str}}, N)] \approx \{\mathrm{COV}^2(K_d) + \mathrm{COV}^2[G(\theta_m)] + \mathrm{COV}^2[C_{p,\mathrm{pk}}(\theta_m)] + 4\mathrm{COV}^2[U_{\mathrm{str}}^{\mathrm{obj}}(N)]\}^{1/2} \quad (15)$$

The factors c, $E[K_d]$, $E[G(\theta_m)]$, and $E[C_{p,\mathrm{pk}}(\theta_m)]$ are the same in Eqs. (11) and (14). Therefore, from Eqs. (11), (13), and (14)

$$\frac{E[p_{\mathrm{pk}}^{\mathrm{std}}(z_{\mathrm{str}}, N)]}{E[p_{\mathrm{pk}}^{\mathrm{obj}}(z_{\mathrm{str}}, N)]} \approx \frac{E[K_z]\{E[U_{\mathrm{open}}^{\mathrm{subj}}(N)]\}^2}{\{E[U_{\mathrm{str}}^{\mathrm{obj}}(N)]\}^2} \approx \frac{\{E[U_{\mathrm{str}}^{\mathrm{subj}}(N)]\}^2}{\{E[U_{\mathrm{str}}^{\mathrm{obj}}(N)]\}^2} \quad (16a)$$

where the second approximation follows, because

$$E[K_z] \approx \frac{\{E[U_{\mathrm{str}}^{\mathrm{subj}}(N)]\}^2}{\{E[U_{\mathrm{open}}^{\mathrm{subj}}(N)\}^2} \quad (16b)$$

The approach described so far in this section conforms to the original load and resistance factor design approach. A modified load and resistance factor design (LRFD) approach was used in the ASCE 7-10 and 7-16 standards, wherein the wind load factor, denoted by $\gamma_{w\,\mathrm{mod}}$, where "mod" stands for "modified," was set to be unity, that is, $\gamma_{w\,\mathrm{mod}} = 1$.

The design wind load is then defined by the expression

$$p_{\mathrm{des}}^{\mathrm{mod}}(z_{\mathrm{str}}, N_{\mathrm{mod}}) = E[p_{\mathrm{pk}}(z_{\mathrm{str}}, N_{\mathrm{mod}})] \quad (17)$$

where the value of the modified MRI N_{mod} is such that

$$p_{\mathrm{pk\,des}}^{\mathrm{mod}}(z_{\mathrm{str}}, N_{\mathrm{mod}}) = p_{\mathrm{pk\,des}}(z_{\mathrm{str}}, N) \quad (18)$$

The following relationship was used to obtain the value of N_{mod} specified in the ASCE 7-10 and ASCE 7-16 standards:

$$N_{\mathrm{mod}} = 0.00228 \exp\{[3.6 + \ln(12N)]\sqrt{\gamma_w}\} \quad (19)$$

for more details, see the section titled, "Return Periods for Design with a Wind Load Factor of 1.0" in Vickery et al. (2010) and Eqs. (13) and (14) therein]. For example, let (1) $N = 50$ years and γ_w be approximately 1.6; and (2) $N = 100$ years and γ_w be approximately 1.6. Eq. (19) yields N_{mod} equal to approximately 700 years and N_{mod} equal to approximately 1,700 years for cases (1) and (2), respectively, as in the ASCE 7-10 and 7-16 Standards. Because they depend on γ_w of approximately 1.6, which depends, in turn, on subjectively estimated surface roughness lengths, these values are also based on subjectively estimated surface roughness lengths. The effects of basing the estimation of N_{mod} on objectively estimated roughness lengths could be significant, as will be shown in the following section. We now consider an example mainly devoted to comparing results yielded by Eqs. (11) and (12) on the one hand and Eqs. (14) and (15) on the other hand, using for both cases the same values of the means and standard deviations of K_d, $G(\theta_m)$, and $C_{p,\mathrm{pk}}(\theta_m)$ and the same safety index $\beta = 2$.

