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Codification of wind loads on buildings using bluff body aerodynamics and climatological data bases

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Abstract

Current data storage and computational capabilities allow the development of a new generation of standards whose provisions on wind loads can be structured as knowledge-based systems drawing the requisite information from large data bases. We show several examples demonstrating that such provisions could be significantly more realistic and risk-consistent than their conventional counterparts, which are of necessity based on reductive formulas, tables and plots. We point out the necessary interaction between development of knowledge-based standard provisions and the acquisition of aerodynamics and wind climatology data. Finally, we suggest that in addition to serving structural designers' needs, knowledge-based standard provisions could serve the insurance industry as certified hazard assessment tools that would be more realistic and dependable than similar tools developed without the benefit of careful public scrutiny and broad professional consensus.

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1. Introduction

A few decades ago significant efforts were still being devoted to the development of approximate methods for calculating moments in linearly elastic frames. With the emergence of modern computational capabilities the need for such efforts has largely disappeared. A similar change from pre-computer to modern approaches is now in order for the codification of wind loads.

The information content of conventional standard provisions for wind loads is consistent with the modest storage, processing and computational capabilities available to designers in the past. For this reason such provisions were – and still are – based on simplified aerodynamics and climatological models and on summary information supplied in reductive tables and plots. Therefore, conventional standard

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provisions contain significant inconsistencies with respect to risk, and do not include information allowing designers to account realistically and comprehensively for spatio-temporal wind load effects on either linear or nonlinear structural behavior.

ASCE 7-95 Standard [1] writers have attempted to reduce the limitations of earlier versions of the standard by producing the most elaborate set of wind loading provisions ever developed in the US. Such is the complexity of those provisions that it was necessary to develop a computer program for verifying their correctness, completeness and consistency, and for allowing calculations to be performed dependably and fast [2]. It was also found necessary to work on the development of an alternative, simplified set of provisions that would be less cumbersome for routine use. Even more elaborate than the ASCE 7-95 Standard is the 1995 British Standard 6399, Part 2 [3], which contains, among others, provisions accounting explicitly for wind directionality.

While such elaborate wind loading provisions contain useful additions and improvements over earlier versions, they still suffer from many of the limitations and shortcomings typical of conventional standards. In our opinion, a lesson to be learned from the development of those provisions is that there is a practical limit to improving codification by making conventional standards ever bulkier and more complex. Rather, an approach to codification is called for that takes advantage of modern computational and information storage capabilities. The new type of standard we propose would consist of (1) sets of rules adopted by consensus, (2) comprehensive aerodynamic and climatological data bases meeting minimum acceptance criteria, and (3) functions or algorithms describing various relevant quantities (e.g., gust effect factors). The rules, data bases, and functions or algorithms could be updated as needed by mechanisms ensuring effective scrutiny. The loads would be functions of design parameters that would include building geometry and, whenever necessary, building orientation, position with respect to and geometry of neighboring buildings, built-up terrain roughness defined by the type and number of buildings per unit area, and so forth. The proposed approach would allow the designer to target specific situations, rather than providing blanket coverage for broad ranges of situations, as is done in conventional standard provisions. It would allow the calculation of wind effects on nonlinear structures or on structures with influence lines that may differ from those assumed in the development of ASCE 7-95 Standard provisions. In short, the proposed approach would help to make wind loading provisions more realistic and risk consistent.

In this paper we discuss examples of inconsistencies with respect to risk due to simplifications inherent in reductive standard provisions. The examples pertain to gust effect factors for rigid structures, across-wind response of tall buildings, wind load factors, directional wind effects, dependence of aerodynamic coefficients on building geometry, and estimates of wind effects on nonlinear structures or structures with arbitrary types of influence lines. We then show how such reductive provisions can be replaced by rules, data, and functions or algorithms that allow for more realistic and risk-consistent designs. From our discussion there emerges the need to plan research and data acquisition with a view to improving the usefulness of aerodynamics and climatological information from a standards development point of view. We also discuss the potential alternative use of the proposed type of standard provisions as certified, consensus-based hazard assessment tools for insurance purposes.

