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Impact of structural design criteria on the comfort assessment of tall buildings author names and affiliations

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A B S T R A C T

Assessing tall building oscillation due to wind-induced motion is a multidisciplinary task that involves knowledge from several fields of study, including: structural engineering, wind engineering, reliability, and even human physiology. With the modern high strength structural materials and the latest tendencies in tall buildings construction, new structural systems have become slender and new buildings have reached greater heights as time passes. This context leads to a situation where these slender structures become sensitive to the dynamic effects of wind loads, case in which the human comfort is often the prevailing criterion for the structural design. This paper addresses criteria from finite element modelling, modal truncation, wind directionality, and comfort assessment applied to two building studies (buildings A and B) subjected to wind tunnel testing. Then, the impact of structural design criteria on many different disciplines is exposed, establishing a comparison between different criteria. This investigation intends to bring precision to the procedure, while creating a reliable set of criteria to perform an assessment of the dynamic response from the wind tunnel testing of tall buildings.

1. Context, introduction and reasons for the study

1.1. Context

In today's context of big cities, the category of tall building construction has quickly gained ground due to environmental and economic issues (Ali and Moon, 2007; Drew et al., 2014). These new constructions require extensive and multidisciplinary knowledge to make them feasible, leaving a great deal of responsibility to a multidisciplinary group of areas of study: structural engineering, wind engineering and comfort assessment. This paper is focused on the understanding of the set of criteria of each discipline, on the use of these data to perform a tall building's motion assessment, and on the impact of each criterion on the final motion assessment.

Latest advances in structural materials, including 65psi (450MPa) high strength steel, high strength concrete, and new composite structures allow for a great reduction in the use of material in tall buildings (Rosa et al., 2012; Sarkisian, 2012). These improvements enable both slender structures and slender structural systems, which lead to an overall reduction of the building stiffness. These slender structural systems are commonly used in tall building design and often present fundamental modes of vibration with a behavior very similar to a cantilever beam (Wu et al., 2007; Sarkisian, 2012).

Moreover, these structural systems often present important torsional modes of vibration and a greater number of natural frequencies under 1.0Hz, making them more susceptible to dynamic effects of wind loads (Rosa et al., 2012). These circumstances emphasize the importance of service limit state (SLS) studies on tall buildings for comfort assessment when compared to ultimate limit state (ULS), due to: higher modal contribution, torsional acceleration and cantilever behavior of the structural system (Hansen et al., 1973; ISO10137, 2007; Kim et al., 2009; Rosa et al., 2012).

1.2. Introduction: structural data, wind tunnel testing and comfort assessment

The structural data have a clear importance in the assessment of the response of wind-induced motions in tall buildings. For a specific approach to structures of multi-story tall buildings subjected to wind tunnel testing (WTT), these data can be summarized as: natural frequencies; mode shapes or mode deflection shapes; mass matrix; and damping of the system.

Finite-element (FE) models are not always as precise as they might look when it comes to finding out the natural frequencies of a building.

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Kim et al. (2009) performed field measurements in three buildings to acquire the first three natural frequencies of each building, and found discrepancies of up to 33% between the measured values and the results of the finite element model. The results showed a great underestimation of the natural frequencies for the FE models, where the authors investigated the phenomena through several axes of investigation, among which the most relevant ones for this paper were the flexural stiffness of floor slabs and the increase in the modulus of elasticity of structural members due to concrete ageing. Structural data are gathered and analyzed for both buildings (A and B) for different FE models and for different sets of criteria, concrete ageing, and floor slab modelling. Then, dynamic responses are analyzed for the different models created.

The increased modulus of elasticity is the Young's modulus for "$t \to \infty$" in eq. (1) of the Brazilian concrete code NBR6118-2014. This equation shows the increase in the elasticity modulus with the increase of the concrete age "t":

$$E_{Ci,\infty} = \lim_{t\to\infty} E_{Ci,28}\left\{\exp\left\{s\left[1-(28/t)^{0.5}\right]\right\}\right\}^{0.5} = E_{Ci,28}\exp(s/2) \qquad (1)$$

where:

- $E_{Ci,28}$ is the Young's Modulus of the concrete after 28 days, according to NBR6118-2014;
- s is a coefficient depending on the category of cement: in the tall buildings analyzed in this paper, this coefficient has the value of 0.25;
- $E_{Ci,\infty}$ stands for the Young's Modulus of the matured concrete, referred to here as probable E.