Example

We analyze a 30-storm record of simulated peak hurricane mean hourly wind speeds $U_{i\,\mathrm{open}}^{\mathrm{obj}} = \max_j\{U_{ij}(z_{\mathrm{open}}, z_{0\,\mathrm{open}}^{\mathrm{obj}}),\ i = 1, 2, 3, \ldots, 30$, at $z_{\mathrm{open}} = 10$ m over terrain with the subjectively determined open exposure $z_{0\,\mathrm{open}}^{\mathrm{subj}} = 0.03$ m. In this example, we suppress dependence on the direction j; that is, we assume that the terrain exposures are the same in all directions. The location being considered is Miami, Florida (milepost 1,450), where the estimated storm arrival rate is 0.56/year (see www.nist.gov/wind); therefore, a 50-year MRI corresponds to 50 years $\times$ 0.56/year = 28 storms. The record consists of the estimated largest speeds in storms 1 through 30 (see the last column in the listing of the speeds in www.nist.gov/wind); the sample mean, standard deviation, and coefficient of variation are $E[U_{i\,\mathrm{open}}^{\mathrm{obj}}] = 20.72\ \mathrm{m \cdot s^{-1}}$, $\mathrm{SD}[U_{i\,\mathrm{open}}^{\mathrm{obj}}] = 6.87\ \mathrm{m \cdot s^{-1}}$, and $\mathrm{COV}[U_{i\,\mathrm{open}}^{\mathrm{obj}}] = 0.33$. By taking $z_{0\,\mathrm{open}}^{\mathrm{subj}} = 0.03$ m and $z_{0\,\mathrm{str}}^{\mathrm{subj}} = 0.3$ m and applying Eq. (7) to the 30 wind speeds $U_{i\,\mathrm{open}}^{\mathrm{obj}}$, we arrive at the results in Table 1.

Next, estimated wind effects $U_{\mathrm{str}}^{\mathrm{subj}}$ ($N = 50$ years) and corresponding standard deviations are obtained by the Monte Carlo procedure as described previously in this paper, but instead of sampling from the appropriate distribution of objectively determined

Table 1. Mean, standard deviation, and coefficient of variation of $U_{i\,\mathrm{str}}^{\mathrm{subj}}$ by applying Eq. (7) to the 30 values of $U_{i\,\mathrm{open}}^{\mathrm{obj}}$ assuming $z_{0\,\mathrm{open}}^{\mathrm{subj}} = 0.03$ m and $z_{0\,\mathrm{str}}^{\mathrm{subj}} = 0.3$ m

z_{str} (m)	E $[U_{i\,\mathrm{str}}^{\mathrm{subj}}]$ $(\mathrm{m \cdot s^{-1}})$	SD $[[U_{i\,\mathrm{str}}^{\mathrm{subj}}]](\mathrm{m \cdot s^{-1}})$	COV $[U_{i\,sr}^{\mathrm{subj}}]$
10	14.73	4.88	0.33
20	17.64	5.85	0.33
40	20.55	6.81	0.33
120	25.17	8.34	0.33

Table 2. Mean, standard deviation, and coefficient of variation of $U_{\mathrm{str}}^{\mathrm{subj}}$ $(N = 50$ years) as obtained by Monte Carlo simulation with $z_{0\,\mathrm{open}}^{\mathrm{subj}} = 0.03$ m and $z_{0\,\mathrm{str}}^{\mathrm{subj}} = 0.3$ m

z_{str} (m)	E $([U_{\mathrm{str}}^{\mathrm{subj}}$ $(N = 50$ years)] $(\mathrm{m \cdot s^{-1}})$	SD $[U_{\mathrm{str}}^{\mathrm{subj}}$ $(N = 50$ years)] $(\mathrm{m \cdot s^{-1}})$	COV $[U_{\mathrm{str}}^{\mathrm{subj}}$ $(N = 50$ years)]
10	25.4	2.1	0.08
20	30.50	2.5	0.08
40	35.60	3.00	0.08
120	43.50	3.70	0.09

roughness lengths, the roughness lengths are assumed to be fixed at their subjectively determined values 0.03 and 0.3 for the meteorological site and structure, respectively. We obtain the values in Table 2. These are differentiated from the wind effects $U_{\mathrm{str}}^{\mathrm{obj}}(N)$ described in the Monte Carlo procedure by the superscript "subj" to indicate that uncertainty due to the subjectively estimated roughness lengths is not included.

