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Emerging issues and new frameworks for wind loading on structures in mixed climates

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Abstract. Starting from an overview on the research on thunderstorms in the last forty years, this paper provides a general discussion on some emerging issues and new frameworks for wind loading on structures in mixed climates. Omitting for sake of simplicity tropical cyclones and tornadoes, three main aspects are pointed out. The first concerns the separation and classification of different intense wind events into extra-tropical depressions, thunderstorms and gust fronts, with the aim of improving the interpretation of the phenomena of engineering interest, the probabilistic analysis of the maximum wind velocity, the determination of the wind-induced response and the safety format for structures. The second deals with the use of the response spectrum technique, not only as a potentially efficient tool for calculating the structural response to thunderstorms, but also as a mean for revisiting the whole wind-excited response in a more general and comprehensive framework. The third involves the statistical analysis of extreme wind velocities in mixed climates, pointing out some shortcomings of the approaches currently used for evaluating wind loading on structures and depicting a new scenario for a more rational scheme aiming to pursue structural safety. The paper is set in the spirit of mostly simplified analyses and mainly qualitative remarks, in order to capture the conceptual aspects of the problems dealt with and put on the table ideas open to discussion and further developments.

Keywords: depression; gust front; mixed climate; response spectrum; thunderstorm; wind monitoring

1. Introduction

Under suitable microphysical and thermodynamic conditions, a thunderstorm may cause an air downdraft that impinging on the ground may give rise to radial outflows. The whole of these air movements is called downburst and is subdivided into macroburst and microbursts depending on its size (Fujita 1985).

The study of the thunderstorms and their actions and effects on structures is a dominant topic of the research in wind engineering over the last forty years (Letchford *et al*. 2002). This depends firstly on the fact that methods currently applied to determine wind actions on structures are still mostly based on models coherent with the stationary phenomena at the synoptic scale that occur in neutral thermal atmospheric conditions, with velocity profiles in equilibrium with the Planetary Boundary Layer (PBL). Thunderstorms are non-stationary phenomena at the mesoscale, which

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occur in convective conditions with velocity profiles substantially different from those that are typical of the PBL. Design wind velocities with mean return periods greater than 10-20 years are often associated with such phenomena.

Aiming at providing a general framework of the research carried out on this matter, four main topics are pointed out: 1) wind statistics and climate; 2) field detection and measurements; 3) modeling and simulation; 4) wind actions and effects on structures.

The research on wind statistics and climate began in 1967 when Thom (1967) first proposed to deal with the mixed populations of extra-tropical and tropical cyclones by means of two combined distributions, then showed that one third of the yearly peak wind velocities in U.S. occur during thunderstorms (Thom 1968). Gomes and Vickery (1976) carried out a study of the extreme wind velocities in Australia, in which they separated thunderstorm from non-thunderstorm winds, determined the distributions of these two phenomena and derived a mixed distribution later extended to more phenomena of different nature (Gomes and Vickery 1977, 1978); this latter paper is a milestone of this topic. Analogous aspects were discussed by Riera *et al*. (1977) and later by Riera and Nanni (1989), Twisdale and Vickery (1992), Holmes (1999), Choi (1999), Choi and Tanurdjaja (2002), Cook *et al*. (2003) and Solari *et al*. (2013b). The role of the thunderstorm size in evaluating its occurrence probability at a site was examined by Oliver *et al*. (2000) and Li (2000). Kasperski (2002) introduced the idea that in temperate climates at mid latitudes, thunderstorms cannot be separated clearly from frontal depressions, since a third class of phenomena exist, called gust fronts, with intermediate properties; he also proposed a criterion to subdivide the data belonging to different phenomena, whose application is strongly conditioned by the effectively available measures. Lombardo *et al*. (2009) investigated the separation between thunderstorm and non-thunderstorm winds, implementing an automated method for U.S.. De Gaetano *et al*. (2014) developed a semi-automated procedure to separate and classify extra-tropical depressions, thunderstorms and gust fronts by a suitable mix of quantitative controls and qualitative judgments.

The study of the phenomenology of thunderstorms and of the related wind fields has received great impulse from the evolution of detection and measurement systems - mainly anemometers installed on antenna masts, radar doppler and aircrafts instrumented for meteorological surveys – and from the first monitoring campaigns – above all those carried out for the projects NIMROD (Northern Illinois Meteorological Research on Downbursts, 1978), JAWS (Joint Airport Weather Studies 1982) and MIST (Microburst and Severe Thunderstorms 1986) (Fujita 1990). The literature on this matter has followed two complementary pathways. On the one hand, a research line has been developed, of meteorological imprint, which studies the causes, the morphology and the life cycle of thunderstorms also with reference to their classification (Goff 1976, Fujita 1981, Fujita and Wakimoto 1981, Wakimoto 1982, Wilson *et al*. 1984, Sherman 1987, Hjemfelt 1988). On the other hand, in a typical engineering spirit, there has been a proliferation of measurements and their interpretation in accordance with schemes aimed at evaluating thunderstorm actions on structures (Choi 2000, Choi and Hidayat 2002a, Choi 2004, Gast and Shroeder 2003, Chen and Letchford 2005a, 2005b, 2006, Orwig and Schroeder 2007, Holmes *et al*. 2008, Duranona *et al*. 2006, Kasperski 2009, Rowcroft 2011, Gunter and Schroeder 2013, Lombardo *et al*. 2014).

The modeling and simulation of thunderstorms have followed three main lines associated with experimental, numerical and analytical methods.

Experimental methods can be framed, in turn, into three main families.

The first family, pioneered by Lundgren *et al*. (1992), Alahyari and Longmire (1995) and Yao and Lundgren (1996), involves the release of a liquid mass into a body of less dense liquid; this allows to simulate the effects of buoyancy and to produce the classical ring vortex, favoring the study of the morphology and physics of thunderstorms. However, it is limited to small geometric and velocity scales, not suitable to determine wind loading on structures.

The second family involves the use of wind tunnels, where a jet is impinged on a flat surface to create a wall radial outflow. The first impinging wall jet tests were carried out by Bakke (1957) to investigate experimentally the wall jet theory formulated by Glauert (1956). Advances of this technique are reported Poreh *et al*. (1967), Donaldson and Snedeker (1971), Launder and Rodi (1981), Didden and Ho (1985), Landreth and Adrian (1990), Letchford and Illidge (1999) and Wood *et al*. (2001). Chay and Letchford (2002) first studied the downburst by means of a classical stationary wall jet simulation, then realized an equipment to reproduce the effects of a moving downburst (Letchford and Chay 2002). Mason *et al*. (2005) developed the method of the pulsed wall jet. Xu and Hangan (2008) discussed the scaling criteria between model experiments and full-scale conditions; this topic is also the focus of the studies presented by McConville *et al*. (2009) and Sterling *et al*. (2011).

The third family involves the techniques that modify the traditional axial flow of a wind tunnel in order to simulate the outflow of a downburst. This family includes the stationary and non-stationary slot jet technique (Lin and Savory 2006, Lin *et al*. 2007), the method of the pivoted plate suddenly introduced in the oncoming flow (Butler and Kareem 2007), the generation of gust fronts by a multiple fan wind tunnel with individually controlled fans (Cao *et al*. 2002, Butler and Kareem 2007), and the use of shutter mechanisms (Matsumoto *et al*. 2007).

Also numerical methods may be classified into three main groups.

The first group includes the full-cloud models that simulate the whole region, the life cycle and the complex microphysical processes involved by thunderstorms. The first full-cloud models, appeared in 2-D version in the ‘60s (Orville 1965, Liu and Orville 1969, Wisner 1972) and in 3-D version in the ‘70s (Steiner 1973, Miller and Pearce 1974, Pastushkov 1975), were conditioned by the computational limits and by the scarcity of observed data. This situation improved in the mid ‘80s, thanks to the evolution of the computing power and to the first experimental campaigns. Among many others, the 3-D model named Terminal Area Simulation System (TASS) (Proctor 1987a, b) and the studies carried out by Hjelmfelt *et al*. (1989), Knupp (1989) and Straka and Anderson (1993) deserve special mention. Nicholls *et al*. (1993) simulated first the actions induced by a downburst on a building by a multi-scale LES 3-D model.

The second group includes the sub-cloud models; they waive to simulate the whole thunderstorm to focus on the near-ground flow dynamics, i.e., on the domain of major interest for engineering applications. With such aim, the sub-cloud models are driven by a sort of thermal forcing, imposed under the cloud at an elevated region of the domain, which simulates the cooling processes of microphysical nature. This method, introduced by Mitchell and Hovermale (1977), was developed later by Srivastava (1985), Droegemeier and Wilhelmson (1987), Proctor (1988, 1989), Anderson *et al*. (1992), Straka and Anderson (1993), Orf *et al*. (1997), Orf and Anderson (1999), Lin *et al*. (2007), Mason *et al*. (2009, 2010), Vermeire *et al*. (2011a). Orf *et al*. (2012) pointed out that future computational advances will allow to use full-cloud models also for wind engineering applications.

