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Vibration of tall buildings under wind loads

Padilha, A. Caio[1], Vieira D. Janine[1], Carvalho L. M. Eliane[1]

[1] *Civil Engineering Department, Universidade Federal Fluminense (UFF)*
Rua Passo da Pátria, 156, São Domingos, 24210-240, Niterói/RJ, Brazil
caioandrade@id.uff.br, janinedv@id.uff.br, elianemaria@id.uff.br

Abstract. The evaluation of the dynamic response of tall buildings exposed to wind loads is an important complex subject that is usually treated through different simplify method which are addressed in this study. The first one is Mario Franco's "Synthetic Wind Method", which allows simulating the fluctuation of the wind from the superposition of harmonics obtained from a power spectrum of wind speed. It was also studied methods for the assessment of dynamic torsional moments caused by turbulent wind, and its influence on the total dynamic response of tall buildings. The torsional dynamic wind loads were simulated trough literature available power spectra. All load methods were addressed on case studies which involved two different tall buildings modelled on commercial software's based on Finite Element Method. It was observed that reliability of the obtained results depends strongly on the choosing of the method appropriate for the buildings geometry. Also, the disregarding the floating torsional moments due to wind load in the dynamic analysis of tall buildings can lead to major error in the human comfort analysis.

Keywords: Dynamic analysis; Reinforced concrete buildings; Wind action; M. Direct Wind; Wind-induced Torsion.

1 Introduction

The measuring of dynamic effects caused by wind on tall structures is a matter of growing importance, with the current construction trend of tall and slender buildings. In this sense, there are several formulations that allow us to describe floating wind in its along-wind action. However, the torsional action caused by wind on buildings is of more complex to evaluate, as the torsional moments power spectra are functions of more factors such as the buildings shape, atmospheric turbulence, and surrounding buildings. It is important to considerate the torsional effects of wind when calculating the dynamic response of buildings, as combined to along wind loads for accessing serviceability and ultimate limit states. In current available literature, it was not found any studies related to the combined effects of dynamic torsional moments and pressure induced by wind, when acting simultaneously. Therefore, the full superposition of those actions were adopted as a worst case scenario, leading to upper limits of the total dynamic response. Thus, the aim of this study was to evaluated the effects of the torsional moment due to the wind in the dymanic responses of two slender buildings with different cross sectional shapes.

2 Methodologies for dynamic analysis of buildings under wind action:

It was considered that the torsional effects caused by wind on buildings may occur simultaneously with along wind fluctuating pressure, and so allowing the calculation of an upper limit to the dynamic response of buildings under wind action.

2.1 Simulation of wind action

The fluctuating pressure was simulated by using the Synthetic Wind Method [1], where the wind loading was obtained by the superposition of harmonic functions with random phase angles. In this method, the total loading is represented by a sum of wind harmonics, defined on the expression (2.1).

$$p'(t) \cong \sum_{k=1}^{m} c_k p' \cos\left(\frac{2\pi}{T_k} t + \phi_k\right). \tag{2.1}$$

Where:
p' is the total fluctuating pressure load;
c_k is a coefficient based on wind velocity spectrum integration;
T_k is the period of the harmonic k;
ϕ_k is a random phase angle.

For the simulation of torsional floating loads, it was used the Harmonic Superposition Method [2], through a power spectrum available in literature. In order to simulate wind's stochastic nature, it was used random phase angles for each harmonic, and the characteristic response was extracted by statistical treatments. The torsional total loading is represented by the expression (2.2).

$$M_T(t) = \sqrt{2} \sum_{k=1}^{N} \sqrt{S_u(f_k)\Delta f} \cos(2\pi\, f_k\, t + \phi_k) \tag{2.2}$$

Where:
$M_T(t)$ is the time torsional moment;
S_u is obtained from the density spectrum of torsional dynamic moment;
f_k is the frequency of the harmonic k;
Δf is the value of the frequency increment used in the integration of the power spectrum.

2.2 Torsional wind power spectrum

To simulate the torsional wind dynamic loads, it was used two different spectrum available in literature as described below:

In Carini's [3] approach, although the formulation presents curves of the power spectrum of the torsional moment due to the action of the wind for structures with different geometries, in the case of buildings with rectangular cross section, the formulation of the power spectrum presents a softened peak, resulting in lost of precision, as the real spectrum presents higher peaks.

