Thunderstorm Outflows and their Impact on Structures

edited by
Maria Pia Repetto
Massimiliano Burlando

GENOVA UNIVERSITY PRESS

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This volume is a collection of original contributions of the invited speakers to the International Advanced School and the Workshop on New Frontiers on *Thunderstorm Outflows and their Impact on Structures*, held in Genoa on October 4-8, 2021.

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INTERNATIONAL ADVANCED SCHOOL ON THUNDERSTORM OUTFLOWS AND THEIR IMPACT ON STRUCTURES

LECTURES

Course introduction and THUNDERR project*

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The lecture opens the International Advanced School on *Thunderstorm outflows and their impact on structures* (4-6 October 2021) and the Workshop on *New frontiers on thunderstorm outflows and their impact on structures* (7-8 October 2021) organized by the University of Genoa as a conclusion of the THUNDERR project.

Europe and many countries in the world are exposed to cyclones and thunderstorms. Cyclones are known since the 1920s, their actions on construction were framed since the 1960s, and engineering still uses these models. Thunderstorms are complex and devastating phenomena that result in actions often more intense than cyclonic ones. Despite this awareness and a huge amount of research in this field, there is no model of thunderstorms and their actions similar to that established over half a century ago for cyclones. This occurs because their complexity makes it difficult to set realistic and simple models; their short duration and small size limit available measures; there is a gap between atmospheric sciences and wind engineering. Awarded by the European Research Council (ERC) to Prof. Giovanni Solari by means of an Advanced Grant, the project THUNDERR (Solari *et al.*, 2020)

* https://www.youtube.com/watch?v=qDJAMFSDg9U&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=1

is addressed to «Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures» (www.thunderr.eu; https://cordis.europa.eu/article/id/436252-thunderstorm-analysis-offers-wind-safer-construction).

The Lecture introduces the overall objectives of the project, describing the structure of the three main aims (Figure 1): the measure, comprehension and modelling of thunderstorm phenomenon (I), the analysis of its effects on structures (II) and the dissemination to the scientific community and industry sector of this new knowledge (III).

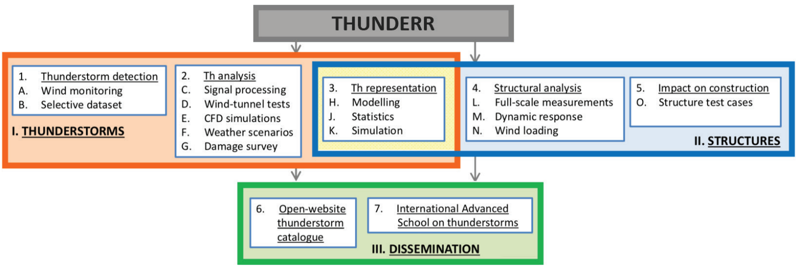

Figure 1. Structure of the THUNDERR project.

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Wind monitoring and thunderstorm detection[*]

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Thunderstorm detection has been a fundamental issue in atmospheric sciences and wind engineering since the beginning of thunderstorm investigation in the 40's of last century (Byers and Braham, 1949). The difficulty of thunderstorm detection is strictly related to codified atmospheric monitoring procedures because the small spatial/temporal scale of these phenomena makes challenging their detection adopting the standard meteorological measurements' recommendations by WMO, which are thought to monitor larger and longer-lasting phenomena instead. Accordingly, ad-hoc measurement campaigns must be designed to properly measure thunderstorm outflows, as during NIMROD (Fujita, 1978) and JAWS (McCarthy *et al.*, 1982) projects.

This lecture focuses on «Wind monitoring and thunderstorm detection» in an attempt to describe how wind measurements of thunderstorm outflows should be taken in order to properly record all the relevant information. This aspect is dealt with in terms both of monitoring network and wind sensors characteristics. In addition, the problem of the recognition of thunderstorm records by automated met-stations is also discussed.

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[*] https://www.youtube.com/watch?v=O_pl3fIAPcA&list=PLbF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=2

Figure 1. Downburst over Genova, 24 October 2020 (Credits Michela Canalis, www.instagram.com\mikina76).

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Downbursts modelling and signal analysis*

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This lecture is the companion lecture of the one in «Wind monitoring and thunderstorm detection». When properly detected and measured, thunderstorm outflows show a typical signature that can be related to downbursts (Fujita, 1985). The analysis of the recorded wind time series is discussed in terms of signal decomposition into a slowly-varying mean component and residual fluctuations (Zhang *et al.*, 2019). This is a somehow different decomposition with respect to the classical Reynolds decomposition, which is the standard in meteorology, that allows taking into account the statistical non-stationarity of thunderstorm outflows as well as wind speed and direction unsteadiness. State-of-the-art high-resolution lidars (vertical profilers and scanning lidars) for thunderstorm outflows measurements is also presented and shortly described.

Finally, downburst modelling is presented based on two different strategies that were adopted in the THUNDERR project (Solari *et al.*, 2020): CFD (Computational Fluid Dynamics) numerical simulations according to the sub-cloud representation of thunderstorm outflows using URANS and LES techniques, and the downburst-like impinging jet experimental investigation carried out at the WindEEE

* https://www.youtube.com/watch?v=0sLaoyGdwPk&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=3

Research Institute (https://www.eng.uwo.ca/windeee/index.html) wind tunnel facility.

Figure 1. Leosphere vertical profiler Windcube V2 (left) and scanning lidar Windcube 400S (right) installed in the port of Genoa (Italy).

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CFD simulation of downbursts*

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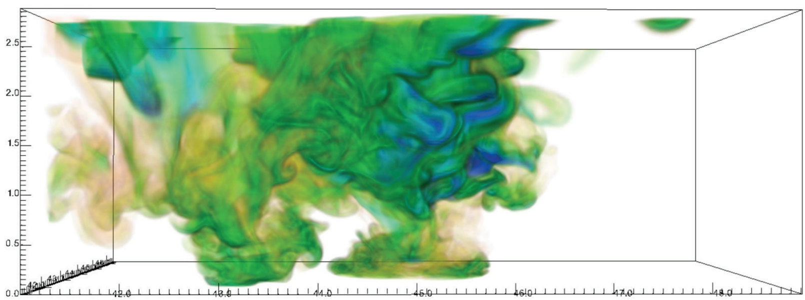

Figure 1. Multiple interacting downbursts forming within a fully physical 3D thunderstorm CFD model. Negative values of the potential temperature field are shown, with the dark blue air being the densest/coldest.

This presentation focuses on the simulation of downbursts using numerical models. Downbursts have been studied since they were recognized in storm damage patterns by Dr. Ted Fujita, who pioneered downburst research at the University of Chicago. Downbursts are forced by thermodynamic cooling and precipitation drag occurring under specific atmospheric conditions. Downbursts have been numerically simulated

* https://www.youtube.com/watch?v=vtHTmnDxCww&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=4

using two primary forcing methodologies: impinging jet and cooling source. Full physical thunderstorm models can also be used to simulate the entire life cycle of downburst producing thunderstorms (see Figure 1) such that the physical mechanisms behind downburst formation can be better understood. Computationally expensive cloud model simulations can help researchers improve simpler downburst CFD modeling approaches that are commonly used in wind engineering. A history of downburst modeling from the 1980s to the present day will be discussed, focusing on specific discoveries related to downbursts and their role in causing storm related damage and creating significant hazard to aircraft in the takeoff or landing phases of flight.
See orf.media/thunderr2021 for more.

Monte Carlo simulation of wind velocity fields*

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Modern structural systems are becoming increasingly complex and numerical simulation of the potential loads with which they will be affected is critical for analysis, design, and optimization of safe and reliable structures. Monte Carlo analysis approaches are often used, which involve the input of loads into a structural model and the output of responses. Besides being necessary for numerical analysis, digitally simulated data is also necessary to drive computer controlled test facilities. Both approaches necessitate an ensemble of input signals that accurately represents what the structure may expect to experience during its lifetime. Therefore, simulation of time histories of wind velocity, pressure, and force fluctuations are necessary, in addition to simulation of structural response, which allows assessment of attendant functionality and safety under service and design loads, respectively.

Random processes simulated for analysis purposes are often assumed to be Gaussian and stationary for simplicity. Many wind events, however, are characterized by non-stationarity and non-Gaussianity. Therefore, simulation methodologies are necessary for univariate and multivariate processes, unidimensional and multi-dimensional fields,

* https://www.youtube.com/watch?v=9dMn4HJT_AQ&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=5

Gaussian and non-Gaussian data, stationary and non-stationary processes, and conditional and unconditional cases. In order to accomplish this task, methods based on the time, frequency, and time-frequency domains are employed (Zhao *et al.*, 2021; Wang *et al.*, 2014).

This paper summarizes a historical perspective, recent developments, and future challenges for simulation. Also included in the discussion are computational tools employed for data and response analysis. Examples are presented to illustrate some of the topics discussed. The presentation also discussed current trends in computational wind engineering based simulation of wind effects. It also addresses the role of the wavelet, shaplet and spavelet transforms (Arul and Kareem, 2021). The role of PODs and DMDs in the modelling the evolving dynamics of pressure field around structures is highlighted (Luo and Kareem, 2021). Recent developments in cyberspace involving virtual organizations, crowdsourcing, citizen engineering, citizen sensing, computational intelligence, sensing and actuation, web-enabled analysis and design, scientific machine learning (SciML), AutoTSC (time series classification using AutoML) and cloud-based computing are discussed (Kareem, 2020).

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Synoptic and Mesoscale Meteorology*

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Local wind extremes do not come out of the blue, but are related to synoptic-scale weather situations and embedded meteorological features. The lecture provides an introduction into basic concepts, starting with the explanation for wind from an idealized dynamic standpoint. Extreme wind events related to pressure gradient and centrifugal force, for example, occur in conjunction with hurricanes / typhoons in the low latitudes or in conjunction with strong convective systems as tornadoes. In the mid-latitudes, they occur in conjunction with cyclones, within their respective cold and warm air masses or at fronts. The relation of cyclone cores and windstorm centres in the North Atlantic area reveals a clear preference of windstorm-fields south of the cyclone core. There seems to be a fairly close temporal relationship between cyclone core development and windstorm development. Thus, known factors for intense cyclone development are also relevant for windstorms.

Statistics based on a large ensemble of windstorm forecasts shows that a windstorm's maximum average size becomes larger with increasing duration. On the other hand, there are small scale features like the so-called sting jet or the isallobaric (ageostrophic) wind component

* https://www.youtube.com/watch?v=YsWiJmy9ysg&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=6

which can enhance windspeeds regionally. Results from numerical experiments conducted with convection permitting regional models suggest no strong link between extreme rain at a grid point and extreme wind at the same place and the same time, at least not as a general feature. In line with the general concepts, however, there appears a significantly high chance to have intense winds in the vicinity of a grid point with heavy rainfall. The detailed relationships between the quantities appear to be specific to the event structures.

Local extreme gusts can occur in conjunction with the self-organization of convective systems, in particular with the gust fronts and cold air outbreaks induced by heavy rainfall. Current research suggests that the generation of such cold pools can also be related to self-organization.

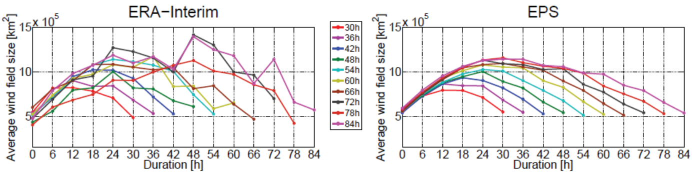

Figure 1. Wind field size during storm duration, according to ERA-Interim reanalysis data and average from an Ensemble Prediction Forecasting system. From: Osinski et a., 2016: *Nat. Hazards Earth Syst. Sci.*, 16, 255-268.

Windstorms and Climate Changes*

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Wind storm and hail risk are jointly included in typical German insurance of residential buildings. They exceed loss induced by other hazards. Past trends can more clearly be seen when looking into global event counts, with storm and hydrological events increasing in the past decades, while geological hazards remain fairly unaltered. For extremely intense hydrological events like the summer 2020 flooding in western Germany the loss sum exceeds that of typical winter storms in spite of a comparatively small affected area.

Wind storm induced loss with residential buildings starts when a certain wind speed is exceeded. As a rule-of-thumb threshold, the 98^{th} percentile of local wind speed can be taken. This particular approach assumes that regional buildings are adapted in their resilience to local wind climate. Based on this approach, damage-relevant storm tracks can be identified from meteorological data of the past, and from climate scenario simulations. These can be quantified into a climatology, for example, by the average track density in a region. For the western European countries, about 20 tracks per winter are counted from re-analysis data. According to this approach, there is significant year-to

* https://www.youtube.com/watch?v=PJ5h0HQnhJI&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=7

year-variability, but not a clear trend. Taking another approach however, like the storm weather type approach, has suggested an increasing trend in the recent decades. This may be one of the reasons why the IPCC (2021) states that there is low confidence in projected changes in the North Atlantic storm tracks. Another reason seems to be related to the spatial and height structure of climate scenario signals. Maximum temperature increases are found for the upper atmosphere in the tropics and sub-tropics, while in the lower atmosphere the same is the case in the polar reasons. Thus, meridional temperature differences as a factor of mid-latitude cyclones and, as a further consequence, the risk of windstorms is not generally clear. With a minimum surface warming spot in the central North Atlantic (related to the changing ocean circulation), an increase of storminess in north-western Europe can be partially understood. New (CMIP6) simulations do not show this result as clearly as the former ones. This is a matter of current research.