The third group includes the CFD models that simulate the impinging wall jet experiments. For this reason they have analogous properties to the sub-cloud models: they waive to simulate the whole thunderstorm to focus on the near-ground flow field; diversely from the sub-cloud models, however, the forcing source is not thermal but mechanical. This technique, introduced in a pioneering paper of Selvam and Holmes (1992), was developed later by Wood *et al*. (2001), Chay *et al*. (2006), Kim and Hangan (2007), Sengupta and Sarkar (2008), Vermeire *et al*. (2011b).

The formulation of the analytical models has get leverage from measurements, experiments and simulations. At least initially, these models applied basic fluid dynamic laws to stationary flows, in order to obtain simplified analytical expressions, independent of time, of the vertical and radial components of the wind velocity. This led to the development of the impinging wall jet and of the vortex ring models. The first originated from the theory formulated by Glauert (1956) and was developed by Oseguera and Bowles (1988). The second was due to Zhu and Etkin (1985), Ivan (1986) and Vicroy (1991, 1992). Wood and Kwok (1998) formulated an empirical model of the vertical profile of the radial wind velocity that has had great success for engineering applications. Holmes and Oliver (2000) developed the impinging wall jet model by providing a simplified expression of the radial component of the wind velocity as a function of the distance from the jet axis and of the time; they also expressed the horizontal velocity as the vector summation of the stationary radial velocity and the moving or background velocity of the downburst. Li *et al*. (2012) and Abd-Elaal *et al*. (2013) first proposed analytical models of the vertical and radial profiles of the horizontal and vertical components of the wind velocity, which take into account the non-linear growth of the surface boundary layer.

The turning point in the analytical modeling of thunderstorms is represented by a paper in which Choi and Hidayat (2002b) expressed the instantaneous wind velocity as the sum of its time-varying mean part, averaged on a suitable moving period, plus a zero mean fluctuation dealt with as a stationary random process. This approach was developed by Chen and Letchford (2004a, 2005a, b, 2006), who expressed the time-varying mean part of the wind velocity as the product of a function depending on space, provided by the previous time-independent analytical models, and a function slowly varying with time. The fluctuation, dealt with as non-stationary, is given by the product of its time-varying standard deviation by a random stationary Gaussian process with zero mean and unit standard deviation; Chen and Letchford (2005a, 2006) discussed the vertical and horizontal coherences of the fluctuations. New developments are reported by Chay *et al*. (2006, 2008) and by Ponte and Riera (2007). Huang and Chen (2009) represented the fluctuations by wavelet transforms and evolutionary spectra. Ponte and Riera (2010) merged these models into a Monte Carlo algorithm aimed at providing the distribution of the maximum velocity in mixed climates. De Gaetano and Solari (2013) studied the role of the wind velocity decomposition and of the moving average period.

The study of wind actions and effects on structures has followed two main pathways dealing with transient bluff-body aerodynamics and with the dynamic wind-excited response.

The first research topic is still mainly circumscribed to wind tunnel experiments involving the transient nature of the oncoming flow. These experiments can be separated into two families. The first includes the tests on slender elements (Sarpkaya 1963, Okajima *et al*. 1997, Matsumoto *et al*. 2007, Butler and Kareem 2007). The second concerns the tests on 3-D bluff-bodies (Chay and Letchford 2002, Letchford and Chay 2002). All the available results show that a sudden increase of the oncoming wind velocity may give rise to aerodynamic wind loads up to 25% greater than those produced by classic quasi-steady conditions.

The analysis of the wind-excited response of structures to thunderstorm winds, still limited to the alongwind direction, concerns two main topics.

The first, aimed at understanding the conceptual aspects of the structural response, deals with idealized reference structures. Choi and Hidayat (2002b) studied for the first the dynamic response of a Single-Degree-Of-Freedom (SDOF) system to thunderstorms identically coherent in space, in order to generalize the classic gust factor technique (Davenport 1961). This study was developed by Chen and Letchford (2004b) and by Chay and Albermani (2005), who analyzed the behavior of SDOF systems through one parameter, referred to as the Maximum Dynamic Magnification Factor (MDMF) and the Dynamic Response Factor (DRF), respectively, given by the ratio between the maximum dynamic response and the static response to the peak loading. Kwon and Kareem (2009, 2013) introduced a so-called gust front factor, by means of which the gust factor technique is generalized from stationary to non-stationary wind actions and effects. Solari *et al*. (2013a) evaluated the dynamic alongwind response to thunderstorms by the response spectrum technique.

The second topic is addressed to real structures, especially the transmission towers that suffer the largest damage and collapses due to thunderstorms. In this framework, thunderstorms are simulated by CFD codes or analytical models, whose output is transformed into aerodynamic loads applied on finite element structural models by automated procedural chains (Savory *et al*. 2001, Shehata *et al*. 2005, 2007, Darwish *et al*. 2010, 2011).

In spite of this impressive amount of research, the understanding and the representation of thunderstorms are topics still full of uncertainties and problems to be clarified. This depends, on the one side, on the complexity of this phenomenon, and, on the other, on its short duration and its impact on small areas. The first aspect makes it difficult to formulate models that are physically realistic and simply applicable as in the case of synoptic events. The second aspect makes very limited the available data. This reflects on the determination of thunderstorm actions on structures, where suitable models for engineering calculations and regulatory schemes are still rather limited.

The project “Wind and Ports” (Solari *et al*. 2012) may offer an important contribution to the growth and to the advance of the knowledge on thunderstorms and their effects on structures. Started in 2010 and finished in 2012, this project was financed by the European Territorial Cooperation Objective, Cross-border program “Italia - France Maritime 2007-2013”. It involved the port authorities of the five main ports in the Tyrrhenian Sea, namely Genoa, La Spezia, Livorno, Savona (Italy) and Bastia (France). The Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa was the scientific actuator. The project handled the problem of the wind forecast in port areas and proposed an integrated system including a wide in situ monitoring network, the numerical simulation of wind fields, the statistical analysis of large historical wind velocity databases, and the implementation of algorithms for middle-term (1-3 days) and short-term (0.5-2-hour) wind forecast. The final results are made directly available to the port operators through an integrated Web Gis global system for the safe management of port areas. The prosecution of these activities after 2012 is guaranteed by a formal agreement between the University of Genoa and the Port Authorities involved in the project. A new project involving the same partners, “Wind, Ports and Sea”, has been recently approved by European Community with the scope of continuing and developing further the previous project (Burlando *et al*. 2014).

This paper exploits the data and the knowledge gained during the project “Wind and Ports” in order to investigate some critical aspects of thunderstorms and their effects on structures, to highlight emerging issues not yet studied enough, to depict new scenarios that drawing inspiration from thunderstorms may address, in a more general way, a framework for wind actions and effects on structure more coherent with physical reality. Section 2 describes the monitoring network and the data base of the project “Wind and Ports”, debating the separation and classification of extreme wind events into homogeneous families. Section 3 introduces the response spectrum technique as a potentially efficient tool to evaluate the structural behavior under thunderstorm actions, compares the structural response provided by stationary and non-stationary and by Gaussian and non-Gaussian wind actions, addresses the need of considering intermediate situations, discusses the opportunity of revisiting this whole matter in a more general and comprehensive framework. Section 4 deals with the statistical analysis of extreme wind velocities in mixed climates, points out some shortcomings of the approaches currently used for evaluating wind loading on structures, introduces new ideas with reference to a more general and rational scheme to pursue structural safety. The paper is set in the spirit of mostly simplified analyses and mainly qualitative remarks, in order to capture the conceptual aspects of the problems dealt with and put on the table ideas open to discussion and further developments. All the examples introduced herein are based on data provided by a specific case study and refer to a specific wind climate; however, the concepts and the methods discussed by using this data can be dealt with as very general.

2. Separation and classification of intense wind events

The monitoring network realized for the project “Wind and Ports” (Solari *et al*. 2012) consists of 22 ultrasonic anemometers, most of them tri-axial and the others bi-axial, distributed in the ports of Genoa (2), Savona (6), La Spezia (4), Livorno (5) and Bastia (5). In addition to this initial realization, 11 ultrasonic anemometers have been installed in the ports of Genoa (9), Savona (1) and La Spezia (1). In the framework of the new project “Wind, Ports and Sea” (Burlando *et al*. 2014), 7 ultrasonic anemometers will be installed in the ports of Genoa (1), Savona (1), La Spezia (1), Livorno (2) and Ile-Rousse (2); besides, 3 lidars will be installed in the ports of Genoa, Savona and Livorno. Thus, within 2014, a monitoring network constituted by 38 ultrasonic anemometers and 3 lidars will be operative in the High Tyrrhenian Sea.