Liang [4], in his work analyzed only rectangular shaped buildings, presenting formulations that lead to sharp peaks on power spectra, and that better represents such buildings on that matter. However, In the case of different shaped buildings, the energy distribution on the power spectra may lead to very conservative results. If the frequency peak is not close to the structure's torsional mode frequency, the results could be non-conservative.

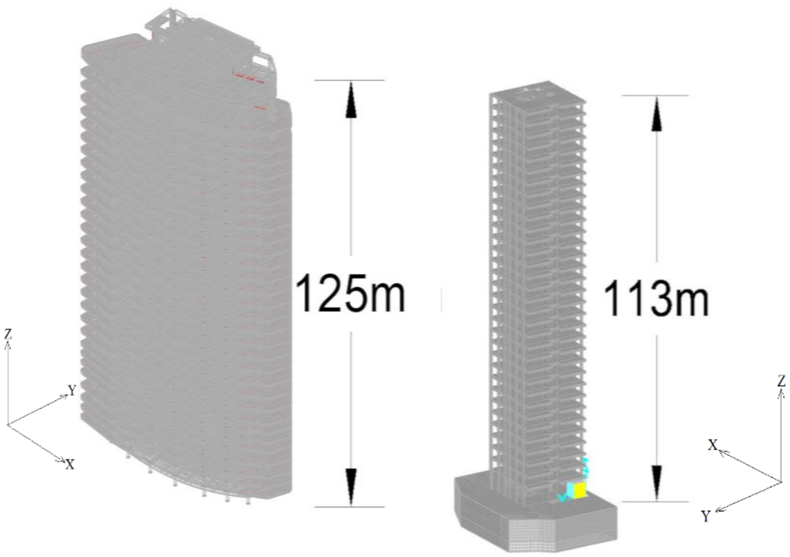
3 Case Studies

3.1 Description of the buildings

For the case studies, two buildings were analyzed, one measuring 125m of height with irregular shaped section (Building1 – B1) and the other with123m of height and square cross section (Building 2 – B2). Figure 1 shows the 3D views of the buildings.

3.2 Numerical Modelling

The structures were modelled using commercial software SAP2000 based on the finite-element method, with shell elements for the floor slabs and shear walls, and frame elements for the columns and beams. Stiffness reduction by concrete cracking was not considered for the serviceability dynamic analysis.



Building 1 – B1 Building 2 – B2

Figure 1 - Schemes of the analyzed buildings.

3.3 Modal Analysis

The first performed analysis for the buildings was the undamped free-vibration modal analysis, allowing to identify the buildings natural frequencies and compare them with power wind spectra. Figure 2 presents the results for the three first vibrations modes of the two buildings.

After the modal analysis, it was noted that both buildings have natural frequencies located on zones of considerable energy of power wind spectra, therefore susceptible to resonance phenomenon. Figure 3 shows the velocity along-wind action and torsional moments power spectra, used in the time domain analysis.

3.4 Time Domain Analisys

From the spectra presented in Figure 3, time history loads were simulated for drag forces (Figure 3a and equation 2.1) along wind direction and the torsion moment (Figure 3b and equation 2.2). These loads were applied in the model for each analyzed load case considering variety of wind directions and phase angles for the random harmonics.

The fluctuating wind pressure was applied as a distributed load on the beams and the torsional moments through nodal concentrated force torques in the numerical model (Fig.4).