The wind effects $U_{\mathrm{str}}^{\mathrm{obj}}(N = 50 \text{ years})$ at $z_{\mathrm{str}} = 10$ m, 20 m, 40 m, and 120 m over terrain with $z_{0\,\mathrm{open}}^{\mathrm{subj}} = 0.03$ m and $z_{0\,\mathrm{str}}^{\mathrm{subj}} = 0.30$ m are shown in Table 3.

With reference to the second column of Table 3, the reader may be curious why accounting for uncertainty in the estimated surface roughness lengths has a consequential impact on the mean value of the wind effect of interest. From Fig. 3, as expected, accounting for uncertainty in the surface roughness lengths increases the spread of the distribution of wind effects. This can be seen by comparing the top panel of Fig. 3 to the bottom panel. However, it also skews the distribution toward higher wind effects, which then pulls the mean toward those higher values. This can be seen in the bottom panel of Fig. 3.

Consider now a comparison of the subjectively and objectively estimated wind effects implied by the wind speeds with 50-year MRI from Tables 2 and 3. It follows from Eqs. (9)–(12) and (14)–(16) that

$$\frac{p_{\mathrm{pk\,des}}^{\mathrm{std}}(z_{\mathrm{str}}, N = 50 \text{ years})}{p_{\mathrm{pk\,des}}^{\mathrm{obj}}(z_{\mathrm{str}}, N = 50 \text{ years})} \approx \frac{\{E[U_{\mathrm{str}}^{\mathrm{subj}}(N = 50 \text{ years})]\}^2}{\{E[U_{\mathrm{str}}^{\mathrm{obj}}(N = 50 \text{ years})]\}^2} \frac{\gamma_{w\,\mathrm{std}}}{\gamma_{w\,\mathrm{obj}}} = R(z_{\mathrm{str}}, N = 50 \text{ years}) \quad (20)$$

may be defined to be the wind loading underestimation ratio associated with neglecting uncertainty in subjectively determined roughness lengths. Consider the case $z_{\mathrm{str}} = 10$ m. We have

$$\frac{\{E[U_{\mathrm{str}}^{subj}(N = 50 \text{ years})]\}^2}{\{E[U_{\mathrm{str}}^{\mathrm{obj}}(N = 50 \text{ years})]\}^2} = \left(\frac{25.4}{29.8}\right)^2 = 0.73 \quad (21)$$

From Eq. (15), with $\mathrm{COV}[C_{p,\mathrm{pk}}(\theta_m)] = 0.12$, $\mathrm{COV}[G(\theta_m)] = 0.11$, $\mathrm{COV}(K_d) = 0.05$, and $\mathrm{COV}[U_{\mathrm{str}}^{\mathrm{obj}}(N = 50 \text{ years})] = 0.27$ (see Table 3), it follows that COV $[p_{\mathrm{pk}}^{\mathrm{obj}}$ $(z_{\mathrm{str}} = 10$ m, $N = 50$ years)] $= \{0.05^2 + 0.11^2 + 0.12^2 + 4 \times 0.27^2\}^{1/2} = 0.57$. The

Table 3. Mean, standard deviation, and coefficient of variation of $U_{\mathrm{str}}^{\mathrm{obj}}$ $(N = 50$ years)

z_{str} (m)	E $([U_{\mathrm{str}}^{\mathrm{obj}}$ $(N = 50$ years)] $(\mathrm{m \cdot s^{-1}})$	SD $[U_{\mathrm{str}}^{\mathrm{obj}}$ $(N = 50$ years)] $(\mathrm{m \cdot s^{-1}})$	COV $[U_{\mathrm{str}}^{\mathrm{obj}}$ $(N = 50$ years)]
10	29.80	7.90	0.27
20	35.10	8.30	0.24
40	40.20	8.80	0.22
120	48.20	9.50	0.20

