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The acrosswind effect on the performance-based assessment of tall steel buildings in multi-hazard environment

Anastasia Athanasiou [1], Lucia Tirca [2], Ted Stathopoulos [3]

[1] *Research Associate, Concordia University, Montreal, Canada, anaj.athanasiou@gmail.com*
[2] *Associate professor, Concordia University, Montreal, Canada, lucia.tirca@concordia.ca*
[3] *Professor, Concordia University, Montreal, Canada, statho@bcee.concordia.ca*

SUMMARY:
The effect of acrosswind loads on buildings has been studied since the 1980s, however, only a few researchers reported on the nonlinear response of tall buildings under acrosswind loads of increasing intensity. Acrosswind gust spectra are characterized by rich frequency content in the period range of interest of typical tall buildings, and may trigger the resonant response of such structures resulting to excessive structural damage. In order to establish a robust performance-based wind design procedure the following steps should be taken: i) conduct reliable simulations of the acrosswind loads based on experimental data; ii) investigate the dynamic behaviour of tall buildings under strong wind excitation; and iii) implement incremental dynamic analyses and fragility functions to quantify probabilistically the building performance. Current design following the Canada and U.S. building codes is prescriptive in nature and does not account for the inherent system overstrength and nonlinearity. Herein, local aerodynamic data are used to produce reliable estimations of the acrosswind history loadings acting on buildings at design level and beyond. Then, advanced finite element models are employed to assess the performance of a 15-storey hospital building in Montreal, Canada.

Keywords: wind, earthquake, performance-based

1. INTRODUCTION

Since the 1980s several researchers have recognised the significant effect of acrosswind loads on the resonant response of tall buildings and have used wind tunnel data to validate mathematical models that predict the acrosswind response. Solari (1985) proposed a probabilistic model that simulates mean wind loads and fluctuating components arising due to alongwind and acrosswind turbulence and wake excitations. Tsukagoshi et al (1993) generated uncoupled sets of alongwind and acrosswind load histories; then, implemented modal analysis in the time domain to assess the performance of a tall building with and without tuned mass dampers. Tamura et al (2001) performed nonlinear wind response history analyses to investigate the ductile behaviour of 2D tall steel building models subject to acrosswind loads. The generated winds refer to urban terrain and 1-in-2000 years mean wind speed U_{10m} = 28.5m/s, i.e. 12% greater than the 1-in-500 years design velocity U_{10m}=25.4m/s. Liang et al (2002) developed a frequency domain method to simulate the design acrosswind loads acting on rectangular tall buildings and showed that in buildings with aspect ratios > 3 the acrosswind response tends to exceed the alongwind; thus, it becomes critical in the design.

The ASCE/SEI 7-16 (2017) and NBC (2015) provisions use consistent expressions for alongwind loads based on the conventional gust loading factor approach. For approximation of acrosswind and torsional loads, both ASCE/SEI 7-16 and NBC prescribe the partial loading of alongwind face areas of building, with the two methods leading however to scattered responses (Kwon and Kareem, 2013). As the state-of-knowledge in wind engineering advances, there is an increased need to provide reliable representations of 3D wind loads on buildings to address performance-related design criteria and enhance structural economy and resilience. Aiming to advance wind design and enhance sustainability and public safety, the Performance-Based Wind Design (PBWD) prestandard (ASCE, 2019) was recently released.

The purpose of this study is to advance the state-of-art in the performance-based assessment of tall buildings located in wind and earthquake environment, by incorporating the acrosswind effect. To achieve this goal, the proposed steps are: (i) provide reliable representations of the acrosswind loadings on tall buildings using local aerodynamic data; (ii) investigate directionality effects; (iii) assess the system response under winds of increasing intensity by applying a performance-based approach; and (iv) investigate the acrosswind response of tall buildings in the nonlinear range. This work compliments the previous study carried out by Athanasiou et al (2022), where the performance of the same 15-storey hospital building was assessed in the alongwind direction, using incremental dynamic analyses and the fragility concept. In this study, the building model is subjected to directional alongwind and acrosswind forces of increasing amplitude. Differences in the nature of alongwind and acrosswind loads and their effect on the response are highlighted.

2. CASE STUDY

A 15-storey steel hospital building located in Montreal, in Site Class C (firm soil) is designed to respond independently to earthquake and wind loads following the current provisions (NBC, 2015). The building is braced in each orthogonal direction by 4 Concentrically Braced Frames (CBF). The first mode period is 2.9s (N-S) and 2.87s (E-W) and the wind is dominant in N-S, where it governs the design of lower floors (Athanasiou et al,2022).