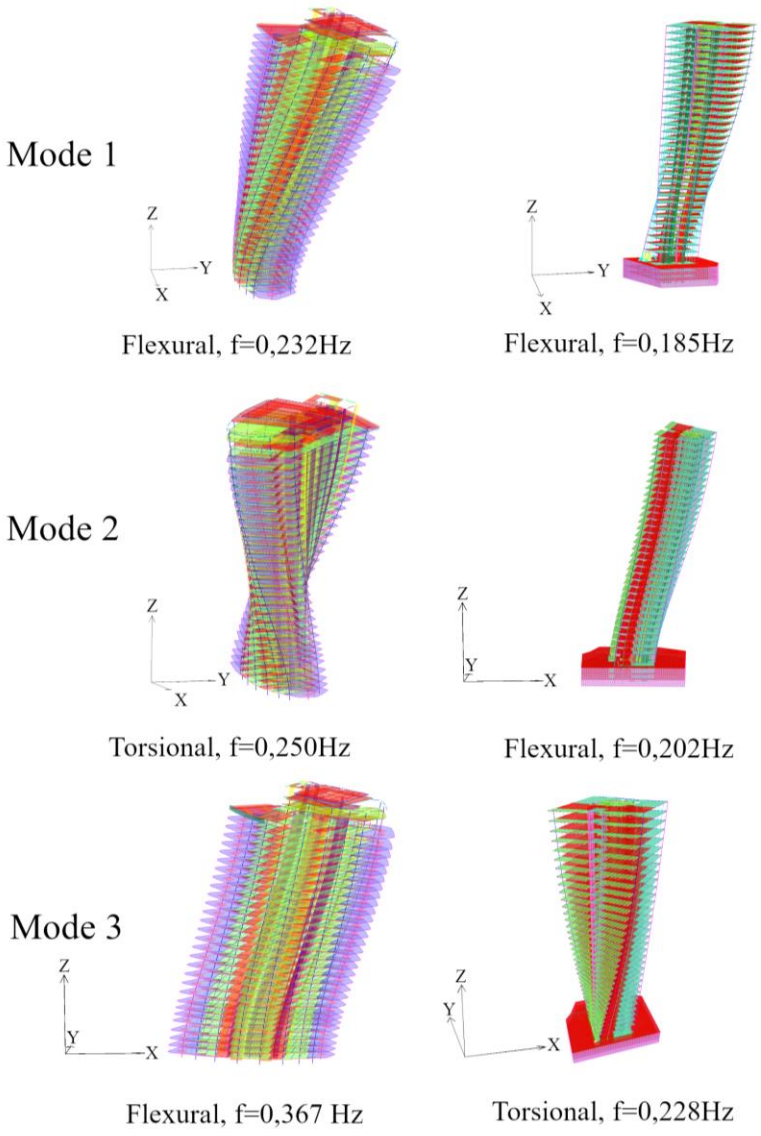
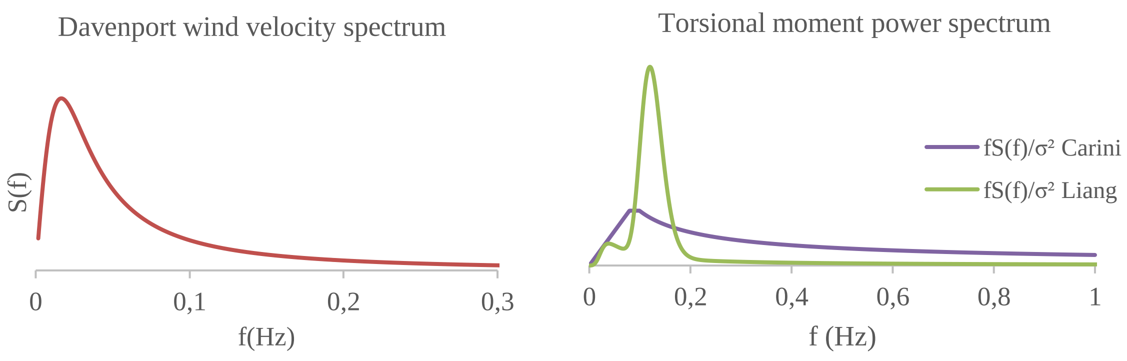


Figure 2 – Modal analysis results of the buildings.



(a) (b)

Figure 3 – (a) velocity along-wind power spectra for 38 m/s wind; (b) torsional moment spectra (Building 1)

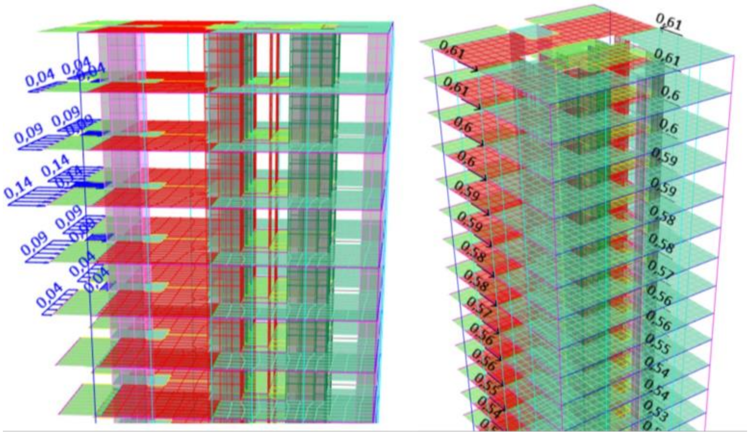


Figure 4 – Applied loadings on Building 2.

The top floors of the buildings have a high occupancy rate and present the maximum accelerations. Thus, the responses were monitored at specific points at those level of the structures, as shown in Figure 5.