wind load factor corresponding to $\beta = 2$ is $\gamma_{w\,\mathrm{obj}} = 1 + \beta$ COV $[p_{\mathrm{pk}}^{\mathrm{obj}}$ $(z_{\mathrm{str}}, N = 50$ years)] $= 1 + 2 \times 0.57 = 2.14$. Because, as was shown in the previous section, $\gamma_{w\,\mathrm{std}} = 1.6$, $\gamma_{w\,\mathrm{std}}/\gamma_{w\,\mathrm{obj}} = 1.6/2.14 = 0.75$. It follows that $R(z_{\mathrm{str}} = 10 \text{ m}, N = 50 \text{ years}) = 0.73 \times 0.75 = 0.55$. Therefore, at a height of 10 m at the structure site, the design peak wind effect with a 50-year MRI, $p_{\mathrm{pk\,des}}(10$ m, $N = 50$ years), obtained by using the wind load factor specified by the ASCE 7-05 standard in conjunction with a 50-year design wind speed, is 45% lower than its counterpart obtained by taking into account uncertainties in surface roughness lengths.

Note that the ratio R remains the same if the standard peak design effect is replaced by its modified counterpart consistent with the ASCE 7-10 and ASCE 7-16 standards, which specify, for most structures, a wind load factor equal to unity in conjunction with a 700-year design wind speed. In this case, by virtue of Eq. (19), the modified MRI N_{mod}, instead of being approximately 700 years (corresponding to a wind load factor of 1.6), is $N_{\mathrm{mod}} = 0.00228 \exp\{[3.6 + \ln(12 \times 50)]\sqrt{2.14}\} = 5{,}120$ years, corresponding to an objectively estimated wind load factor of 2.14.

Following the steps that led to Eq. (20), we obtain the following values of R at other heights: $z_{\mathrm{str}} = 20$ m, $R(50 \text{ years}) = 0.60$; $z_{\mathrm{str}} = 40$ m, $R(50 \text{ years}) = 0.65$; and $z_{\mathrm{str}} = 120$ m, $R(50 \text{ years}) = 0.70$. The underestimation of design wind loads for these values is 40%, 35%, and 30%, respectively. Similar results are obtained for 30 wind speed samples at mileposts 500, 1,450, 1,950, and 2,150 for both 50-year and 100-year MRIs.

For a special category of buildings of exceptional importance, McAllister et al. (2018) proposed a design wind load with a modified MRI $N_{\mathrm{mod}} = 3{,}000$ years based on subjectively determined surface roughness lengths. However, even if $N_{\mathrm{mod}} = 5{,}120$ years based on subjectively determined surface roughness lengths was specified for design purposes, the objective counterpart of this modified MRI would be 700 years. To the specified $N_{\mathrm{mod}} = 3{,}000$ years based on subjectively determined surface lengths there would correspond an objective counterpart of less than 700 years rather than 3,000 years.

Interpretation and Recommendations

We offer the following physical interpretation of the results obtained in this example. For lower values of the surface roughness length, the retardation of the flow decreases; this means that the velocity at the structure site increases. For example, for $z_{0\,\mathrm{str}}^{\mathrm{subj}} = 0.20$ m the fact that, predominantly, $z_{0\,\mathrm{str}}^{\mathrm{obj}} < z_{0\,\mathrm{str}}^{\mathrm{subj}}$ (Fig. 1) results in stronger winds acting on the structure than would be the case if the structural design were based on the value $z_{0\,\mathrm{str}}^{\mathrm{subj}}$. This explanation provides insight into why failure to account for the uncertainties inherent in subjective surface length determinations can significantly underestimate design wind speeds.