2.1. Aerodynamic wind data

Local aerodynamic data from the wind tunnel testing of a geometrically similar building are retrieved from the Tokyo Polytechnic Aerodynamic database. The pressure data are scaled in time and multiplied by the corresponding tributary areas to provide averaged alongwind and acrosswind forces lumped at the floor levels of building. Ten incidence angles are considered: 0^o, 10^o,..90^o. Figures 1 a and b show the time history response and the corresponding gust pressure spectra for the derived drag and lift coefficients at the 13^{th} floor. The illustrated loads refer to wind angle 0^o (parallel to the N-S direction).

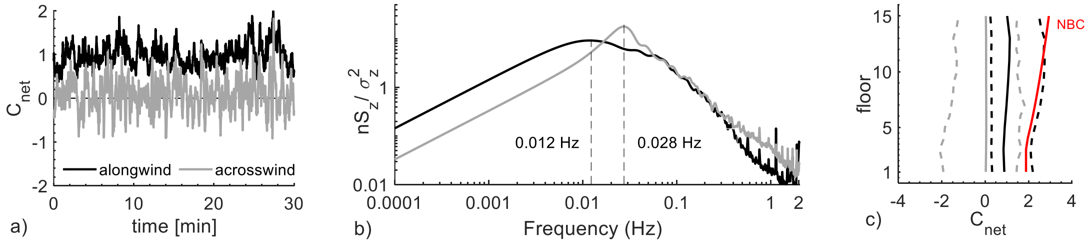

Figure 1. a) Time history of alongwind and acrosswind loads at 13^{th} floor (wind attack angle 0^o), b) associated normalized gust spectra and c) mean and extreme drag and lift coefficients along the building height.

The alongwind loads are characterized by a significant mean component, which is responsible for shifting the equilibrium position during strong wind excitation, and moreover, rich energy content in a wide frequency range, as seen in the corresponding gust spectrum of Fig. 1 b. The acrosswind component has significant energy content at frequencies ~ 0.028Hz (35s). Figure 1c provides the mean and extreme values of the drag and lift coefficients along the building height for wind angle 0º. The maxima of alongwind loads is in good accordance with the code-based design values (NBC, 2015).

2.3. Directional wind response at SLS and ULS

Bidimensional linear models of the structural system in the acrosswind and alongwind directions are developed in MATLAB using mass and stiffness data extracted from the 3D ETABS model. The 2D models approximate well the 3D system response in the linear range. Given that the model has neither geometric nor mass eccentricities and that the wind loads were lumped at the centre of mass of each floor diaphragms, there is no torsion issue. Figure 2 shows the peak alongwind and acrosswind response of the case study, in terms of service level drifts and accelerations under 1-in-10-years wind and shear demands at the strength level (1-in-500-years wind). The responses take their maximum values when the wind blows parallel to the short building direction (N-S, θ=0º). The drift is less than 1/500h_s code limit recommended by NBC; whereas the peak floor acceleration is lower than 15milli-g, an empirical threshold for occupant comfort.

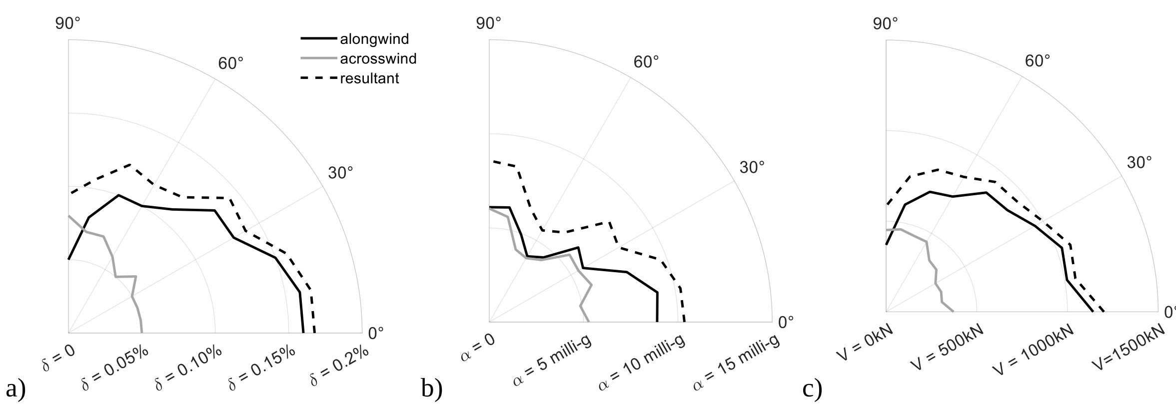

Figure 2. Peak response of the 15-st hospital in the alongwind and acrosswind direction, as a function of the wind attack angle in terms of: a) interstorey drift (SLS), b) floor acceleration (SLS) and c) storey shear demand (ULS).

2.4. Response beyond the design level, wind incidence angles 0º and 90º

Table 1 shows the acceptance criteria for several limit states for different occupancies associated to performance-based assessment of wind-excited buildings.