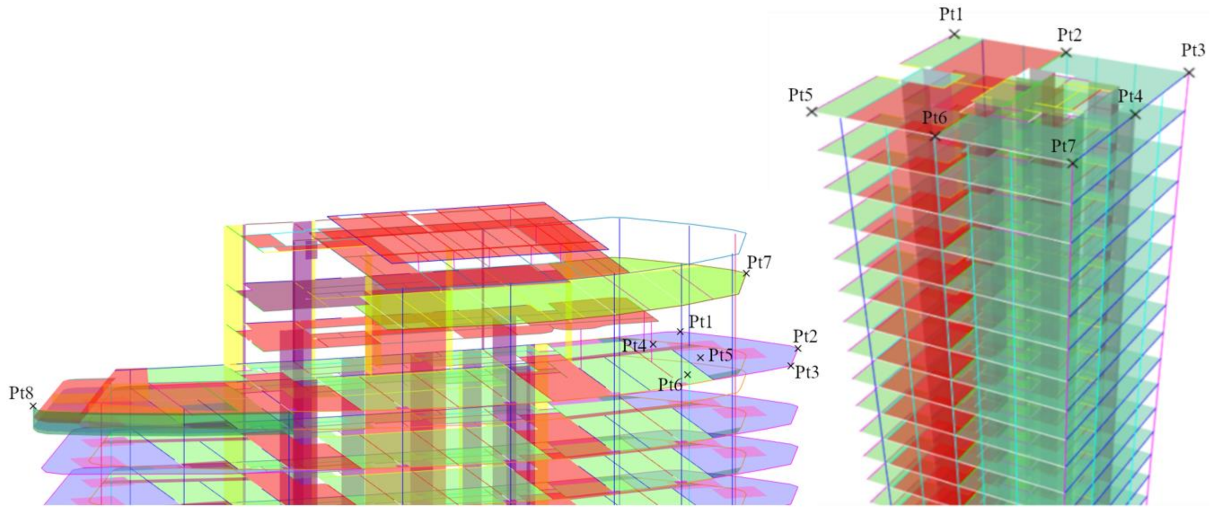


Figure 5 – Observed points of the acceleration responses on the buildings.

4 Results and Discussion:

Figure 6 presents the acceleration responses at point 2 of building 1. Figure 6a shows the response for load along wind while figure 6b shows the total response also considering the torsional moment. It can be observed that the peak value of acceleration for load along wind was 0,088m/s² while for the total response the peak value was 0,147m/s². Figure 7 shows the frequency spectra obtained from the time history accelerations for the same point 2 of building 1.

It is notable for this case the participation of both torsional and flexural modes on the response spectrum (Fig.7). It can be observed that the highest peak on the spectrum is due to dynamic pressure, but the torsional moment load excites more than one global mode, and so doing an important participation on the total response.

For Building 2, square shaped cross-section, the acceleration increase was of 74%, going from 0,101m/s² to 0,176m/s². Similar behavior of the responses to the Building 1 is noted (Fig. 6), with the main difference that the acceleration increases significantly on all the building periphery, meanwhile in Building 1 this is limited to the extreme spots along the greater dimension of the building.

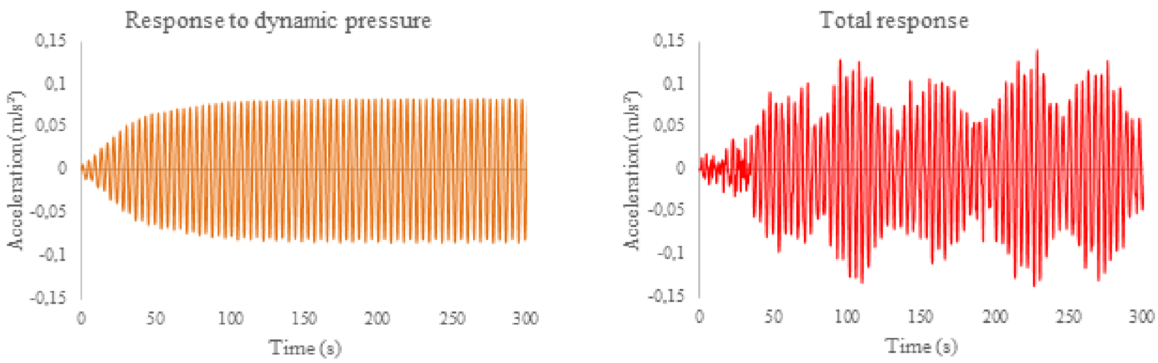


Figure 6 – Time history of Y acceleration for control point 2 on Building 1 for the dynamic pressure load case and combined load case, with Y direction wind.