2. Gust effect factors for rigid structures

As an example of a simplified, reductive standard provision we consider the specification of gust effect factors for rigid structures. According to Section 6.6 of the ASCE 7-95 Standard, the gust effect factor shall be $G = 0.8$ for exposures A and B. According to the Commentary on the ASCE 7-95 Standard, "for very large buildings and for more accuracy", a complete analysis yields the following expression for G:

$$G = 0.9(1 + 7I_zQ)/(1 + 7I_z) \tag{1}$$

(Commentary, Eq. (C6-5)), where $I_z = c(33/z)^{1/6}$ is the intensity of turbulence at height z, $Q = \{1/[1 + 0.63(b + h)^{0.63}/L_z{}^{0.63}]\}^{1/2}$, $L_z = \ell(z/33)^{\varepsilon}$, z is a specified equivalent height of the structure, h and b are the height and width of the building, and c, ℓ and ε are specified constants. For a rigid building with a flat roof, height $h = 18.29$ m (60 ft), width $b = 25.9$ m (85 ft), and terrain exposure A, it can be verified that Eq. (1) yields $G = 0.786$. This is just slightly lower than the value $G = 0.8$, so that the use of the latter would be slightly conservative. For a smaller building one would expect G to be larger. Indeed, if Eq. (1) is applied to a rigid building with a flat roof, $h = 3.05$ m (10 ft), $b = 6.1$ m (20 ft), and terrain exposure B, using Table C6-6 of the Commentary (in which $c = 0.3$, $z = 9.14$ m (30 ft), $\ell = 97.5$ m (320 ft), and $\varepsilon = 1/3$) yields $G = 0.86$. Physically this larger value makes sense, but according to the Standard the value $G = 0.8$, which in this case is unconservative, should be used instead. It is clear that this would entail an inconsistency with respect to risk, that is, everything being equal, the failure risk associated with the use of the factor $G = 0.8$ would be greater for the small building than for the larger one.

3. Across-wind response of tall buildings

The Supplement to the National Building Code of Canada (1990 edition) [4] includes a tentative expression for estimating the rms of the wind-induced across-wind accelerations at the top of rectangular flexible buildings. The expression can be written in the form

$$a_w = 0.0337n_1^2(bd)^{1/2}(1/\zeta^{1/2})(\rho/\rho_b)\{U(h)/[n_1(bd)^{1/2}]\}^2 Y \tag{2a}$$

$$Y \approx 0.0048\{U(h)/[n_1(bd)^{1/2}]\}^{1.3} \tag{2b}$$

where n_1 is the fundamental frequency of vibration, b and d are the across-wind and along-wind dimensions of the building, $\rho \approx 1.25$ kg/m^3 and ρ_b are the specific mass of air and of the building, respectively, ζ is the across-wind damping ratio, and $U(h)$ is the mean wind speed at the building top elevation h. Eqs. (2a) and (2b) do not depend on terrain roughness or on the slenderness ratio $h/(bd)^{1/2}$.

Table 1
Values of $10^2 Y$

		$U(h)/n_1(bd)^{1/2}$	
Terrain	b/h	0.105	0.125
All	All	8.3[a]	6.6[a]
Open	1/4	28.0[b]	8.7[b]
Suburb.	1/3	13.0[c]	10.0[c]
	1/6	23.0[c]	14.0[c]
Urban	1/3	10.0[c]	9.0[c]
	1/6	21.0[c]	18.0[c]
	1/4	11.0[b]	8.8[b]
	1/8.3	10.0[d]	6.3[d]

[a] Ref. [4].
[b] Ref. [5].
[c] Refs. [6, 7].
[d] Ref. [8].

Table 1 shows values of Y based on Eqs. (2a) and (2b) and on tests reported in Refs. [5–8]. These values suggest that the across-wind response depends upon terrain roughness and slenderness ratio. The dependence on terrain roughness is confirmed by data reported in Ref. [9]. The guidance offered to designers on across-wind accelerations could be improved upon by replacing the reductive formula given by Eqs. (2a) and (2b) with an appropriate data base developed from across-wind response wind tunnel and full scale test results.

4. Wind load factors for hurricane and non-hurricane regions

The wind load factor is the ratio of the nominal ultimate wind load to the basic wind load implicit in the standard. The nominal ultimate wind load is by definition the load inducing the strength limit state. The basic wind load is proportional to the square of the estimated basic wind speed. For non-hurricane regions the basic wind speed is the estimated 50 yr speed. For hurricane-prone regions the basic wind load is 1.05^2 times the square of the estimated 50 yr wind speed. The 1.05 factor is referred to in the Commentary on the ASCE 7-95 Standard as a hurricane importance factor. Its use is justified in the Commentary as follows: "Because the probability distributions of hurricane winds and extratropical storms are different (Weibull versus Fisher-Tipett Type I), it is necessary to apply a hurricane importance factor to ensure the same probability of overload in hurricane-prone regions as in other regions".

