Tall building synthetic aerodynamic wind load generation for preliminary design

M Mahdi Salehinejad [1,*], Yin Fai Li [1], Quincy Ma [2] and Richard George James Flay [1]

[1] Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, University of Auckland, Auckland, New Zealand

[2] Department of Civil and Environmental Engineering, Faculty of Engineering, University of Auckland, Auckland, New Zealand

M Mahdi Salehinejad	* msal381@aucklanduni.ac.nz
Yin Fai Li	fai.li@auckland.ac.nz
Quincy Ma	q.ma@auckland.ac.nz
Richard George James flay	r.flay@auckland.ac.nz

ABSTRACT

Despite the wide acceptance of the high frequency force balance and high frequency pressure integration wind tunnel techniques for obtaining wind loads for building final design, they are not very convenient for the preliminary stage of tall building design when the massing of the building is evolving rapidly, and a quick and flexible approach to wind loads is often preferred over accuracy. The most common procedure for generating wind loads in the pre-concept design stage is to use relevant codes and standards, but usually they are limited in their scope and may not be applicable for buildings that are taller than 200 m. Gust loading factor (GLF) schemes usually use frequency domain spectral analyses to estimate dynamic values of loads and wind-induced responses and are constrained by factors such as building shape and height. Also, standards and GLF schemes do not provide the time histories of the aerodynamic wind loads. This paper proposes a synthetic aerodynamic wind load distribution approach in the time domain to predict the time history of wind loads up the height of a tall building. A 1:300 scale rigid model of the benchmark tall building, International Association for Wind Engineering Building A, was selected for a wind tunnel investigation to obtain reference results for validation. From the comparison between the wind loading results from proposed approach and reference wind tunnel results, it is found that the proposed method can predict the time history of wind loads up the height of the tall building with acceptable accuracy for carrying out the preliminary stage of tall building design.

INTRODUCTION

Wind tunnel testing of scale models using the High-Frequency Force Balance (HFFB) and High-Frequency Pressure Integration (HFPI) approaches is currently the most reliable experimental method utilised in the wind engineering community to determine the aerodynamic wind loads on tall buildings (Salehinejad et al. 2024). Despite the wide acceptance of the HFFB and HFPI techniques, these approaches are generally too time-consuming for obtaining the wind loads for the pre-concept design stage when many different building shapes and structural systems are under consideration. Because of this, structural engineers are interested in using a fast and in-house method to gain preliminary approximate wind loads and torsion (Salehinejad and Flay 2021). The most common procedure for generating wind loads in the pre-concept design stage is to use relevant codes and standards, where applicable, but usually they are limited in their scope and may not be applicable for buildings that are taller than 200 m, have non-rectangular planforms, or have natural frequencies lower than 0.2 Hz . Gust loading factor (GLF) schemes usually use frequency domain spectral analyses to estimate extreme dynamic values of loads as equivalent static wind loads (ESWLs) and wind-induced responses. An improved 3D GLF framework have been established to predict the ESWLs in the across-wind as well as the along-wind direction (Kareem and Zhou 2003) and an aerodynamic base moment database beased on HFFB measurements in all three directions presented (Zhou et al. 2003). While valuable aerodynamic databases and semi-empirical formulae have been established through these GLF schemes using wind tunnel tests the development of such GLF schemes are limited by a multitude of factors such as building shape, terrain roughness, building height, linear/non-linear and uncoupled/coupled mode shapes, the number of mode shapes, and the effect of higher order mode shapes, and along-wind/across-wind directions. Also, standards and GLF schemes do not provide the time histories of the aerodynamic wind loads.

In this paper, a new framework is proposed to generate synthetic aerodynamic wind loads over the height of tall buildings for time domain application. The idea put forward in this novel synthetic aerodynamic wind load distribution (SAWLD) framework is to first simulate the time histories of the base building aerodynamic loading, and then to calculate realistic instantaneous time varying aerodynamic wind loading distributions up the height of the building that reproduce the building base loading. The SAWLD framework involves two parts: simulating base shear forces and moments using statistical information, and then applying the wind load distribution approach up the height of the building as published in (Salehinejad et al. 2024; Salehinejad et al. 2023). To obtain this statistical information without requiring wind tunnel testing, it is possible to use information published in the open literature that provides valuable aerodynamic databases and formulae based on building geometry and wind structure. A 1:300 pressure-tapped scale model of Building A, a benchmark tall rectangular building (Holmes and Tse 2014), was built and wind tunnel tested with the wind direction normal to the wide face of the building as the subject to evaluate the SAWLD method. To measure the surface pressure distributions, 396 pressure time histories were acquired from 18 levels of 22 taps. The pressure data were used to obtain reference wind load distributions. Subsequently, the vertical distributions of the aerodynamic wind loads were generated synthetically for same case using the proposed SAWLD approach with some selected statistical information available in the published literature ('NatHaz Aerodynamic Loads Database' ; Gu and Quan 2004) for comparison purposes.

