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Abstract

Currently, there are several codes and standards for wind design that propose the use of perception curves of acceleration, that are employed to check serviceability limit state. These perception curves are associated with return period values from one to ten years. Some codes and standards that include these perception curves are: ISO10137 (2007), National Building Code of Canada (2005) and Architectural Institute of Japan (2004). In Mexico, the Manual of Design of Civil Structures (2008) also proposes the use of two perception limits of acceleration. Moreover, the Federal District Design Code of Mexico for wind design (2004) also includes a limit of acceleration. The criteria proposed in these codes and standards do not incorporate the uncertainty in the structural response, the dynamic properties and wind characteristics; although some recent investigations have incorporated the effect of uncertainty associated with the limits of perception. With the growing construction rate of tall buildings in Mexico, together with the use of new technologies that allow the construction of more resistant and light buildings, with a low damping ratio, it is necessary to develop a serviceability limit state to check the excessive accelerations induced by wind in tall buildings that include the wind characteristics of the Mexican wind climate. The latter is the main objective of this work. For the development of the serviceability limit state, the characteristics of the Mexican wind climate, uncertainty in the structural response and dynamic properties are considered. To illustrate the employ of the serviceability limit state proposed, a mathematical model of one of the tallest buildings in Mexico is developed.

Keywords: Mexican wind climate, Perception curves, Tall buildings, Wind.

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Introduction

Due to the increase in population worldwide, there is a need for new spaces like residential or office buildings, shopping malls, sports centers, etc. Due to limited space in some cities, the horizontal model building is no longer an alternative, and the vertical construction of tall slender buildings appears to be a solution.

In large cities, like Mexico City, the construction of tall buildings started in the 50's with the construction of the Latino Tower, with a total height of 182 m, during the 80's a new tower was built with a total height of 241 m (Pemex Tower). In 2003, Mayor Tower (225 m height) was built in the financial zone of the city. More recently, Reforma Tower and Bancomer Tower, with 244 and 235 m height, respectively, were built in the same zone. Most of these buildings were designed according to international standards and the local normativity.

With the use of new construction materials, with high resistance, the ultimate limit state of tall buildings under wind loading is usually satisfied; however, excessive and unwanted vibrations can be experienced by the occupants of these buildings during a wind event due to the small structural damping. Several studies have proposed perception curves in terms of peak or root-mean-square (RMS) acceleration to be used as serviceability limit states. These studies include the works by Irwin (1978), who indicated that the acceptable measurement of the movement of a building in a windstorm is over the worst 10 minutes with a return period of 5 years, Chen and Robertson (1972) showed a range of human perception to motion from 10% to 98% of the inhabitants of a building. More recently, Pozos et al. (2014) carried out a parametric analysis to estimate the unconditional probability of perception of acceleration applied to some codes and standards. Unfortunately, in the Mexican code and standards, there are no perception curves of acceleration or expressions that help to evaluate a serviceability limit sate of the tall buildings. For this reason, the main objective of this work is to develop an expression that can be used to verify the serviceability limit state, that include the characteristics of the Mexican wind climate, uncertainty in the structural response and dynamic properties of the structure. One of the tallest buildings in Mexico is employed as an example to illustrate the use of the serviceability limit state proposed.

Probabilistic Characterization of the Peak Acceleration

Excessive and unwanted accelerations on a structure can be induced by the wind. Traditionally, two types of measures are usually adopted to study wind-induced vibration, one is the mean peak acceleration and the other one is the RMS of acceleration. Mean peak acceleration is associated with seek for safety while the RMS of acceleration is associated with physical illness. Based on random vibration theory, these two measures can be related through a peak factor (g) as follows:

$$\hat{a} = g\sigma_a\left(v\right) \qquad (1)$$

where $\hat{a}$ is the mean peak acceleration and $\sigma_a(v)$ is the RMS of acceleration for a given wind speed *v*. Equation (1) can be employed as measure of wind-induced vibration. To take into account uncertainty in the structural response, dynamic properties and wind speed, a probabilistic characterization of the peak response is needed.

For the probabilistic characterization of the peak response, the mean peak acceleration is adopted as a measure. The probability distribution of the peak response (acceleration), $\hat{A}$, conditioned on a given mean wind speed *v* can be written as (Davenport, 1964):

$$F_{\hat{A}}(\hat{a}) = \exp\left(-\exp\left(-\sqrt{2\ln(f_0T)}\Big/\sigma_a(v)\left(\hat{a}-\sqrt{2\ln(f_0T)}\sigma_a(v)\right)\right)\right) \quad (2)$$

where f_0 is the frequency of the structure and *T* is the time of observation.