The wind load factor specified in the ASCE 7-95 Standard for most design situations is 1.3 (Section 2.3.2). Under the assumption that errors associated with epistemic uncertainties are small, this means that the strength limit state for members stressed predominantly by wind loads and insensitive to wind direction effects is approximately proportional to $1.3V^2$, where V is the basic wind speed.

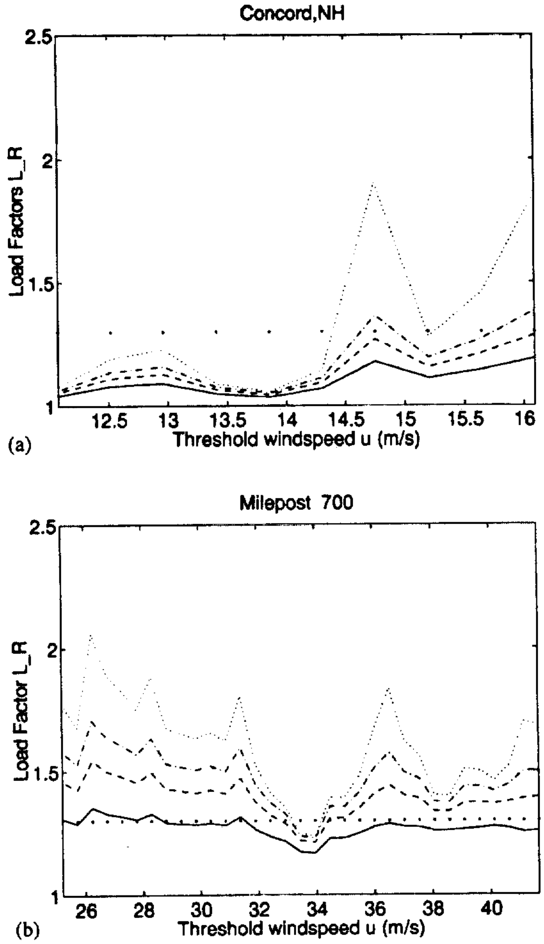

Fig. 1. Examples of estimated load factors L_R corresponding to mean recurrence intervals of the nominal ultimate wind load $R = 500$ yr (solid line), $R = 2000$ yr (interrupted line), $R = 10\,000$ yr (dotted-interrupted line), $R = \infty$ (dotted line). Line L_R = 1.3 represents value of ASCE Standard 7-95 load factor: (a) Concord, N.H.; (b) milepost 700 (coastline location between New Orleans, Louisiana and Biloxi, Mississippi) [2].

Recent extreme wind studies [10] suggest that a load factor of 1.3 is typically appropriate for non-hurricane regions, that is, it appears to result in strength limit states with very long nominal mean recurrence intervals, estimated to be predominantly as long as perhaps up to 10^6 yr or longer. On the other hand, according to estimates of hurricane wind speeds reported in Refs. [11, 12], for hurricane-prone regions a load factor value of 1.3 results in strength limit states with nominal mean recurrence intervals that can be as low as a few hundred years [11, 12]. This suggests that the hurricane importance factor value used in the ASCE 7-95 Standard (or the load factor value of 1.3 used in conjunction with the 1.05 hurricane importance factor) is inadequate. The large number of failures experienced during recent strong hurricanes in the US would tend to support this view. Fig. 1 shows examples of estimated load factors for various nominal mean recurrence intervals of the ultimate wind load in a non-hurricane and a hurricane-prone region. The estimated load factors depend on the magnitude of the speed threshold, that is, on the minimum speed included in the data sample. In spite of estimation errors it is clear from the examples – and from similar plots given in [12] – that the nominal mean recurrence interval corresponding to a load factor value of 1.3 is much lower for hurricane winds than for extratropical winds.

The parameters of extreme value distributions can depend significantly on geographical location. One may therefore expect that this is also the case for wind load factors. The use of a single wind load factor for all non-hurricane regions and of another single load factor for all hurricane-prone regions is therefore a simplification that might not be justifiable on climatological grounds. Also, according to Refs. [10–12], it is not the case that best fitting extreme wind distributions are typically Fisher-Typett Type I in non-hurricane regions and Weibull in hurricane-prone regions; rather, there is evidence that typically they are reverse Weibull in both cases, with considerably longer distribution tails for hurricane than for non-hurricane winds. It may be expected that a knowledge-based format would allow the implementation of a more differentiated and realistic approach to accounting for distribution tail lengths than is possible within the framework of a conventional standard's reductive approach.