THE NEW FRAMEWORK

The SAWLD framework includes two parts. In the first part, the base shear forces and moments are simulated synthetically using exisiting statistical information (mean and standard deviation values, frequency contents, etc.) of these base building loading time histories. This information serves as the input for the proposed SAWLD framework and can be obtained through ('NatHaz Aerodynamic Loads Database' ; Gu and Quan 2004) for the case study of this paper. Then the simulated base time histories are used to derive a wind load distribution up the building height in the time domain as output.

Building Base Wind Loading Simulation

The mean values of base shear force in the *x*-direction and base overturning moment force in the *y*-direction can be estimated as follows:

$$\bar{f}_{x_i} = 1/2\, \rho\, C_D U_i^2\, W\, \Delta H_i \tag{1}$$

$$\bar{F}_{x_{base}} = \int_0^H \bar{f}_{x_i}\, dz \tag{2}$$

$$\bar{M}_{y_{base}} = \int_0^H \bar{f}_{x_i}\, z_i\, dz \tag{3}$$

$$U_i = U_H \left(\frac{z_i}{H}\right)^{\alpha} \tag{4}$$

$$\Delta H_i = z_i - z_{i-1} \tag{5}$$

where z_i and U_i is the height and wind speed of the ith floor of the building, respectively. U_H, W, C_D, H, and ρ are the the wind speed at the top of the building, the width of the building, the drag coefficient, the overall height of the building, and the air density, respectively. The standard deviation value of base overturning moment force in the *y*-direction can be estimated as follows:

$$\sigma_{M_{y\,base}} = \sigma_{C_{My_{base}}} \times M'_D \tag{6}$$

$$M'_D = 1/2\ \rho\, U_H^2\, W\, H^2 \tag{7}$$

where $\sigma_{C_{My_{base}}}$ is the RMS base moment coefficient in the *y*-direction which can be obtain by choosing the appropriate side ratio, aspect ratio and wind terrain from the NatHaz Aerodynamic Loads Database (NALD) ('NatHaz Aerodynamic Loads Database'). The standard deviation of base shear force in the x-direction can be roughly predicted from $\sigma_{M_{y\,base}}$ as follows:

$$\sigma_{F_{x\,base}} \cong \frac{\sigma_{M_{y\,base}}}{H_{eq}} \tag{8}$$

$$H_{eq} = \frac{\bar{M}_{y_{base}}}{\bar{F}_{x_{base}}} \tag{9}$$

where H_{eq} is an equivalent lever arm for calculating the resultant moment from the resultant force.

Typically, in the case of most symmetric buildings, the mean base shears and base moments in the across wind direction are either negligible or zero when the wind is aligned normal to a flat face of a symmetrical building. To estimate the standard deviation values of the base shear force in the *y*-direction, and the base overturning moment in the *x*-direction, the semi-empirical formulae from (Gu and Quan 2004) are employed as follows

$$\sigma_{F_{y\,base}} = C'_{F_y} \times (0.5\, \rho\, U_H^2\ \ W\, H) \tag{10}$$

$$\sigma_{M_{x\,base}} = C'_{M_x} \times (0.5\, \rho\, U_H^2\ \ W\, H^2) \tag{11}$$

where C'_{F_y} and C'_{M_x} are the RMS coefficient of the base shear force and the base moment, respectively, which are provided based on wind terrain and building geometry parameters in (Gu and Quan 2004). Regarding the loading frequency content, it is possible to employ the spectra provided in the NALD database ('NatHaz Aerodynamic Loads Database') for both directions.