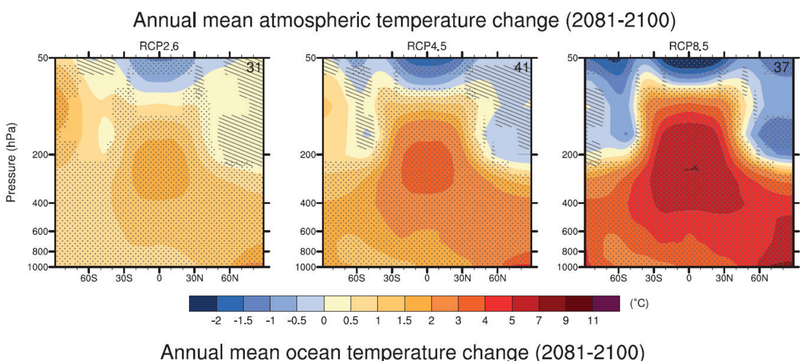

Figure 1. Mean climate change signals for different climate scenarios from IPCC (2013), Chapter 12, Figure 12.11.

Fundamentals of bluff-body aerodynamics*

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The lectures are intended to provide an outline of the main aspects of bluff-body aerodynamics with direct relevance to wind engineering. The topics are divided in three parts, each contained in a different set of slides, and are briefly described in the following.

1 – Steady flow and stationary bodies.

Definition of aerodynamic and bluff bodies, differences in flow fields, loads and prediction procedures. Classification of bluff bodies, influence of geometry and flow conditions on the aerodynamic drag. Brief description of some methods for drag reduction.

Vortex shedding from two-dimensional bodies: introduction, forces due to vortex shedding and methods for their modification.

Three-dimensional configurations.

Possible influence of small changes in geometrical parameters.

2 – Aeroelastic phenomena.

Introduction and brief recap on linear forced vibrations and buffeting.

Aerodynamic damping: derivation and discussion.

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* https://www.youtube.com/watch?v=_Kw1GB_1YSY&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=8

Oscillations induced by vortex shedding: non-linearity, limit cycle, frequency synchronization. Dependence of response on mass ratio and damping, definition and role of the Scruton number, outline of prediction procedures. Methods to avoid or reduce vortex-induced oscillations.

Galloping: description, general features, basic treatment and relevant assumptions. Methods to avoid galloping oscillations.

3 – Effects of transient flow conditions.

The energetic interpretation of drag and introduction to added mass. Discussion on assumptions for the prediction of the added mass forces through the potential flow approach.

The Froude- Krylov force: origin and evaluation for time-varying uniform flows.

The Morison equation and its application to evaluate the dynamical response of a body in transient flows. Velocity fields in thunderstorms and discussion on possible effects of wind accelerations.

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Laboratory simulations of downbursts*

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This presentation aims at constructing a frame for downburst laboratory simulations based on recent experimental campaigns conducted at the WindEEE Research Institute, Western University, Canada.

Downbursts occur in thunderstorms which are part of the family of non-synoptic winds which also include gust fronts, tornadoes, lake and sea breezes, katabatic winds, etc. (Hangan and Kareem, 2021). Their associated wind profiles depart drastically from atmospheric boundary layer (ABL) synoptic winds having a maximum velocity very close to the ground. Downbursts are highly three-dimensional with intense ring vortices producing non-stationary, dynamic and non-Gaussian flows (Hangan *et al.*, 2019). While the best way to study downburst is based on full scale data that is rare and difficult to obtain. Therefore numerical and physical simulations are important. These simulations may employ a cooling source, a wall jet or impinging jet technique. The latest presents advantages in terms of simplicity and conserving the main vortex features of the flow.

Full scale data studies have been performed at Western based on a collection of events from Europe, USA and Australia (Romanic *et al.*,

* https://www.youtube.com/watch?v=KnCC_zOWgpo&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=9

2020a). Based on these data sets a method was devised to produce an objective segmentation of the data sets, based on which, it was found that the majority of the 37 cases studied have durations of less than 5 minutes and ramp times of less than 1 minute. There were no significant statistical differences between downburst events on the three continents.

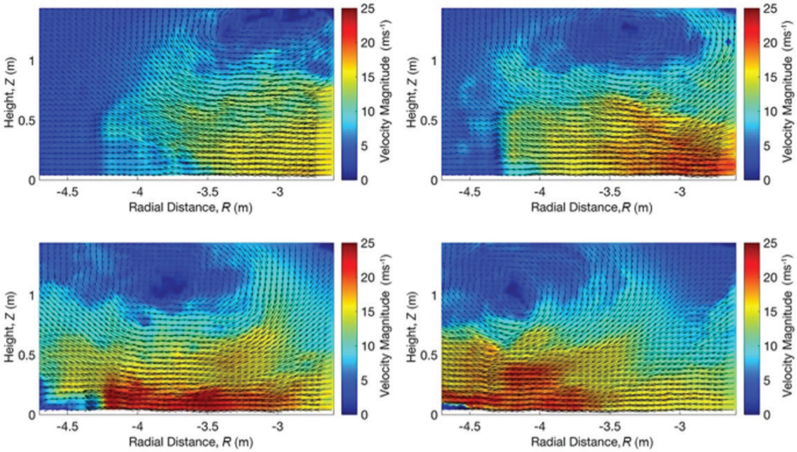

Figure 1. PIV measurements of downburst flow in WindEEE; Vortex evolution.

Two scaling approaches were proposed: (i) one based on velocity scale and both mean and turbulent time scales (Romanic et al, 2020b) and the other following a set of criteria (Junayed *et al.*, 2019). Both methods produce similar results with the downbursts in WindEEE having overall velocity scales between ½ and ¼, and length scales between 1/80 to 1/140 compared to full scale data. All mean (γ), turbulent (μ_ς) and peak ($\hat{G}$) speed ratios in WindEEE were found to be in excellent agreement to the ones in the full scale data.

The WindEEE data was further analyzed based on detailed PIV measurements and it was found that the vortex dynamics and associated wind fields agree well with both the model proposed by Hjelmfelt (1988) and with the data recorded by Wakimoto (1982). The experiments were extended to a unique set of inclined downbursts and the superposition of downburst and ABL flows representative of the embedding of downbursts in parent storms (Canepa *et al.*, 2021).

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Downbursts wind loading of structures*

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* https://www.youtube.com/watch?v=N1nn60iWRqE&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=10

Damage to buildings and structures due to severe local storms and wind speed estimations*

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This lecture is separated into two parts: Damage to buildings and structures (Part 1); and Damage-based wind speed rating (Part 2).

Part 1 introduces «various types of winds causing disasters», «damage to buildings and structures due to tropical cyclones» and “damage to buildings and structures due to tornados/thunderstorms around the world”, including Bangladesh, China, India, Indonesia, Japan, Malaysia, Poland, South Africa, and USA. Regarding damage to general buildings and structures due to strong winds, the following matters are emphasized:

- importance of cladding/component design and maintenance
- significance of debris impacts
- predominance of damage to roofs
- predominance of damage to window panes
- non-negligible «human errors»
- importance of storm shutters

It is also emphasized that there is a crucial difference between tropical cyclones and severe local storms (thunderstorms, tornados, gust

* https://www.youtube.com/watch?v=Jr__JAxXJIU&list=PLbF0BXX_6CPK-gfxrWeqmjfWcjqL2C9E1a&index=11

fronts, etc.). An efficient warning system has already been established for tropical cyclones, and we can prepare for strong winds a few days prior to the events. On the other hand, severe local storms cannot be well predicted, and no efficient warning system is available for them. Thus, we encounter severe local storms without any preparations. Therefore, infrastructures and society are more vulnerable to severe local storms than tropical cyclones. In particular, conditional and temporary buildings such as cranes, scaffolds, train cars, net supporting structures and so on are designed under the assumption of special cures and treatments for strong winds, which require prediction of strong wind events.

Part 2 first introduces «various wind scales» including, Beaufort Scale, Saffir-Simpson Hurricane Wind Scale, and TORRO Scale. The relations between damage rates and peak gusts are also shown for wooden houses in Japan. Next, four damage-based wind speed rating methods for tornados are introduced: the Fujita-Scale (F-Scale); the Enhanced Fujita-Scale (EF-Scale); the Canadian Enhanced Fujita-Scale (CEF-Scale); and the Japanese Enhanced Fujita-Scale (JEF-Scale). The F-Scale was proposed in 1971 based on US houses and buildings by Prof. Tetsuya Fujita, University of Chicago. Professors James R. McDonald and Kishor Mehta lead the wind engineering group of Texas Tech University, and proposed the EF-Scale in 2004. This was the first introduction of a wind speed rating method based on Damage Indicators (DIs) and Degrees of Damage (DODs), and 28 DIs are used in the EF-Scale. The CEF-Scale was proposed in 2013 by Environment Canada, closely following the EF-Scale, while the CEF-Scale uses 31 DIs. The JEF-Scale with 30 DIs was proposed in 2015 by the Japan Meteorological Agency, and considers the special features of building construction methods and other environmental conditions in Japan. Estimated wind speeds by the JEF-Scale are equivalent stationary straight winds (ESSWs), causing the same damage as that due to tornado winds, which include unsteady effects such as sudden change in wind speed/direction, pressure depression, vertical component, and so on. Therefore, they are not necessarily equal to the actually observed wind speeds due to tornados, but are applicable to wind-induced damage due to tropical cyclones and others.

Thunderstorm response spectrum technique*

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The methods currently applied to determine the wind-excited response of structures are still mostly based on models related to the synoptic phenomena that evolve in about 3 days on around 1000 km on the horizontal. They give rise to nearly stationary wind fields with velocity profiles in equilibrium with the atmospheric boundary layer (ABL). Thunderstorms are atmospheric phenomena that evolve in short space and time scales and give rise to intense transient downdrafts that impact the earth's surface followed by radial outflows with a typical 'nose' profile and horizontal ring vortices.

The literature is rich in contributions to determine the dynamic response of Single-Degree-Of-Freedom (SDOF) systems, N-DOF (NDOF) systems and slender beams to thunderstorm outflows. It exhibits a wide panorama of procedures whose complexity matches the complexity of these phenomena.

The lesson introduces the thunderstorm response spectrum (TRS) technique for evaluating the response of structures to thunderstorm outflows.

* https://www.youtube.com/watch?v=ycm35ftL38s&list=PLbF0BXX_6CPK-gfxrWeqmjfWcjqL2C9E1a&index=12. The lecture has been given by Maria Pia Repetto on the basis of the slides prepared by Prof. Giovanni Solari† in 2019.

Firstly, the response spectrum technique widely used in the seismic field is introduced and generalized to thunderstorm outflows for SDOF systems subjected to wind actions perfectly coherent over the exposed structural surface. Then, the generalization to real space MDOF systems subjected to partially coherent wind fields with assigned velocity profile and turbulence properties is described. For sake of simplicity, the structure is modelled as a continuous slender vertical cantilever beam. Analyses are carried out by making recourse to the equivalent wind spectrum technique, a method developed for synoptic stationary winds, the use of which is extended here to non-synoptic nonstationary conditions. In spite of a rather complex formulation, the application of the thunderstorm response spectrum technique is straightforward: the equivalent static force is the product of the peak wind loading by a non-dimensional quantity, the equivalent response spectrum, given by a simple diagram.

The applicability of the TRS technique is proved, showing some applications to real cases. In particular, the response of the Cologno Monzese Tower to thunderstorm outflows is obtained by means of a hybrid strategy to simulate transient wind velocity fields of thunderstorm outflows and time-domain integrations of the wind-induced response. The same problem is solved using the TRS technique, leading to results that substantially agree, especially considering conceptual and operative diversities, faced with the complexity of the exciting phenomenon. This confirms, on the one hand, the potential of the response spectrum technique to become a suitable engineering tool for calculating the thunderstorm loading of structures, and, on the other hand, the high efficiency of hybrid simulations to investigate, with a limited computational burden, advanced issues such as the multi-modal response and the non-linear behaviour of structures.

Although basic theory and methodology has been defined, many issues have not been addressed yet (directional effects, higher modes and modal combination rules). Many parameters are still uncertain and need more research validation with real structures monitoring data are essential to confirm the numerical results.

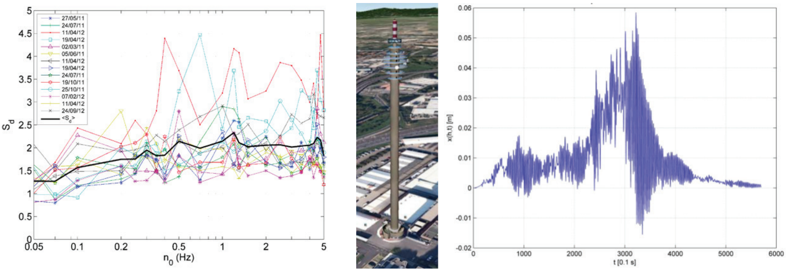

Figure 1. (A) SDOF TRS based on 14 thunderstorm records measured in La Spezia; (B) Cologno Monzese Tower's top displacement time-history obtained by means of hybrid simulation technique.

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Gust front factor (GFF) technique: A recent framework for wind load effects on structures subjected to non-synoptic winds*

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Non-synoptic wind storms such as hurricane/typhoon/cyclone, thunderstorm/downburst, tornado, etc., have been of great interest in structural and wind engineering communities due to their enormous impact on structures. From codification viewpoint, hurricanes/typhoons have been generally treated by increasing design wind speed (as compared to synoptic winds) in specific areas where the probability of occurrence of the storm is much higher, e.g., ASCE 7-16 wind map. Hurricanes/typhoons have been treated as large synoptic-scale events based on experimental observations. However, recent studies reported the existence of the non-stationarity and its vertical profile showed a distinct difference from synoptic boundary layer winds. Recent ASCE 7-16 Commentary includes more information concerning tornados, though it has not been considered in the wind load provision because of their very low probability of occurrence. The Commentary included the Enhanced Fujita (EF) records and design wind speed maps for tornado safe rooms in the United States. In addition, it has been suggested that the calculations of the equivalent static wind pressure/load procedure should use the gust effect factor. A simplified method has also been introduced in terms of the Tornado Factor (TF).