The position of the instruments currently in use has been chosen to cover homogeneously the five port areas involved in the project and to register undisturbed wind velocity histories. The anemometers are mounted on high rise towers or on antenna masts at the top of buildings, at least at 10 m height above ground level, with special attention to avoid local effects contaminating the measures. The sampling rate of the instruments is 10 Hz, with the exception of the anemometers in the Port of Bastia whose sampling rate is 2 Hz. Wind measurements are collected with a precision of 0.01 m/s and 1 degrees for intensity and direction, respectively.

A set of local servers, placed in each port authority headquarter, receives the measures acquired by the anemometers in their own port area and elaborates the basic statistics on 10-minutes periods, namely the mean and peak wind velocities and the mean wind direction. Each server automatically sends this information to the central server located in DICCA. Two files are transferred every 10 minutes containing, for each anemometer, the raw data and the statistical values of the previous 10-minutes periods. The operational center of DICCA receives this data and stores it into a central dataset, after having systematically checked and validated the data received. The real time transfer is crucial for short term forecasting (Burlando *et al*. 2013).

An examination of this huge amount of data shows that intense wind events can be classified into three families characterized by different properties:

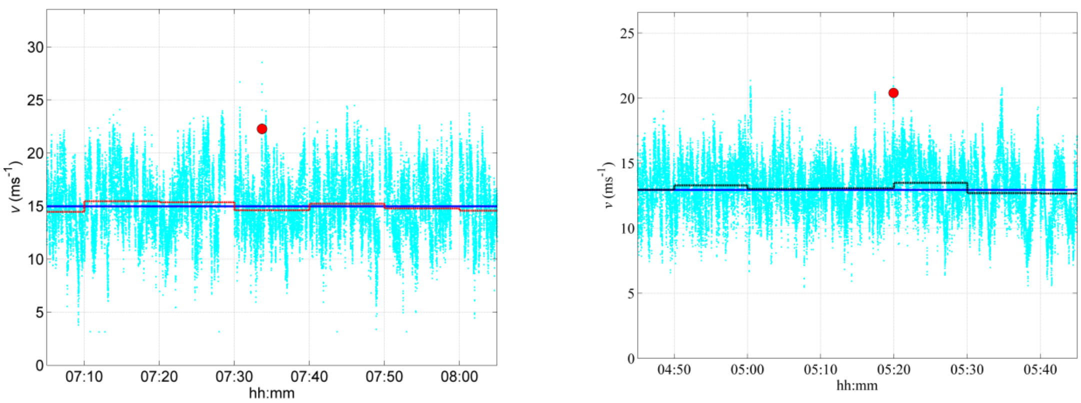
1) stationary (S) Gaussian (G) events (Fig. 1), with relatively large mean wind velocities and small gust factors; such events usually correspond to neutral synoptic atmospheric conditions; they are referred to as extended pressure systems by Gomes and Vickery (1976, 1977, 1978) and strong frontal depressions by Kasperski (2002, 2009); they are called here extra-tropical depressions (D);

2) non-stationary (NS) non-Gaussian (NG) events (Fig. 2), with large peak wind velocities and

gust factors but relatively small mean wind velocities; coherently with the current literature, they are referred herein to as thunderstorms (T),

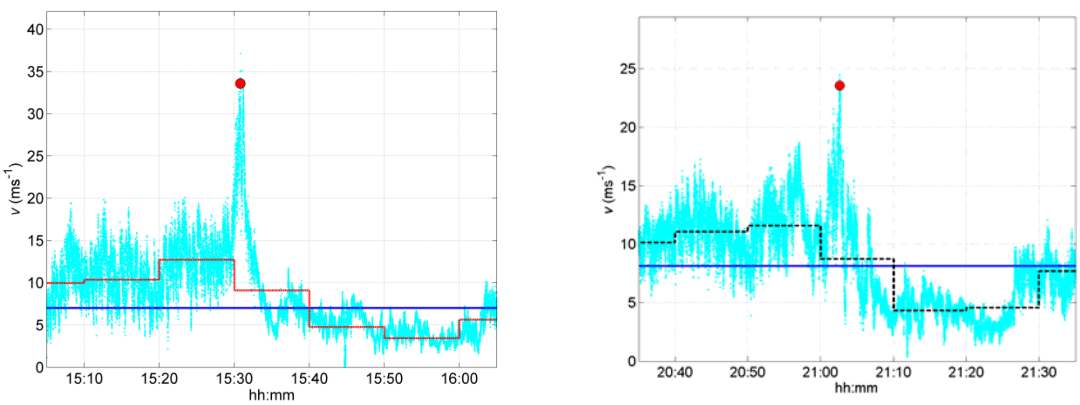
3) stationary (S) non-Gaussian (NG) events (Fig. 3), with relatively small mean wind velocities but large peaks and gust factors; they are referred to as intermediate events, or gust fronts (F), by Kasperski (2002); in spite of a total lack of meteorological interpretations, it seems reasonable to assume that such events are associated with strongly unstable atmospheric conditions.

The schemes in Figs. 1-3 show the time-history of the wind velocity raw data, the mean value over a 1-hour period (horizontal line), the mean values over 10-minutes subsequent periods (dotted line), and the 1-s peak (circle) (obviously smaller than the instantaneous peak). A record is referred to as stationary, when it exhibits statistical regularity for a time period of 10-minutes. All the records reported in the present paper refer to the 1-hour interval centered on the considered 10-minutes record, with the aim of providing a more general overview of the examined wind event.



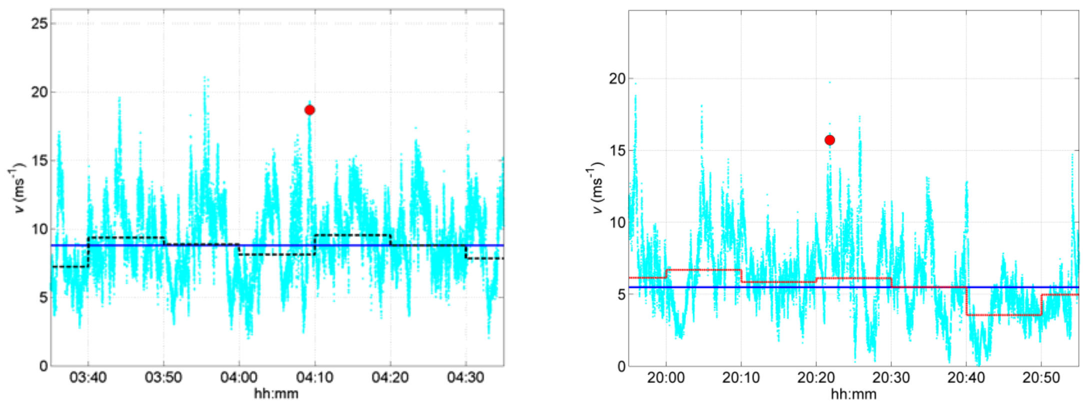
(a) Port of Savona, 22nd November 2011 (b) Port of La Spezia, 7th October 2011

Fig. 1 1-hour wind speed raw data associated to extra-tropical depressions



(a) Port of La Spezia, 25th October 2011 (b) Port of La Spezia, 19th October 2011

Fig. 2 1-hour wind speed raw data associated to thunderstorms



(a) Port of La Spezia, 16th December 2011 (b)

Fig. 3 1-hour wind speed raw data associated to gust fronts

The separation and classification of intense wind phenomena into homogeneous families is a key topic to interpret the events of engineering interest, to study the wind-excited response of structures, to determine the distribution of extreme wind velocities and of extreme wind-induced effects. De Gaetano *et al*. (2014) developed a semi-automated procedure aimed at separating and classifying independent extreme extra-tropical depressions, thunderstorms and gust fronts through a suitable mix of quantitative controls and qualitative judgments.

Two aspects have particular relevance. First, as Kasperski (2002) pointed out for the first, it is not possible to separate clearly S G extra-tropical depressions from NS NG thunderstorms. At least a third class of wind phenomena exist, defined herein as S NG intermediate events, or gust fronts, which complicate the "binary" approach that prevails in the literature. Second, in order to separate and classify intense wind phenomena, several statistical parameters not usually available should be examined and recourse should be made to qualitative judgments (De Gaetano *et al*. 2014). This throws quite a few shadows on some extraction and classification criteria reported in the literature. Since the separation of wind events is functional to carry out more refined analyses, their meaning becomes somewhat questionable if it is not equally accurate the preliminary separation process. These aspects have deep impact in terms of both the dynamic wind-excited response of structures (Section 3) and the mixed statistics of extreme wind velocities and wind-induced effects (Section 4).

