Experimental investigation of thunderstorm effects on tall buildings

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SUMMARY:
In mixed wind climate, thunderstorms can strongly influence the design wind speeds. Thunderstorms have different features in comparison with synoptic events, including a typical nose-shaped mean wind speed profile and non-stationary characteristics in time intervals of 10 minutes to 1 hour. In this study, experimental tests are carried out in a Boundary Layer Wind Tunnel (BLWT) to reproduce the mean wind speed profile of thunderstorms using a passive device designed for this purpose, neglecting the non-stationary features of the physical phenomenon. The intention of the authors is to investigate the possibility of adopting a simpler approach to qualitatively assess if thunderstorm events could in some cases dominate the design of tall buildings. High frequency pressure integration tests are performed on a tall building to evaluate the wind loads induced by thunderstorms and synoptic events. Three analyses are performed varying the mean wind speed profile and design wind speeds obtained from a statistical analysis of wind data recorded in a mixed climate region. The paper compares the wind loading induced by thunderstorms and synoptic events and provides a discussion on the limitations and advantages of using a BLWT to assess the significance of thunderstorm events in tall building design.

Keywords: Boundary Layer Wind Tunnel experiments, thunderstorms, tall building.

1. INTRODUCTION

Tall buildings are very sensitive to wind-induced excitation. Wind-induced loads and cladding pressures are usually estimated through design wind codes or wind tunnel studies. The methodology is based on models developed for synoptic events and design wind speeds from codes or derived from statistical analysis carried out without separating different phenomena. In mixed wind climate, extreme wind speed analysis, performed by separating the data related to different types of events, has shown that design wind speeds can be significantly affected by thunderstorms (Zhang et al., 2018). Thus, the study of the influence of thunderstorms on tall structures has taken a relevant importance in the wind engineering field. Several investigations have confirmed that the are key differences between thunderstorm and synoptic events and therefore they would require separate treatment in terms of the assessment of wind loading for civil structures (e.g., Canepa et al., 2020). Despite the effort of many researchers in the study of thunderstorms, there is still no codified approach that would allow to accurately and reliably model their actions on structures. Thunderstorms have caused the collapse of many low-rise structures around the world, hence the main studies of thunderstorm-downburst induced actions have been focussed on these types of structures, while the investigations on high-rise buildings are still very scarce. In the case of tall buildings, it is believed that the current standard methodology is most likely conservative, as design wind speeds due to thunderstorms are directly associated to synoptic wind characteristics. The aim of this research is to study the impact of these non-standard wind profiles on tall buildings.

Wind tunnel testing constitutes an effective tool to determine wind-induced effects on tall buildings and has been widely used for the last 50 years primarily to verify structures again synoptic and typhoon events. The worst case characteristics of a thunderstorm in terms of wind loading on tall buildings, could be experimentally modelled in BLWT by modifying the horizontal flow using active devices that allow the simulation of the non-stationary flow characteristics, besides the nose-shaped mean wind speed profile (Aboutabikh et al., 2019; Le & Caracoglia, 2019).

The objective of this work is to directly compare the wind actions induced by thunderstorm-downburst and synoptic events on a tall building through experimental tests in a classic BLWT. A critical mean wind speed profile for tall buildings is considered and the non-stationary characteristic of the outflows is disregarded. The nose-shaped mean wind speed profile is reproduced using a passive device. Based on a statistical analysis from a mixed wind climate area taking into account the nature of the events, design wind speeds are evaluated for mixed statistics, thunderstorms and synoptic events. The base wind loads, as well as the floor-by-floor loads of a tall building are analysed. This work represents the first stage of a research project aimed at assessing if wind effects due to thunderstorms can be ruled out when designing a tall building and / or defining cases where their assessment is required.

2. WIND TUNNEL TEST

The tests were carried out at the "Giovanni Solari" WT facility at the University of Genoa. The experimental tests were divided in two stages. The first was aimed at stimulating the characteristic of a thunderstorm event in terms of wind and turbulence profiles in a conventional BLWT. The objective of the second stage was to measure the response of a tall building to thunderstorm and synoptic events via the technique of high frequency pressure integration.