* https://www.youtube.com/watch?v=IERUi0jTL2w&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=13

On the other hand, thunderstorms are almost ubiquitous around the world, e.g., as many as 40,000 thunderstorm occurrences each day worldwide, and an estimated 100,000 thunderstorms annually occur in the US as reported by NOAA/NWS. They produce two extreme wind events such as a tornado and downburst, and the latter is known to be much more frequent than the former. Winds associated with thunderstorms/downbursts cause a variety of damage to residential houses, buildings, transmission towers, wind turbines, and temporary structures, threatening human lives and property losses. Munich Re report in 2017 for natural catastrophes shows an escalation of losses due to thunderstorms. Observations have suggested that winds associated with gust fronts originating from a thunderstorm/downburst exhibit rapid changes during a short time period which may be accompanied by changes in direction and by a pressure rise. For several decades, a number of studies have been focused on identifying the characteristics of such non-stationary gust front winds in a variety of manners such as experimental/numerical methods and full-scale measurements. Yet, beginning the dialogue on any guidelines for design practice has thus far not evolved, in part due to a limited consensus on such characteristics among studies in conjunction with a paucity of available data needed for vetting and validating, which is further influenced by the presence of non-stationary features. Thus, design loads in gust front winds obtained from conventional analysis frameworks included in codes and standards, such as the gust loading/effect factor approach (e.g., Solari and Kareem, 1998), would not be appropriate, calling for a careful examination of traditional design procedures.

In an effort to establish a new design procedure for this type of wind load effect on structures, the gust front factor (GFF) framework has been proposed by Kwon and Kareem (2009) that encapsulates both the kinematic and dynamic features of gust front induced wind effects on structures, which distinguish themselves from those experienced in conventional boundary layer flows. Rather than introducing a different framework for such non-synoptic winds, the proposed methodology based on the GFF consisted of a multiplier, embodying unique kinematic and dynamic features of non-synoptic winds to ASCE 7 gust loading/effect factor formulation for boundary layer winds (Figure 1). In the absence of a definitive procedure to quantify the effect of gust front winds on structures, this approach has offered an effective framework to capture, in a rational manner, the influence of various distinctive features of gust fronts that distinguishes those from synoptic winds. A modified framework for assessing gust front wind loading effects on wind turbine towers has also been presented in Kwon *et al.* (2012). A generalized version of the gust front factor (G-GFF) framework was later introduced in Kwon and Kareem (2013), which was intended not only to analytically encapsulate dynamic load effects associated with gust front winds independent of any reference design standard (e.g., ASCE 7) but also to highlight other general features like those found in conventional gust loading factor scheme. In view of the complexity of the treatment of non-stationarity, a web-based portal for the evaluation of gust front factor and associated loads in an e-design format was introduced available at https://vortex-winds.org to facilitate expeditious utilization of the GFF framework in design practice. More recently, Kwon and Kareem (2019) revisited the GFF approach from a model-based and data-driven perspective.

This study revisits the gust front factor framework seeking to take the next step toward a possible initial framework for a codification of gust front winds from model-based and data-driven perspectives. A modular and extensible web-enabled framework to estimate gust front related wind load effects is envisaged to rationally and holistically quantify design loads. This would promote design practice to enhance the disaster resilience of the built environment. In this context, a closed-form expression concerning nonstationary fluctuations for a case of long pulse duration is derived to facilitate rapid evaluation of nonstationary turbulence effects. A preliminary uncertainty analysis is also carried out to assess the influence of uncertainties associated with the load effects of gust front winds and the reliability of GFF. In addition, a comparison of the model-based gust front factor with a recently introduced thunderstorm response spectrum technique to assess their relative performance is carried out.

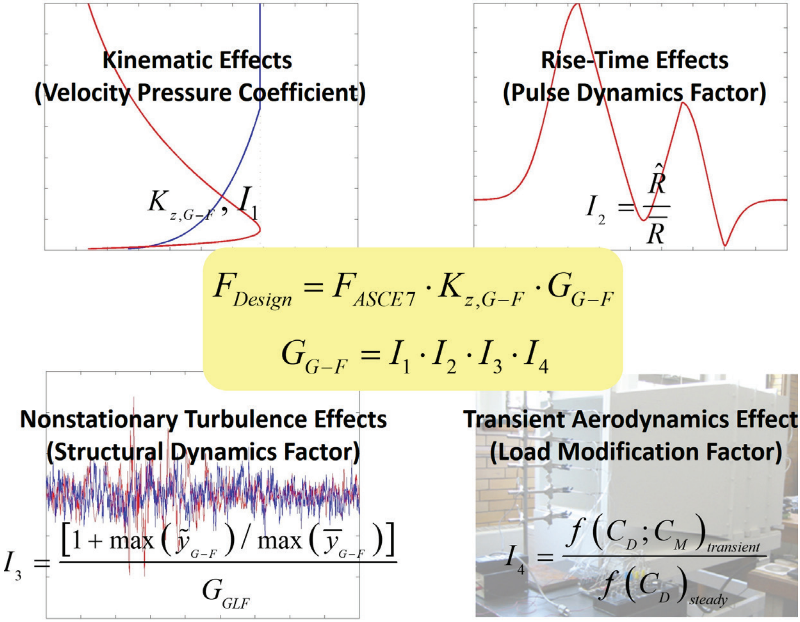

Figure 1. Schematic diagram of the gust front factor framework.

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Thunderstorms and transmission lines*

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Transmission lines (TL) are one of the most vulnerable structures to wind hazard events including downbursts (thunderstorm-generated wind events). Failures of TL structures during downbursts have been observed very frequently in many countries around the globe including Canada. An extensive research program was conducted on this subject at the University of Western Ontario (UWO), Canada, during the past twenty years. Various aspects of this research program and the main research findings are summarized in this lecture. These include the numerical characterization of the downburst wind fields and the development of a nonlinear structural analysis program that incorporated these wind fields together with the modeling of all elements of a TL system including the towers, the insulators and the conductors. All components of this numerical model have been validated through unique tests conducted on aeroelastic multi-span TL models at the Wind Engineering Energy and Environment (WindEEE) facility. Special attention is given in this lecture to the findings related to the contribution of the resonant component to the response of a TL system under downburst loading. A major outcome of this research program was the develop-

* https://www.youtube.com/watch?v=AngC-lCUuJE&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=14

ment of a set of load cases simulating the critical effects of downburst on TL structures that were recently incorporated into the guidelines of the American Society of Civil Engineers (ASCE 74, 2020). On-going research projects including the development and the experimental validation of a numerical tool for studying the collapse of a TL as it progresses from tower to another are presented as well in this lecture.

Non-synoptic winds on buildings: Wind standards and codes of practice perspectives*

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The growing incidence of strong-wind phenomena (i.e., non-synoptic winds: hurricanes, tornadoes, or downbursts) that can claim lives and cause severe property damages has strongly urged wind engineers, including wind code and standard committees, to explore and find means to safeguard society against such phenomena. Recently, there have been some advances in the development of research approaches and design guidelines in the national wind codes and standards. This presentation is prepared for the benefit of researchers in wind engineering, senior civil engineers and building scientists to enrich their awareness of the recent developments in wind codes and standards. Against this background, this presentation pronounces the following learning objectives: recall briefly the fundamental principles of wind aerodynamic loadings and their developments for synoptic winds (normal wind conditions) over the years in wind codes and standards; review the progress made on the wind code/standard provisions, including ASCE 7 (2010 and 2016), NBCC (2010, 2015), for non-synoptic wind design; and state future tornado loads in ASCE 7 (2022) for buildings and other structures. Participants will be able to understand and distinguish how the

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* https://www.youtube.com/watch?v=pRathYnpReM&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=15

basic design loads of synoptic and non-synoptic winds for buildings are evaluated using design procedures of ASCE 7 (2010, 2016 and 2022), as ASCE 7 is considered pioneering in adopting provisions for design loads for tornado events.

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Perspectives of research on the effects of non-synoptic winds on buildings*

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The growing incidence of strong-wind phenomena (i.e., non-synoptic winds: hurricanes, tornadoes, or downbursts) that can claim lives and cause severe property damages has strongly urged wind engineers, including wind code and standard committees, to explore and find means to safeguard society against such phenomena. Recently, there have been some advances in the development of research facilities for simulating non-synoptic winds, mainly for tornadoes and downbursts, that have contributed significantly in crystallizing the available knowledge about such events. This presentation is prepared for the benefit of researchers in wind engineering, senior civil engineers and building scientists to enrich their awareness of the recent developments in physical simulation of non-synoptic winds. Against this background, this presentation pronounces the following learning objectives: recall briefly the fundamental simulation requirements for atmospheric wind tunnels; and indicate main research facilities dealing with non-synoptic wind simulation (tornados and downbursts) with sample study results on their research activities. Particular emphasis is made on the discrepancy of geometric scales and the experimental results provided. The

* https://www.youtube.com/watch?v=7uuCd5EZt3Q&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=16

absence of full-scale measurements, which would be necessary for the calibration of laboratory results is stressed. Participants will be able to figure out the current status of experimental activities and the knowledge available about the non-synoptic winds.

NEW FRONTIERS IN RESEARCH ON THUNDERSTORM OUTFLOWS AND THEIR IMPACT ON STRUCTURES

WORKSHOP

Classification, Generation and Synthesis of Thunderstorm Outflows*

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Thunderstorm outflows possess high wind speed, and hence present violent impact on civil infrastructure in the atmospheric boundary layer. Actually, the design wind speeds with relatively high return periods are usually dominated by the thunderstorm outflows. Compared to the classical boundary-layer winds, the thunderstorm outflows are featured with so-called nose-shape profiles, time-varying mean values and nonstationary fluctuations. Thus, it is necessary to revisit the current wind load effect analysis framework based on the assumption of stationary winds, and advance it to thunderstorm outflow considerations. As shown in Figure 1, the proposed wind load effect analysis framework for thunderstorm outflows consists essentially of field-measurement wind classification to obtain representative records, experimental wind generation to characterize transient aerodynamics and aeroelasticity, and numerical wind synthesis to calculate extreme wind-induced structural performance.

* https://www.youtube.com/watch?v=n7-g0AHBeUs&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=17

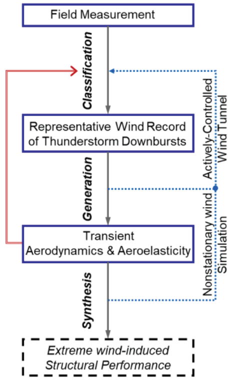

Figure 1. A wind load effect analysis framework for thunderstorm outflows.

With increasingly available full-scale wind data from long-term monitoring networks, the major motivation of wind classification is that the consideration of thunderstorm outflows and associated structural aerodynamics and dynamics usually involves more time and effort in comparison of classical boundary-layer case. In this contribution, the unsupervised signal classification (clustering) technique is discussed with knowledge-enhanced machine learning methodology. Specifically, the encoder-decoder architecture is utilized to extract latent features from field-measurement wind signals, and these latent features are then employed for the classification. The multi-level nonstationarity index is integrated into the unsupervised learning as domain knowledge to further enhance the machine learning-based classification results (Wang and Wu, 2021a). It is noted that a comprehensive wind signal classification framework needs to strike a balance between complexity involved in experimental generation/numerical simulation of thunderstorm outflows and importance of transient aerodynamics and aeroelasticity in the consideration of wind load effect on structures (as indicated in Figure 1).

With the obtained representative wind records of thunderstorm outflows (using aforementioned knowledge-enhanced unsupervised learning classification), it is actually a challenging task to generate (or reproduce) them in a conventional boundary-layer wind tunnel. As a promising alternative, the actively controlled multiple-fan wind tunnel has emerged to effectively generate the laboratory-scale, spatiotemporally varying wind fields. The tracking accuracy of target wind speed histories at selected locations in the multiple-fan wind tunnel depends on the control signals input to individual fans. In this contribution, a deep reinforcement learning (RL)-based control scheme is discussed to realize the prescribed spatiotemporally varying wind field in a multiple-fan wind tunnel (Li *et al.*, 2021). Specifically, the fully connected deep neural network (DNN) is trained using RL methodology to perform active flow control in the multiple-fan wind tunnel. Accordingly, the optimal parameters (network weights) of the DNN-based nonlinear controller are obtained based on an automated trial-and-error process. The 'model-free' and 'automation' features of RL paradigm eliminate the need of expensive modelling of fluid dynamics and costly hand tuning of control parameters. Numerical results of the transient winds during a moving downburst event (including nose-shape vertical profiles, time-varying mean wind speeds, and nonstationary fluctuations) present good performance of the proposed deep RL-based control strategy in a simulation environment of the multiple-fan wind tunnel at the University at Buffalo. It is noted that the transient aerodynamics and aeroelasticity characterizing the mapping relationships between thunderstorm outflow and wind loading on structures may not be well captured by available linear/nonlinear models. On the other hand, the artificial neural networks (ANNs) have been demonstrated good ability to simultaneously achieve high simulation accuracy and efficiency in modelling complex dynamic systems. Hence, this contribution suggested a convolutional neural network (CNN) for transient aerodynamics and aeroelasticity since it can be considered as a special multi-layer neural network with sparse convolutional matrices and is particularly good at handling input-output data with a known grid-like topology.

With the identified transient aerodynamics and aeroelasticity represented by a fast model (e.g., CNN), accurate and efficient simulations of a large set of nonstationary wind signals (with sufficient long duration) are needed to evaluate structural performance under thunderstorm outflows.

