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Experimental and numerical tools for assessing the wind loading of structures due to thunderstorm outflows

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ABSTRACT

Thunderstorms are frequent events causing wind speeds and damage often greater than cyclones. This paper describes an extensive monitoring network including unique devices, an unprecedented database of transient wind speed records, a broad spectrum of numerical tools for elaborating this data and extracting their properties relevant to the wind loading of structures, wind tunnel tests, CFD simulations, weather scenarios and damage surveys aiming to complete the information provided by field measurements. Based on these premises a new generation of wind loading models is being developed – response spectrum technique, hybrid simulation and time-domain integration, evolutionary spectra - robustly coherent with measured data and intrinsically coherent between each other. These studies are being carried in the framework of an ERC Project aimed at producing outcomes physically correct, transferable to design and standards, suitable to modify the current wind loading format and to make construction wind-safer and cost-efficient.

1 INTRODUCTION

Thunderstorms are complex, mysterious and devastating natural phenomena. Their modern study started when Byers and Braham (1949) showed that they consist of convective cells that develop in a few kilometre and evolve in about 30 minutes through 3 stages in which an updraft of warm air is followed by a downdraft of cold air. Fujita (1990) proved that the downdraft that impinges on the terrain causes intense radial outflows. The whole of these air movements is said downburst (Figure 1). Differently from synoptic winds, it exhibits a non-stationary and non-Gaussian speed field with a nose profile that increases up to 50-75 m height, then decreases above (Hjelmfelt 1988).

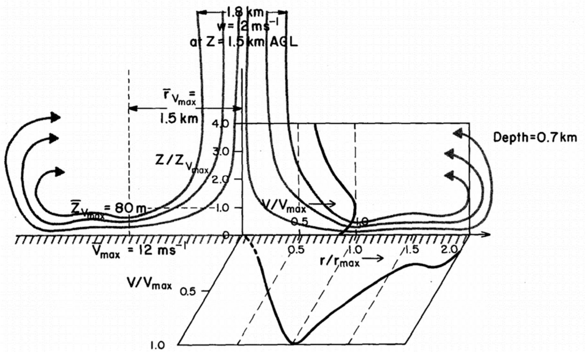

Figure 1: Thunderstorm downburst and nose speed profile in the radial outflow (Hjelmfelt 1988).

Despite the huge research carried out in wind engineering and atmospheric sciences in the last 30 years (Letchford et al 2002, Solari 2014), this matter is still dominated by large uncertainties and there is not yet a shared model of the thunderstorm outflows and their loading of structures as that developed over half century ago for synoptic phenomena (Davenport 1961). This happens because thunderstorm complexity makes it difficult to set physically realistic and simple models. Their short duration and small size make few data available. There is a large gap between wind engineering and atmospheric sciences.

The research carried out at the University of Genoa on thunderstorms originates from two European projects, “Wind and Ports” (WP) (Solari et al 2012) and “Wind, Ports and Sea” (WPS) (Repetto et al 2017), financed by European Cross-border program “Italy–France Maritime 2007-2013”. They handled the wind safe management and risk assessment of the High Tyrrhenian Ports. This aim was pursued through an integrated set of tools including an extensive monitoring network, multi-scale numerical models, medium- and short-term forecast algorithms, statistical analyses. Results are available to port operators through an innovative Web GIS platform (Repetto et al 2018).

Realized in a geographic area known for its violent convective activity and its often dramatic consequences, the wind monitoring network has produced an unprecedented number of transient records related to thunderstorms. This inspired the Project THUNDERR - Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures – financed by an Advanced Grant of the European Research Council (ERC) under Horizon 2020.

Within this framework, this paper describes the wind monitoring network and its unique devices (Section 2), an unprecedented database of transient speed records (Section 3), numerical tools for analyzing this data and extracting their properties (Section 4), statistical analysis in a mixed wind climate (Section 5), the link between wind speed records and weather scenarios (Section 6), the modelling of downburst wind fields merging the data provided by field measurements, wind tunnel tests and CFD simulations (Section 7). Then, a new generation of wind loading models is introduced – firstly the response spectrum technique (Section 8) and hybrid simulations (Section 9) – robustly coherent with measured data and intrinsically coherent between each other. Section 10 summarizes the main partial results and draws some prospects for prosecuting this research project aiming to produce outcomes physically correct, transferable to design and codes, suitable to modify existing wind loading formats and to make construction wind-safer and cost-efficient.