We have argued that the use of data obtained by Masters et al. (2010) shows that failure to account for the uncertainties inherent in

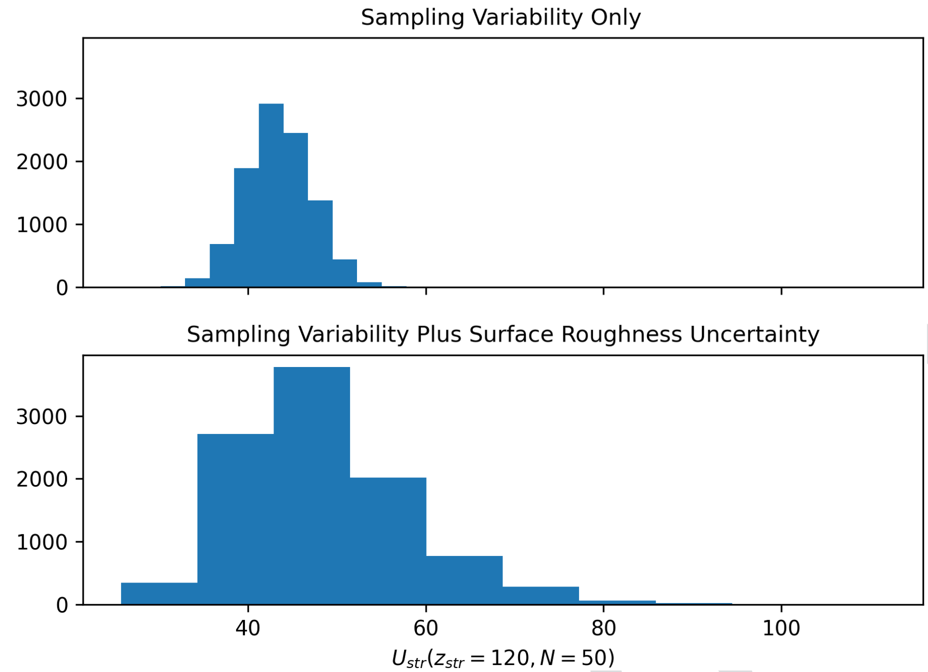

Fig. 3. Histograms of the distribution of the wind effect of interest considering sampling variability only, and sampling variability plus uncertainty in the estimated surface roughness lengths.

subjectively determined roughness lengths can result in significant underestimation of wind loads acting on structures sited in terrain with open and suburban exposures, with adverse consequences from the point of view of structural safety and community resilience under powerful windstorms. We submit that this can be corrected by effecting two changes in the provisions of the ASCE 7 standard. Before the inception of a construction project, measurements of the relevant surface roughness lengths should be performed so that no resort to their subjective estimation is necessary. For effective procedures for performing such measurements, see, for example, Masters et al. (2010) if historical data are available and Simiu and Yeo (2019) (Example 2.14, p. 35) if historical data are not available but a limited number of turbulence intensity data can be obtained. If only subjective data are available, standard provisions should be developed that account for the uncertainties inherent in those data.

Conclusions

The effects of uncertainty in subjective determinations of surface roughness lengths on the estimation of design wind loads for structures with open and suburban exposures have not been considered in the past due to a lack of relevant data and methods. This paper described tools for propagating uncertainties in determinations of surface roughness lengths and applied them using comprehensive data produced jointly by the University of Florida, Applied Research Associates, and the National Hurricane Center. Estimates of design wind loads were made using wind load factors as defined in the original load and resistance factor design approach in conjunction with wind speeds with mean recurrence intervals on the order of 100 years. A typical example was presented; it was found that failure to adequately account for uncertainty in the subjective determination of surface roughness lengths resulted in estimates of design wind loads lower than their counterparts based on objectively determined roughness lengths by 45%, 40%, 35%, and 30% for 10-, 20-, 40-, and 120-m elevations above the surface, respectively. This finding was shown to be equally applicable to estimates of design wind loads obtained using a wind load factor equal to unity in conjunction with wind speeds with MRIs on the order of 1,000 years as specified in recent versions of the ASCE 7 Standard.

For reliability estimates to be useful, uncertainty quantification procedures applicable to engineering structures need to be developed for all factors that determine wind effects. Results of such procedures will enable the determination of the reasons for the large discrepancies noted in publicly available interlaboratory comparisons—for example, those reported in SOM (2004) and Fritz et al. (2008)—and the development of standard provisions resulting in safer, better performing structures.