3. Wind-excited response and response spectrum technique

The dynamic alongwind response of structures is a cornerstone of wind engineering. The classical formulation of this problem deals with synoptic events in neutral atmospheric conditions, and assumes that the wind velocity in a time interval between 10 minutes and 1 hour is a stationary Gaussian process (Davenport 1961). The wind velocity is transformed into an aerodynamic action by assuming that turbulence is small and neglecting the contribution of the quadratic term of the fluctuations; so, as the wind velocity, also the aerodynamic action is Gaussian. Thus, dealing with the structure as a linear system, also its response is Gaussian. Davenport (1964) described the maximum value of the response by a distribution function obtained assuming that the up-crossings of a suitably high threshold are rare and independent events, so they have Poissonian distribution. Since the density function of the maximum response is usually narrow and sharp, its mean is considered sufficiently representative of the maximum response.

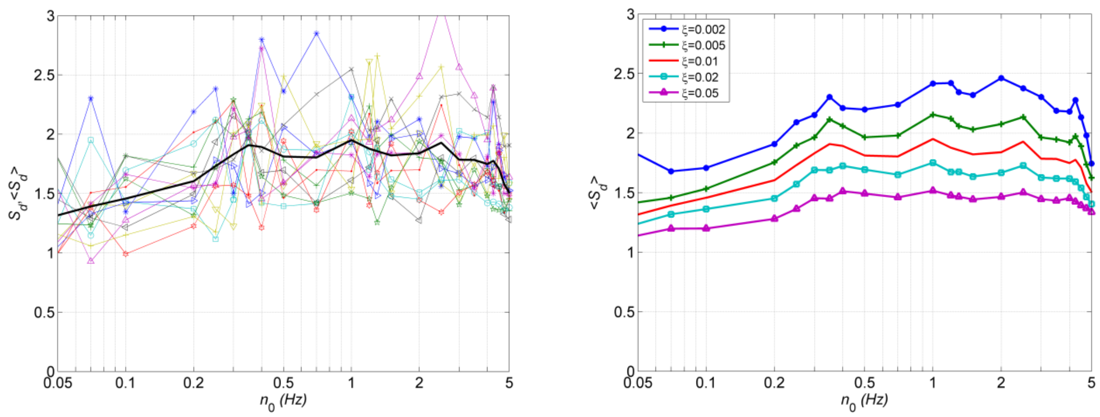
As far as concerns thunderstorms, as already noted in the introduction, the literature of wind engineering has gradually oriented towards increasingly refined techniques by means of which the wind velocity is first decomposed at different scales through mobile mean operators (Choi and Hidayat 2002, De Gaetano and Solari 2013), empirical mode decomposition (Xu and Chen 2004), wavelet shrinkage and Hilbert transforms (Chen and Letchford 2005a, b, 2006). Each scale of the wind velocities is then represented by deterministic and/or stochastic models in time and/or in frequency domain (Chen and Letchford 2004a), using for instance the evolutionary power spectral density function or the wavelet transforms (Huang and Chen 2009). Though widely expected and desired, simple models for engineering applications and regulatory schemes are still largely missing.

The literature in seismic engineering has followed different paths. Born in the middle of the twentieth century, so older and more consolidated than the literature on thunderstorms, it has been oriented immediately towards simplified models founded, almost exclusively, on the response spectrum technique (Housner 1959, Housner and Martel 1953). The dissemination and the fame of this technique have been favored, on the one hand, by the riches of the data on real earthquakes, and, on the other, by the simplicity of a method rapidly and easily entered the engineering and codification sectors. Only later, with the evolution of process theory, signal analysis and random dynamics, the research in seismic engineering has followed different advanced ways. However, in spite of this recent, the seismic field has remained faithful to the response spectrum technique. Such technique has a more general and broad field of application in all those sectors in which the dynamic response of structures is due to transient phenomena of short duration, such as impacts, explosions and wave-fronts (Kappos 2001).

In the field of wind engineering, the response spectrum technique was first applied by Solari (1989) in order to deal with seismic and (synoptic) wind actions in a unitary way. The concept of response spectrum was implicitly taken again by Chen and Letchford (2004b) and by Chai and Albermani (2005) to evaluate the dynamic alongwind response of Single-Degree-Of-Freedom (SDOF) systems and buildings to thunderstorm winds. Chen and Letchford (2004b) introduced a parameter, called Maximum Dynamic Magnification Factor (MDMF), of which they noted the analogies with the seismic response spectrum; in reality, the MDMF is just a response spectrum. It is worth noting that authors concluded their paper urging the use of more refined models aimed at improving the comprehension of thunderstorms and simulating them through Monte Carlo techniques. Chai and Albermani (2005) introduced a so-called Dynamic Response Factor (DRF), coincident with the MDMF. Carassale and Brunenghi (2013) used the response spectrum technique with the purpose of studying the dynamic response of trackside structures to passing trains.

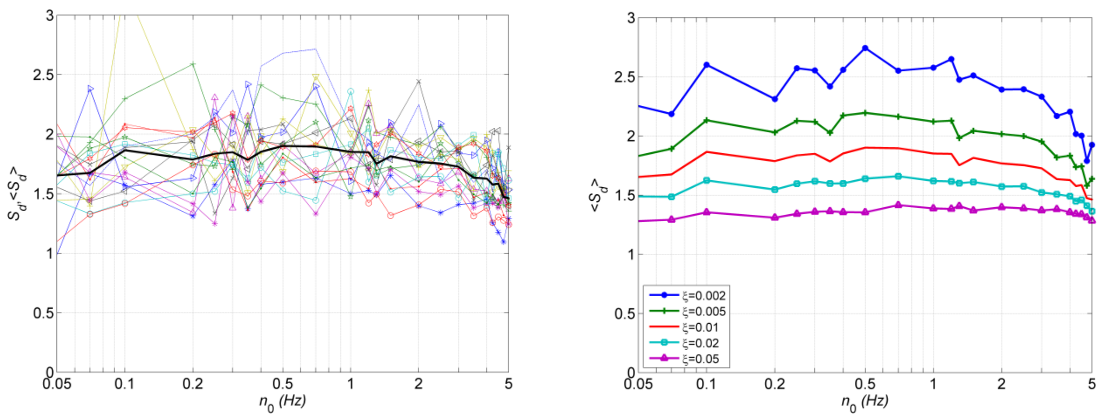
Taking into account, on the one hand, the transient nature and short duration of thunderstorms, and, on the other, the need to offer more early the engineering and codification sectors a calculation tool suitable to capture the main aspects of the wind-excited response of structures to such a phenomenon, the response spectrum technique seems to be a natural candidate to solve most of these problems. Solari *et al*. (2013a) developed this method by defining the thunderstorm response spectrum, or more in general the wind response spectrum, S_d, as the ratio between the maximum dynamic displacement of a SDOF system subjected to an identically coherent wind field, and the static displacement due to the aerodynamic action associated with the peak wind velocity V_p averaged over a short time interval $\tau = 1$ s. S_d depends, besides the excitation, on the fundamental frequency n_0 and on the damping coefficient ξ of the structure. By virtue of this definition, for $n_0 =$

0, S_d = 0; for n_0 tending to infinite, S_d tends to the square of the ratio between the instantaneous peak wind velocity and the peak wind velocity averaged on τ. The equivalent static pressure Q_e is the product of the peak wind velocity pressure $Q_p = (1/2)\rho V_p^2$, ρ being the air density, by the response spectrum S_d. S_d identifies itself with the MDMF (Chen and Letchford 2004b), with the DRF (Chai and Albermani 2005), and with the dynamic coefficient C_d adopted, for instance, by the Eurocode 1 (2005).