2 WIND MONITORING NETWORK

The WP Project created a network of 23 ultrasonic anemometers in the Ports of Genoa (2), La Spezia (5), Livorno (5), Savona and Vado (6) (Italy), and Bastia (5) (France). The WPS Project enhanced it by 5 new ultrasonic anemometers in the Ports of Savona (1), La Spezia (1), Livorno (1) and L’Île Rousse (2), 3 LiDAR (Light Detection And Ranging) wind profilers and 3 weather stations, each one including another ultrasonic anemometer, a barometer, a thermometer and a hygrometer in the Ports of Savona, Genoa and Livorno (Figure 2). New sensors installed by Port Authorities are going to become parts of this network.

The ultrasonic anemometers detect wind speed and direction with a precision of 0.01 m/s and 1 degree, respectively. Their sampling rate is 10 Hz with the exception of one sensor in the Port of Savona, with sampling frequency 1 Hz, and of those in the Ports of Bastia and L’Île Rousse, with sampling frequency 2 Hz. To register undisturbed wind speeds, sensors are mounted on high-rise towers and on some antenna masts at the top of buildings, at least at 10 m height above ground level (AGL). The LiDAR profilers detect the 3 components of the wind speed at 12 heights between 40 and 250 m AGL with a sampling rate of 1 Hz.

A set of servers placed in each port authority headquarter receives the local records and elaborates basic statistics on 10-min periods, namely mean and peak wind speeds and wind direction. Each server automatically sends this and raw data recordings to the central server in DICCA at UNIGE. DICCA performs a preliminary check and stores the data into a database.

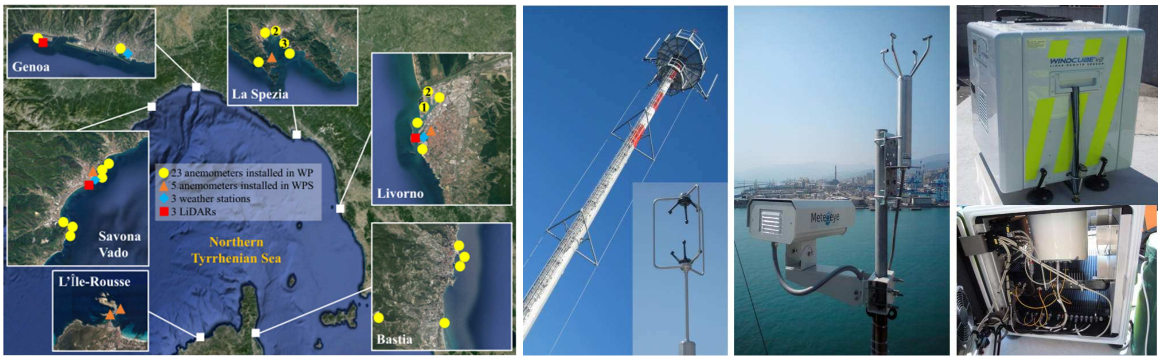

Figure 2: WP and WPS wind monitoring network and sensors.

The THUNDERR Project has recently enriched this monitoring network with a Windcube 400S pulsed LiDAR scanning system in the Port of Genoa. It measures the wind speed up to a distance of 12 km with a sampling frequency of 1 Hz and involves a specific software to record and display data in real time. According to ISO standards it has a unique Figure of Merit. Differently from the other sensors of the network the measurements are directly transferred to DICCA.

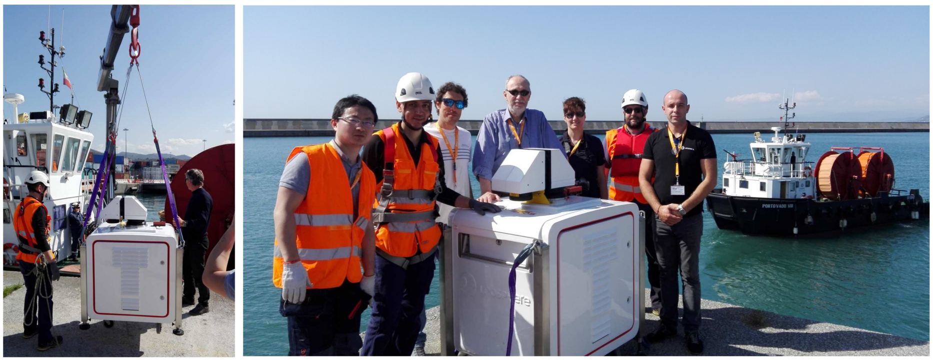

Figure 3: Windcube 400S pulsed LiDAR scanning system.