Appendix. Python Code for Monte Carlo Procedure

Function Definitions

```
import numpy as np
import scipy.optimize
import pandas as pd
import numpy as np
```

```
def ll(theta, x):
    mu = theta[0]
    lbeta = theta[1]
    beta = np.exp(lbeta)
    n = len(x)
    term1 = n*lbeta
    term2 = (1/beta)*(np.sum(x) - n*mu)
    term3 = np.sum(np.exp((mu - x)/beta))
    return term1+term2+term3
def gumbel_mle(x):
    beta_hat = np.sqrt(6)/np.pi*np.std(x)
    mu_hat = np.mean(x) - beta_hat*np.euler_gamma
    lbeta_hat = np.log(beta_hat)
    mle = scipy.optimize.minimize(ll, np.array([mu_hat, lbeta_hat]),
                                  args=(x))
    tmp = mle.x.copy()
    mle_est = np.array([tmp[0], np.exp(tmp[1])])
    tmp = mle.hess_inv.copy()
    mle_vcov = np.array([[tmp[0, 0], tmp[0, 1]*mle_est[1]],
                         [tmp[0, 1]*mle_est[1], tmp[1, 1]*mle_est[1]**2]])
    return mle_est, mle_vcov
def gumbel_return_value(x, m, N):
    mle_est, mle_vcov = gumbel_mle(x)
    mu = mle_est[0]
    beta = mle_est[1]
    term1 = beta*np.log(m)
    term3 = beta*np.log(np.log(N) - np.log(N - 1))
    return term1 + mu - term3
def a_mult(z0obj_str, z0obj_open, z_str, z_open):
    term1 = (z0obj_str/z0obj_open)**0.071
    term2num = np.log(z_str/z0obj_str)
    term2denom = np.log(z_open/z0obj_open)
    return term1*(term2num/term2denom)
def boot_rep(wind_speeds, m, N,
             z0obj_str, z0obj_open,
             z_str, z_open,
             z0subj_str, z0subj_open):
    wind_speeds_star = np.random.choice(wind_speeds,
                                        wind_speeds.shape[0])
    a_subj = a_mult(z0subj_str, z0subj_open, z_str, z_open)
    N_year_star = gumbel_return_value(a_subj*wind_speeds_star,
                                      m, N)
    z0obj_str_star = np.random.choice(z0obj_str, 1)
    z0obj_open_star = np.random.choice(z0obj_open, 1)
    a_star = a_mult(z0obj_str_star, z0obj_open_star,
                    z_str, z_open)
    N_year_star_a = gumbel_return_value(a_star*wind_speeds_star,
                                        m, N)
    return [N_year_star, N_year_star_a]
```

Script to Read Data and Generate Monte Carlo Samples

```
# Constants to define for the simulation
z0subj_str = 0.3
z0subj_open = 0.03
z_str = 10
z_open = 10
N = 50
windspeed_file = './milepost1450.txt'
n_boot = 10000
# ' +' is the regular expression for one or more spaces
wind_speeds = pd.read_table(windspeed_file,
                            skiprows=3, header=None, sep=' +')
# the factor is to translate from 1-min speeds in knots to mean hourly
# WSP in m/s
wind_speeds = 0.447*1.15*(1.0/1.24)*wind_speeds.iloc[0:30, -2].to_numpy()
with open(windspeed_file, 'r') as file:
```

```
    for i in range(3):
        storm_rate = file.readline()
storms_per_year = float(storm_rate.split()[0])
z_vals = pd.read_csv('./tidy_z0_data.csv')
obj_not_nan = np.logical_not(np.isnan(z_vals.Objective))
vis_not_nan = np.logical_not(np.isnan(z_vals.Visual))
z_vals = z_vals[np.logical_and(obj_not_nan, vis_not_nan)]
z0obj_str = z_vals.Objective[z_vals.Visual == z0subj_str]
z0obj_open = z_vals.Objective[z_vals.Visual == z0subj_open]
N_year_boot = [boot_rep(wind_speeds, storms_per_year, N,
                        z0obj_str, z0obj_open,
                        z_str, z_open,
                        z0subj_str, z0subj_open)
               for i in range(n_boot)]
N_year_boot = np.array(N_year_boot)
```

Data Availability Statement

All data, models, or code generated or used during the study are available in a repository online (www.nist.gov/wind) in accordance with funder data retention policies.