(a) (b)

Fig. 4 (a) Response spectra (ξ = 0.01) and, (b) mean response spectra for 14 thunderstorms



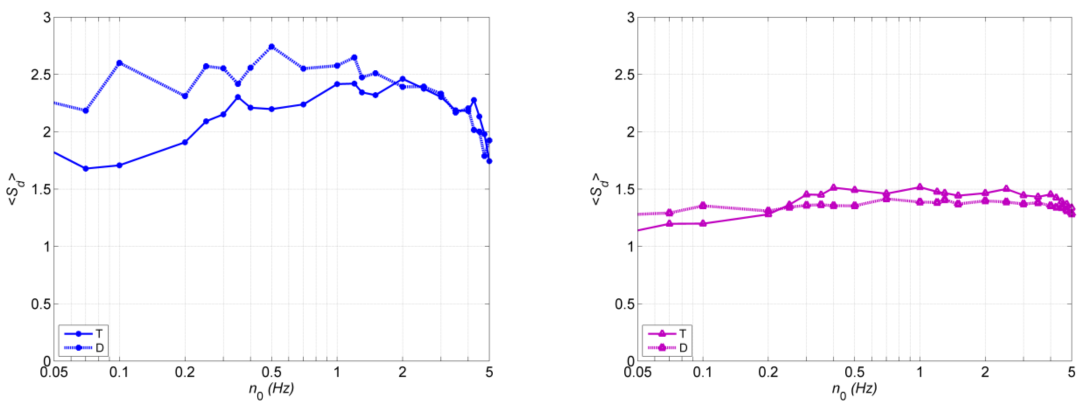
(a) (b)

Fig. 5 (a) Response spectra (ξ = 0.01) and, (b) mean response spectra for 17 depressions

Fig. 4(a) shows the response spectra S_d (for ξ = 0.01, thin lines) of 14 thunderstorms (T) occurred in La Spezia in the period 2011-2012 (Solari *et al.* 2013a); the thick line corresponds to the mean response spectrum $<S_d>$, i.e. the mean value of the response spectra due to each thunderstorm; this value is coherent with the mean maximum value of the response classically adopted for representing the wind-excited response of structures. The dispersion of the results is similar to that usually obtained for earthquakes; some thunderstorms give rise to very intense responses for particular values of n_0. Fig. 4(b) shows the mean response spectra $<S_d>$ of the above 14 events for ξ = 0.002, 0.005, 0.01, 0.02 and 0.05. $<S_d>$ increases on decreasing ξ; it tends to increase on increasing the fundamental frequency up to about n_0 = 0.4 Hz; it is rather uniform in the range between n_0 = 0.4 and 2-3 Hz; it decreases on increasing n_0 above 2-3 Hz.

Fig. 5(a) shows the response spectra S_d (for ξ = 0.01, thin lines) of 17 depressions (D) occurred in La Spezia in the period 2011-2012 (Solari *et al.* 2013a); the thick line corresponds to the mean response spectrum $<S_d>$. Also in this case the dispersion of the results is similar to that of earthquakes. Fig. 5(b) shows the mean response spectra $<S_d>$ of the above 17 events for ξ = 0.002, 0.005, 0.01, 0.02 and 0.05; $<S_d>$ increases on decreasing ξ; it is relatively uniform for n_0 = 0.1-1 Hz, while it assumes progressively decreasing values in the high frequency range.

Fig. 6 compares the mean response spectra of thunderstorms (T) (Fig. 4(b)) and depressions (D) (Fig. 5(b)) for ξ = 0.002 (a) and 0.05 (b), respectively. In the case of low damped systems (ξ = 0.002), for small values of n_0 the mean response spectrum of depressions is much greater than that corresponding to thunderstorms; this mainly happens because the system is struggling to develop fully the resonance under actions with short duration; for large values of n_0, the spectra of thunderstorms and depressions are comparable. In the case of high damped systems (ξ = 0.05), for small values of n_0 the mean response spectra of depressions are moderately greater than those corresponding to thunderstorms; for large values of n_0 this trend is reversed, and the mean response spectra of thunderstorms prevail over those of depressions. This comparison is only partially coherent with the results of Chen and Letchford (2004b); due to the higher sampling rate, the present results provide a better and more reliable picture of the high frequency range.



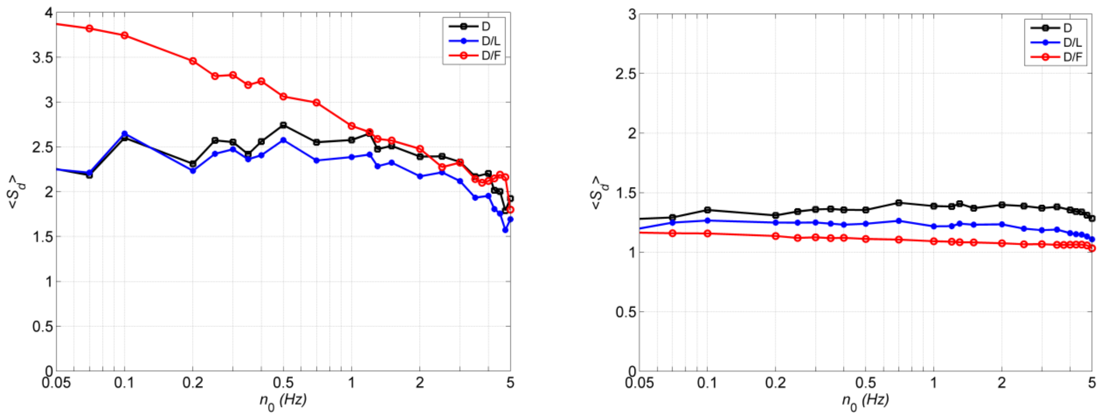
(a) ξ = 0.002 (b) ξ = 0.05

Fig. 6 (a) Mean response spectra for thunderstorms and depressions

Fig. 7 puts in comparison the mean response spectra of depressions (D) (Fig. 5(b)) for $\xi = 0.002$ (a) and 0.05 (b), respectively, with the mean response spectra given by two different approaches. Diagrams D/L correspond to the application of the response spectrum technique by neglecting the quadratic term of the fluctuations. Diagrams D/F correspond to the frequency domain solution obtained starting from the mean power spectral density (PSD) of the 17 depressions considered, and determining the mean maximum value of the response by Davenport's distribution. Therefore, diagrams D/F represent the typical results provided by engineering and code evaluations. There are relevant differences depending on the evaluation approach and on the values of n_0 and ξ.

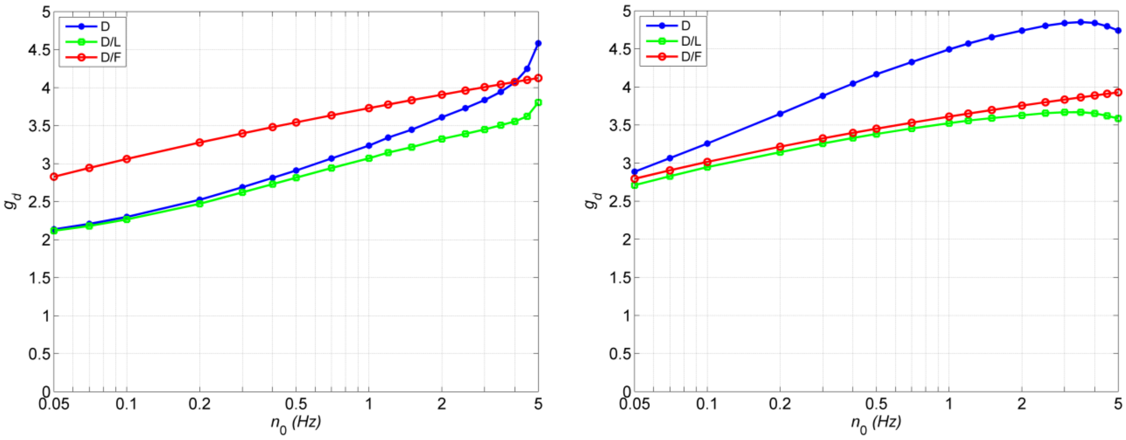
Fig. 7(a) refers to low damped systems. The mean response spectrum evaluated neglecting the quadratic term of the fluctuations (D/L) involves limited underestimates that tend to increase on increasing n_0. The frequency domain analysis (D/F) gives rise to results that are increasingly higher than the solution D/L on decreasing n_0. Fig. 7(b) refers to high damped systems. The mean response spectrum evaluated neglecting the quadratic term of the fluctuations (D/L) is clearly less that that determined by retaining such term; also in this case the reduction increases on increasing n_0. The frequency domain analysis (D/F) gives rise to results that are moderately lower than the solution D/L.

In order to clarify the differences involved by the above three methods (D, D/L, D/F), a Monte Carlo procedure has been implemented aimed at generating 10000 wind velocity histories with the mean value and the PSD of the 17 depressions already considered. This study confirms that the standard deviation and the expected frequency of the displacement of the SDOF system is the same, for any value of n_0 and ξ, regardless of the fact that the equations of motion are solved in the time domain, neglecting the quadratic term of the fluctuations (E/L), or in the frequency domain (E/F). On the other hand, large differences occur with reference to the peak coefficient of the displacement g_d, i.e., the difference between the mean maximum value and the mean value of the displacement divided by its standard deviation.



