Exploring wind engineering challenges in super-slender buildings

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1 INTRODUCTION

In recent years, there has been a remarkable surge in the design of tall and supertall buildings, characterized by increasing heights and slenderer profiles. This trend poses significant challenges to wind and structural engineers in particular with respect to vortex-induced responses that tend to occur well within the design wind speeds (e.g., [1]). Recently, a project for a 2 km skyscraper in Riyadh has commenced which exceeds twice the current height record. This advancement in engineering and architecture could suggests that buildings below 200 m could be designed and constructed without notable challenges in terms of wind action. However, the importance to build structure in prime locations has led developers and designers to build tall building with smaller and smaller footprints introducing therefore a new category of structures of relatively standard height but that can be considered super slender. Moreover, to optimize floor space usage, these buildings often adopt a uniform cross-sectional design, which can lead to enhance wind responses.

This paper presents findings from a series of wind engineering studies based on high-frequency pressure integration wind tunnel tests (HFPI) on similar super slender buildings. These experiments were aimed at evaluating the wind effects relevant to the structural and serviceability design of nine tall and slender buildings located in the same region of South America. All of them share common geometrical features, such as small footprint dimensions, and heights not exceeding 250m, reaching an extremely high slenderness aspect ratio. Additionally, all buildings exhibit structural properties indicating frequencies significantly lower than those predicted by internationally recognised codes and standards. Across all cases, notable vortex-induced vibrations were observed, leading to elevated base loads and accelerations surpassing maximum recommended criteria (e.g., [2]-[4]).

2 CHARACTERISTICS AND PROPERTIES OF THE TALL BUILDINGS

All the structures studied in this paper are residential concreate building characterised by heights ranging from 140 m to 220 m, and mass densities between 300 kg/m^3 to 500 kg/m^3. The cross-sections of the buildings are nearly constant with height, and are characterized by an aspect ratio ranging from 1 to 2.5. Only two of the buildings exhibited aspect ratios significantly greater, approximately equal to 5. Based on the definition reported in [5], the slenderness ratio can be defined as

$$\lambda = \frac{H}{\sqrt{BD}} \tag{1}$$

where H is the reference height of the building, and D and B are the main section dimensions. All the buildings are characterized by a slenderness ratio ranging from 1:6 and 1:11, approximately. BMT Fluid Mechanics (BMT) conducted a study of several tall building in 2017 and have built a large database [6]. The authors have reviewed the slender ratios for the proposed buildings and, comparing these slenderness values with the BMT database, noted that these are significantly lower than the expected ones. In particular, Figure 1-A illustrates the comparison between the buildings object of this study and the BMT's prediction trend line. However, it is important to emphasize that the slenderness definition provided by formulation (1) may be misleading when the cross-sectional aspect ratio is particularly high. For instance, in two cases with an aspect ratio of five, the slenderness ratio can increases substantially using the reference height and the smallest dimension, moving from 6 to 14, and from 8 to 17. Adopting the smallest dimension for slenderness assessment in elongated cross-sections can offer a clearer understanding of the real potential structural issues.

Beyond the notable geometric challenges, these buildings are also characterised by dynamic properties that are considered potentially problematic in terms of wind-induced effects. Indeed, the fundamental bending modes of these structures are associated with natural frequencies ranging from 0.15 Hz to 0.25 Hz, which are significantly lower than the approximated values provided by Eurocode [7], but not so far

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from the expected BMT values ([6]). Figure 1-B shows the comparison between the buildings properties object of this study, the BMT and Eurocode 's expected lines.

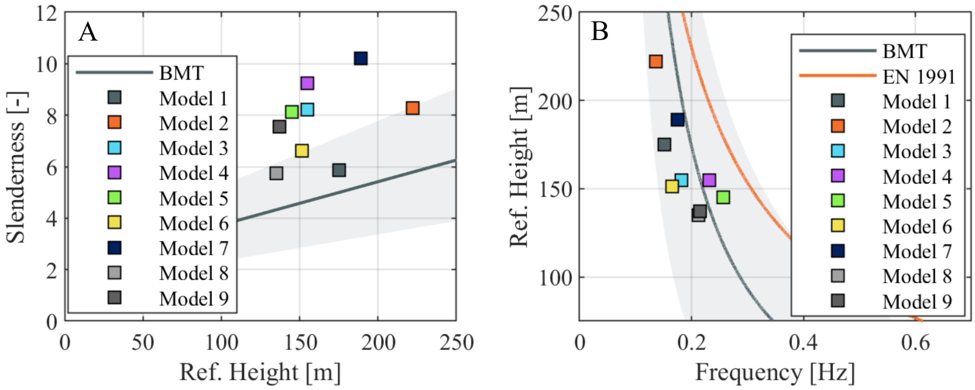

Figure 1, A) Comparison the BMT expected values [6] and the slenderness of the studied buildings. B) Comparison the BMT expected values [6], Eurocode [7], and the provided frequencies

From the outset, preliminary observations of the geometric and structural characteristics of these buildings indicate potential and significant issues associated with wind loading. The pronounced geometric slenderness, coupled with a low structural frequency and a uniform cross-section along the height, creates a potentially critical situation. It is likely that, following the wind tunnel studies, these structures will require substantial structural modifications to mitigate both wind loads and accelerations.