Notation

The following symbols are used in this paper:

a_{jrs} = Monte Carlo sample of a_j;
a_j = amount by which wind speeds in open terrain at elevation z_{open} are modified as functions of objective surface roughnesses $z_{0\,\text{open}\,j}^{\text{obj}}$ and $z_{0\,\text{str}\,j}^{\text{obj}}$ and measurement heights z_{open} and z_{str};
$C_{p,\text{pk}}(\theta_m)$ = peak pressure coefficient;
$G(\theta_m)$ = dynamic response factor;
$i = 1, 2, \ldots, i_{\max}$ = storm index;
$j = 1, 2, \ldots, j_{\max}$ = direction index;
K = directionality reduction factor;
$p_{\text{pk des}}(z_{\text{str}}, N)$ = design peak wind effect with an N-year MRI;
$p_{\text{pk}}(z_{\text{str}}, N)$ = peak wind effect with an N-year MRI;
$R(z_{\text{str}}, N)$ = wind loading underestimation ratio associated with neglecting uncertainty in subjectively determined roughness lengths;
r and s = superscripts indicating Monte Carlo samples;
$U_{ij}(z_{\text{open}}, z_{0\,\text{open}\,j}^{\text{obj}})$ = wind speed for storm i from direction j at height z_{open} for surface roughness length $z_{0\,\text{open}\,j}^{\text{obj}}$;
$U_{ij}(z_{\text{str}}, z_{0\,\text{str}\,j}^{\text{obj}})$ = wind speed for storm i from direction j at height z_{str} for surface roughness length $z_{0\,\text{str}\,j}^{\text{obj}}$;
$U_{i\,\text{str}}^{\text{obj}\,rs}$ = Monte Carlo sample of the maximum wind speed taken over direction j;
$U_{i^*\text{str}}^{\text{obj}\,rs}$ = bootstrap sample of the Monte Carlo sample of the maximum wind speed taken over direction j;
$U_{\text{open}}^{\text{subj}}(N)$ = wind effect at the meteorological site with N-year MRI assuming the subjectively determined surface roughness length;
$U_{\text{str}}^{\text{obj}\,rs}(N)$ = Monte Carlo sample of the true wind effect at the structure with N-year MRI;
$U_{\text{str}}^{\text{subj}}(N)$ = wind effect at the structure with N-year MRI assuming the subjectively determined surface roughness length;
$u_{*ij\,\text{open}}^{\text{obj}}$ = friction velocity for storm i from direction j at the meteorological site;
$u_{*ij\,\text{str}}^{\text{obj}}$ = friction velocity for storm i from direction j at the structure;
z_{open} = Height of wind speed measurements at the meteorological site;
$z_{0\,\text{open}\,j}^{\text{obj}}$ = true surface roughness length at the meteorological site for direction j;
$z_{0\,\text{open}\,j}^{\text{obj}\,r}$ = Monte Carlo sample of the surface roughness length at the meteorological site from direction j given $z_{0\,\text{open}\,j}^{\text{subj}}$;
$z_{0\,\text{open}\,j}^{\text{subj}}$ = subjectively determined surface roughness length at the meteorological site for direction j;
$z_{0\,\text{str}\,j}^{\text{obj}}$ = true surface roughness length at the structure for direction j;
$z_{0\,\text{str}\,j}^{\text{obj}s}$ = Monte Carlo sample of the surface roughness length at the meteorological site from direction j given $z_{0\,\text{str}\,j}^{\text{subj}}$;
$z_{0\,\text{str}\,j}^{\text{subj}}$ = subjectively determined surface roughness length at the structure for direction j;
z = height of structure;
$\gamma_w(N)$ = wind load factor; and
θ_m = aerodynamically most unfavorable direction.

References

ASCE. 2005. *Minimum design loads for buildings and other structures*. Reston, VA: ASCE.