The mean and standard deviation of $\hat{A}$, are given respectively by:

$$m_{\hat{A}} = g\sigma_a(v) \quad (3)$$

$$\sigma_{\hat{A}} = \pi\sigma_a(v)\Big/\left(\sqrt{6}\sqrt{2\ln(f_0T)}\right) \quad (4)$$

By using the total probability theorem and by incorporating uncertainty in structural properties (i.e., frequency and damping), response and wind speed, the unconditional probability of perception can be written as:

$$P_{fP} = \int P_{P|\hat{a}}\left(R_a(\tilde{v})\hat{a}\right) f_{\hat{A}}(\hat{a})\, f_{\tilde{V}}(\tilde{v})\, f_{\tilde{F}_{D0}}\left(\tilde{F}_{D0}\right) f_{\tilde{f}_n}\left(\tilde{f}_n\right) f_{\tilde{\xi}}\left(\tilde{\xi}\right) d\tilde{\xi}\, d\tilde{f}_n\, d\tilde{F}_{D0}\, d\tilde{v}\, d\hat{a} \quad (5)$$

where the random variables $\tilde{v}$, $\tilde{F}_{D0}$, $\tilde{f}_n$, $\tilde{\xi}$ represent normalized random variables with respect to their mean value of the wind speed, transformation factor from wind speed to force, frequency and damping ratio, respectively, with probability density functions defined respectively as $f_{\tilde{V}}(\tilde{v})$, $f_{\tilde{F}_{D0}}$, $f_{\tilde{f}_n}$, $f_{\tilde{\xi}}$. $P_{P|\hat{a}}(\hat{a})$ is defined by a standard normal distribution and written as (Burton, 2006):

$$P_{P|\hat{a}}\left(R_a(\tilde{v})\hat{a}\right) = \Phi\left(\frac{\ln\left(R_a(\tilde{v})\hat{a}/c_1\right)}{c_2}\right) \quad (6)$$

where c_1 and c_2 are parameters of the model that depend on the frequency of vibration, and the function $R_a(\tilde{v})$ is defined as:

$$R_a(\tilde{v}) = \frac{a_{cr}}{g}\cdot\frac{\tilde{v}m_v\tilde{F}_{D0}\sqrt{S\left(\tilde{f}_n m_{f_n}, I_v, \tilde{v}m_v\right)}}{v_T\sqrt{S\left(m_{f_n}, I_v, v_T\right)}\tilde{\xi}} \quad (7)$$

where a_{cr} is a target acceleration that can be used for design checking, m_v is the mean value of *v*, v_T is the maximum wind speed for a given return period *T*, m_{f_n} is the mean value of f_n, and I_v is the turbulence intensity.

Development of a Serviceability Limit State

Statistics of Mean Wind Speed for Mexico

The Institute of Electrical Research (IIE) of Mexico elaborates contour maps of wind speed for different return periods for the Mexican Republic. According to Sanchez-Sesma et al. (2003), a Gumbel distribution was employed to fit the data to develop the maps. If the Gumbel model is adopted, the following table summarizes typical coefficient of variation values of the wind speed, δ_v, for some Mexican cities.

Table 1. *Typical Coefficient of Variation Values of the Wind Speed Considering the Mexican Wind Climate*

City	COV (δ_v)
Mexico City	0.09
Baja California	0.37
Cancun	0.51

A more detail analysis was carried out to identify the range of values of δ_v, according to the Mexican wind climate. The analyses indicate that δ_v varies from 0.08 to 0.6.

Characterization of Probability Models

In is necessary to define the probabilistic models of each of the parameters of Equation (5) in order to propose an expression that can be used to verify the serviceability limit state. The lognormal distribution is considered adequate for the random variables $\tilde{F}_{D0}$, $\tilde{f}_n$, $\tilde{\xi}$ (Davenport, 2000; Kareem, 1990; Haviland, 1976). Further, the Gumbel distribution is used to characterize $\tilde{v}$ (Simiu and Scanlan, 1996). The following table presents the COV values of the random variables $\tilde{F}_{D0}$, $\tilde{f}_n$, $\tilde{\xi}$ employed in the analysis.