(a) $\xi = 0.002$ (b) $\xi = 0.05$

Fig. 7 Mean response spectra for depressions, using three different evaluation approaches



(a) ξ = 0.002 (b) ξ = 0.05

Fig. 8 Peak coefficient of the displacement of a SDOF system subjected to depressions

Fig. 8 shows the peak coefficient of the displacement of a SDOF system subjected to the above simulated depressions, for ξ = 0.002 (a) and 0.05 (b), respectively. The time-domain solution obtained neglecting the quadratic term of the fluctuations (D/L) underestimates the exact solution (D) greater, the greater are the values of n_0 and ξ. For small values of ξ, the frequency domain solution (D/F) largely overestimates the linearized solution (D/L); for large values of ξ, the frequency domain solution (D/F) provides a rather accurate approximation on the safe side of the linearized solution (D/L). Three remarks are worth noticing.

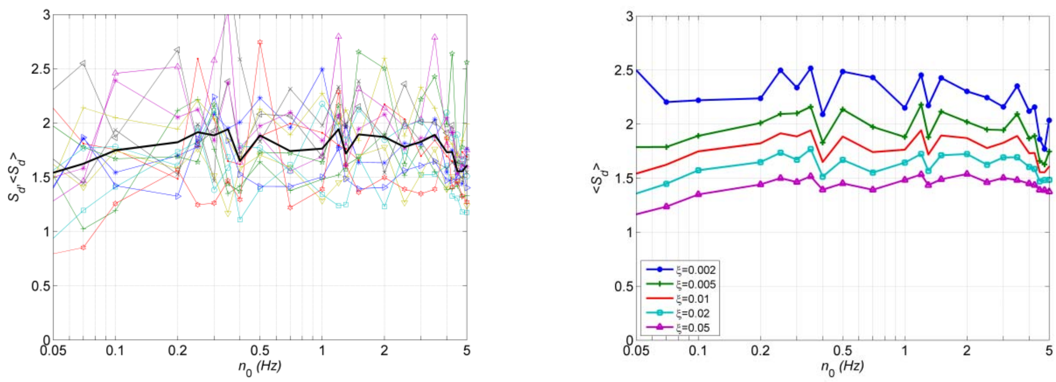
First, for small values of n_0 and ξ, the depressions give rise to a narrow band response, of prevailing dynamic nature, which makes limited the contribution of the quadratic term of the fluctuations. On the other hand, since the peaks of the response occur in clumps, the threshold up-crossings are not independent; it follows that the Davenport's distribution loses validity and leads to overestimates of the maximum response even high (Vanmarcke 1975). This fact is well known from a conceptual viewpoint but perhaps not so recognized in quantitative terms: to the knowledge of author, the literature of wind engineering literature does not seem fully aware of overestimates even greater than 50%.

Second, for large values of n_0 and ξ, the depressions give rise to a broad band response, characterized by mainly independent threshold up-crossing; thus, the Davenport's distribution is correctly applied. On the other hand, mainly because the response is prevailingly quasi-static, neglecting the quadratic term of the fluctuations leads to underestimates of the maximum response even serious as previously stated, for instance, by Soize (1978), Grigoriu (1986), Chen and Huang (2009), Kwon and Kareem (2011).

Third, the comparison between the dynamic response of a SDOF system to thunderstorms and to depressions is very different depending on whether depressions are analyzed in the time domain retaining the quadratic term of the fluctuations, for instance by means of the response spectrum technique, or in the frequency domain, neglecting the quadratic term of the fluctuations and using the Davenport's distribution. The former approach is rigorous but unusual; the latter is classical but, in the aforementioned terms, not fully realistic.

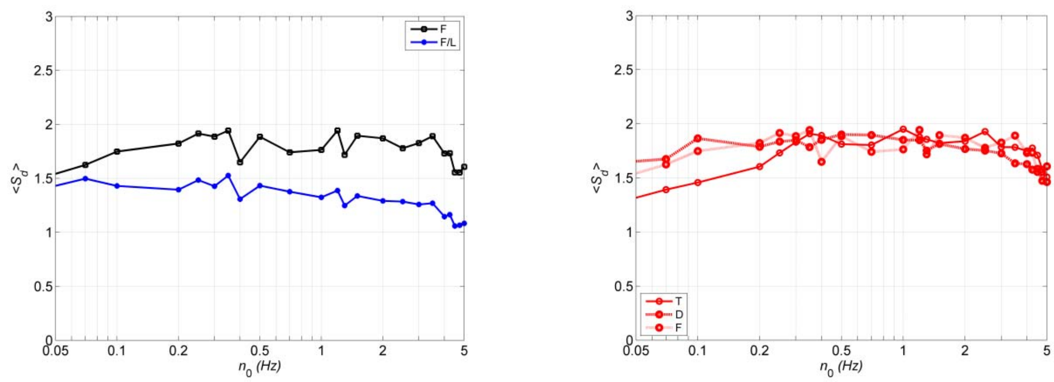
It should be added that, considering the quadratic term of the fluctuations and waiving the hypothesis of independent peaks, the distribution of the maximum response deeply changes compared with the Davenport’s one; thus, at least in principle, analyses can no longer be limited to the mean maximum value of the response, i.e. to the peak coefficient (Kwon and Kareem 2011). This points out the opportunity of re-examining more systematically this whole matter, regardless of thunderstorms, putting into play also some well-established concepts.

Fig. 9(a) shows the response spectra S_d (for $\xi = 0.01$, thin lines) of 14 gust fronts (F) occurred in La Spezia in the period 2011-2012 (Solari *et al*. 2013a); the thick line corresponds to the mean response spectrum $\langle S_d \rangle$. Also in this case the dispersion of the results is similar to that of earthquakes. Fig. 9(b) shows the mean response spectra $\langle S_d \rangle$ of the above 14 events for $\xi = 0.002$, 0.005, 0.01, 0.02 and 0.05; $\langle S_d \rangle$ increases on decreasing ξ; it is relatively uniform for $n_0 = 0.3$-3 Hz, while assumes progressively decreasing values in both the low and high frequency ranges. To Author’s knowledge, no previous research has been carried out on the response of structures to such wind phenomenon.



(a) (b)

Fig. 9 (a) Response spectra ($\xi = 0.01$) and, (b) mean response spectra for 14 gust fronts



(a) (b)

Fig. 10 (a) Comparison between the mean response spectra of gust fronts ($\xi = 0.01$), with and without the quadratic term of the fluctuations and (b) comparison between the mean response spectra of depressions, thunderstorms and gust fronts ($\xi = 0.01$), with the quadratic term of the fluctuations

Fig. 10(a) shows a comparison between the mean response spectra $<S_d>$ of the above gust fronts, for $\xi = 0.01$, evaluated retaining (F) or not retaining (F/L) the quadratic term of the fluctuations; in this case, the classical linearized theory falls seriously in defect to the detriment of safety; this points out again the problem of characterizing the maximum response not only through its mean value. Fig. 10(b) shows a comparison between the mean response spectra $<S_d>$ of depressions (D), thunderstorms (T) and gust fronts (F), taking into account the quadratic term of the fluctuations; the response to gust fronts is often greater than the response to thunderstorms and, in some cases, than the response to depressions; this may be explained by the fact that the duration of gust fronts gives the system enough time to develop the resonance, similarly to what happens for depressions.

Fig. 10(b) shows that the envelope of the maximum values of the mean response spectra $<S_d>$ of depressions, thunderstorms and gust fronts in the typical range of the fundamental frequencies of structures (n_0 = 0.3-3 Hz) has a trend substantially independent of n_0; this seems to contradict the classical concept in accordance with which the dynamic coefficient decreases on increasing n_0. Though this remark is widely justified by the foregoing, it draws attention on the circumstance that analyses carried out in this section consider the wind field as identically coherent on the structural surface exposed to wind, so they involve a unit aerodynamic admittance function. The overcoming of this assumption, also in the prospect of extending this formulation from SDOF to Multi-Degree-Of-Freedom (MDOF) systems, will shed new light on the role of the fundamental frequency and, more in general, on the dynamic response of structures to wind events with different properties.

4. Mixed velocity and loading statistics

Taking a cue from the pioneering paper of Gomes and Vickery (1977,1978), and omitting for sake of simplicity tropical cyclones and tornadoes, the statistical analysis of the maximum wind velocity is usually carried out in accordance with three steps: 1) different wind events, namely extra-tropical depressions, thunderstorms and gust fronts, are separated; 2) for each event the distribution of the maximum velocity is determined; 3) such distributions are combined in one mixed distribution of the maximum velocity. If the ultimate aim of the analysis is to determine the distribution of the maximum peak wind velocity (as for instance in U.S. and in Australia), the distributions of the maximum velocity linked with different wind events may be combined without any intermediate step. If the ultimate aim of the analysis is to determine the distribution of the maximum mean wind velocity (as for instance in Europe), an intermediate step should be carried out in order to make the different events first homogeneous (Kasperski 2002); this is possible, for example, by transforming the peak wind velocities of thunderstorms and gust fronts, through suitable reference gust factors, into equivalent mean wind velocities associated with depressions. It is worth noting that, once obtained the mixed distribution of the maximum peak or mean wind velocity, so the design wind velocity associated with a given mean return period, this quantity loses the memory of its genesis and of the events that contributed to its estimation.