3 WIND SPEED DATABASE

Considering that first sensors were installed in 2010 and most sensors detect the wind speed in continuous mode with a sampling frequency of 10 Hz, a huge dataset has been created. At present it consists of about 1.4 TB, including indexing and metadata, and it increases every day of more than 20 million of new measures.

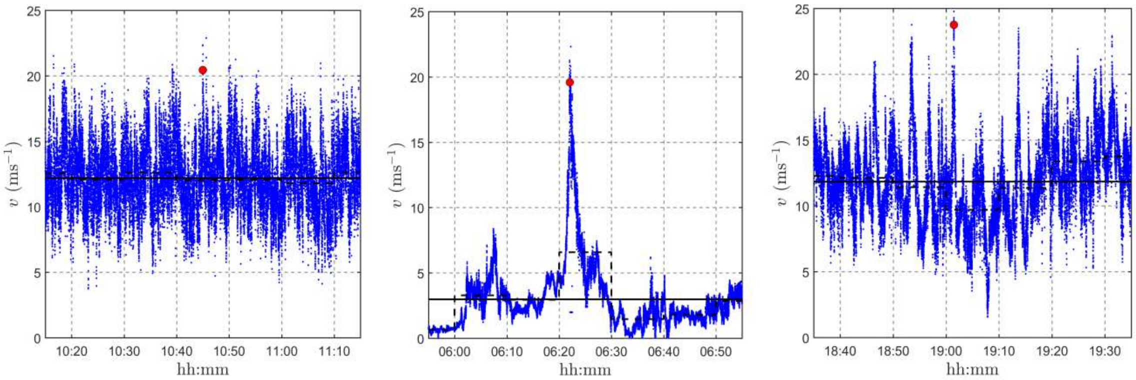

Figure 4: Records of an extra-tropical cyclone, a thunderstorm outflow and an intermediate event.

The records detected by ultrasonic anemometers include different events, namely extra-tropical cyclones, thunderstorm outflows and intermediate events (Figure 4). Therefore, a semi-automatic procedure was implemented to extract downbursts (De Gaetano et al 2014) based on few synthetic elements provided by sole anemometric records, without carrying out prohibitive meteorological surveys. Initially 93 transient records labelled as thunderstorm outflows have been extracted. Later on, on increasing the number of the available data, 247 thunderstorm records have been gathered.

A similar procedure was implemented to extract transient wind speeds from LiDAR profilers (Burlando et al 2017a). Preliminary analyses on a limited number of evolutionary profiles show that the wind speed profile is initially in equilibrium with the atmospheric boundary layer (ABL). It takes the nose shape at the base of the ramp-up part of the record and retains it for no more than 30-40 s. In proximity of the peak wind speed it becomes almost flat and rapidly returns to be ABL (Figure 5). Work is in progress to extract thunderstorm events from the new LiDAR scanner.

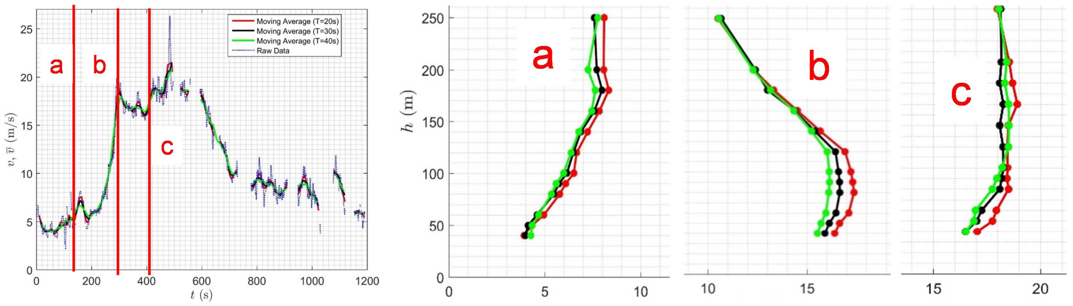

Figure 5: Evolutionary wind velocity profile detected by a LiDAR profiler.