The schematics of the categories of concrete strength for each structural element are given in Fig. 1 for both buildings (buildings A and B). The studies of Kim et al. (2009) showed a sensitive increase in the natural frequencies of buildings due to concrete ageing (up to 12%), which lead to an important effect in the final acceleration assessed on the top of the building.

Intended for the scope of wind effects on tall buildings, a lumped mass system approach was used to model the dynamic behavior of the structure (NBR6123, 1988; Rosa et al., 2012). Based on the rigid floor diaphragm hypothesis, this approach neglected in-plane floor deformations and the restricted motion of each floor to three degrees of freedom (DOF): translations on x and y-axes and rotation around the z-axis of the building (Rosa et al., 2012).

As for the damping ratio, there are several types of damping that might contribute to the control of a tall building's motion, including: structural damping "ζ_s"; damping ratios "ζ_d" originated by dampers; and aerodynamic damping "ζ_a." In the case studies conducted in this paper, the overall damping value will be equal to 1.25% for building A and 1.00% for building B, which is consistent with the results obtained by Wu et al. (2007) for the overall damping during SLS winds, and with the Brazilian wind code NBR6123, 1988.

The WTT of both buildings used the high frequency pressure integration (HFPI) method. Along with the building's structural data, this test can evaluate overall forces at the base (background and resonant), and modal loads acting on each mode of vibration. In addition, due to the assessment of precise loads over the building's height, this test allows for a better evaluation of higher modal loads, i.e., for modes of vibration after each fundamental sway/torsional mode (Irwin et al., 2013). Moreover, this test provides a detailed time history of loads distribution on the building's façade, enabling a precise time domain analysis. These features make the HFPI a powerful tool to evaluate the responses of tall buildings to wind-induced loads.

Finally, the users' comfort during motion in this paper was evaluated by the acceleration at the floor of interest (in the case studies it was the highest occupied floor). Lateral drift, angular velocity, angular acceleration (yaw), derivative of acceleration (jerk), and frequency of movement are important parameters, as well as age, body posture, and quality of insulation, among other physiological and psychological features. These parameters and features were extensively discussed by Ferrareto et al. (2015), from where we gathered the compilation of comfort criteria used in this paper for the current approach to human comfort. This compilation represents the current and most frequently used assessment criteria, according to several national/international standards.

1.3. Reasons for the study

Nowadays, most of the responsibility for the post-treatment of WTT's results lies mainly on the hands of the wind tunnel facility, with the exception of structural data. With the set of criteria studied in this paper, WTT's results may achieve more accurate results and so may structural engineers.

As a final point, this paper brings knowledge about the impact of structural design throughout different disciplines and intends to bring better understanding and verification tools for the whole procedure to all fields of study that take part in the WTT. This paper provides tools to enable control and responsibility increasing the role of the structural engineer during the WTT's analysis of results.

2. Case study and methodology

The choice of the tall buildings studied in this chapter is justified by their representative features when it comes to their technical context and location. Together, the buildings represent two of the most used

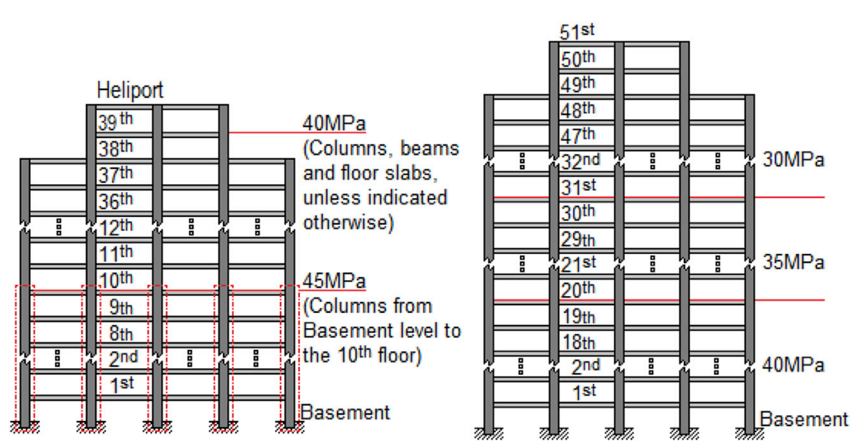

Fig. 1. Concrete strength for each building: A (left) and B (right).