It is also worth noticing that, as already pointed out in Section 3, while there is a consolidated literature on the structural behavior due to extra-tropical depressions, there is a persistent lack of simple and reliable engineering method to determine the structural behavior due to thunderstorms and even more to gust fronts. For this reason, once determined the distribution or the design value of the wind velocity through mixed statistics, such velocity is traditionally put into calculation models and regulatory schemes based upon extra-tropical depressions. This is clearly at odds with the awareness that the wind velocities that most affect the tail of the distribution of the maximum are often related to thunderstorms and sometimes to gust fronts. Using a distribution of the maximum or a design wind velocity without any link with its genesis is even more striking in the light of the different behavior of structures with regard to different wind exciting phenomena (Section 3).

To better illustrate this problem, Table 1 shows the main properties of 15 wind events among those examined in Section 2 (Solari *et al*. 2013a). Five of them are associated with depressions (D), five with thunderstorms (T) and five with gust fronts (F). These events are selected in such a way that the peak wind velocities V_p of the depressions are less than the peak wind velocities of the gust fronts, which are substantially less than the peak wind velocities of the thunderstorms. Fig. 11 shows the peak velocity pressure Q_p related to these 15 events and provides an interpretation key for the Figs. 12 and 13, which show the equivalent static pressure Q_e caused by the above 15 events on two test SDOF systems denoted by A and B, respectively. System A has a fundamental frequency n_0 = 0.4 Hz and a damping coefficient ξ = 0.002. System B as a fundamental frequency n_0 = 2 Hz and a damping coefficient ξ = 0.01.

Q_e is evaluated by three different methods corresponding, respectively, to the schemes (a), (b) and (c) in Figs. 12 and 13.

(a) Q_e is evaluated by multiplying Q_p (Fig. 11) by the dynamic coefficient C_d. As typical of engineering methods and regulatory schemes, this parameter is determined in the frequency domain, starting from the PSD of the extra-tropical depressions previously studied in Section 3; analyses are carried out by neglecting the quadratic term of the fluctuations and expressing the maximum structural response through the mean value of the Davenport's distribution. Due to these assumptions, C_d depends on the structure (C_{dA} = 3.23, C_{dB} = 1.45) but not on the exciting event. As such, it uniformly scales the Q_p values without altering the order and the proportion of the wind loads (Figs. 12(a) and 13(a)).

Table 1 Main properties of the selected depressions (D), thunderstorms (T) and gust fronts (F) recorded in the Port of La Spezia in the period 2011-2012

Event	No.	Anemometer	Date	Hour	V_p (m/s)	Q_p (N/m^2)
D	1	3	18/04/2012	22:50	14.64	133.96
	2	3	19/10/2011	23:00	14.74	135.79
	3	2	20/10/2011	00:10	15.37	147.65
	4	3	07/10/2011	02:40	15.59	151.91
	5	3	24/04/2012	05:10	15.62	152.49
F	1	3	03/02/2012	11:30	16.47	169.54
	2	2	06/01/2012	05:40	16.83	177.03
	3	3	24/01/2012	13:20	19.13	228.72
	4	3	10/02/2012	06:10	19.55	238.88
	5	3	06/01/2012	05:40	22.29	310.53
T	1	3	24/09/2012	13:50	22.09	304.98
	2	3	11/04/2012	07:20	22.67	321.21
	3	3	19/10/2011	21:10	23.57	347.22
	4	2	11/04/2012	07:20	29.42	540.96
	5	3	25/10/2011	15:40	33.58	704.76

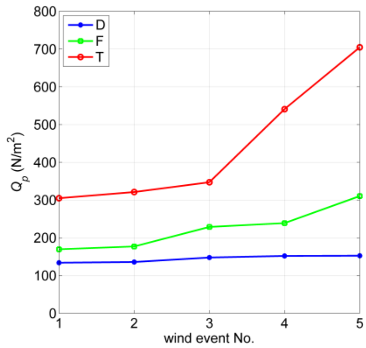


Fig. 11 Peak velocity pressure for the selected depressions (5), thunderstorms (5) and gust fronts (5)

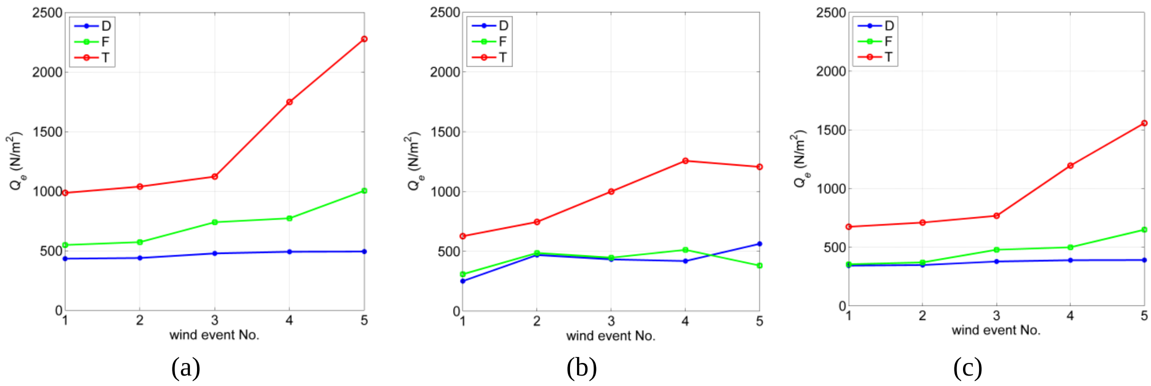
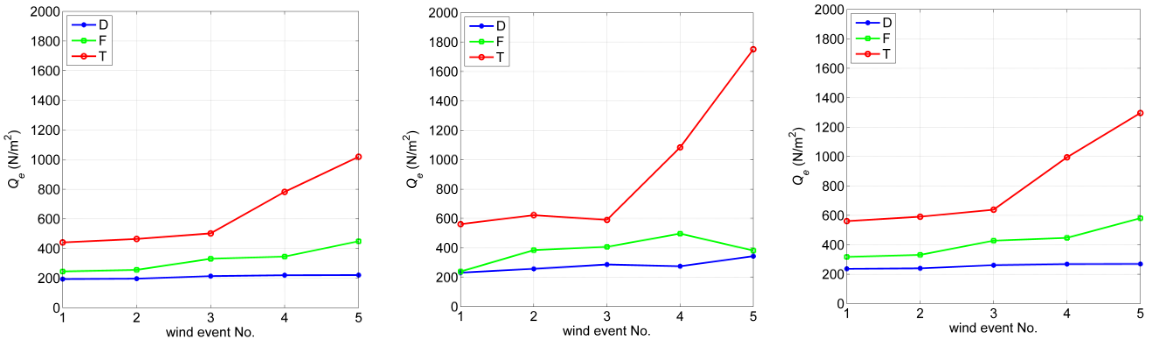


Fig. 12 Equivalent static pressure on System A, determined by the dynamic coefficient (a), the response spectrum (b) and the mean response spectrum (c)

(b) Q_e is evaluated by multiplying Q_p (Fig. 11) by the response spectrum S_d of each event. Such parameter is determined by solving the rigorous equation of motion of the SDOF system in the time domain. Figs. 12(b) and 13(b) point out the extreme sensitivity of the structural response - not captured by calibrating the dynamic coefficient on extra-tropical depressions and extending this position to gust fronts and thunderstorms - to the specific properties of the exciting events. This sensitivity is enough to upset the order and the proportion of the wind loads.

(c) Q_e is evaluated by multiplying Q_p (Fig. 11) by the mean response spectrum $<S_d>$ of each family of events ($<S_{dA}>$ = 2.60 and $<S_{dB}>$ = 1.78 for depressions, $<S_{dA}>$ = 2.09 and $<S_{dB}>$ = 1.87 for gust fronts, $<S_{dA}>$ = 2.21 and $<S_{dB}>$ = 1.84 for thunderstorms). As shown by Figs. 12(c) and 13(c), this approach does not involve a disruption of the type mentioned above but, nevertheless, it is sufficient to significantly change the order and the proportion of the wind loads.