The construction of the above database represents the first step to create a science gateway for sharing measurements, software tools and experiences concerning the identification and analysis of downbursts events (Burlando et al 2018). To this extent, an initial set of selected thunderstorm events will be released to public soon through a Web-based interface. More events will be added over time with the aim of gathering contributions throughout the wind engineering community.

4 WIND SPEED DECOMPOSITION AND ANALYSIS

The records labelled as thunderstorm outflows has been gathered and decomposed by the classic approach (Chen and Letchford 2004, Holmes et al 2008) depicted in Figure 6 (Solari et al 2015a, Zhang et al 2018a). The wind speed is expressed as the sum of a slowly-varying mean part and a residual fluctuation which, in turn, is given by the product of its slowly-varying standard deviation by a reduced turbulent fluctuation dealt with as stationary and Gaussian with zero mean and unit standard deviation. The ratio between the standard deviation and the mean wind speed is referred to as the slowly-varying turbulence intensity. The ratio between the peak wind velocity and the maximum value of the slowly-varying mean wind velocity is referred to as the gust factor.

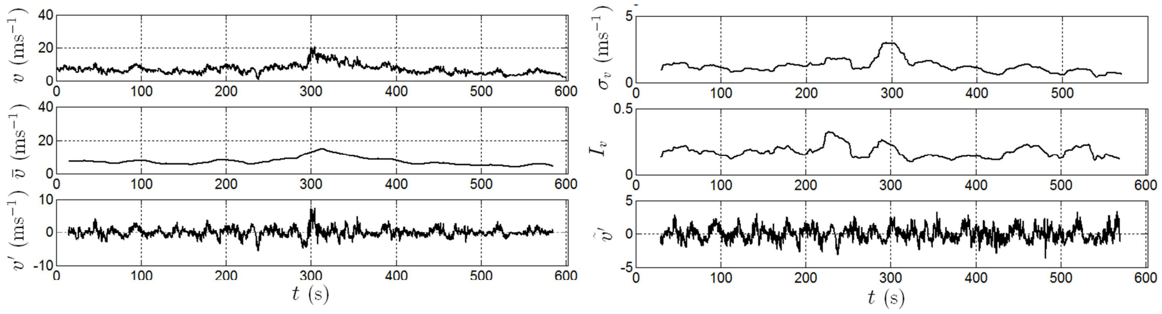

Figure 6: Thunderstorm outflow wind speed decomposition.

Based on this study thunderstorm records have been divided into 2 families depending on whether the peak associated with the gust front passage is clear in a 10-min or 1-h period. In addition, they have been divided into 4 groups depending on the peak wind speed. Criteria to define the duration of the gust front passage have been set and different shapes of thunderstorm outflows have been classified. Diversely from synoptic winds, the average value of the turbulence intensity is nearly independent of the roughness length. Higher values of the turbulence intensity of synoptic winds are fictitiously linked to the moving average filter used to extract the slowly-varying speed. The power spectral density of the reduced turbulence closely matches the synoptic trend in the inertial sub-range. Its parameterization calls for a reduced frequency in which the height AGL is replaced by the integral length scale. As the turbulence intensity, also the integral length scale is almost independent of the roughness length and higher values for synoptic winds are fictitious as well.

Solari et al (2018) have proposed a novel strategy to extract and decompose signals by taking into account both wind speed and direction. Differently from the classic scheme described above, this method establish a perfect parallelism between thunderstorm outflows and synoptic winds.

5 EXTREME WIND SPEED DISTRIBUTION

A preliminary statistical analysis of the extreme wind speed distribution was carried out for two anemometers in the Port of Livorno (LI_01, LI_02) and two anemometers in the Port of La Spezia (SP_02, SP_03) (Zhang et al 2018b): they have been detecting continuous data for nearly 6 years. Single distributions of the maximum yearly peak wind speed for depressions (D), thunderstorms (T) and intermediate events (IN) were estimated. Distributions based on mixed statistics (M) were derived (Gomes and Vickery 1977/1978). Extreme wind speed values were gathered into a unique dataset and ensemble distributions (E) were calculated (Lombardo et al 2009).