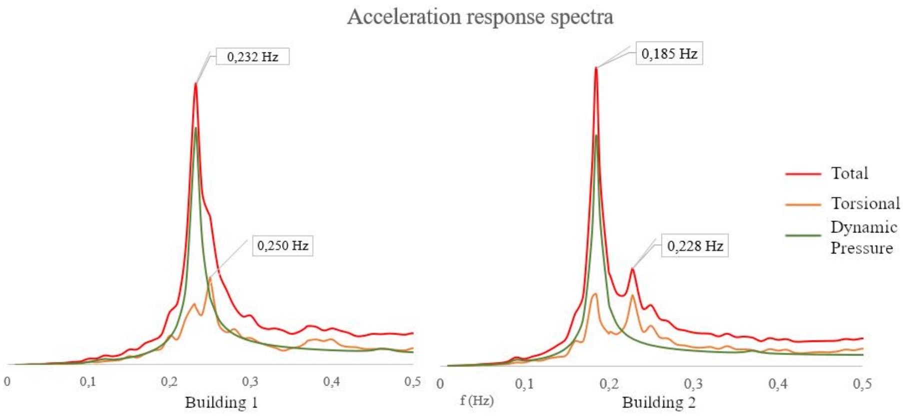


Figure 7 – Response spectra for Y direction acceleration, for control point 1, of Building 2, with Y direction wind, using Liang formulation for torsion power spectrum.

Maximum accelerations for Buildings 1 and 2 for all simulated cases are presented on Figure 8, and the corresponding simulation cases are listed on Table. 1

Table 1 – Wind direction and power spectra used for load case definitions.

Building 1	1	2	3	4
	Y wind, S(f) Carini	Y wind, S(f) Liang	X wind, S(f) Carini	X wind, S(f) Liang
Building 2	5	6	7	8
	Y wind, S(f) Liang	Y wind, S(f) Carini	X wind, S(f) Liang	X wind, S(f) Carini

By comparing the maximum acceleration results, for the taken control points on the structures in each considered wind load conditions, it becomes clear that the torsional loads cause significant responses, as the accelerations have the same magnitude as the dynamic pressure induced. Also, the combination of those, although not fully adding the amplitude of each response, leads to significant raises to the acceleration values.

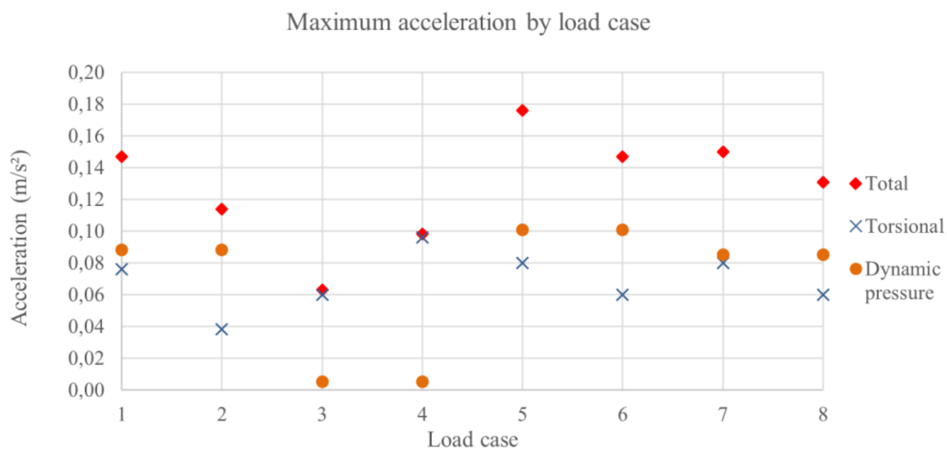


Figure 8 – Maximum acceleration for simulated wind load conditions

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5 Conclusions

For every simulated case, it is noted that the combination of torsional loads induced by wind significantly increased the acceleration peaks, as compared to the fluctuating pressures only analysis. However, some generalist hypotheses were taken for the calculations which might lead to super conservative results, as for the Strohudal number and rms torque coefficient .

The present work shows the importance of considering combined torsional and dynamic pressure loads on tall building analysis, while presenting a methodology for the calculation of upper limits to the combined responses. While we still lack information on how the torsional moments and dynamic pressure may occur simultaneously, the full combination of those may be useful in practical problems as preliminary studies, being performed prior to wind tunnel tests.

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