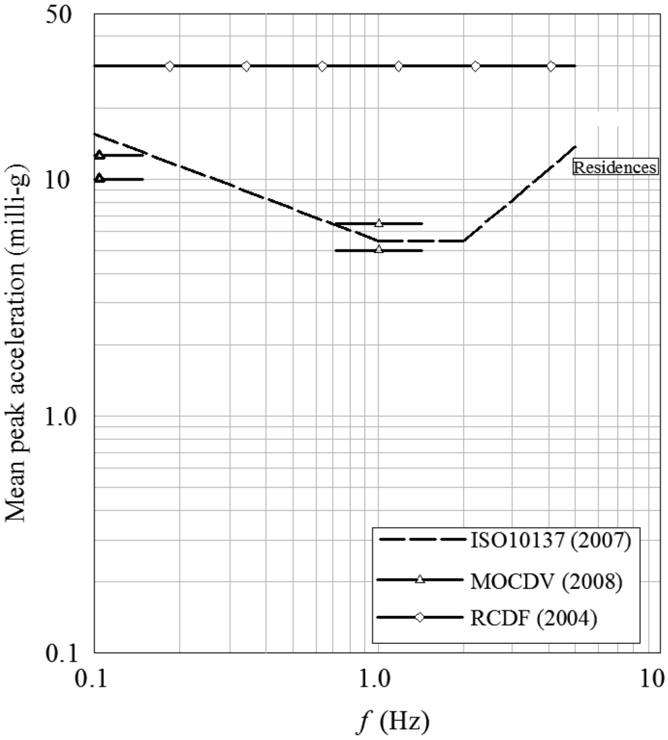
Table 2. *Statistics of Parameters Used in Eq. (5)*

Parameter	COV	Parameter	COV
$\tilde{F}_{D0}$	0.125	$\tilde{\xi}$	0.275
$\tilde{f}_n$	0.175	$\tilde{v}$	0.08 to 0.6

Calibration of an Expression to Verify the Serviceability Limit

Two factors are of paramount importance in the serviceability checking of the wind-induced acceleration of a building: the first one is the total probability of perception of acceleration, P_{fp}, and the second one is a factor that takes into account the characteristics of the wind climate at the location of the building. These two parameters will be used as inputs in the proposed expression. Further, the employ of a perception curve is also needed for design checking. In the following, the perception curve of acceleration proposed by ISO10137 (2007) for residential use is adopted (Figure 1).

Figure 1. *Perception Curve of Acceleration Proposed by ISO1037 (2007)*



It is observed from Figure 1 that the perception limits of acceleration in ISO10137 (2007) depend on the type of use of the building and frequency. Further, the perception limits defined in the Federal District Design Code (RCDF 2004) and the Manual of Design of Civil Structures (MOCDV, 2008) are also shown in Figure 1. Two important observations can be made from Figure 1, the first one is that the limit from RCDF (2004) does not depend on the frequency of vibration, and the second one is that the perception limits from MOCDV (2008) are specified only for two vibration frequencies (0.1 and 1 Hz).

For the analysis, the curve of perception of acceleration from ISO10137 (2007) for residence use is employed, since the values of acceleration are consistent with those currently used in MOCDV (2008).

By using Equation (5) and the statistics from Table 2, the following expression can be used for design checking of wind-induced acceleration on a building, considering the wind climate of Mexico.

$$F_{A_l}\left(P_{fP}, F_c\right) = \alpha\left(F_c\right)\cdot\ln\left(P_{fP}\right) + \beta\left(F_c\right) \tag{8}$$

where F_{Al} is an acceleration factor used for design checking, P_{fp} is the total probability of perception and F_c is a wind-climate factor that depends on the site of construction of the building. α and β are functions that incorporate the characteristics of the wind climate of Mexico in the calculation of F_{Al}, and are defined as:

$$\alpha\left(F_c\right) = -0.135\cdot\ln\left(F_c\right) - 1.69 \tag{9}$$

$$\beta\left(F_c\right) = -0.655\cdot\ln\left(F_c\right) - 0.50 \tag{10}$$

The use of Equations (8) to (10) and the perception curve of acceleration proposed by ISO10137 (2007) for residential use is described with detail in the following section.

Numerical Example

For the numerical example consider a tall building of 244 m height, located in Mexico City. The 10-year return period value of wind speed at the top of the building is equal to 50.64 m/s. The natural frequency of the first two sway modes of the structure are equal to 0.2 and 0.3 (Hz) for the X- and Z-direction, respectively. Some views of the mathematical model of the building are presented in Figure 2.

