Engineering Structures 103 (2015) 53–62

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Wind load factors for dynamically sensitive structures with uncertainties

Dae Kun Kwon [a,*], Ahsan Kareem [a], Rachel Stansel [b], Bruce R. Ellingwood [c]

[a] Department of Civil & Environmental Engineering & Earth Sciences, Univ. of Notre Dame, Notre Dame, IN 46556, United States
[b] ABS Consulting, San Antonio, TX 78232, United States
[c] School of Civil and Environmental Engineering, Colorado State University, Ft. Collins, CO 80517, United States

ARTICLE INFO

Article history:
Received 5 February 2015
Revised 10 August 2015
Accepted 19 August 2015
Available online 11 September 2015

Keywords:
Buildings (codes)
Design (buildings)
Hurricanes
Structural engineering
Uncertainty
Wind engineering
Wind load factors

ABSTRACT

The current recommendations for the load factors on wind load in *ASCE Standard 7* are based on an analysis of performance of rigid buildings, which may not be adequate for dynamically sensitive structures. In light of the uncertainties associated with dynamic characteristics of flexible buildings such as natural frequency and damping ratio, the load factors for such buildings may deviate from that in ASCE 7. This study investigates the efficacy of the current wind load factor for dynamically sensitive structures in the presence of uncertainties. A systematic analysis is performed using Monte Carlo simulations. Uncertainties associated with each component of the wind load effects such as the wind speeds, natural frequency and damping ratio of a building are incorporated in the load effects based on both *ASCE Standard 7-05* and *ASCE Standard 7-10*. In addition, a database-enabled design (DED) procedure is utilized to support the analysis of the wind load factor, especially for the acrosswind case where *ASCE 7* does not offer any guidance. In addition, the effects of terrain conditions, amplitude-dependent frequency and damping, and negative aerodynamic damping on the wind load factor are also discussed. Recommendations are made for wind load factors for dynamically sensitive structures both in the alongwind and acrosswind directions and for non-hurricane and hurricane winds.

1. Introduction

The wind load factor recommended in *ASCE Standard 7* [1–3] for load combinations involving wind load are based on an analysis of performance of rigid buildings [17,18]. It accounts for deviations in the actual loads from the nominal loads and for the uncertainties associated with the load effects. To estimate this factor realistically, studies have been carried out to account for the effects of both aleatory and epistemic uncertainties, including those in the estimation of extreme wind speeds, wind load effect model, wind tunnel experiment results, etc., which significantly influence the wind effects on rigid buildings (e.g., [37,15,16]).

Wind effects on flexible buildings are more significant than those on rigid buildings, and the dynamic response parameters, especially frequency and damping, contribute additional uncertainty to the response (e.g., [19,5,10]). In light of these uncertainties and the fact that the building response is no longer proportional to the square of the wind velocity, a wind load factor (or load factors) that are more conservative than the factor currently used in ASCE 7 may be required for tall building design. The aforementioned studies considered a sample building to determine wind induced effects such as wind pressures/loads, base moments and top displacements based on wind tunnel datasets. Uncertainties associated with wind speeds, frequency and damping, and other parameters such as errors in wind tunnel experiments and measured datasets were taken into account. Overall trends from the studies have indicated an increase of the load factor.

A number of issues remain concerning wind load factors for flexible buildings. First, *ASCE 7-10* [3] has introduced new wind maps based on a mean recurrence interval (MRI) of 700 years for basic wind speed for the Category II buildings [44,45], which replaced the 50-year MRI wind speed map in *ASCE 7-05* [2]. Along with this change, the wind load factor was reduced from 1.6 to 1.0 for the load combinations in which the wind load is the principal action. Most previous studies of tall, flexible buildings have focused on the wind loads and wind load factors in *ASCE Standard 7-05*. These earlier studies must be revisited to explore how these recent changes might affect the wind load factors and other wind load requirements for flexible buildings in the current edition of

* Corresponding author.
E-mail addresses: dkwon@nd.edu (D.K. Kwon), kareem@nd.edu (A. Kareem), rstansel@eagle.org (R. Stansel), bruce.ellingwood@colostate.edu (B.R. Ellingwood).

http://dx.doi.org/10.1016/j.engstruct.2015.08.031
0141-0296/

ASCE 7. Second, although past studies (e.g., [19,5,10]) have concluded that the load factor for flexible buildings should be higher than that for rigid buildings, the results among these studies were inconsistent. In addition, given that the effect of the uncertainties on the acrosswind response of tall buildings would be different from their alongwind response due to more significant aerodynamic interactions and negligibly small contribution of the mean response, the load factor in the acrosswind direction may also be different from that in the alongwind direction. For example, Gabbai et al. [19] reported that overall wind load factors for selected members of an example tall building using synchronous pressure measurement data ranged from 1.9 to 3.5 for the alongwind and acrosswind top displacements based on the probabilistic peak wind load effects used in rigid buildings [37,16]. However, these load factors for the case of rigid building ranged from 1.9 to 2.3, which depart from the expected load factor of 1.5–1.7 in Ellingwood and Tekie [18] and 1.51 in Bashor and Kareem [5]. In addition, the load factors reported in Gabbai et al. [19] were very close in the alongwind and acrosswind cases, while Bashor and Kareem [5] reported that load factors for the acrosswind response were larger than those for the alongwind response. This suggested that the current load factor might not be adequate to account for the acrosswind load effects. Overall, the load factors suggested by Gabbai et al. [19] were considerably higher than those suggested by others (e.g., [5]). Chen and Huang [10] also examined wind load factors, quantifying the probabilistic wind load effects with the assumption of parametric variations of wind speed and extreme load coefficient and finding that the structural response was proportional to the wind velocity to the power of 2–3 for flexible buildings. Their load factor was close to that reported in Bashor and Kareem [5] when the power was 2.5. Third, there has been little consideration of the impact of different terrain conditions (exposures) on response of dynamically sensitive buildings, which may be one of the key parameters for proper assessment of the wind load factor. Finally, there is limited information for the load factor associated with hurricane winds, which might be higher due to inherently higher uncertainties in hurricane wind speeds, as shown in the literature for rigid buildings (e.g., [18,37,15,16]).