To this end, this contribution discussed the simultaneous matrix diagonalization (SMD) technique to accelerate the Hilbert-wavelet simulation of nonstationary wind fields (Wang and Wu, 2021b). Specifically, the SMD effectively obtains the target spatial correlation by the linear combination of uncorrelated wavelet subcomponents of the multivariate wind process. In addition, memory usage in the simulation of time-variant spatial correlation is greatly reduced using SMD. The SMD technique is usually implemented with iterative algorithms. To further improve the simulation efficiency, two-dimensional singular value decomposition (2dSVD) is employed to achieve a noniterative SMD. The high simulation fidelity and efficiency of the proposed Hilbert-wavelet-SMD approach are demonstrated by numerical examples. It is noted that the structural behaviour is allowed to be nonlinear and inelastic with the recently advanced performance-based wind design philosophy. Accordingly, the high-fidelity estimation of thunderstorm outflow-induced structural response (e.g., using finite element modelling) may be very time consuming. To address this issue, the recently developed knowledge-enhanced machine learning can be leveraged for an efficient assessment of extreme wind-induced structural performance (Wang and Wu, 2020).

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Nonstationary typhoon winds and their impact on long-span bridges*

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Typhoon winds are often assumed as stationary random processes when wind effects on long-span cable-supported bridges are concerned. However, recent field measurements show that the assumption of stationary processes may not be valid for typhoon winds that are close to the external eye wall of a strong typhoon because of its vortex and convective origin. Furthermore, typhoon wind speeds near the external eye wall of a strong typhoon are often very high. A deep understanding and an appropriate modelling of such typhoon winds and their impact on long-span bridges are imperative and essential. This paper presents a summary of research activities on the topic carried out by The Hong Kong Polytechnic University in the past 10 years.

A wind and structural health monitoring system was installed in the Stonecutters cable-stayed bridge in Hong Kong in the year of 2011. The bridge has a total length of 1,596 m and a main span of 1,018m (see Figure 1). The monitoring system is composed of over 1,500 sensors in 15 types. A total of twelve Gill R3-50 tri-axial ultrasonic anemometers were installed on the bridge, in which the ten anemometers numbered 2 to 11 were installed on the bridge deck via the cantilever

* https://www.youtube.com/watch?v=OurfwaylkCc&list=PLbF0BXX_6CPK-gfxrWeqmjfWcjqL2C9E1a&index=18

booms and the two anemometers numbered 1 and 12 were installed at the top of the west and east tower respectively. The distance between the anemometer and the edge of the bridge deck via the cantilever boom is 7 m. The height of the anemometers installed in the bridge deck is 73.5 m above the sea level. The anemometers with even numbers are on the northeast side and those with odd numbers are on the southwest side. Except that the distance between No. 4 and No. 6 anemometers and between No. 5 and No. 7 anemometers is 21.05 m, the distance between other two adjacent anemometers is 18 m. The measurement range of wind speed of the anemometers spans from 0.01 m/s to 50 m/s and the sampling frequency is 50 Hz.

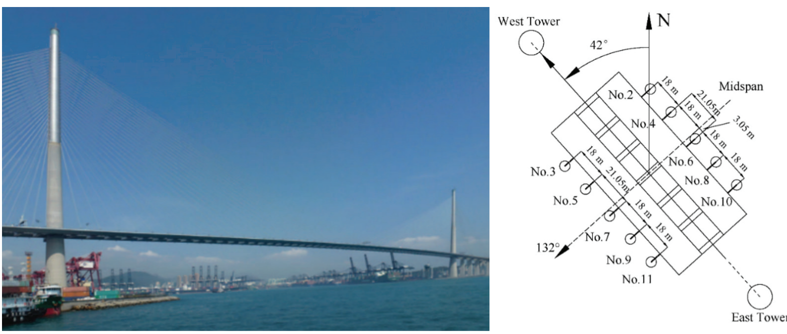

Figure 1. Stonecutters cable-stayed bridge and 10 tri-axial ultrasonic anemometers.

An S-transform-based method was proposed for estimating the time-varying power spectra and coherences of multivariate nonstationary processes (Huang *et al.*, 2020). The accuracy of the proposed S-transform-based method was examined through a comparison with currently used two methods. The analytical expressions of time-varying power spectra and coherences of non-stationary typhoon winds was then proposed by introducing time-varying parameters into the stationary Von Karman wind spectra and the stationary Krenk wind coherence functions respectively. The S-transform-based method was finally applied to the wind data recorded by the multiple anemometers installed in the Stonecutters Bridge during Typhoon Hato. The results showed that the typhoon winds recorded during Typhoon Hato are clearly nonstationary and that the time-varying Von Karman wind spectra and Krenk wind coherence functions could well fit the wind data recorded during Typhoon Hato.

A conditional simulation method was then developed for multivariate nonstationary typhoon winds with time-varying coherences for long-span cable-supported bridges (Huang *et al.*, 2021). Based on the field-measured nonstationary typhoon wind time histories and the time-varying spectrum and coherence models established for the Stonecutters Bridge during Typhoon Hato, the proposed conditional simulation method was applied to the bridge and validated by comparing the simulated typhoon wind time histories with the measured ones as well as the unconditional simulation results. The comparative results demonstrated that the conditionally simulated wind time histories are similar to the measured ones and that the proposed conditional simulation method could be used to provide a better typhoon wind field than the unconditional simulation method.

A framework for predicting nonstationary buffeting response of long-span cable-supported bridges was also presented (Hu *et al.*, 2013; Tao *et al.*, 2020). Typhoon-induced wind loading on a bridge deck was represented by time-varying mean wind force, non-stationary buffeting force associated with time-dependent aerodynamic coefficients, and self-excited force characterized by time-dependent aerodynamic derivatives. A nonlinear static analysis was performed to determine time-varying mean wind response, whereas the time-frequency domain method was employed to compute the EPSD-expressed non-stationary buffeting response of a long-span bridge. The proposed framework was finally applied to the Stonecutters Bridge under Typhoon Hato. The computed responses were compared with the measured responses and the other two cases with time-invariant coherence functions. The comparative results demonstrated the feasibility and accuracy of the framework.

The formulas for determining approximate probabilistic characteristics of extreme nonstationary responses were finally derived by extending the currently used Poisson and Vanmarcke approximations (Hu and Xu, 2014). By comparing with the Monte Carlo solution, the extended approximations for extreme value of nonstationary responses were found reliable and accurate enough. Particularly, the extended Vanmarcke approximation could give closer results to the Monte Carlo solution than the extended Poisson approximation. The extended Vanmarcke approximation was finally applied to the Stonecutters Bridge to find the extreme value of typhoon-induced nonstationary buffeting responses of the bridge. The results showed that the extreme displacement responses of the bridge from the non-stationary buffeting analysis are larger than those predicted by the stationary buffeting analysis.

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Investigation of the role of outflow transience and boundary layer structure on the wind loading of buildings*

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* https://www.youtube.com/watch?v=wiT_S4rRzn0&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=19

A complete physical characterization of impinging-jet downburst-like winds at large scale and applicability to full scale*

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Upon the downdraft hits the ground, the flux of momentum changes from vertical to horizontal and the outflow spreads mightily with ideal radial symmetry (Fujita, 1985). However, in nature downburst outflows at the ground keep memory of the translation velocity of the parent cloud aloft, which inherently affects intensity and direction of the surface winds. Furthermore, the moving thunderstorm cloud as well as the developing downdraft are embedded into the background atmospheric boundary layer (ABL) winds which can be characterized with pronounced wind shear and directional change with height. A limited research has been done on how to properly account for the superposition of these effects (e.g. Mason and Wood, 2005; Romanic and Hangan, 2019). Within field measurements, high-sampling-rate sensors can measure in detail the time evolution of these phenomena,

* https://www.youtube.com/watch?v=6FcywH_-DF0&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=20

but the limited number of stations equipped by sonic anemometers makes their spatial reconstruction still lacking. This latter consideration is even more remarked in the perspective of reconstructing the complex interactions mentioned above.

The physical approaches to create downburst-like impinging flows in wind simulators are mainly based on the impinging jet (IJ) technique. Currently, the largest geometric scales of physically produced IJ are achieved at the WindEEE Dome (Hangan *et al.*, 2017) with reported scales of 1:250 or more (Junayed *et al.*, 2019). Here, resuming previous experiments by Burlando *et al.* (2019), a very large and unique experimental campaign was recently carried out where the mutual interplay among the different component flows was investigated in detail by means of a very refined 3D grid of measurements, described in Table 1 and Figure 1b. Figure 1a schematically shows the 4 tested configurations of downburst-like flows: (1) reproduces the pure vertical downburst case (radial symmetric outflow); (2) is the same of case (1) but supplemented with background ABL-like flow; (3) investigates the inclination of the jet axis to replicate the effect of thunderstorm translation (Fujita, 1985); finally, (4) combines the three above contributions.

Table 1. Experiment setups: Case name (Case); Jet diameter (D); Jet inclination (θ); Jet velocity (w_{IJ}); ABL-flow velocity (u_{ABL}); Azimuthal (α) and radial (r/D) locations; Cobra probe heights (z/z_{max}), z_{max}=0.1 m. IJ defines the probes oriented towards the IJ touchdown, and ABL those oriented towards the direction of incoming ABL flow.

Case	D [m]	θ [°]	w_{IJ} [m s^{-1}]	u_{ABL} [m s^{-1}]	α [°]	r/D	z/z_{max}
(1a)	3.2	\	8.9	\	90	0.2:0.2:2.0	0.4, 1.0, 1.5, 2.0,
(1b)	3.2	\	16.4	\	90	0.2:0.2:2.0	2.7, 4.2, 5.0 (IJ)
(2a)	3.2	\	12.4	2.3	0:30:180	0.2:0.2:2.0	0.4, 0.7, 1.0,
(2b)	3.2	\	11.8	3.9	0:30:180	0.2:0.2:2.0	1.25, 1.5, 3.0,
(3a)	3.2	30	12.4	2.3	0:30:180	0.2:0.2:2.0	5.0, 7.0 (IJ)
(3b)	3.2	30	11.8	3.9	0:30:180	0.2:0.2:2.0	0.4, 1.0, 3.0, 5.0
(4)	3.2	30	11.8	3.9	0:30:180	0.2:0.2:2.0	(ABL, cases (2) – (4))

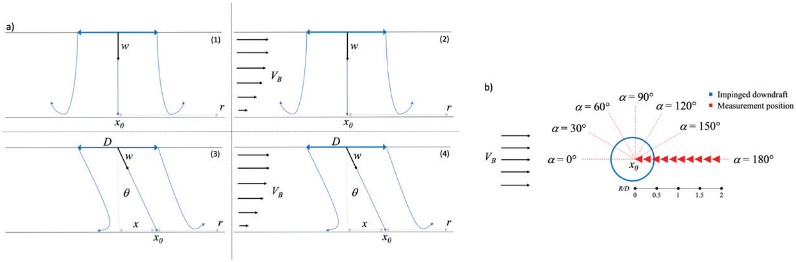

Figure 1. (a) downburst-like configurations tested at WindEEE (side view); (b) measurement locations (top view).

Measurements were performed only for half of the circle, i.e. 0°≤α≤180°, with increment Δα=30°. Due to the symmetry, the results can be mirrored to 180°≤α≤360°.

Acknowledgements

The authors are deeply grateful to Prof. Giovanni Solari for his essential contributions to the conceptualization and supervision of this research. The contribution of F. Canepa, M. Burlando and D. Romanic to this research is funded by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (Grant agreement No. 741273) for the project THUNDERR – Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures – supported by an Advanced Grant 2016. Support from the WindEEE Dome Project sponsored by Canada Foundation for Innovation is also acknowledged.

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Large eddy simulations of the experimentally produced downburst winds*

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Extending codes and standards for structural design to consider wind loading not only for synoptic atmospheric boundary layer winds, but also for non-synoptic winds have been (and still is) one of the major challenges in the wind engineering community. An example of such non-synoptic winds are downburst winds. Downburst winds are thunderstorm-related winds that are characterized by the vertically sinking air column that causes the flow to deflect and diverge radially outward in horizontal direction after the touchdown at the Earth's surface (Fujita, 1981). This radially propagating flow is accompanied with the passage of vortex rings caused by high levels of wind shear aloft that lead to the formation of Kelvin-Helmholtz (KH) instabilities. As they propagate above the surface, these ring vortices cause substantial localized radial velocities which might have severe implications for the integrity of low-rise structures. Combining the complex underlying nature of the thunderstorm lifecycle, localized area in which it takes place, its short duration and heavily transient flow features makes it difficult to record the full-scale event with sufficient spatial and tempo-

* https://www.youtube.com/watch?v=VwkbDqsb9f4&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=21

ral resolution that would allow for studying flow characteristics. To mitigate this restriction, thunderstorm downbursts are commonly investigated in specialized wind simulators at the reduced scale as vertically impinging jets which allow the flow reconstruction. In that perspective, a spatially stationary isolated vertical downburst was reconstructed in the WindEEE Dome (Hangan *et al.*, 2017) in the experimental campaign which was additionally supported by the Large Eddy Simulations (LES) of the same experimental campaign. In contrast to experiments, the LES simulations provide the full field representation of the downburst flow. Therefore the analysis presented in this study is mainly focused on the LES simulation results.