3 LOCATION

These building have been selected for the present study since they were tested in similar wind conditions, both in terms of wind and turbulence profiles, adopting a similar surrounding condition. Indeed, all the structures will be built in the same city area of Brazil. Such city is one of the Brazilian areas that has recently experienced a notable surge in construction activity. This growth has been particularly marked by the rapid increase in luxury residential high-rise towers. Currently, the area is primarily characterized by medium to high-rise residential and commercial buildings situated to the south, southwest, west, and northwest of the town centre. The open sea adjoins the developments to the northeast and east. Figure 2 showed an approximate location for all the studied buildings within the surrounding area.

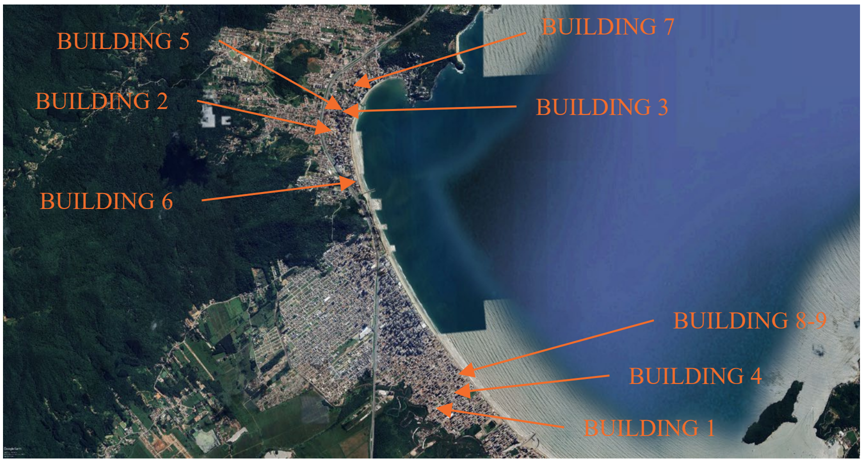

Figure 2 Location of the studied buildings.

4 METHODOLOGY

4.1 Facility and experimental conditions

The wind tunnel experiments were conducted in the closed-loop subsonic wind tunnel at the DICCA laboratory, University of Genoa. This facility features a test chamber with a cross-sectional area of 1.7 × 1.35 m (width × height). The facility is equipped with a simultaneous 368-channels low range pressure

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scanning using Sensor Techniques low range SLP004D differential transducers. The frequency response of the transducers is 2000 Hz.

The wind tunnel tests were conducted by simulating the appropriate boundary layer profiles of the area. Both mean wind and turbulence profiles were reproduced in the wind tunnel, with all dimensional quantities scaled according to the geometric model scale. Measurements were taken for a full range of wind directions in increments of 10°.

4.2 Wind tunnel models

All models were constructed at a geometric scale of 1:300-400. The 3D printed models of the buildings were developed with sufficient details to accurately replicate full-scale flow characteristics and with the highest geometrical precision allowed by the small scale and available prototyping tools. Each model, fabricated using state-of-the-art rapid prototyping (RP) techniques, was fitted with the maximum number of pressures taps appropriate for the chosen scale, capturing all relevant aerodynamic behaviours of the model. Figure 3 shows some examples of wind tunnel models.