To address the above issues, this study investigates the applicability of the current wind load factor for dynamically sensitive structures in the presence of uncertainties. A systematic analysis is performed using Monte Carlo simulations in which uncertainties associated with each parameter involved in the wind load effects, such as wind speeds, natural frequency and damping ratio, are incorporated using both *ASCE Standard 7-05* and *ASCE Standard 7-10* procedures. In addition, a database-enabled design (DED) procedure [48,33,34] is also included to validate the assessment of the wind load factor, especially for the acrosswind direction where *ASCE Standard 7* does not offer any guidance. Finally, recommendations are made for wind load factors for dynamically sensitive structures loaded in both the alongwind and acrosswind directions as well as in non-hurricane and hurricane wind regimes.

2. Wind load factor in *ASCE Standard 7*

2.1. Background of the wind load factor for load combinations in ASCE 7

The wind load factor (γ_w) in *ASCE Standard 7* is defined using the first-order reliability method (FORM) as [17,18]:

$$\gamma_w = \left(\frac{\mu_W}{W_n}\right)(1 + \alpha\beta V_W) \tag{1}$$

where μ_W/W_n = the bias or ratio between the mean and the nominal wind loads/pressures, where the nominal value (W_n) is determined in accordance with the ASCE 7 criteria; β = the reliability index; α = the sensitivity coefficient; and V_W = the coefficient of variation (COV) in the wind load/pressure. Using the values for a rigid building reported by Ellingwood and Tekie [18], i.e., $\mu_W/W_n = 0.78$, $\beta = 2.5$, $\alpha = 0.75$, $V_W = 0.37$, the load factor defined in Eq. (1) results in $\gamma_w = 1.32$, which is equivalent to the load factor (1.3) used in *ASCE 7-95*. The mean wind load/pressure in that study implicitly included a wind directionality factor of 0.85. When an explicit wind directionality coefficient, $K_d = 0.85$ was added to the ASCE 7 provisions for rectangular buildings in 1998, the corresponding wind load factor (=1.3/0.85), excluding the directionality factor, was increased to 1.6. When Ellingwood and Tekie [18] later revisited the choice of probability distribution for modeling the extreme wind speed and the difference between wind speed models in hurricane zones versus non-hurricane zones, they concluded that the reliability index, β, for wind loads should be approximately 3.0. A single wind load factor of 1.6 was employed for editions of ASCE 7 between 1998 and 2005.

In *ASCE Standard 7-10*, the wind load factor in combinations 4 and 6 was reduced to 1.0 because of the change in the specification of the design wind speed. The wind speeds for strength design were re-mapped at much longer MRIs, which are 700–1700 years depending on the Occupancy Category (Figure 26.5 in the ASCE 7-10), thus eliminating the need for an importance factor for different building risk categories and the discontinuity in the risk between the hurricane-prone coastal areas and the remainder of the country, and better aligning the treatment of wind and earthquake effects (C2.3.2 in ASCE 7-10).

2.2. Relationship between the wind load factor and MRI of wind speed in ASCE 7

The wind pressures/loads in ASCE Standard 7 are calculated from the 3-s gust wind speed, $V_{3\text{-}s}$. The ratio of this wind speed for any MRI, T, (V_T) to the 50-yr MRI wind speed (V_{50}) in non-hurricane prone regions is (e.g., [38]):

$$\frac{V_T}{V_{50}} = 0.36 + 0.1\ln(12T) \tag{2}$$

When the wind speed maps in ASCE 7-2010 were developed, the wind load factor (γ_w) was defined as the ratio between the point estimates of the T-yr and 50-yr wind speeds as:

$$\gamma_w = \left(\frac{V_T}{V_{50}}\right)^n \tag{3}$$

where n equals 2, which is based on the behavior of rigid buildings in the absence of any dynamic amplification. Eq. (3) implies that all uncertainty in the wind load is vested in the uncertainty in the wind speed. Using the load factor of 1.6 defined in *ASCE 7-05*, Eqs. 2 and 3 yield T = 709 years for Risk Category II structures (where the importance factor (I) is 1.0). Accordingly, T was set equal to 700 years in in developing the wind speed maps in *ASCE 7-10* and γ_w was set equal to 1.0. For example, V_{50} defined in *ASCE 7-05* was 40 m/s in the Midwest region; using T = 700-yr MRI and V_{50} = 40 m/s in Eq. (2) for the Risk Category II structures (I = 1.0), V_{700} becomes 51 m/s, which is the new basic wind speed defined in *ASCE 7-10*.

For rigid buildings such as low-rise structures, the wind loads are proportional to the square of the wind speed because the wind responses are governed by mean (static) and background turbulence effects (quasi-static). However, in the case of flexible buildings, n may exceed 2 because the response is dominated by inertial effects (e.g., [10]). For example, assuming that n = 2.5 and T = 700-yr, V_{700} = 51 m/s; with V_{50} = 40 m/s, as before, the implied wind load factor based on Eq. (3) would increase from 1.6 to 1.84 for flexible buildings. Such increases will be considered in more detail in the sequel.