Experiments (Burlando *et al.*, 2019) were performed by pressurizing the air and then releasing it through the nozzle into the testing chamber with a 9 m/s mean vertical velocity (w_{jet}). Inflow velocity was kept constant for about 4 seconds, followed by the sudden closure of the nozzle louvres, to model the phenomenon's dissipation. LES simulations were performed by generating a computational domain of the detailed geometry of the WindEEE Dome chamber with exact dimensions of the hexagonal chamber and bell-mouth nozzle. The computational grid was generated by considering half of the WindEEE Dome due to flow symmetry. Spatially and temporally correlated turbulent scales of eddies at the nozzle inflow were synthesized by adopting the anisotropic turbulent spot method (Kröger and Kornev, 2018). LES simulations resolve the flow turbulence at the scales greater than the grid size, while the part of the turbulence energy spectrum associated to sub-grid scales was modeled by dynamic calculation of Smagorinsky constant through Lagrangian averaging across streamlines. The no-slip condition was imposed at the walls with zero static gauge pressure at the outlet boundary. The near-wall flow was modeled with wall functions for smooth surfaces. Discretization schemes for equations were set to second order and the PISO algorithm solver was adopted for pressure-velocity coupling. Aspect ratio of cells was kept below 1.1 and the dimensionless distance from the walls y^+ reported average values greater than 30. The generated computational grid counted 16.5 million hexahedral cells. To reconstruct the experimental campaign, simulations were divided in two parts: (*i*) 9 m/s fixed mean vertical inflow velocity at the nozzle, and (*ii*) zero-inflow velocity (*i.e.* closed inflow) to model the gradual flow dissipation.

LES simulation results were used to focus on the ring vortices (*i.e.* the primary vortex (PV) and trailing ring vortices) because of their high impact on structures due to high-velocities associated with their passage. In particular, Figure 1a shows the structure of the PV and of the counter-rotating secondary vortex visualized by iso-contours of *Q*-criterion in the moment of highest radial velocity outflow with the indications of the absolute radial velocity maximum (U_{max}) location with respect to the location of the PV core. U_{max} is located underneath the PV, but displaced slightly backwards with respect to the PV core in the radial coordinate, *R*. The vertical profile of outflow radial velocity through the *R/D* location (*D* is the jet diameter) of the U_{max} shows the characteristic "nose shape". LES simulations were used to track the magnitude and location of the instantaneous radial velocity maxima (u_{max}) throughout the event. These time histories are presented in Figure 1(b, c), which show that u_{max} gradually decreases in time. u_{max} also continuously changes its location both in terms of radial and vertical coordinate. The radial location maxima $(R/D)_{max}$ flips back and forth in the range of *R/D* between 0.8 and 1.8, indicating u_{max} is associated not only with the passage of the PV, but also with trailing ring vortices which keep shedding due to the KH instability. The height at which u_{max} takes place oscillates as well: when u_{max} exhibits local peaks, the height z_{max} decreases as the passage of each vortex speed up the velocity below its core.

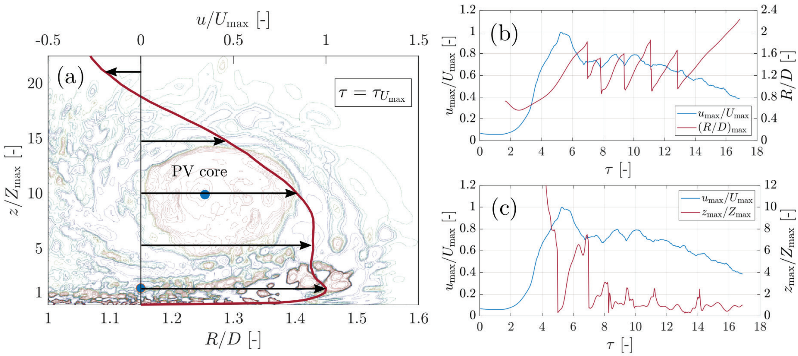

Figure 1. LES simulation results: (a) vortex structures in the time instance of the overall radial velocity maximum (U_{max}), and the vertical velocity profile through the location of the U_{max}, (b) time histories of the radial velocity maxima (u_{max}) and their radial location $(R/D)_{max}$, (c) time histories of u_{max} and their heights z_{max}.

Acknowledgements

This work was carried out on the Dutch national e-infrastructure with the support of SURF Cooperative. The cooperation with the WindEEE Dome Research Institute is greatly acknowledged. J. Žužul and M. Burlando acknowledge the support of the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement no. 741273) for the project THUNDERR – Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures – funded with an Advanced Grant 2016. The authors are deeply grateful to Prof. Giovanni Solari for his essential contributions to the conceptualization and supervision of this research.

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Downburst Wind Field Analytical Modelling through a Global Optimization Technique*

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Severe winds produced by thunderstorm outflows, particularly downbursts, may reach high wind speeds and threaten human safety and structures. Due to their high frequency of occurrence and low spatial extent, downbursts can be considered one of the most dangerous weather phenomena, especially in mid-latitudes countries. In this work, the authors used an analytical model to describe some kinematic parameters associated with a real downburst event which took place at Sânnicolau Mare, Romania on June 26, 2021. The analytical model employed in this paper was developed by the authors and an exhaustive description is given in Xhelaj *et al.* (2020). The model simulates the mean horizontal wind speed and direction, evaluated at a fixed height above the ground level, originating from a travelling downburst whose outflow is embedded in a low-level, large-scale ABL wind. The analytical model includes 10 field parameters that are needed to simulate a thunderstorm event. The estimation of these parameters is performed using a global optimization algorithm which minimizes a single objective function evaluated starting from simulations and recorded data. The algo-

* https://www.youtube.com/watch?v=xbKjFiOiAPw&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=22

rithm used for the minimization is the Teaching Learning Based Optimization (TLBO) technique (Rao *et al.*, 2011).

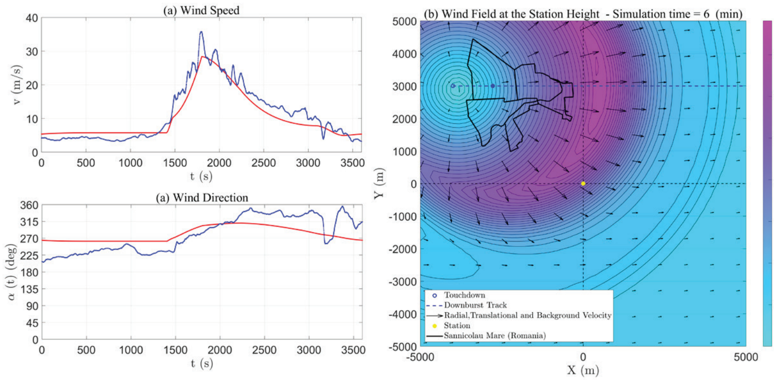

Figure 1. Simulation of the Sânnicolau Mare downburst, June 26, 2021. (a) Comparison between measured and simulated wind speed and direction. (b) Reconstruction of the outflow wind field at the simulation time equal to 6 minutes after touchdown.

Figure 1 illustrates the downburst reconstruction achieved using the TLBO algorithm applied to the real event in Sânnicolau Mare. The event was measured by an anemometer located at 50 m above the ground level in the vicinity of the city (Calotescu *et al.*, 2021; Calotescu and Repetto, 2022). Figure 1a reports the comparison between the slowly varying (30 s averaged) recorded and simulated wind speed and direction. Figure 1b shows the reconstruction of the outflow velocity field 6 minutes after the touchdown and highlights how the downburst passed over the city travelling from west to east. The Sânnicolau Mare downburst was a very strong event that caused hail damage to the facades of many buildings in the town. After this strong event, a damage survey was carried out in collaboration between the University of Genoa (Italy) and the University of Bucharest (Romania). The damage survey (Calotescu *et al.*, 2022) identifies the location of the building in Sânnicolau Mare that suffered hail damage during the event. Using the wind field simulated through the analytical model, the simulated damage ‘footprint’ (i.e., the maximum wind speed that occurred at a given place at any time during the passage of the downburst) was calculated. Figure 2a shows the footprint for the entire downburst, whereas Figure 2b shows an enlarged view of the footprint over the city, overlapping the simulated maximum wind velocity vectors (blue arrows) onto hail damages, also represented as vectors pointing to the damaged facades (red arrows).

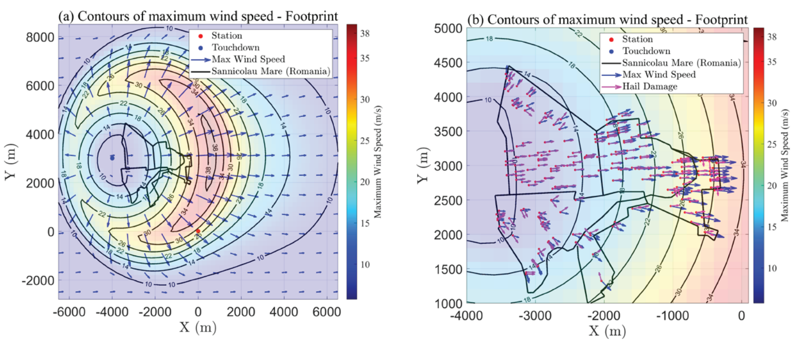

Figure 2. (a) Simulated damage footprint for the Sânnicolau Mare Downburst. (b) Comparison between the hail damage and the maximum simulated wind speed during the passage of the downburst.

Acknowledgments

The author gratefully acknowledges the contribution of I. Calotescu, X. Li, M.T. Mengistu and M.P. Repetto who furnished the measured data and the map of the damage survey of the thunderstorm event that occurred in Sânnicolau Mare, Romania, on 25 June 2021. The monitoring system and damage survey have been carried out through a research cooperation between University of Genova (UniGe) and Technical University of Civil Engineering Bucharest (UTCB), funded by the European Research Council (ERC) under the European Union’s Horizon 2020 re-search and innovation program (Grant Agreement No. 741273) for the Project THUNDERR - Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures, supported by an Advanced Grant (AdG) 2016. The authors are deeply grateful to Prof. Giovanni Solari for his essential contributions to the conceptualization and supervision of this research.

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The physical simulation of non-synoptic wind loading – a future pathway?*

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The need to accurately model the wind loading due to non-synoptic, extreme wind events (such as thunderstorm downbursts) has been recognised for a number of years (Chay and Letchford, 2002). Increasingly complex and large-scale physical simulators have been developed for this purpose. The first simulations of downburst wind-loading on portal-framed buildings at a range of building heights were made at the University of Birmingham (UoB; Jesson *et al.*, 2015b, 2015a) using a transient impinging jet, a technique which is used in the largest current simulator, WindEEE dome (e.g. Romanic and Hangan, 2020). Other physical simulation methods, such as slot jets (Lin, 2010), have also been applied but do not capture the full 3-D variation of the flow field.

The limitations of such techniques are numerous. The scale of these simulations is very small (~1:1600 for the UoB simulator), and there is ongoing debate about how the scale of such simulators should be defined: relative to the height of maximum velocity? To the jet diameter? Further, thunderstorm outflows are rarely as simple as the idealised 'microburst' of Fujita (Fujita, 1985) which these simulators are often

* https://www.youtube.com/watch?v=k3sHC4e-ruo&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=23

designed to replicate, or match the Andrews Air Force Base downburst field often used for simulator validation.

Conversely, the need for advanced physical simulation methods is evident from the complex flow fields generated by thunderstorms. These are statistically non-stationary and have non-negligible vertical components of velocity (Jesson *et al.*, 2019) and, therefore, are beyond standard atmospheric boundary layer tunnel techniques. This presentation discusses one possible method, combining the ideas behind partial turbulence simulation (e.g. Asghari Mooneghi *et al.*, 2016, Wu and Kopp, 2018, 2016) with analysis of full-scale thunderstorm outflow data.

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Modeling and simulation of thunderstorm outflows*

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* https://www.youtube.com/watch?v=BaHCcdcMoGI&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=24

A study of nocturnal thunderstorm outflow*

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Thunderstorm winds are one of the main research topics in atmospheric sciences and wind engineering over the last several decades. Downbursts, being a subclass of thunderstorm winds, are defined as strong downdrafts of cold air that originate in the cloud and spread out radially after impinging on the surface. The research has shown that the main contributors to downdraft development are the evaporation of hydrometeors inside and underneath the cloud, melting of ice, drag exerted by the falling hydrometeors, as well as a vertical non-hydrostatic pressure gradient that can be pronounced non-single cell type thunderstorms. The increase of perturbation pressure with height provides a downward force on the air parcel.

The lack of downburst measurements from tall meteorological towers is one of the reasons (not the only reason though) for the slower progress of thunderstorm boundary-layer research in comparison to reasonably well-established theories that currently exist for the large-scale atmospheric boundary layer winds. Downburst winds are non-stationarity and characterized by strong variability of the flow in space. For example, this unsteadiness and flow inhomogeneity limit the application of

* https://www.youtube.com/watch?v=_D656W1ZerM&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=25

the Monin-Obukhov Similarity Theory (MOST) to the framework of downburst winds. MOST is a generalization of the law-of-the-wall that governs the surface layer fluxes and velocity profiles in a homogeneous fluid to the case of a stratified fluid, such as the Earth's atmosphere.

The goal of this study is to investigate the mean and turbulent flow characteristics of a nocturnal downburst measured on the tall meteorological tower located in The Netherlands-Cabauw tower. While this downburst was nocturnal, thunderstorm winds are overall more frequent in the afternoon. The results presented in this study, therefore, provide some unique insights into the spatiotemporal evolution of nocturnal downbursts and their velocity profiles in this part of Europe.

The near-surface (3 m) wind gusts in the outflow exceeded 20 m s^{-1} (Figure 1), while 1-second gusts in the outflow exceeded 30 m s^{-1} at 60 m and above. This wind event was accompanied by an abrupt change of wind direction from southwest to west. While the shift in wind direction corresponded with the change of upwind surface roughness, the time series of turbulence intensity and other turbulence characteristics were not affected (not show in this abstract). This study also demonstrated that primary and secondary vortex structures – secondary vortex being rarely observed in actual downbursts – developed at the forward edge of the cold outflow (Figure 2). The estimated diameter of the downdraft was 1200 m at 70 m above ground.