Figure 7 shows that in the Port of Livorno thunderstorm outflows are dominant, depressions are secondary, and intermediate events are marginal. In the Port of La Spezia thunderstorm outflows are dominant for return periods over 1 year; intermediate events are comparable with depressions.

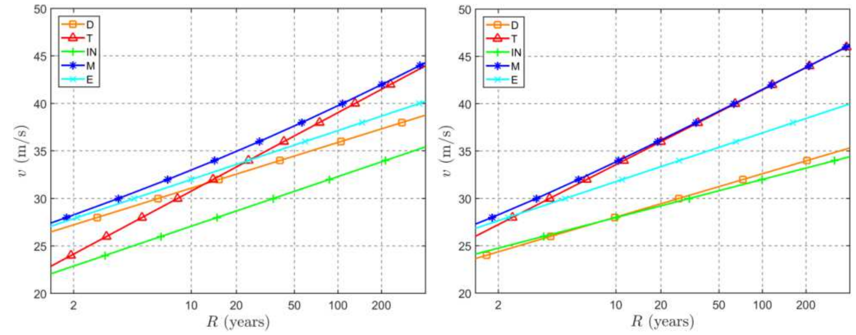

Figure 7: Peak wind speed at the anemometers 02 of the Port of Livorno and 03 of the Port of La Spezia.

More in general, as for many other parts of the world, the most intense wind events that occur in the High Tyrrhenian Sea area are mainly due to thunderstorms. Besides, gathering the ensemble of all the extreme speed values into a unique dataset leads to underestimating the mixed distribution especially for high return periods, where it tends to coincide with the thunderstorm one.

6 WEATHER SCENARIOS

The separation and classification criterion described in Section 3 detects the presence of transient phenomena based on sole anemometric recordings. However, the knowledge of weather scenarios concurrent with these events is crucial to confirm the meteorological nature of the winds classified as thunderstorm outflows. To make a first step in this direction, the downburst occurred on 1 October 2012 on the City of Livorno, Italy (Figure 8a,b) was selected as a reference test case (Burlando et al 2017b). Analyses were carried out of the wind speed and direction detected by the monitoring network. Atmospheric conditions related to this event were studied by gathering all the meteorological data available in this area, i.e. model analyses, standard in-situ data (stations and radio-soundings), remote sensing (radar and satellite), proxy data (lightning, Figure 8c), and visual observations (European Severe Weather Database). This data allowed to reconstruct the weather scenario, to classify this event as a wet downburst, to determine its space-time evolution, to use signal analyses with the aim of extracting the key parameters of the wind loading of structures.

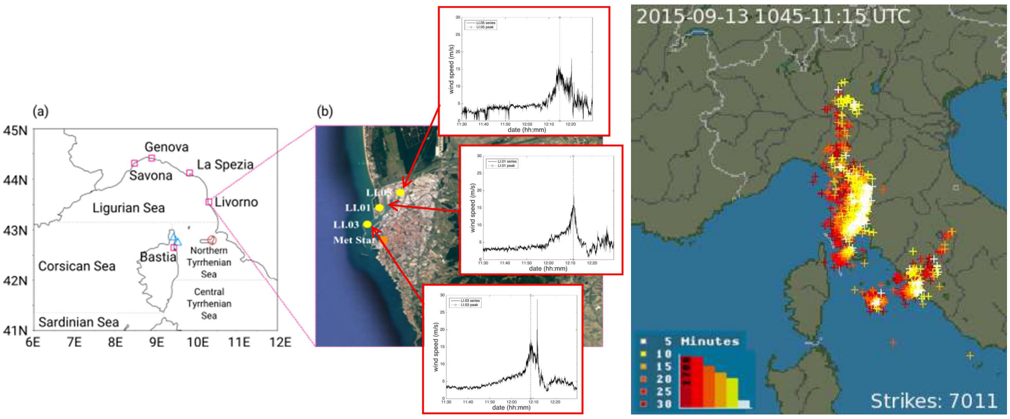

Figure 8: Livorno downburst, 1 October 2012: map, measurements, lighting.