Wind Load Distribution Up the Building

Once the simulated base time histories have been determined, they are used to predict wind load distributions up the building height in the time domain using the method published in (Salehinejad et al. 2024). The simulated time hisories of base shears and moments are used with the relevant equations, instead of HFFB time histories, to estimate the the fluctuating wind loads in the translational directions (x- and y-directions) at building height z ($f_x(z,t)$ and $f_y(z,t)$). The sectional wind load coefficients along the principal axes, *x* and *y*, are defined in Eq. (12, 13)

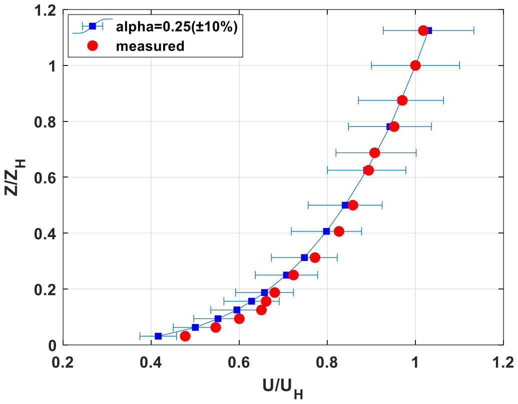
$$C_{F_l} = \frac{f_{l_{section}}}{0.5\, \rho\, U_H^2\ \ w(z)} \qquad with\ l = x, y \tag{12}$$

$$f_{l_{section}} = \frac{f_l}{\Delta H(z)} \qquad with\ l = x, y \tag{13}$$

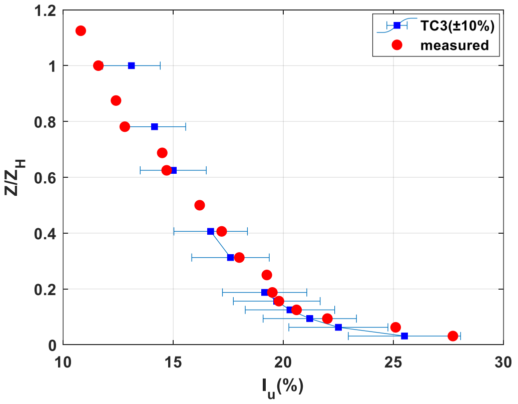
where f_l, $f_{l_{section}}$, and $w(z)$ are the wind load, the sectional wind load, and the width of the building, respectively.

EXPERIMENTAL SETUP

The HFPI test was conducted in the University of Auckland boundary layer wind tunnel. A suburban terrain flow was simulated. The mean wind speed profile followed a power law with an exponent $\alpha = 0.25$ equivalent to a roughness length of 0.2 m. This is consistent with Terrain Category 3 (TC3) as defined in the Standard AS/NZS 1170.2:2021. Figure 1 depicts the normalised mean velocity profile (with respect to the velocity at a reference height of 800 mm, the top of the Building A model) and the turbulence intensity profile. These profiles are compared with the target profiles specified in AS/NZS 1170.2:2021 for TC3.



a



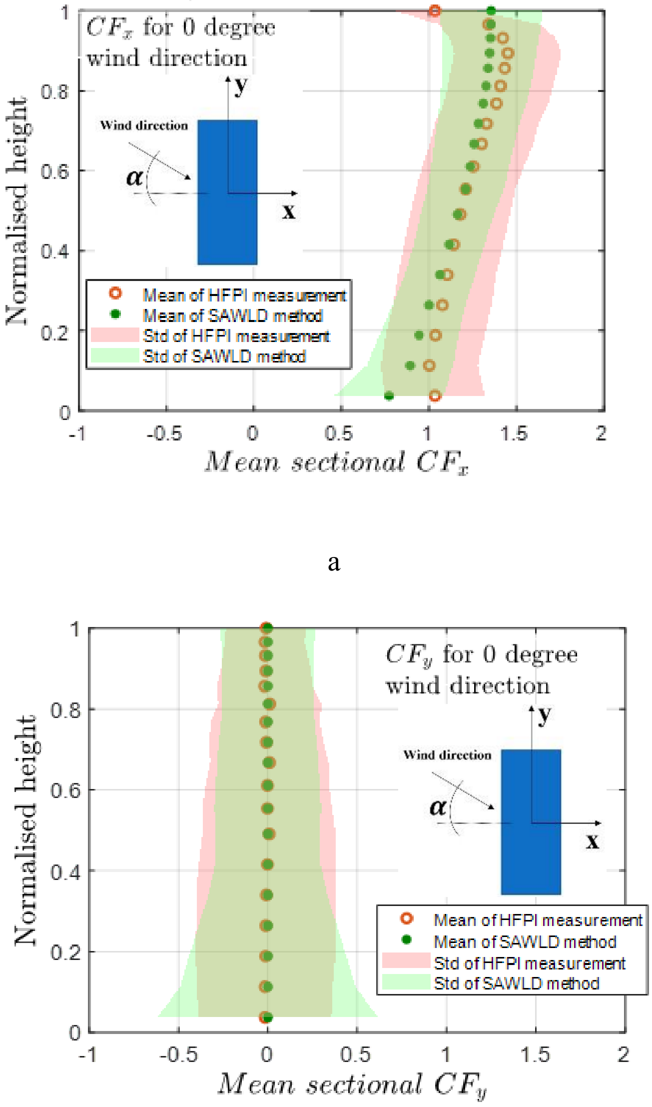
b

Figure 1. Wind tunnel flow simulation: a) Mean speed profile, b) Turbulence intensity profile.