ASCE. 2010. *Minimum design loads for buildings and other structures*. Reston, VA: ASCE.

ASCE. 2016. *Minimum design loads for buildings and other structures*. Reston, VA: ASCE.

CEN (European Committee for Standardization). 2005 *Comite Europeen de Normalisation*. EN 1991-1-4. Brussels, Belgium: CEN.

Coffman, B. J., J. A. Main, D. Duthinh, and E. Simiu. 2010. "Wind effects on low-rise metal buildings: Database-assisted design versus ASCE 7-05 standard estimates." *J. Struct. Eng.* 136 (6): 744–748.

Duthinh, D., A. L. Pintar, and E. Simiu. 2017. "Estimating peaks of stationary random processes: A peaks-over-threshold approach." *ASCE-ASME J. Risk Uncertainty Eng. Syst. Part A: Civ. Eng.* 3 (4): 04017028. https://doi.org/10.1061/AJRUA6.0000933.

Efron, B., and R. J. Tibshirani. 1994. *An introduction to the bootstrap*. Boca Raton, FL: CRC Press.

Ellingwood, B., T. V. Galambos, J. G. MacGregor, and C. A. Cornell. 1980. *Development of a probability-based load criterion for American national standard A58: NBS special publication 577*. Washington, DC: National Bureau of Standards.

Fritz, W., B. Benkiewicz, B. Cui, O. Flamand, T. Ho, H. Kikitsu, C. Letchford, and E. Simiu. 2008. “International comparison of wind tunnel estimates of wind effects on low-rise buildings: Test related uncertainties.” *J. Struct. Eng.* 134 (12): 1887–1890. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:12(1887).

Habte, E., A. Chowdhury Gan, D. Yeo, and E. Simiu. 2015. “Wind directionality factors for nonhurricane and hurricane-prone regions.” *J. Struct. Eng.* 141 (8): 04014208. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001180.

Lieblein, J. 1974. *Efficient methods of extreme-value methodology.* NBSIR-602. Washington, DC: National Bureau of Standards.

Masters, F. J., P. J. Vickery, P. Bacon, and E. N. Rappaport. 2010. “Toward objective, standardized intensity estimates from surface wind speed observations.” *Bull. Am. Meteorol. Soc.* 91 (12): 1665. https://doi.org/10.1175/2010BAMS2942.1.

McAllister, T., N. Wang, and B. R. Ellingwood. 2018. “Risk-informed mean recurrence intervals for update wind maps in ASCE 7-16.” *J. Struct. Eng.* 144 (5). https://doi.org/10.1061/(ASCE)ST.1943-541X.0002011.

NIST. 2005. “WTC disaster study recommendations.” https://www.nist.gov/topics/disaster-failure-studies/world-trade-center-disaster-study/recommendations.

Simiu, E., M. J. Changery, and J. J. Filliben. 1979. *Extreme wind speeds at 129 stations in the contiguous United States: Building science series 118*. Washington, DC: National Bureau of Standards.

Simiu, E., P. Vickery, and A. Kareem. 2007. “Relation between Saffir–Simpson hurricane scale wind speeds and peak 3-s gust speeds over open Terrain.” *J. Struct. Eng.* 34 (5): 1043–1045. https://doi.org/10.1061/(ASCE)0733-9445(2007)133:7(1043).

Simiu, E., and D. Yeo. 2019. *Wind effects on structures: Modern structural design for wind*. 4th ed. Hoboken: Wiley/Blackwell.

SOM (Skidmore Owings and Merrill). 2004. “World trade center response to wind, NCSTAR1–2, Appendix D.” http://wtc.nist.gov/NCSTAR1/NCSTAR1-2index.htm.

Vickery, P. J., D. Wadhera, J. Galsworthy, J. A. Peterka, P. A. Irwin, and L. A. Griffis. 2010. “Ultimate wind load design gust wind speeds in the United States for use in ASCE-7.” *J. Struct. Eng.* 136 (5): 613–625. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000145.

Queries

1. Please check and confirm that all the math corrections are incorporated correctly.