Table 1. Wind performance objectives and associated limit states

Limit state	Return period	Acceptance criteria
Serviceability LS (SLS in NBC, 2015) Occupant Comfort (OC-LS in ASCE,2019)	10 years	Linear response; drift ≤ 1/500 h_s accel. ≤ 15-25milli-g
Ultimate LS (ULS in NBC, 2015)	500 years (offices) 3,000years (hospitals)	Linear response
Continuous Occupancy LS (OC-LS in ASCE, 2019)	700 years (offices) 3,000 years (hospitals)	Controlled inelasticity allowed in detailed members
Collapse prevention (CP-LS in ASCE, 2019)	10,000 years	Damage allowed, no collapse

Incremental dynamic analyses (IDA) provide insight into building responses ranging from the linear to the nonlinear range. Figure 3 shows the wind IDA curves for acrosswind and alongwind loads acting at the hospital building face at angles 0º and 90º. Each curve shows the evolution of peak response, in terms of drift and floor acceleration, with increasing velocity intensity. Then, the data required to develop the fragility curves that map functionality to performance objectives, can be easily retrieved from the IDA curves.

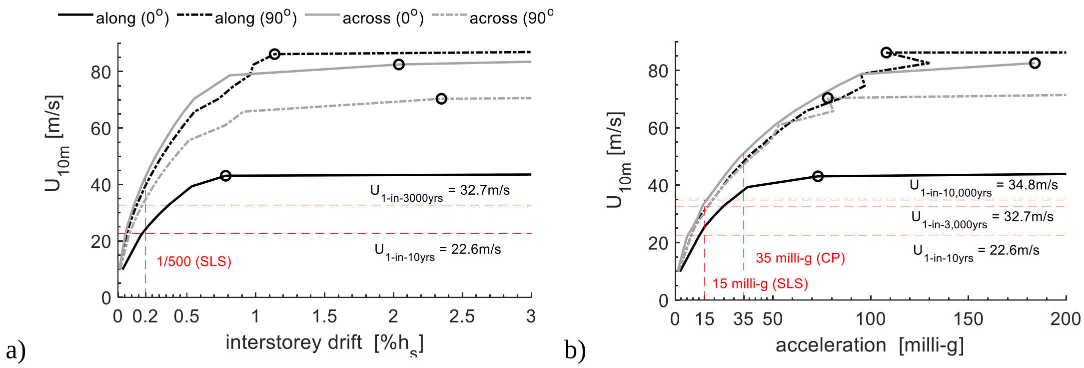

Figure 3. Alongwind and acrosswind IDA curves for wind incidence angles 0º and 90º, in terms of: a) interstorey drifts and b) floor accelerations. The collapse point is indicated by a circle.

3. CONCLUSIONS

A 15-storey hospital building in Montreal, designed to resist wind and earthquake, is subjected to acrosswind and alongwind loads derived from directional wind tunnel tests. The building response is assessed according to a performance-based framework, which encompasses: detailed models of structural system; consideration of the inherent CBF's members plasticity and system overstrength; nonlinear response history analyses at design level and beyond; investigation of directionality effects and establishment of acceptance criteria at predefined limit states. The preliminary findings show the overconservativeness of current wind design methodologies, the importance of considering directionality effects and reliable representations of the acrosswind loads in tall buildings, and stress the necessity to develop a robust PBWD method to achieve resilient built environment. Future work shall enhance the findings, considering taller buildings and further experimental data.

REFERENCES

ASCE, 2017. Minimum design loads and associated criteria for buildings and other structures. ASCE/SEI 7-16. Reston, VA: ASCE.

ASCE, 2019. Pre-standard for Performance-based Wind Design. American Society of Civil Engineers, Reston, VA.

Athanasiou, A., Tirca, L., and Stathopoulos, T., 2022. Nonlinear wind and earthquake loads on tall steel braced frame buildings. Journal of Structural Engineering, ASCE, 148(8): 04022098.

Kwon, D.K., and Kareem, A., 2013. Comparative study of major international wind codes and standards for wind effects on tall buildings, Engineering Structures, 51, 23-35.

Liang, S., Liu, S., Li, Q.S., Zhang, L., Gu, M. 2002. Mathematical model of acrosswind dynamic loads on rectangular tall buildings, Journal of Wind Engineering and Industrial Aerodynamics, 90, 1757–1770.

National Research Council of Canada, 2015. National Building Code of Canada, 14th ed, Ottawa, ON.

Solari, G. 1985. Mathematical model to predict 3-D wind loading on buildings, Journal of Engineering Mechanics, ASCE 111 (2), 254-276.

Tamura, Y., Yasui, H. And Marukawa, H., 2001. Non-elastic responses of tall steel buildings subjected to across-wind forces. Wind and Structures, 4(2), 147-162.

Tsukagoshi, H., Tamura, Y., Sasaki, A., and Kanai, H. 1993. Mathematical model of acrosswind dynamic loads on rectangular tall buildings, Journal of Wind Engineering and Industrial Aerodynamics, 46&47, 497-506.