(a) (b) (c)

Fig. 13 Equivalent static pressure on System B, determined by the dynamic coefficient (a), the response spectrum (b) and the mean response spectrum and (c)

Coherently with the results in Section 3, system A, flexible and low damped, exalts the effects of depressions and mitigates those of thunderstorms; system B, stiff and rather damped, exalts the effects of thunderstorms and mitigates those of depressions. In the first case, the Q_e values due to the most intense depressions prevail on the least violent gust fronts. In the second case, especially the differences among the Q_e values due to gust fronts and depressions are amplified. It is worth noting that these evaluations are referred to ideal SDOF systems, so they do not take into account the vertical profile of the wind velocity. Remembering the substantial differences between the velocity profiles of depressions and thunderstorm (Section 1), the variations of the equivalent static pressure on vertical structures is intended to amplify greatly. There are not yet enough elements to discuss this problem with reference to gust fronts.

The above three methods assume special conceptual and operative interest if embedded within a more general framework aimed at determining wind loading on structures. In such a framework they are referred to as the Dynamic Coefficient Method (DCM), the Database Assisted Design (DAD) and the Independent Loading Technique (ILT) (Solari *et al*. 2013b).

(a) DCM is the typical approach currently used in the wind engineering and codification sectors. It involves the following procedure: 1) consider the series of the maximum values of the wind velocity V_{Ei} (regardless of whether they are mean or peak values), where $E = D, T, F$ and $i = 1, 2, \ldots n_E$ are, respectively, the type and the order number of wind events; 2) determine the distribution of the maximum value of the velocity F_{VE} for each event E; 3) using mixed statistics, determine the distribution of the maximum value of the wind velocity, $F_V = \Pi_E F_{VE}$; 4) determine the design wind velocity V_d and the design peak velocity pressure Q_{pd} associated with a suitable value of the design return period T_d; 5) determine the design equivalent static pressure $Q_{ed} = Q_{pd} \cdot C_d$, where C_d is the dynamic coefficient of extra-tropical depressions, and the design wind-induced response R_d. The use of the same dynamic coefficient for any wind event is clearly not correct.

(b) DAD is coherent with the methods recently proposed by Yeo (2011) and Lombardo (2012). It involves the following procedure: 1) consider the records of the wind velocities associated with the series of maximum values V_{Ei} ($E = D, T, F$; $i = 1, 2, \ldots n_E$); 2) integrating the equations of motion, for instance using the response spectrum S_d of each event, determine the series of the maximum values of the equivalent static pressure Q_{eEi} and of the wind-induced response R_{Ei}; 3) determine the distribution of the maximum values of the equivalent static pressure F_{Qe} and of the wind-induced response F_R; 4) determine the design equivalent static pressure Q_{ed} and the design wind-induced response R_d associated with a suitable value of the design return period T_d. Differently from DCM, this method involves the statistical analysis of the equivalent static pressure and response instead of the wind velocity. It provides refined solutions through the use of systematic and burdensome computational analyses, in an advanced environment not yet familiar to most engineers.

(c) ILT is a novel approach aimed at overcoming the shortcomings of DCM, in the meanwhile avoiding the computational burden of DAD. Established in a framework that is different but not overwhelming engineering practice, it involves the following procedure: 1) consider the series of the maximum values of the wind velocity V_{Ei} (E = D, T, F; i = 1, 2, ... n_E); 2) determine the distribution of the maximum value of the velocity F_{VE} for each event E; 3) determine the design wind velocity V_{Ed} associated with a suitable value of the design return period T_d, for each event E; 4) using the mean response spectrum $<S_d>$ of each event E, determine the design equivalent static pressure Q_{ed} and the design wind-induced response R_{Ed}. This method gives rise to several independent wind loading conditions - namely one loading condition for depressions, one for thunderstorms and one for gust fronts, respectively - in place of the classical unique wind loading condition joining different wind events through mixed statistics.

This approach is robustly supported by the deep diversity of each wind event, not only for the stationary or non-stationary and Gaussian or non-Gaussian character of the velocity time-histories (Sections 2 and 3) but, even more, for the shape of the vertical profile of the mean wind velocity (Goff 1976, Oseguera and Bowles 1988, Vicroy 1992, Selvam and Holmes 1992, Wood *et al*. 2001), for the parameterization of the wind fields with reference to the roughness length (Xu and Hangan 2008, Vermeire *et al*. 2011, Orf *et al*. 2012) and to the thermal stratification (Sterling *et al*. 2011), for the effects of topography (Selvam and Holmes 1992, Wood *et al*. 2001, Orf *et al*. 2012), and for the intensity, size, duration and recurrence of the different phenomena.

It is worth noticing that transferring wind data from one site to another considering height, roughness and topography changes is a cornerstone of wind engineering. This principle is well-established for vast and intense extra-tropical depressions, for which it is appropriate to consider the PBL in local equilibrium and neutrally stratified. Similar principles are anything but traditional and consolidated for unstable atmospheric phenomena such as gust fronts. Even more, they are completely missing for short duration and limited extension events such as thunderstorms. In the light of these remarks, unify the treatment of thunderstorms and gust fronts in the unique reference model of the extra-tropical depressions means to distort reality and to force the use of concepts and rules definitely outside their correct application domain.

It is also worth noting that phenomena with different size, duration and recurrence do not lend themselves to be represented by the unique set of partial safety coefficients and combination factors traditionally used in safety formats for the unique wind loading condition. Separating such unique wind loading condition into a set of independent wind loading conditions, each one associated to depressions, thunderstorms and gust fronts, leads to the striking proposal of fully revisiting the classical combination rules of the loadings, at least introducing a new set of partial safety coefficients and combination factors. Make these concepts operative is far from immediate; however, it is worth investing future research and speculative efforts.

5. Conclusions

This paper exploits the data and the knowledge gained during the project “Wind and Ports”, in order to investigate some critical aspects of thunderstorms and their effects on structures, to highlight emerging issues on mixed climates, to depict new scenarios that drawing inspiration from thunderstorms may address a more general and rational framework for wind actions and effects on structure. Omitting for sake of simplicity tropical cyclones and tornadoes, three main aspects have been pointed out.

The first aspect concerns the separation and classification of different intense wind events. While the technical literature tends to apply a “binary” separation between stationary Gaussian extra-tropical depressions and non-stationary non-Gaussian thunderstorms, this paper points out the existence and the importance of at least a third class of stationary non-Gaussian intermediate events that makes the above separation a very critical issue. This throws a few shadows on some extraction and classification criteria reported in the literature. Since the separation of wind events in different families is functional to carry out more precise analyses, their meaning is somewhat questionable if it is not equally accurate the preliminary process of separation.

The second aspect deals with the use of the response spectrum technique, not only as a potentially efficient tool for calculating the structural response to transient events with short duration such as the thunderstorms, but also as a mean and a starting point for revisiting the whole the wind-excited response in a more comprehensive framework, putting into play also some well-established concepts. Especially the use of the classical Davenport’s distribution of the maximum response of flexible and low-damped structures to stationary wind events may give rise to extremely severe errors; this aspect is well-known from a conceptual viewpoint but not so recognized in quantitative terms; in particular, errors may become so large as to distort some classical concepts as the reduction of the response on increasing the structural frequency.

The third aspect involves the statistical analysis of extreme wind velocities in mixed climates. The literature is substantially oriented towards an approach in three steps: 1) different wind events are separated; 2) the distribution of the maximum velocity for each event is evaluated; 3) these distributions are combined into one mixed distribution of the maximum velocity. Once this distribution has been determined, the design wind velocity is usually put into calculation models and regulatory schemes typical of extra-tropical depressions. This is at odds with the awareness that the tails of the distribution of the maximum velocity are often linked with thunderstorms. Even more, this is striking considering several differences among different events, namely the response of structures to stationary/non-stationary and Gaussian/non-Gaussian events, the shape of the vertical profile of the mean wind velocity, the parameterization of the wind field with reference to the roughness length and to the thermal stratification, the topography effects. In the light of such remarks, unify the treatment of thunderstorms and gust fronts under the umbrella of the unique reference model of extra-tropical depressions means to distort reality and to force the use of concepts and rules definitely outside their correct application domain. It is also worth noting that phenomena with different size, duration and recurrence do not lend themselves to be represented by the unique set of partial safety coefficients and combination factors. From here takes the cue the novel proposal of the Independent Wind Loading technique. It consists in separating the classical unique wind loading condition into a set of independent wind loading conditions, each one associated to depressions, thunderstorms and gust fronts - providing different calculation models for each event and revisiting the classical combination rules involving wind loading at least introducing a new set of partial safety coefficients and combination factors. Make these concepts operative is far from immediate; however, it is worth investing future research and speculative efforts.

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