Unfortunately, the framework depicted above may represent a utopian prospect for long historical series of thunderstorm events, due to the burden of collecting so many data from different sources and performing joint analyses. Finding a balance between expeditionary evaluations calibrated on detected wind records and studies that encapsulate the above information within a meteorological surveys is a difficult and ambitious task. With this aim, the development of a synthetic procedure is in progress, which is coherent with but easier than the above one. Preliminary results show that some events, initially misclassified as thunderstorms, are synoptic events with a rapid evolution.

The Project THUNDERR involves a cooperation with the Institut für Meteorologie of the Freie Universität Berlin, aiming to fill the gap between wind engineering and atmospheric sciences, as well as to investigate the role of climate changes on the evolution of thunderstorms (Nissen 2014, Púcik et al 2017). A co-operation was also opened with the European Severe Storm Laboratory that operates the European Severe Weather Database, in order to study the same topic and to perform advanced damage surveys.

7 WIND FIELD MODELLING

Thanks to several distributed ultrasonic anemometers, the monitoring network provides a fine description of the local time evolution of thunderstorm outflows and, at LiDAR profiler sites, also of their vertical configuration. In addition, thanks to the LiDAR scanning system, a unique point of view on the time-space structure of downbursts will be soon available. However, this data will not be enough to derive a detailed description of the space structure of these phenomena.

To overcome this limitation wind tunnel tests are planned at the WindEEE Dome (Hangan 2014) of Western University (Figure 9a) to simulate and detect a comprehensive and unprecedented set of large-scale downbursts on varying the downdraft diameter, its translational speed, the terrain roughness and the background wind field. Some wind tunnel simulations will be carried out also in smaller scale laboratories, to interpret the key and still mostly unknown role of scale effects.

In parallel, CFD simulations will be carried out with the Urban Physics and Environmental Wind Engineering Research Centre at the Technical University of Eindhoven (Blocken 2014). Figure 9b shows a preliminary simulation of an impinging jet by LES. Likewise for wind tunnel tests the THUNDERR Project aims to produce clear indications on the best CFD tools to obtain suitable estimates of the slowly-varying mean wind speed and of the turbulence field. Analyses will be carried out by sub-cloud and impinging jet models using RANS and LES. Especially the use of LES in sub-cloud models will be regarded as a novel tool with highly unexplored potential.

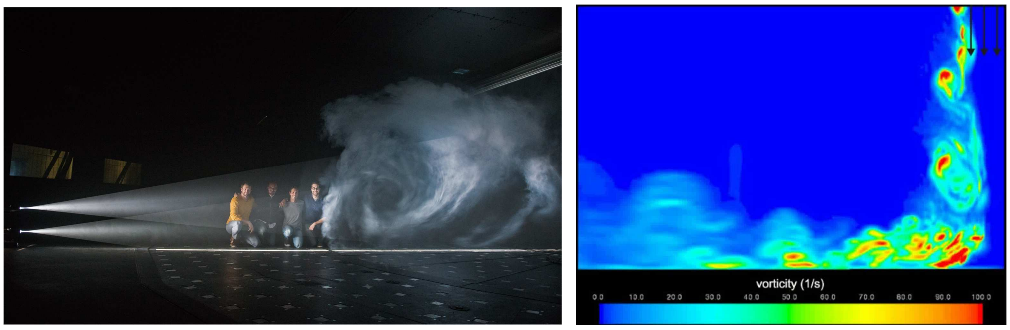

Figure 9: Wind tunnel tests (courtesy Prof. Hangan) and CFD simulations (courtesy Prof. Blocken).

Results obtained by wind tunnel tests and CFD simulations will be processed by signal analyses and compared with the outcomes of field measures in order to establish a physically realistic model of the thunderstorm outflows, simple enough to be used in the engineering and design practice for representing the wind loading of structures.

8 THUNDERSTORM RESPONSE SPECTRUM TECHNIQUE

The study of the thunderstorm loading and response of structures (Kwon and Kareem 2009) took a cue from the consideration that thunderstorms are transient phenomena with short duration and the structural response to transient phenomena, most notably to earthquakes, is usually evaluated by the response spectrum technique. Based on this remark, a “new” method was formulated to generalise the “old” response spectrum technique from earthquakes to thunderstorms.