Turbulent wind forces were simulated based on an ARMA model (Samaras et al., 1985) and applied to the mathematical model of the building along its height in the X-direction. A time history analysis was carried out to calculate time histories of acceleration. Figure 3 presents envelopes of the maximum and minimum acceleration in the X-direction.

Figure 2. *Views of the Mathematical Model of the Building Considered*

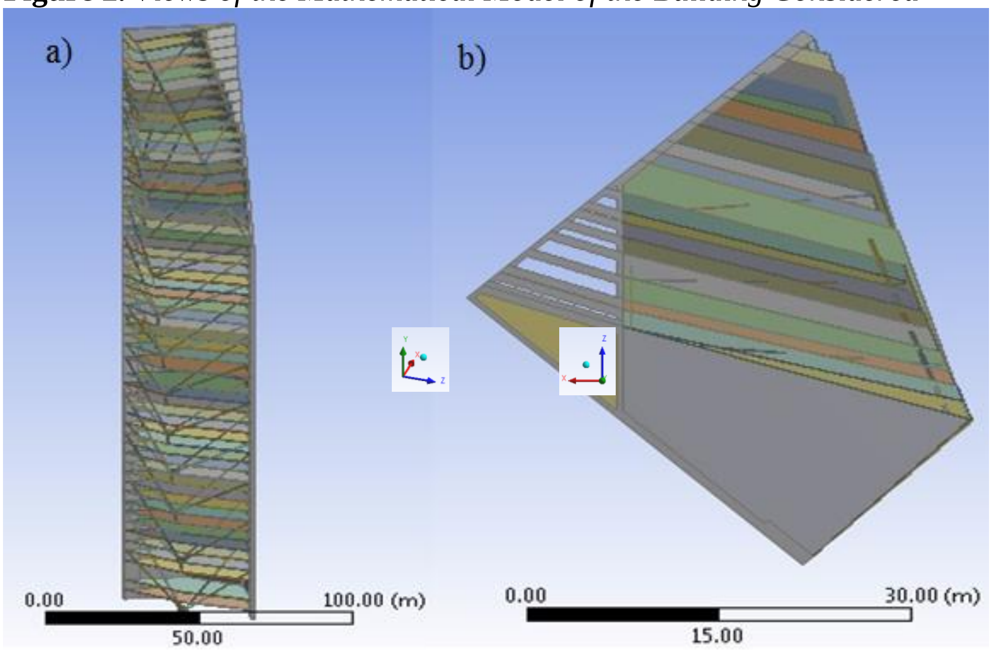
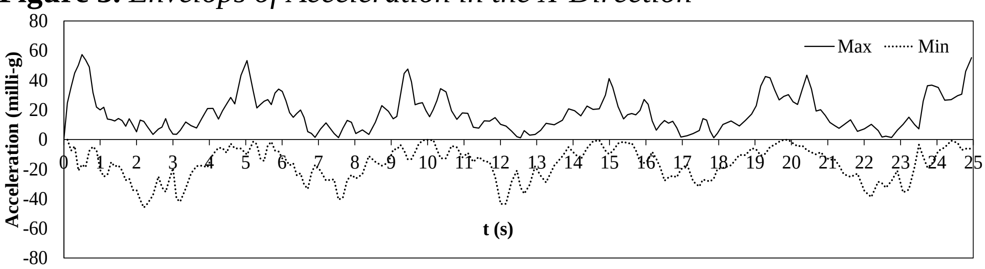


Figure 3. *Envelops of Acceleration in the X-Direction*



The maximum acceleration identified from Figure 3 is about 61 milli-g. To verify whether this acceleration is acceptable, Equation (8) together with the curve of perception of acceleration from the ISO10137 (2007) for residential use should be employed as follows:

1) Read from Figure 1 the mean peak acceleration for a frequency equal to 0.2 Hz. The mean peak acceleration for this frequency is equal to 12 milli-g.
2) Calculate the acceleration factor, F_{Al}, by using Equation (8). For the use of Equation (8) it is necessary to define P_{fp} and F_c. For Mexico City, the F_c factor is equal to 0.09, and it is assumed that the building owner accepts a total probability of perception, P_{fp}, of 0.8. With these parameters, the acceleration factor equals 1.38.
3) Factorize the maximum wind-induced acceleration calculated from the time history analysis (61 milli-g) by using the acceleration factor (1.38). The factorized acceleration is equal to 84 milli-g (1.38 x 61 milli-g).
4) Verify that the factorized acceleration (84 milli-g) is less or equal to the limit specified in the curve of perception of acceleration (12 milli-g). This comparison indicates that the design is far from acceptable for the parameters considered.