While not discussed in this abstract, the measured velocity profiles and friction velocity were compared against theoretical predictions of the MOST. MOST without stratification adjustment overestimated measured friction velocity twofold. Alternative values for surface roughness during the outflow were derived based on the measured friction velocity and MOST-based fit of measured velocity profiles. Ceilometer and radar measurements were also used in this analysis. More research is needed on the dynamics of nocturnal thunderstorm winds.

The rest of this research is presented in Romanic (2021).

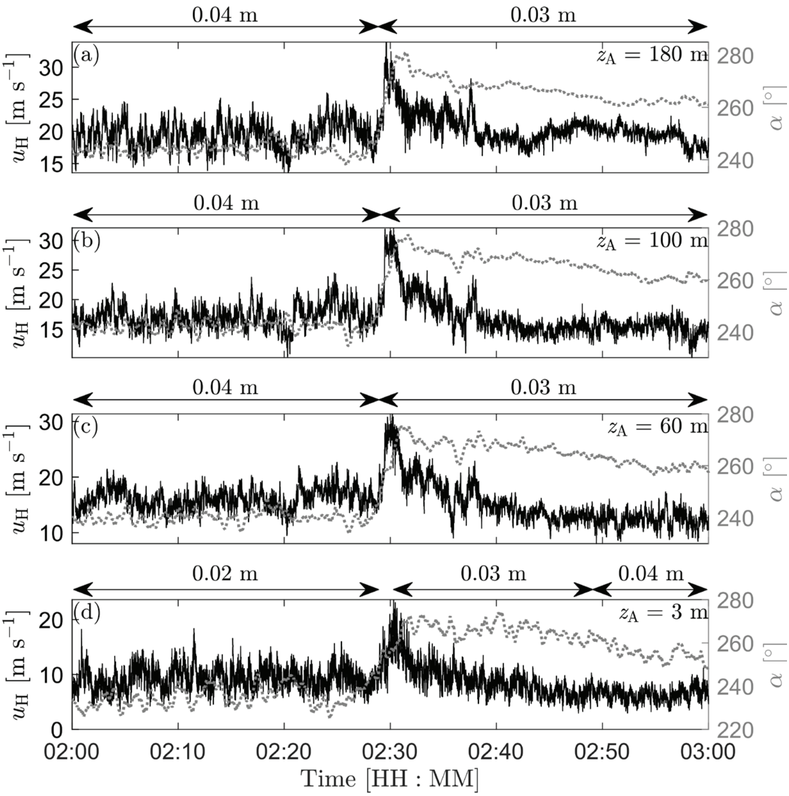

Figure 1. Instantaneous horizontal velocity (u_H, back lines and the left ordinate) and the slowly-varying mean of wind direction (α, grey dots and the right ordinate) during the downburst passage over the Cabauw site on 12 March 2008. The anemometers were positioned at four different heights AGL (z_A). The arrows above each plot indicate the winter value of surface roughness for different wind directional sectors.

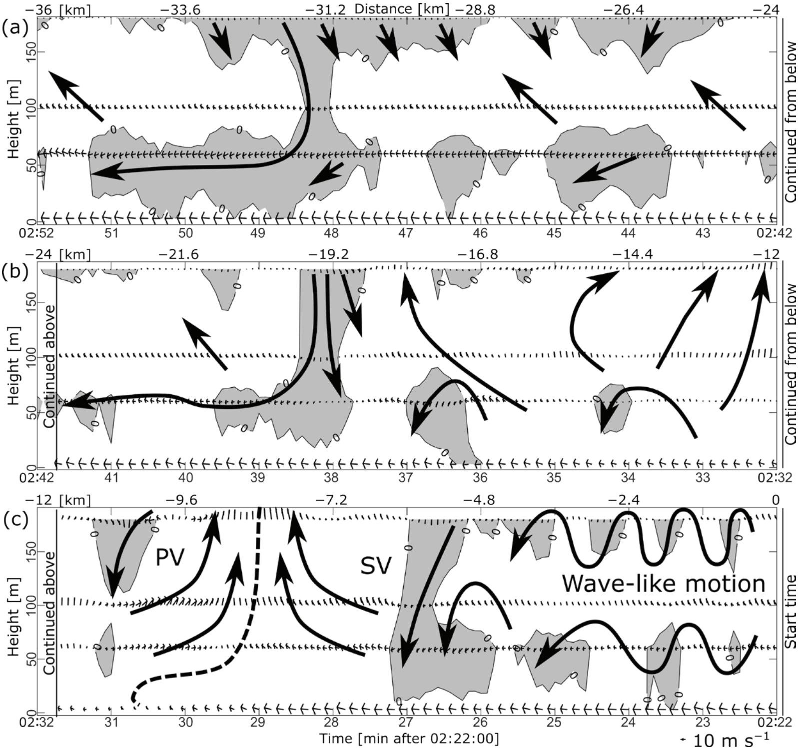

Figure 2. Wind vectors during the passage of downburst over the Cabauw tower using time-space transformation. 30-s mean values of velocity are plotted every 5 s for at the upper three levels and every 10 s at 3 m. Shaded regions are . All vectors are storm-relative and the storm motion was 20 m s^{-1} toward the east. Identified flow structures are additionally highlighted using thick arrows. PV and SV stand for primary vortex and secondary vortex, respectively. The dotted line around 02:29 shows the estimated position of the frontal line between the PV and SV. Notice that the three subplots are one continuous figure that is split into three rows indicated by the continuation labels.

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Tornadoes in Italy: climatology and numerical simulations of tornado-spawning supercells*

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Although rare, severe tornadoes may occasionally strike Italy, sometimes causing severe damage and even fatalities. The tornado in Pantelleria of 11 September 2021, which caused two victims, and the outbreak of 7 tornadoes in northern Italy on 19 September 2021 have recently raised the interest of the mass media in this topic in the recent past. An overview of tornado research in Italy is provided in the present paper.

On 28 November 2012, one of the most devastating tornadoes in Italy hit Taranto, Apulia region, and particularly ILVA, the largest steel plant in Europe, causing one victim and an estimated damage of 60 M€ (Miglietta and Rotunno, 2016). The tornado was classified as category 3 on the EF (Enhanced Fujita) scale. The presence of multiple vortices, the high translation speed (21-22 m/s), the strong low-level wind shear (the nearby Brindisi sounding measured 28 m/s at 600 m height), the large diameter (estimated at 500 m in the phase of maximum intensity) made clear that this case was exceptional for Italy for several reasons.

Numerical simulations performed with the WRF model (Skamarock *et al.*, 2008), using three nested grids of 9, 3, 1 km (Miglietta *et al.*, 2017a), were able to correctly reproduce the track of the tor-

* https://www.youtube.com/watch?v=H3jWAAJX9ig&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=26

nado-spawning supercell and its landfall near Taranto (Figure 1).

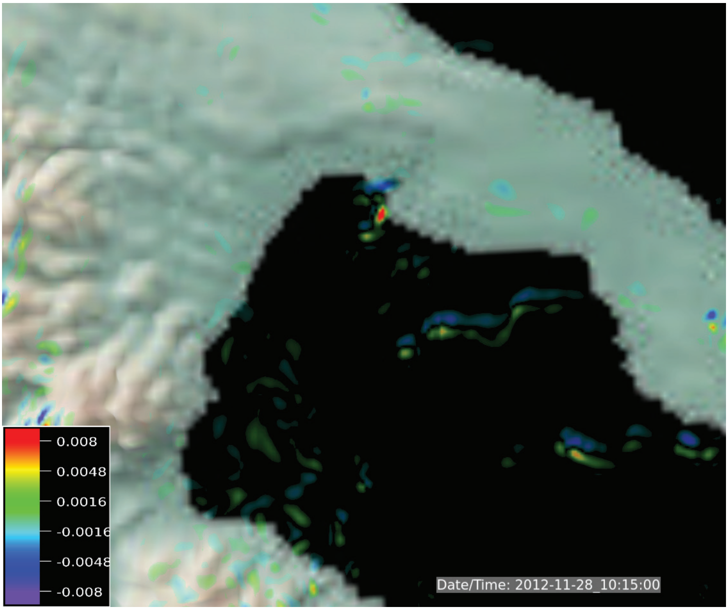

Figure 1. Vertical component of relative vorticity at 2000 m at 10:15 UTC, 28 November 2012; WRF-ARW model simulation, 1 km grid spacing (initialization with ECMWF-IFS analysis/forecast starting at 00:00 UTC, 27 November 2012).

The simulations were able to identify the mechanisms responsible for the development of the supercell: after the triggering of convection on the orography of the Calabria region, the cells were advected downstream on the Ionian Sea, where they were supplied with heat and moisture by convective rolls moving north over the sea; at the same time, increasing values of Convective Available Potential Energy (CAPE) and of low-level wind shear have made the environment extremely favourable for the development of supercells.

Considering that the tornado developed in the presence of a positive Ionian sea surface temperature (SST) anomaly of about 2 K, sensitivity experiments were performed by modifying the SST by 0.5 K and by 1.0 K. The simulations revealed that a much stronger supercell would have developed by increasing the SST by 1 K, while no supercell would have been formed by decreasing the SST by 1 K. Hence, an SST value close to the climatology would have prevented the development of the supercell (Miglietta *et al.*, 2017b).

However, the tornado in Taranto was not the strongest recorded in Italy. A 10-year climatology has been recently developed (Miglietta and Matsangouras, 2018), showing that even violent tornadoes can occasionally strike Italy. The strongest tornadoes typically occur in the early afternoon, during late spring-early summer in the northern regions and during autumn in southern Italy and Sicily. This seasonal distribution reflects the diverse nature of tornadoes, which generally originate inland in the former case, offshore in the latter. Some areas with greater frequency of occurrence have also been identified: the Venetian plain and the Po valley, the extreme southern tip of Apulia, the Tyrrhenian and Ligurian coasts, Sicily.

Using an extended dataset including 19 years of data and hourly ERA-5 reanalysis, the application of dynamical similarity criteria allowed the identification of 5 different tornado clusters: Sicily, Southeast Italy, Central Tyrrhenian coast, Northern Italy, Northeast Italy. The analysis of the environment in which tornadoes developed revealed that the conditions favorable to tornadogenesis in Italy change with the subregions considered:

- In Southern Italy, the dynamic forcing is relatively weak, while strong wind shear and moderate humidity content, advected toward the area of interest, are present.
- In Northern Italy, convection is generally triggered by the arrival of colder air over the Po Valley above very hot and moist low levels; the high humidity content is, due to the strong evaporation typical of the season of occurrence (summer); hence, the specific humidity anomaly is weak.
- In Central Italy, the characteristics are intermediate between northern and southern cases. Further investigation is needed to better understand the nature of these cases.

Lastly, positive SST anomalies are observed mainly in the case of Ionian tornadoes. Stronger tornadoes are associated with higher SST anomalies.

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Damage assessments of tornadic winds in Europe: the International Fujita scale*

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* https://www.youtube.com/watch?v=Ou5oFPKLX3Q&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=27

Resilience of structural systems damaged by thunderstorm wind hazards*

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The presentation discusses recent study activities, examining the response of tall buildings and tower structures against thunderstorm wind hazards. These structures are sensitive to fluid-structure interaction and susceptible to damage induced by wind loads. The research directly considers the quantification of uncertain wind loads, associated with localized, nonstationary downbursts events. Quantification accounts for both modelling uncertainty and load estimation 'errors', e.g., in a wind tunnel test. The latter is rather important since there are very few experimental facilities where thunderstorm wind loads can be adequately estimated. The presentation examines two methodologies for predicting structural response and damage. The first methodology, analytically based and numerically implemented, exploits the formalism of stochastic calculus to find the evolutionary probability density function of the structural response. The second methodology employs numerical Monte-Carlo sampling and massive computer experiments to determine response and damage. The study also discusses the use of the quasi-steady aerodynamic theory to approximate short-lived, spa-

* https://www.youtube.com/watch?v=vkkN6c7OGnE&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=28

tially evolving thunderstorm loads; conversely, it assesses the use of an actively controlled multi-blade flow device that reproduces the main features of the downburst ring vortex in a 'standard' wind tunnel.

The first methodology adapts the standard approach for building aerodynamics to construct a reduced-order dynamic model. It assumes that the main resisting structural system remains linear during the thunderstorm wind event. Damage is primarily observed on the façade, secondary building systems and non-structural elements. The CAARC benchmark building is employed as the reference structure (Melbourne, 1980); the structure has a rectangular floor-plan of dimensions D_x=*30* m and D_v=45 m and height h=183 m. The downburst wind model considers the effect of a severe thunderstorm downburst of short duration, typically between 300 s and 600 s (Solari, 2016). The model mainly reproduces the nonstationary or rapidly evolving features of nonstationary turbulence and examines damage during the fully developed stage of the storm. The effect of slowly varying downburst translation velocity, i.e., the 'mean' load effect is not directly included. Figure 1 presents an example of numerical results.

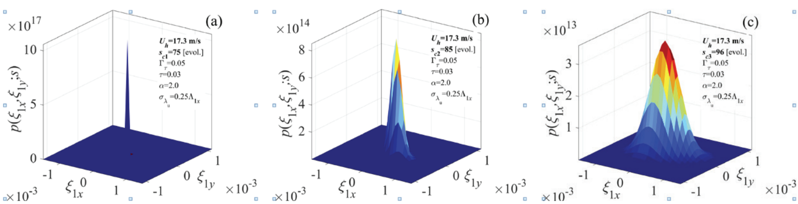

Figure 1. Example of rooftop along-wind (ξ_{1x}) vs. across-wind (ξ_{1y}) response of the CAARC building due to evolutionary downburst with maximum radial speed $\bar{U}_{max}$=20m/s at z_{max}=80m. Joint-PDF ρ of dimensionless response, normalized to building width D_x, at times (a) s_{c1}=75, (b) s_{c1}=85, (c) s_{c3}=96. [Figure reproduced from L. Caracoglia, Parametric study on the use of the Fokker-Planck Equation to examine the nonstationary wind-induced dynamics of tall buildings, Procedia Engineering 199 (2017) 3434-3439, DOI: 10.1016/j.proeng.2017.09.492]

The figure examines the structural response of the CAARC building's rooftop and presents the joint probability density function

(PDF) of the along-wind (ξ_{1x}) vs. across-wind (ξ_{1y}) dynamic vibration. As dimensionless times elapses from s_{c1} to s_{c3}, the downburst intensifies and the rapidly evolving load increases. As a consequence, the structural response exhibits a clear departure from stationary vibration, evident from the examination of the standard deviations and cross-correlation between ξ_{1x} and ξ_{1y}. More details are available from Caracoglia (2018).