Initially, this problem was formulated for an ideal point-like Single-Degree-Of-Freedom (SDOF) system (Solari et al 2015b) subjected to perfectly coherent wind actions over the exposed surface. It was proved that in such a system the equivalent static wind loading is given by the product of the peak wind force by a non-dimensional quantity, the thunderstorm response spectrum, that depends on the structural fundamental frequency and on the damping ratio (Figure 10).

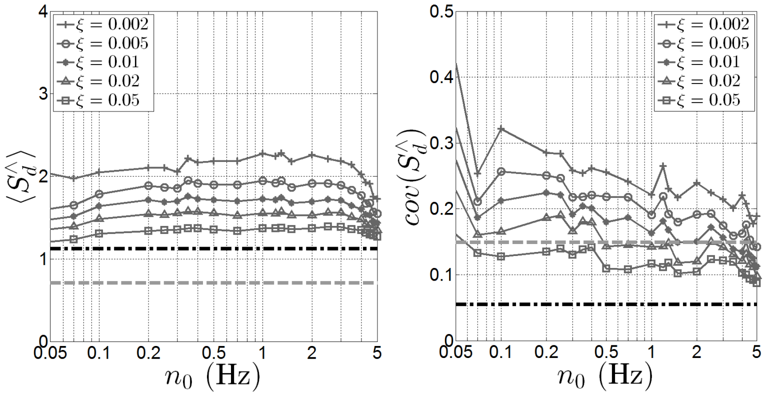

Figure 10: Mean value and coefficient of variation of the thunderstorm response spectrum for a SDOF system on varying the fundamental frequency and the damping ratio.

Later on, this formulation was generalized to a real space Multi-Degree-Of-Freedom (MDOF) system (Solari 2016) subjected to partially coherent wind fields with assigned speed profile and turbulence properties; for sake of simplicity structure was modelled as a slender vertical cantilever beam the dynamic response of which depends on the sole first mode of vibration. Analyses were carried out by making recourse to the generalised equivalent wind spectrum technique (Piccardo and Solari 1998), a method by which a multi-variate stationary wind velocity field is replaced by an equivalent mono-variate one. In spite of a rather complex treatment, the use of the thunderstorm response spectrum technique (TRST) is straightforward: the equivalent static force is given by the product of the peak wind loading by a non-dimensional quantity, the equivalent response spectrum, that depends on the structural fundamental frequency, on the damping ratio and on a reference size that takes into account the aerodynamic admittance of structure (Figure 11).

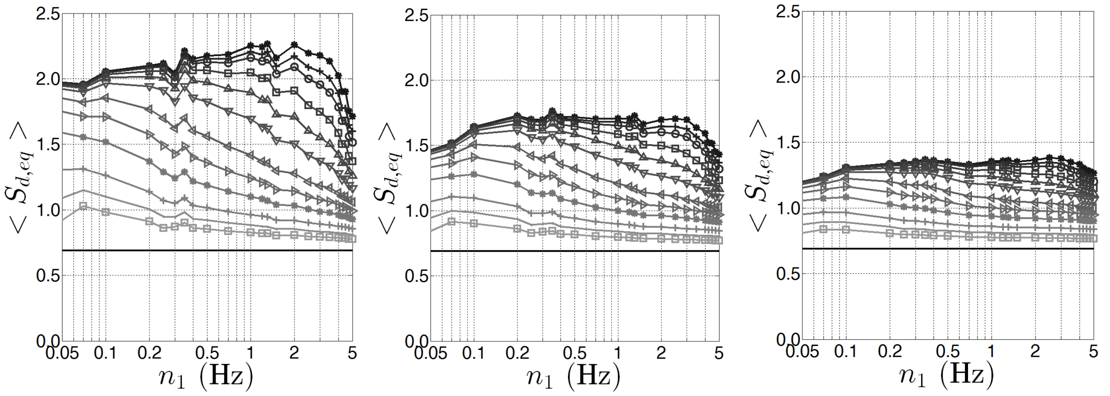

Figure 11: Mean value of the thunderstorm equivalent response spectrum for a MDOF system on varying the fundamental frequency, the damping ratio and the reference size of the structure.