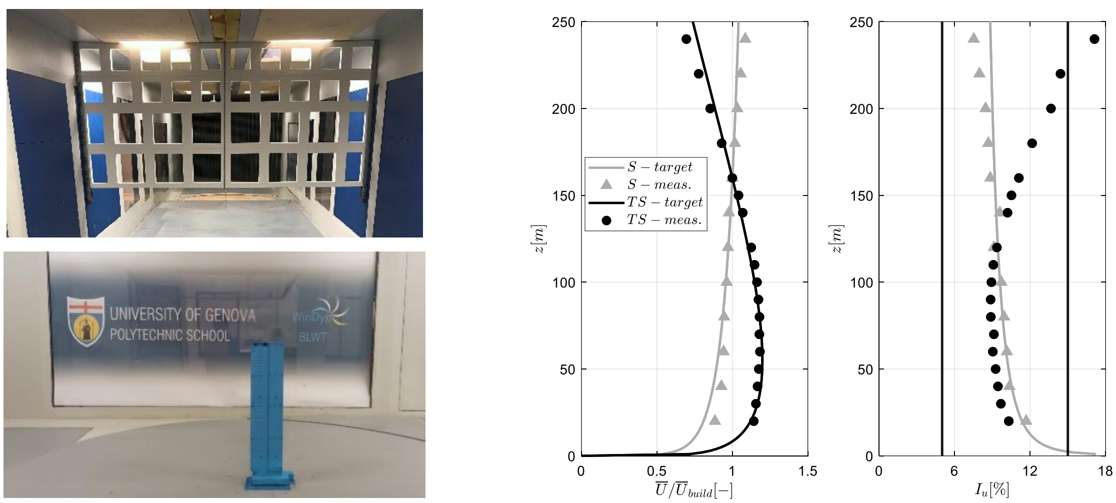
2.1. Simulation of wind properties

The mean wind velocity target profile of the thunderstorm has been defined according to Wood and Kwok model (Wood & Kwok, 1998). Based on available full-scale measurements in literature (e.g., Canepa et al., 2020), a full-scale height of the nose (z_m =50 m) that could be significant for tall buildings was considered. In terms of longitudinal turbulence intensity, there are no consolidated models that define its vertical profile due to the lack of multi-point full-scale measurements for these phenomena. Therefore, based on the information available in the current literature, values of longitudinal turbulence between 5% to 15 % along the height of the building were considered acceptable (Canepa et al., 2020; Solari et al., 2015). EN1991-1-4 (2004) was employed to obtain the mean wind speed and turbulence intensity profiles for synoptic events, considering a roughness length for areas exposed to open sea, z_0 =0.003 m, in order to obtain turbulence intensities consistent with those considered for thunderstorm downbursts.

In order to find the best match to the target profiles, the turbulent boundary layer was set up using different arrangements of roughness elements. A new passive grid-like device was purposely designed to reproduce the nose-shaped profile of a thunderstorm. The partial grid is composed by modules spanning the full width of the wind tunnel including square openings of different dimensions (Fig. 1a). Target and measured profiles in terms of mean wind speed normalized with respect to the velocity at the top of the building $\overline{U}_{build}$ and turbulence intensity for thunderstorm (TS) and synoptic events (S) are shown in Fig. 1b and 1c, respectively.

2.2 Wind Loading Studies - Case study

A specific tall building, approximately 160 meters tall and of constant bluff cross section, was tested using the high frequency pressure integration technique (Fig. 1a). The model was built at scale of 1:400 and instrumented with 293 pressure sensors distributed across all surfaces. The model was tested in isolation to accurately capture the key differences between the two weather phenomena.



a) b) c)

Figure 1. a) Passive grid device and model, b) Mean wind speed profiles, c) Turbulence intensity profiles.

4. RESULTS AND DISCUSSION

The measured time histories of pressures on the model were analysed to determine the full-scale wind base loads including mean, peak static and peak dynamic effects for 50 years return period. Three analyses are performed varying the mean wind speed profile and design wind speeds at a reference height $z_{ref} = 10$ m, called here Synoptic (S), Thunderstorm (TS) and Conventional (C) analyses. Table 1 shows the reference wind speed and the profile used in the wind tunnel for the three analyses.