The second methodology examines life-cycle cost assessment as a non-prescriptive approach to investigate the risks and consequences that structural systems face from wind-related phenomena in the context of performance-based wind engineering. The aim is to characterize structural damage with respect to hazard demand parameters, describing nonstationary downburst phenomena. Dynamic simulations are conducted using two downburst wind field models and data from Northeastern University's wind tunnel experiments. Performance failure probabilities are calculated to find and compare the accumulation of intervention costs (e.g., maintenance and repair). The key components include fragility, hazard and loss analysis; they are tailored, in a holistic framework, to consider the risks posed by these nonstationary windstorms and their occurrence likelihood. The CAARC building and a monopole tall structure are studied, located in the State of Oklahoma, USA as two preliminary examples. Wind-induced damage and cost accumulation is extended to a lifetime period of more than 100 years to evaluate both expected intervention costs and tolerance intervals to study modeling and experimental uncertainty. Finally, results are compared against tornado-induced damage cost accumulation over the same temporal horizon to demonstrate that downburst-induced damage costs can exceed tornado load effects, under special circumstances. More details can be found in Le and Caracoglia (2021).

The research emphasizes the need for risk-consistent wind load and response analysis of nonstationary windstorms. The ultimate research goal is the systematic assessment of wind-related damage over time in the context of risk analysis and structural resilience.

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Downburst Simulations at the Wall of Wind Experimental Facility*

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Extreme wind events in the form of downbursts are defined as stochastic, nonstationary, localized, highly turbulent, extreme weather phenomena which present several challenges to engineering and social scientists. These challenges include, among others: (1) the complexity in measuring the events in the field due to their unpredicted nature; (2) the lack of information on the reoccurrence frequency and the frequently impacted areas of such events in comparison to hurricanes; (3) the special nonstationary and non-Gaussian nature of the wind field which results in unique statistical characteristics that require new advances in data analysis. In addition, recent reports indicate an increasing number of strong convective thunderstorms, which accounts for billions of dollars in infrastructure damage and more than 150 fatalities on a yearly basis in the United States and worldwide (Hoogewind *et al.*, 2017; NOAA, 2018). In parallel, extreme wind events in the form of tornadoes and downbursts constitute 70% of the worldwide natural hazards and the corresponding disasters (Solari, 2016).

Yet, there is a lack of research and knowledge on this non-synoptic wind phenomenon regarding the corresponding downburst-induced

* https://www.youtube.com/watch?v=hfM5ia8r_80&list=PLbF0BXX_6CPK-gfxrWeqmjfWcjqL2C9E1a&index=29

aerodynamic loading on and dynamic response of different infrastructure systems and buildings. Filling these knowledge gaps is further hindered due to the localized nature of the event in space and in time, which means that the field measurement is a challenge.

Motivated by the prior facts, a large-scale downburst simulator has been recently designed and constructed at the US National Science Foundation (NSF)-Natural Hazard Engineering Research Infrastructure (NHERI) Wall of Wind (WOW) Experimental Facility (EF), see Figure 1-A. The traditional WOW is equipped with 12 electric fans in an arc shape that produce a wind field of 6.1 m wide and 4.3 m high, which allows testing of holistic building systems and other structures at multiple scales. Automated spires and floor roughness elements help develop Atmospheric Boundary Layer (ABL) mean wind velocity profiles and turbulence characteristics for different terrains. The WOW provides distinct multi-scale test capabilities: (1) high-speed holistic full-scale testing up to simulated Category 5 hurricane winds on Saffir-Simpson scale (70 m/s); (2) wind-driven rain simulations to study water intrusion through the building envelope; (3) destructive testing under extreme environments to study progressive damage, enhance designs, and develop new mitigation techniques; (4) large-scale aerodynamic/aeroelastic testing at high Reynolds number (Re) (Gan Chowdhury *et al.*, 2017).

The new downburst simulator at the WOW adopts the 2-D wall jet method which enables transforming the available ABL wind simulator at the WOW into downburst winds by adding an external modification device to the exit of the flow management box (Lin and Savory, 2010, Le and Caracoglia, 2019). Before constructing the large-scale downburst simulator at the national facility, numerical simulations using CFD

methods (Levieux *et al.*, 2019) and experimental simulations by implementing the simulator into the small-scale 1:15 WOW testbed (Gan Chowdhury *et al.*, 2017) was conducted to validate the produced flow (Mejia *et al.*, 2018). Figure 1-B shows the validation of the vertical profile of normalized mean horizontal wind velocity measured using the downburst simulator at the WOW EF. The produced vertical profile shows a good match with the range of reported profiles in literature with the characteristic 'nose profile'. In addition, the time history of the horizontal winds shows the characteristic ramp-up and ramp-down behaviour with the ability to control the duration using the open/close mechanism of the simulator. The flow field visualization shows the main rolling vortex, see Figure 1-A.

The new downburst simulator at the NHERI WOW EF enables, for the first time, testing structural models subjected to downburst flows at large length scales that have never been achievable. For example, at the WOW, the maximum downburst speed occurs at a height of ~ 20 cm. The height of the maximum wind speed is expected to further increase for rougher terrains. Such characteristics of the produced flows are important to enable large-scale aerodynamic testing (e.g. capturing Re similarities; enabling higher spatial resolution for pressure measurements) and thus, reduce possible scaling effects.

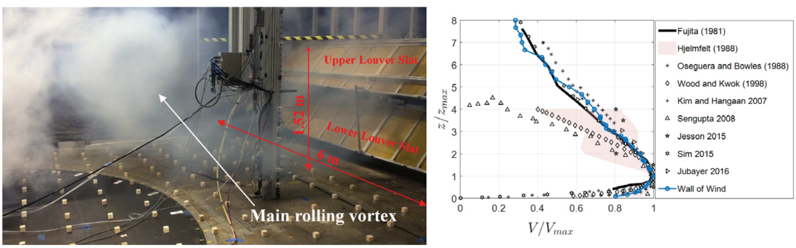

Figure 1. (A) Downburst Flow Visualization at the WOW EF; (B) Vertical Profile Validation

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Nonstationary crosswind load effect of tall buildings: Aeroelastic effect and base isolation*

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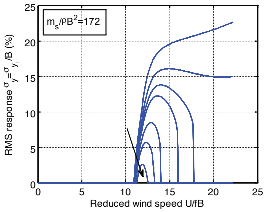
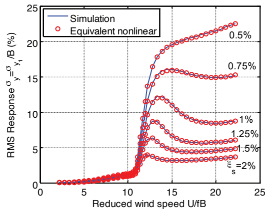
Crosswind response of super tall buildings at the vicinity of vortex lock-in wind speed must be carefully investigated with consideration of amplitude-dependent aerodynamic damping. The aerodynamic damping at a given reduced wind speed can be expressed as a function of nondimensional vibration amplitude, from which the steady-state building vibration amplitude, i.e., amplitude of vertex-induced vibration, can be determined that corresponds to zero system damping. To further address the stochastic crosswind building response, an equivalent nonlinear aerodynamic damping model as a polynomial function of time-varying velocity and/or displacement is required. The relationship of both types of models are established using harmonic balance technique. The method of equivalent nonlinear equation (ENLE) provides analytical solutions of response standard deviation (STD), extreme distribution and fatigue damage.

* https://www.youtube.com/watch?v=wPIC5vpXa5Q&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=30





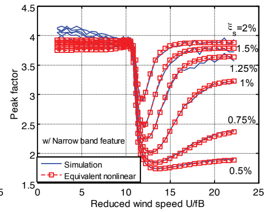
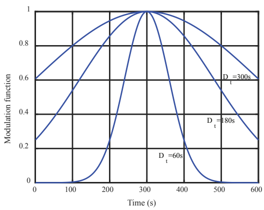


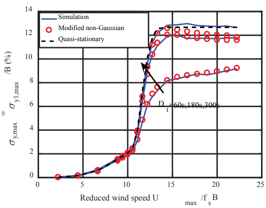
Figure 1. STD of steady-state building top displacement.
Figure 2. STD of stochastic building top displacement.
Figure 3. Peak factor of stochastic building top displacement.

Figure 1 shows the steady-state STD of a tall building top displacement caused by self-excited force only at different levels of structural damping. The STD and peak factor of stochastic building top displacement under the action of both self-excited and buffeting forces are shown in Figures 2 and 3.The ENLE approach provides accurate estimations. The effect of nonlinear aerodynamic damping results in a reduced peak factor attributed to hardening non-Gaussian probability distribution of response.

To further address nonstationary wind effect, the nonstationary wind field is characterized by time-varying mean wind speed and modulated turbulence with time-invariant profiles of mean wind speed and turbulence intensity. It is assumed that the variation of mean wind speed with time (Figure 4) is not significant such that the wind load can be approximately estimated from that under the corresponding stationary wind but with consideration of the time-varying mean wind speed in a quasi-stationary manner. The non-Gaussian moment closure technique is used to estimate the time-varying STD of response from which the maximum STD is determined (Figure 5), where the higher-order moments involved are estimated from kurtosis-based translation process model. The narrowband response characteristics are applied to simplify the non-Gaussian closure approach. The nonstationary extreme response and fatigue damage are further estimated from the time-varying STD and kurtosis of response (Figure 6). The crosswind response under nonstationary wind excitation is lower than that under stationary wind due to transient structural dynamic effect.

The reduction of extreme response and fatigue damage are more significant due to short time duration of high level of response.





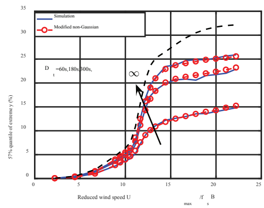
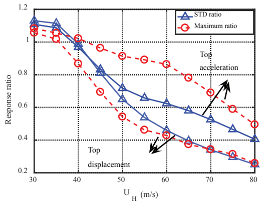
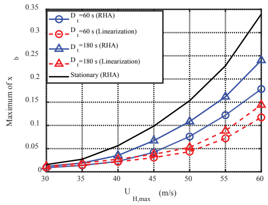


Figure 4. Time-varying function of mean wind speed and turbulence.
Figure 5. Maximum of time-varying STD of building top displacement.
Figure 6. Mean extreme of building top displacement.

The potential benefit of high-rise buildings from base isolation has attracted great attention in recent years for considerations of comfort of occupants, functionality of buildings, non-damage to acceleration-sensitive contents and non-structural elements. A base-isolated tall building of 200 m high is studied. At lower wind speeds, the response of the base-isolated building is larger than that of corresponding fixed-base building due to reduction of building frequency. However, at higher wind speeds, the response is reduced due to the additional hysteretic damping caused by the inelastic response of base isolation (Figure 7).

In terms of nonstationary wind excitation, at low wind speed or when yielding is not significant, the transient effect leads to reduction in response and causes a delay in variation of the response STD compared with that of quasi-stationary response. This transient effect reduces with increasing wind speed as the hysteretic damping by yielding increases (Figures 8 and 9). At high wind speed or large yielding level, the inelastic base displacements exhibit strong non-Gaussian distribution. The absolute building acceleration is weakly non-Gaussian due to the influence of non-Gaussian base acceleration. The building top displacement with respect to base follows almost Gaussian distribution. The statistical linearization with Gaussian assumption approach well captures the transient effect of crosswind responses. When yielding is significant, it underestimates the time-varying base displacement and building acceleration due to their non-Gaussian character.





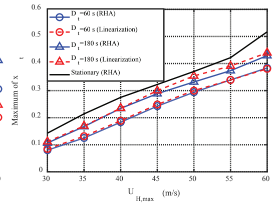


Figure 7. Ratio of response of base-isolated building to that of fixed-base building.
Figure 8. Mean extreme of base displacement.
Figure 9. Mean extreme of building top displacement.

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A simplified impulse load model for assessing structural response from thunderstorm outflows*

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Summary

Thunderstorm wind loading methods are investigated: several thunderstorm records are gathered from Texas and Italy and applied to a structural model of a tall building, first as an equivalent static force using the Thunderstorm Response Spectrum Technique (TRST) and later as a triangular impulse load using a method that assumes a fully correlated wind field over the structure. In this study, the fully correlated assumption is relaxed with a partially correlated wind field over the structure. Different profile shapes are employed- i.e., the power law, uniform and the nose shape- and the structural response is compared based on the loading method, wind profile and geographical origin of the event.

1. Introduction

Studies were carried out to evaluate alternative methods for determining the structural response of tall buildings to thunderstorm downbursts.

* https://www.youtube.com/watch?v=mZI1WfsI9PM&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=31

These transient phenomena render the inapplicability of methods employed for calculating structural response to synoptic wind loading. The response spectrum technique is generalized from earthquake engineering to thunderstorms (TRST) by Solari and colleagues (Solari *et al.*, 2015) and a mean response spectrum is evaluated for recorded downbursts in Italy. Another approach is representing the wind loading with an impulse function as formulated by Chen and Letchford (Chen and Letchford, 2004) where the loading was applied assuming a fully correlated gust front over the structure. This assumption is relaxed here and a partial correlation of the wind field is introduced. These approaches are evaluated using three different wind profiles: the power law profile related to synoptic wind (Davenport, 1960), uniform flow, and the nose-shaped profile established by Wood and colleagues (Wood *et al.*, 2001). The load is applied to a structural model of the CAARC building, and the structural response parameters (base shear, base moment, tip displacement) are used to compare the loading methods, wind profiles and the intensity of the events based on their geographical origin.