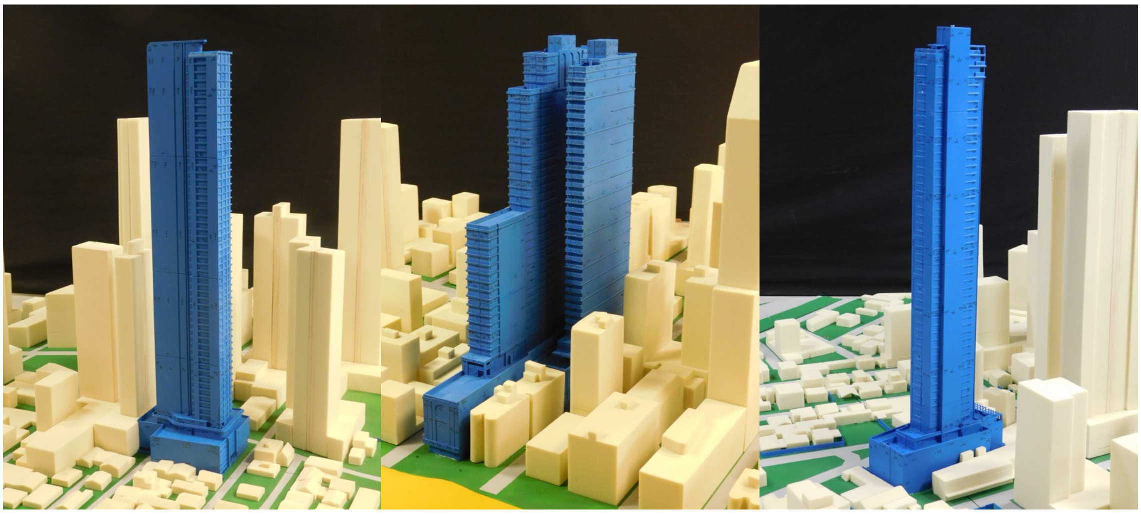

Figure 3, Example of wind tunnel models.

5 RESULTS

Design wind loads (in terms of dynamic base and floor-by-floor loads) have been assessed based on 50-year return period, considering a damping ration of 1.5% (fraction of critical) for each building based on the same design wind speed. Regarding serviceability design, namely wind-induced building accelerations, the building responses have been assessed based on the 1- and 10-year return period design wind speeds at the highest occupied level of each building. Both design loads and serviceability have been estimated in conjunction with the use of uniform directional factors.

The along-wind response derived from HFPI technique have been found to be either lower than or comparable with the values derived from a direct code approach. However, the cross-wind response exhibited a significant dynamic amplification, especially for the wind directions orthogonal to the main axes of the structure. Analysing the base load results, the Dynamic Amplification Factor (DAF) was assessed from the peak static and dynamic responses in each direction. Among the buildings described in this paper, a statistical mean DAF value of 3.2 was determined, with the exception of two cases where the buildings exhibited significantly higher values due to their direct exposure to the most severe wind direction.

Similarly, the acceleration values for 1- and 10-year return periods, were found to be substantially above the recommended limits (e.g., [2]-[4]). In most cases, these extreme accelerations values are attributed to the dynamic response induced by vortex shedding for a narrow wind sector in which the wind action is orthogonal to the main axes of the structure. Figure 4 shows the acceleration results for all the buildings compared with the adopted recommended limits.

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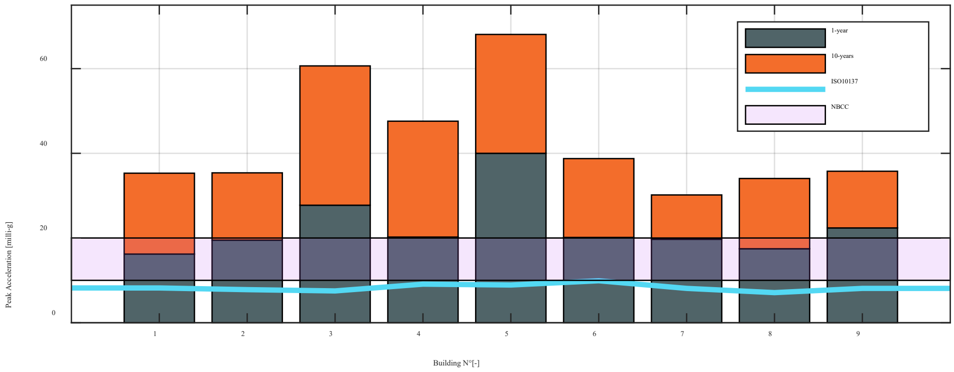

Figure 4, Accelerations results compared with recommended limits for residential buildings ([2]-[4]).

All the aforementioned results pertain to the initial properties of the building as provided by the structural engineers. Additional analyses were conducted based on increased natural frequencies to ensure alignment with relevant standards and code prescriptions. In some cases, revisions to the external envelope of the buildings were implemented to mitigate dynamic responses.

6 CONCLUSION

The primary objective of this paper is emphasizing that slenderness plays a key role in the wind response of a tall building and combined with other factors such as the key dimensions of a footprint, may result in accelerations well above the recommended criteria. Buildings are progressively becoming increasingly slender to maximize the available space, defining new emerging category of super-slender buildings. However, due to these peculiar properties, It would be beneficial for such structures, due to their unconventional design, to be designed based on an aerodynamic shape optimization conducted during the schematic design phase, potentially focusing on corner modifications (e.g., [9], [10]). Implementing these optimizations has the potential to reduce wind loading, resulting in a slimmer structural system that maximizes available footprint space. Furthermore, by integrating aerodynamic principles into the design process, engineers can not only improve structural efficiency but also promote environmentally conscious practices, aligning with global sustainability objectives.

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