Table 1. Design wind speed

Analysis	Synoptic	Thunderstorm	Conventional
$\overline{U}_{ref}$(10 m)- mean hourly	22.9 m/s	31.9 m/s	31.9 m/s
Profile	Synoptic	Thunderstorm	Synoptic

Fig. 2 shows the variation of the mean, peak static and peak dynamic base shear forces (F_x, F_y) for the three cases considered. It can be seen that the actions derived from synoptic and thunderstorms events are comparable, however for some directions TS analysis provides higher values. Anyway C analysis always provides an overestimation of the loading. The differences for the mean and peak static forces are related to the mean wind speed profile used, while peak dynamic forces are also related with vortex shedding that becomes more significant for higher wind speed.

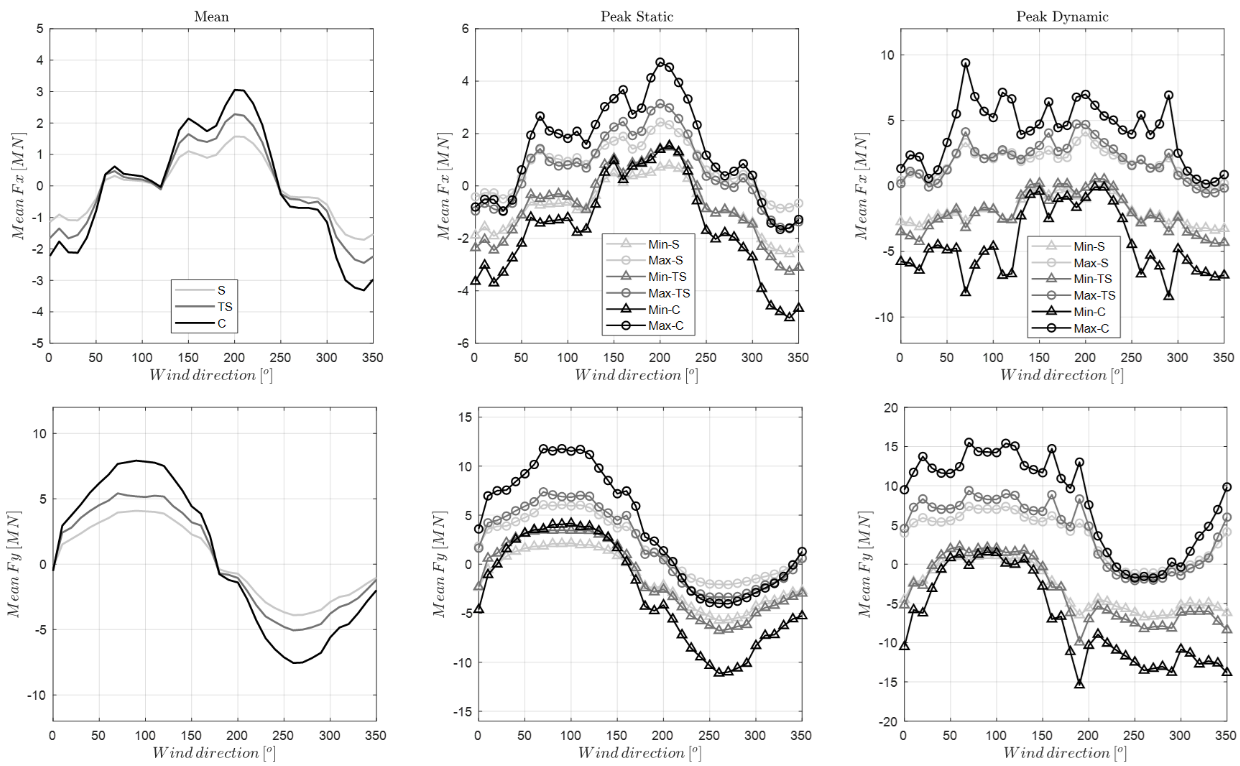


Figure 2. Variation of the base shear forces with wind direction.

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