Note that a more stringent value of P_{fp} would cause the acceleration factor F_{Al} to increase.

Final Remarks

An expression that can be used to verify the serviceability limit state of tall buildings, considering the wind climate of Mexico was proposed. The expression proposed considers uncertainty in the structural response and dynamic properties of the structure. To illustrate the employ of the expression that can be used for design checking of wind-induced acceleration on a building, a mathematical model of one of the tallest buildings in Mexico was developed, and the wind-induced acceleration was calculated from a time history analysis and compared to the factorized acceleration, this factorized acceleration is calculated by multiplying the acceleration factor calculated with Equation (8) and the acceleration obtained from the curve of perception of acceleration of ISO10137 (2007) for residential use.

References

Architectural Institute of Japan Recommendations. 2004. *Guidelines for the evaluation of habitability to building vibration*. AIJES-V001-2004, Tokyo, Japan.

Burton, M.D. 2006. *Effects of low frequency wind-induced building motion on occupant comfort*. PhD. Thesis, Civil Engineering Department, The Hong Kong University of Science and Technology, Hong Kong.

Chen. P. W., and Robertson, L. E. 1972. *Human Perception Thresholds of Horizontal Motion*. Journal of the Structural Division, ASCE, Vol. 98, pp. 1681-1695.

Davenport, A. G. 1964. *Note on the distribution of the largest value of a random function with application to gust loading*. In Proceedings of the Institution of Civil Engineers. Paper No. 6739, 28: 187-196.

Davenport, A. G. 2000. *A comparison of seismic and windstorm hazards*. In Proceedings of the 6th Environmental Specialty Conference of the Canadian Society for Civil Engineering, 7-10 June 2000, London, Ont. Canadian Society for Civil Engineering, Montréal, Que. pp. 504-509.

Haviland, R. 1976. *Evaluation of seismic safety of buildings*. M.Sc. Thesis supervised by J.M. Biggs, E.H. Venmarcke, Massachusetts Institute of Technology.

Irwin, A. W. 1978. *Human response to dynamic motion of structures*. The Structural Engineer. 56A(9): 237-244.

ISO10137-2007 International Organization for Standardization. 2007. Bases for design of structures —*Serviceability of buildings and walkways against vibrations*. ISO 10137:2007(E), International Organization for Standardization, Geneva, Switzerland.

Kareem, A. 1990. *Reliability Analysis of Wind Sensitive Structures*. J. Wind Engineering and Industrial Aerodynamics, Vol. 33, pp. 495-514.

MDOC. 2008. *"Manual de Diseño de Obras Civiles, Diseño por viento. Recomendaciones y Comentarios*" [Manual of Design of Civil Structures, Wind design, Commentaries and Recommendations]. Instituto de Investigaciones Eléctricas, Comisión Federal de Electricidad.

NBCC. 2005. *National Building Code of Canada*, Part 4 Structural Design, Commentary 1, Wind Load Effects.

NTCDF. 2004. *"Normas Técnicas Complementarias para Diseño por Viento"* [Standards for wind design], Reglamento de Construcciones para el Distrito Federal, Gaceta Oficial del Departamento del Distrito Federal.

Pozos-Estrada, A., Isaac F. Lima Castillo, Roberto Gómez Martínez, J. Alberto Escobar Sánchez. 2014. *Wind-induced vibration: a serviceability study. 9th International Conference on Structural Dynamics*, Porto, Portugal, 30 June - 2 July.

Samaras, E., Shonozuka, M. and Tsurui, A. 1985. *ARMA representation of random processes*. Journal of Engineering Mechanics. ASCE, 111(3): 449-461.

Sánchez-Sesma, J., A. López, J. Aguirre and C. J. Muñoz. 2003. *Wind design for Mexico: A review of the period 1964-2003*, 11th International Conference on Wind Engineering (Lubbock, Texas, 2003).

Simiu, E., and Scanlan, R. H. 1996. *Wind effects on structures*. John Wiley & Sons, Inc., New York.