5. Aerodynamic and climatological wind direction effects

The dependence of wind pressures and wind forces on wind speed and direction is of the form

$$p(\theta) = (1/2)\rho c(\theta) v(\theta)^2 \tag{3}$$

where ρ, c, p, v and θ denote air density, the aerodynamic pressure (or force) coefficient, wind pressure, wind velocity, and direction, respectively. Several methods for obtaining extremes of the vector $p(\theta)$ have been proposed (see Refs. [3, 13–15]). As mentioned earlier, while the British Standard BS 6388: Part 2 [3] makes explicit allowance for wind directionality effects, the ASCE 7-95 Standard simplifies matters by not doing so.

In the United Kingdom the strongest winds blow from the southwest to west directions. This fact is used for codification purposes in Ref. [3]. In the United States the directions of the strongest winds depend on geographical location. In our proposed approach to codification the use of one or several of the methods accounting for wind directionality would require the provision of a directional wind speed data base. In addition, rather than making use only of the aerodynamic coefficient corresponding to the aerodynamically most unfavorable wind direction – as is the case for the ASCE 7-95 Standard – our proposed approach would be based on aerodynamic coefficients for a sufficiently large number of directions.

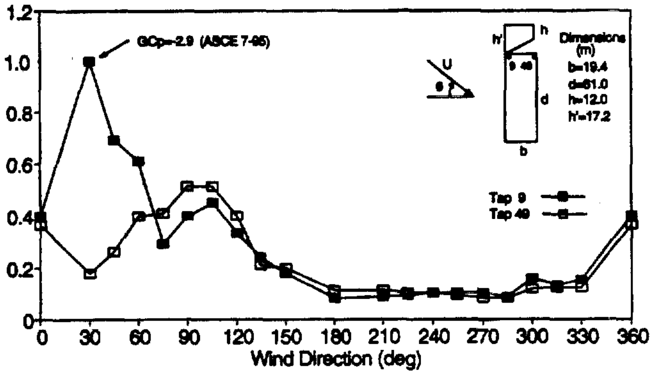

Fig. 2. Wind direction factors for roof corner regions, high corner (around tap 9) and low corner (around tap 49), four-span saw-tooth roof.

Consider the directional factor for aerodynamic pressures defined as the ratio $C_{\mathrm{p\,pk}}(\theta)/GC_{\mathrm{p}}$, where $C_{\mathrm{p\,pk}}(\theta)$ is the largest peak pressure coefficient for direction θ measured within a specified region of the building envelope, and GC_{p} is the maximum of $C_{\mathrm{p\,spk}}(\theta)$ over all values of θ. A typical example of the variation of the directional factor for taps within the roof corner of a sawtooth roof is shown in Fig. 2. Note that the directional factor reaches or is close to its maximum value for a very narrow set of values θ. This reduces the probability that a specified extreme wind pressure will be exceeded during a specified time interval. To allow realistic estimates of probabilities of exceedance of specified pressures or forces, directional aerodynamic and climatological data should therefore be included in standards data bases. For example, during the Insurance Industry/US Department of Commerce Wind Peril Workshop held on 4–5 June 1996, this requirement was invoked to request from the National Weather Service a reprograming of its Automatic Surface Observing System (ASOS) that would make it possible to record and store daily largest wind speeds for each of the eight or sixteen principal compass directions.

6. Dependence of aerodynamic coefficients on building geometry

To simplify wind loading provisions, the ASCE 7-95 Standard and the National Building Code of Canada specify peak pressure coefficients for roof components independently of building height. Fig. 3, taken from Ref. [16], shows peak pressure coefficients near a top corner of a 4.8° monoslope roof for buildings with dimensions in plan 12.2 m × 61 m and eaves heights from 3.66 to 12.20 m. It is seen from Fig. 3 that the simplifying assumption according to which peak pressure coefficients are independent of building height results in large inconsistencies with respect to risk. (Note that peak coefficients GC_{p} specified in the ASCE 7-95 Standard are referenced with respect to peak gust speeds, rather than to mean wind speeds as in Ref. [16].)