9 HYBRID SIMULATIONS AND TIME-DOMAIN INTEGRATIONS

In order to check, calibrate and refine the TRST, time domain analyses were carried out based on a novel hybrid strategy aiming to simulate the wind field of thunderstorm outflows (Solari et al 2017). Diversely from the classic simulations of non-stationary random fields and from methods recently developed with regard to downbursts, this simulation strategy captures the properties of thunderstorm outflows by simple physical concepts and real velocity measurements. It assembles the different component signals that make up the wind velocity field by taking into account their sources of randomness (Figure 12). The high performance and precision of this algorithm were verified by comparing its results with the target wind field model and with measured data.

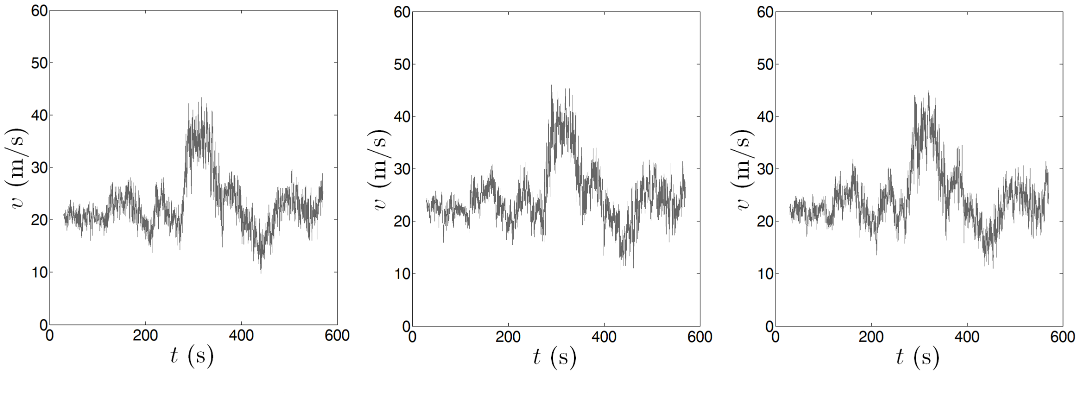

Figure 12: Simulated velocity histories of a thunderstorm outflow at three different heights.

The time-domain integration of the equations of motion based on the simulation strategy outlined above shows that the probability density function of the maximum value of the response induced by thunderstorm outflows is much more spread than that of synoptic cyclones. Thus, differently from classic wind excitation, it is not appropriate, or at least this is much more approximated, to identify the maximum value of the response with its mean value. Despite this, the wind loading and structural response to thunderstorm outflows are qualitatively similar to those due to synoptic events. The displacement is almost unaffected by the higher modes of vibration. The aerodynamic admittance plays a similar role for thunderstorms and cyclones. The resonant part of the response to thunderstorms is slightly lower than that related to synoptic winds but clearly perceivable.

Studies currently in progress to compare the results provided by TRST and time domain analyses show an excellent agreement in terms of mean values. Instead, TRST tends to underestimate the spread of the time-domain solutions. This mainly depends on the fact that the hybrid simulation strategy is based, as it seems at present unavoidable, on fixing the vertical profile of the slowly-varying mean wind speed and generating a target turbulent field. This is not coherent with TRST that starts from fixing the peak wind speed profile. A revised assessment of TRST coherently with time-domain simulations preserves the accuracy of mean values and makes the spread involved by the two methods quite close. Research on this topic is still in progress.

10 CONCLUSIONS AND PROSPECTS

The conduct of interdisciplinary research involving expertise from various sectors is one of the most recurrent recommendations for the research of the present and of the future in any field. In the specific case of this project, an interdisciplinary vision of wind engineering and atmospheric sciences is absolutely necessary to develop a thunderstorm model that in itself constitutes an innovative result and is, at the same time, a physically correct and sufficiently simple starting point to build around it a new method for calculating wind actions induced by thunderstorms on structures. At the same time, the development of this research cannot ignore the widest possible vision that embraces analytical methods, numerical simulations, model and full-scale measures in a unified way. It is finally essential that this vision be articulated on different time and space scales that are closely linked to each other.

Acknowledgements

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