Building A is a 240 m high rectangular cross-section building with plan dimensions 72 m by 24 m. Pressure data were acquired at a sampling frequency of 400 Hz and sampling period of 120 s.

RESULTS AND DISCUSSION

To validate the proposed SAWLD approach, mean sectional wind load distributions along the principal axes were calculated and are shown in Figure 2, where the SAWLD predictions are compared with the HFPI reference data for the wind directions of 0° (i.e. wind normal to the wide face). A range of +/- 1 standard deviations of the data are illustrated using coloured bands. The light green bands show results from the proposed approach and the pink bands show the pressure measurement results.



a

b

Figure 2. Comparison of mean wind force coefficients with ± 1 standard deviations for Building A for a wind direction of 0° estimated by the proposed SAWLD approach (green dots) using published base inputs, and the HFPI reference results (red circles).

To validate the SAWLD framework for the non-zero wind directions, the statistical information obtained through the HFPI approach is used as initial inputs for this framework to simulate the base building loading to predict the time histories of the aerodynamic wind load distribution on the model for different wind directions. Due to page limitations, further details could not be included. In general, the aerodynamic wind load results, including the wind load distributions and wind force correlation structures, for both the HFPI and the SAWLD methods follow similar trends and show good agreement. There are accurate predictions of wind load distributions over most of the building (especially from 0.2 to 0.8 of normalised height) from the proposed SAWLD method, but there are noticeable differences between the estimations and HFPI reference data at heights close to the top and base of the building (Figure 2 (a)). This is attributed to the complex three-dimensional flow structure in these regions (Simiu and Yeo 2019; Holmes 2015).

CONCLUSIONS

In this paper, a new SAWLD approach is presented for time domain application to generate the time histories of aerodynamic wind loads up the height of a tall building. The HFPI measurements were conducted to calculate reference wind load distributions for validating the proposed method. The results demonstrate that the proposed approach can predict the wind loads in the translational directions with reasonable accuracy for carrying out the preliminary stage of tall building design. These predictions enable the estimation of wind-induced and dynamic responses for tall buildings with various mode shapes in the time domain.

Reference List

Gu, M., and Quan, Y., "Across-Wind Loads of Typical Tall Buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, (2004), 92: 1147-65.

Holmes, J. D. (2015). *Wind Loading of Structures* (CRC press).

Holmes, J. D., and Tse, T. K., "International High-Frequency Base Balance Benchmark Study", *Wind and Structures*, (2014), 18: 457-71.

Kareem, A., and Zhou, Y., "Gust Loading Factor—Past, Present and Future", *Journal of Wind Engineering and Industrial Aerodynamics*, (2003), 91: 1301-28.

'NatHaz Aerodynamic Loads Database'. http://aerodata.ce.nd.edu/.

Salehinejad, M. M., and Flay, R. G. J., "A Review of Approaches to Generate Equivalent Static and Synthetic Wind Loads on Tall Buildings for the Preliminary Stage of Design", *Journal of Wind Engineering and Industrial Aerodynamics*, (2021), 219: 104823.

Salehinejad, M. M., li, Y. F., Ma, Q., and Flay, R. G. J. (2023). A Wind Load Distribution Approach for Tall Buildings Based on High Frequency Force Balance Measurements. In 16th International Conference on Wind Engineering ICWE2023. Florence, Italy.

Salehinejad, M. M., Li, Y. F., Ma, Q., and Flay, R. G. J., "Formulation of Justifiable Wind Loading Distributions up Tall Buildings Derived from Hffb Measurements", *Engineering Structures*, (2024), 303: 117455.

Simiu, E., and Yeo, D. (2019). *Wind Effects on Structures: Modern Structural Design for Wind* (John Wiley & Sons).

Zhou, Y., Kijewski, T., and Kareem, A., "Aerodynamic Loads on Tall Buildings: Interactive Database", *Journal of Structural Engineering*, (2003), 129: 394-404.