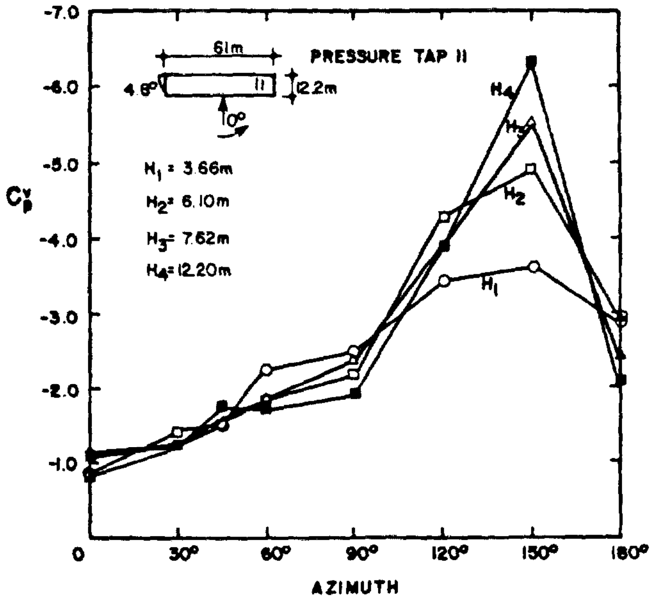

Fig. 3. Corner suctions for buildings with monoslope roof for various heights [16].

Inconsistencies of this type would be greatly reduced by standard provisions relying on data bases containing the full information needed for design. Rather than having the bulk of such information thrown away by code writers, as is currently the case, effective use of the requisite information in the proposed type of standard provisions would result in more rational and risk-consistent designs.

7. Specification of loads for use in conjunction with influence lines or for nonlinear response calculations

The ASCE Standard 7-95 contains wind loading provisions for main wind-force resisting systems that do not describe the actual loads themselves. Rather, they describe fictitious loads that, if applied to the structure, would cause effects (such as bending moments) approximating more or less closely the effects caused by the actual loads. These provisions were developed on the basis of wind tunnel tests in which the measured external loads were multiplied on line by influence coefficients. Those influence coefficients were typical of a number of structural systems for low buildings with flat and gabled roofs.

The provisions just referred to rely on envelope curves resulting in designs that are not risk consistent. If the structure being designed has characteristics that differ from those assumed in the wind tunnel tests, they offer no information on wind loading allowing influence-line-dependent wind effects to be calculated. Nor is any such information available for calculating wind effects for structures with non-linear behavior.

It is therefore desirable to record aerodynamic data that allow the designer to account realistically for both the spatio-temporal variability of the wind loads and for the specific linear or non-linear characteristics of the structure. Rather than recording extrema of weighted sums of pressures acting simultaneously at a sufficient number of taps, it is possible to record the individual time series of those pressures. These can be summed up and weighed as needed to yield time series of the load effect being considered. The knowledge-based type of framework we propose is consistent with such an approach, and would provide the flexibility needed to achieve realistic and risk-consistent estimates of wind effects on any type of linear or non-linear structural system.

8. Conclusions

We showed examples of conventional standard provisions which, owing to the simplified and reductive information contained therein, result in designs that are clearly inconsistent with respect to risk. The examples included: gust response factors for rigid buildings, across-wind response of tall buildings, wind load factors, directional wind effects, dependence of aerodynamic coefficients on building geometry, and the estimation of wind effects on non-linear structures or structures with arbitrary influence lines. Inconsistencies with respect to risk inherent in conventional standard provisions for wind loads could be eliminated or at least significantly reduced by developing standards structured as knowledge-based systems with appropriate aerodynamic and climatological data bases. In developing data bases for such standards it should be kept in mind that the estimation of wind effects requires the integration of climatological information with aerodynamics information. The planning of aerodynamics experiments conducted for structural design purposes should be informed by the need to develop the type of standards we propose.

Not only would the proposed type of standards result in more rational, risk-consistent designs; it would, in addition, reduce or eliminate the proliferation of unscrutinized models and procedures whose validity is not backed by broad consensus. The development of standard provisions requires close professional scrutiny that, owing to the transparency of the proposed approach, would be considerably more effective than is currently the case. Finally, the proposed type of provisions could serve the insurance industry as certified tools for hazard and damage prediction and assessment.

Among the issues to be decided upon as the concept described in this paper evolves is the source of the aerodynamics databases. Although full scale data are desirable, in practice these can serve primarily for the verification and calibration of wind tunnel results. It is also desirable to explore the issue of the differences among results obtained in different wind tunnels so that associated errors be estimated. Finally, computational fluid dynamics is likely to be a useful tool in the near future, especially for data pertaining to wind-force resisting systems, for which the influence of local load fluctuations is much smaller than for components and cladding.

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