2. Application of the trst to mdof systems

The equivalent static load distributed over the height of the building, $f_{eq}(z)$, is defined as:

$$f_{eq}(z)= \hat{f}(z)S_{d,eq} \tag{1}$$

Where, $S_{d,eq}$ is the thunderstorm Equivalent Response Spectrum (ERS); $\hat{f}(z)$ is the peak wind force generated by thunderstorm outflow, given by:

$$\hat{f}(z)=½\rho\,\hat{v}^2(h)\alpha^2(z)b(z)c_D(z) \tag{2}$$

ρ the air density, $\hat{v}(h)$ the peak wind velocity at the anemometer height h, α is the vertical profile of the moving average velocity, assuming that it is similar to that of the peak velocity; b is the crosswind breadth of the structure and c_D is the drag coefficient from BLWT tests. The ERS is defined as:

$$S_{d,eq}=d_{eq,max} \tag{3}$$

Where, is the maximum value of the reduced equivalent displacement found solving the differential equation formulated by Solari (Solari, 2016).

3. The impulse loading method

The impulse method was proposed and employed using a conceptual time function. This approach was inspired by the shape of the wind speed time history of the Andrews AFB downburst simulated by Holmes and Oliver (Holmes and Oliver, 2000). The thunderstorm wind speed distribution $\overline{v}(z,t)$ is assumed to be as follows:

$$\overline{v}(z,t)= \overline{v}_{max}(h)\alpha(z)f(t) \tag{4}$$

Where, $\overline{v}_{max}(h)$ is the maximum value of the moving average wind speed measured at the anemometer height; f is a triangular time function with maximum value of 1, and defined by the following equation:

$$f(t)= \begin{cases} \frac{2}{\Delta T}t & 0\leq t\leq \frac{\Delta T}{2} \\ 1-\frac{2}{\Delta T}(t-\frac{\Delta T}{2}), & \frac{\Delta T}{2}\leq t\leq \Delta T \\ 0, & t\geq \Delta T \end{cases} \tag{5}$$

Where, ΔT is the duration of the triangular impulse (Figure 1).

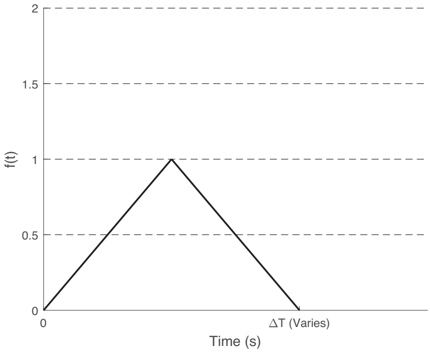

Figure 1. Time function *f(t)* for the pulse wind speed (Chen and Letchford, 2004).

The maximum distributed force over the height of the structure can be rewritten as:

$$F_{max}(z,t) = \frac{1}{2}\rho \overline{v}^2_{max}(h)\alpha^2(z) f^2(t) b(z) c_D(z) G_r \tag{6}$$

Where, G_r is the gust factor of the force, a function of the of the peak factor, average turbulence intensity $\overline{I}_v$ and the background factor B calculated using Eq. (64) in Solari (1993).

4. Structural model

The Commonwealth Advisory Aeronautical Research Council (CAARC) is a «standard tall building model for the comparison of simulated natural winds in wind tunnels» (Wardlaw and Moss, 1970) that is used here to study the impact of thunderstorms on tall buildings. It is characterized with a density of 160 kg/m^3, a height of 200 m above the ground, a crosswind breadth of 50 m and a depth of 33 m (Figure 2). The structure has a first fundamental frequency of 0.2 Hz and a critical damping ratio for all modes is assumed to be ξ = 1.5 %. Therefore, the equivalent height is z_{eq} = 0.6 x 200 = 120 m.

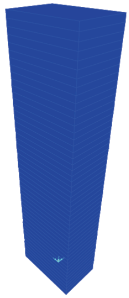

Figure 2. Structural model of the CAARC building used for the study.

Four thunderstorm records are collected from the database of the Department of Civil, Environmental and Chemical Engineering (DICCA) at University of Genova (referred to as events a, b, c and d); and seven records are collected from the database of Texas Tech University (TTU) (events e, f, g, h, i, j and k). The thunderstorm wind loading related to each of these events is calculated using the two methods discussed in the previous sections and applied to the structural model. The TRST is employed using Wood's profile, and the impulse load approach uses; Wood's profile, uniform flow, and a power law profile. The tip displacements, normalized by the maximum value obtained, $\tilde{q}_{max}$ are shown in Table 1 for each loading method and profile used.

Table 1. Normalized tip displacement obtained for the loading methods and wind profiles

$\tilde{q}_{max}$

	TRST	Impulse loading		
Event	Wood	Wood	Uniform	Power law
a	0.4	0.5	0.5	0.9
b	0.3	0.4	0.4	0.7
c	0.2	0.2	0.2	0.3
d	0.1	0.1	0.1	0.2
e	0.2	0.3	0.3	0.5

f	0.4	0.3	0.3	0.6
g	0.3	0.4	0.4	0.7
h	0.3	0.4	0.4	0.8
i	0.5	0.5	0.6	**1.0**
j	0.3	0.3	0.3	0.6
k	0.2	0.3	0.3	0.6

5. Discussion

Comparing the parameters of the structural response obtained from the application of the impulse force with those obtained from the Thunderstorm Response Spectrum Technique using the conceptual profile formulated by Wood *et al.* (2001), the values of the tip displacement, base moment and base shear are slightly higher but comparable for a structure of the height considered. Further analysis must be conducted on structures with different shapes to assess the nuances of each approach more fully. The structural response induced by the uniform profile is comparable with that obtained using Wood's profile.

Acknowledgements

This research is a collaboration between University of Genova, Rensselaer Polytechnic Institute and University of Illinois at Urbana-Champaign and funded by the Ministry of Education, University and Research of Italy (MIUR).

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Developing Thunderstorm Design Wind Speed Map for Ontario and Applications for Low-Cost Storm Shelters*

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Abstract
During the last few decades, the global average temperature has been increasing significantly as a result of climate change, which has increased the number of weather-related disasters drastically (Brooks, 2013). For example, in 2020, there were nine major devastating weather events in Canada, with total loss estimates of around 2.5 billion Dollars. This estimate did not account for the total property and infrastructure losses cost, costing billions more (Environment and Climate Change Canada, 2020). Many of those catastrophic events are caused by small to mesoscale atmospheric events. For instance, in 2012, 93% of natural disasters were weather-related, and 45% of those events were caused by thunderstorms (Guha-Sapir *et al.*, 2012). During a thunderstorm event, cold air at height attitudes is exchanged with warm air at the surface of the ground, which results in the formation of downward air motion (i.e., downdrafts) and upward vertical wind motion (i.e., updrafts). When downdrafts hit the ground, the flow is redirected radially from the point of contact with

* https://www.youtube.com/watch?v=UoZV3T331mo&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=32

the ground causing high horizontal wind speeds (i.e., gust fronts). Strong downdrafts leading to high-speed gust fronts are called downbursts (i.e., DB). Studying thunderstorms is challenging due to the uncertainty of the event occurrence, location, and time.

Storm shelters reduce the effect of local storms (eg. fatalities) during the event especially in rural areas where no reliable shelter exists. Nevertheless, Canada does not have either thunderstorm wind speed maps or design manuals for storm shelters. This research consists of three main steps: i) developing and validating a new method for thunderstorm wind speed evaluation using historical records and Monte Carlo simulation, ii) developing thunderstorm wind speed maps for Canadian provinces suitable for designing structures, and iii) designing affordable storm shelters.

The first step relies on the fact that historical records taken at weather stations contain local thunderstorm activities occurred close to the weather stations. Since the number of recorded thunderstorm events may be limited, a new method to extrapolate the records is developed and validated. The method is based on characterizing the events using a previously validated Computational Fluid Dynamic CFD downburst model to quantify storm parameters and their distribution. Those storm parameters are then employed with Monte Carlo simulation to extend the data by simulating storms occurring in many years beyond the records and evaluate the wind speeds suitable for structural design. This method was utilized and validated to quantify thunderstorm wind speed for Lubbock, Texas, USA. In the second step of this research, thunderstorm wind speed evaluation and extrapolation was conducted for weather stations covering Southern Ontario. A number of 50 stations were analysed and the resulting wind speed maps are shown in Figure 1. The figure shows wind speed maps suitable for designing a single point structure under thunderstorms, an extended structure under thunderstorms and those used presented in the National Building Code of Canada (NBCC, 2015), published by NRC and developed by the Canadian Commission on Building and Fire Codes, sets out technical provisions for the design and construction of new buildings. It also applies to the alteration, change of use and demolition of existing buildings. Over 360 technical changes have been incorporated in this new edition. Thirty-four changes to the NBC and eight changes to the National Fire Code 2015 (NFC under synoptic winds. It appears from the figure that extended structures (i.e. transmission lines) require higher design wind speeds than those of single point structures when subjected to thunderstorms due to their higher probability of encountering a thunderstorm event. In step 3: Wind tunnel testing for storm shelters was conducted in step 3. First, a collection of typical shelter shapes, were chosen and tested experimentally at Ryerson University wind tunnel under DB and boundary layer (BL) flows. This was achieved using: (i) a combination of roughness elements (i.e., moving slats, spires, and roughness blocks) that generate BL flows (Ghazal *et al.*, 2020)suburban and urban, and (ii) a rotatable louver system capable of redirecting the flow suddenly downwards at a specified louver angle to generate the DB profile (Aboutabikh *et al.*, 2019). Both tests were conducted under an open terrain condition encountered in rural areas.

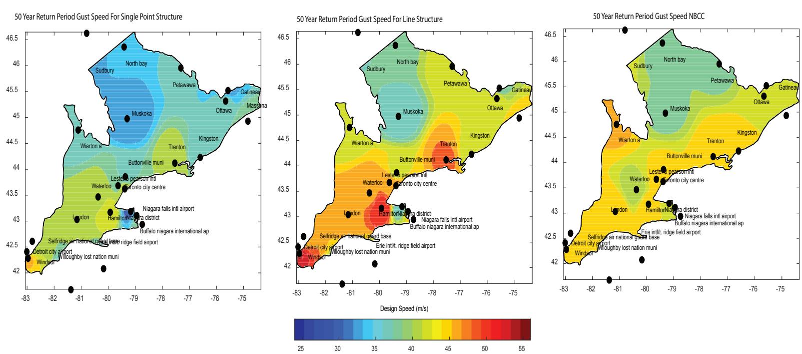

Figure 1. Gust wind speed for 50 years return period for a) Single point structure, b) Line structures, and c) NBCC, 2015.

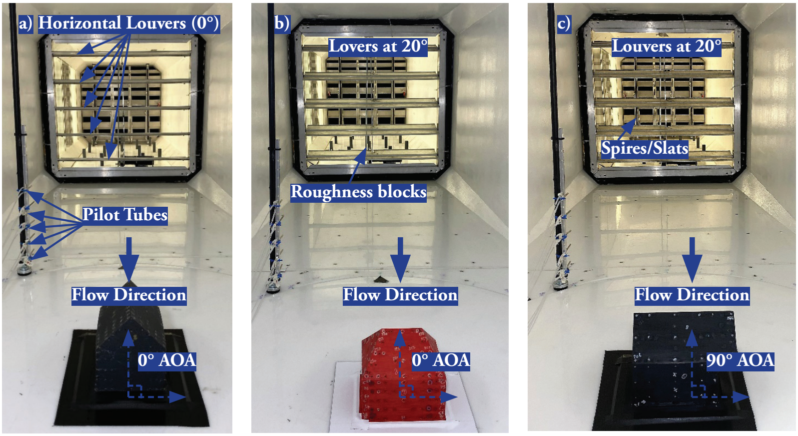

Figure 2. Test setup for a) Angled shape b) Double angled shape, and c) Overhang shape.

The overall aerodynamic forces on the shelter structure as well as the load acting on the cladding elements (i.e., windows and roofing) were evaluated under both DB and BL flows. The normalized forces for DB were scaled using the developed thunderstorms wind speed map shown in Figure 1, while the BL forces were scaled using the wind speed maps in the NBCC 2015. It was found that the design forces are highly dependent on the location where the shelter will be built. For example, at certain locations, the thunderstorm design wind forces are prevailing, such as at Windsor, while at other locations, the BL wind forces can dominate, such as at Niagara. This indicates that the current practice of utilizing the NBCC to design low-rise buildings considering only normal BL wind is not necessarily adequate to cover thunderstorms. Currently the research team is optimizing the design of storm shelters for both structural and cladding components to be constructed in southern Ontario.

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Introduction to the multiple-fan wind tunnel at Tamkang University and examples of its application*

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The multiple-fan wind tunnel at Tamkang University (MFWT-TKU) was designed by referring to the multiple-fan wind tunnel at the University of Tokyo (MFWT-UT). The facility is an actively controlled blow-down tunnel with 72 individually controlled fans. The testing section is 1.32 m x 1.32 m in cross-section, with the section 5.6 m downwind of the inlet contraction. All internal tunnel surfaces are smooth. Differing velocity profiles can be developed by modifying the rotational frequency of fans in each row, with some lateral variability in fan frequency introduced to promote mixing. A schematic diagram of the facility is shown in Figure 1.

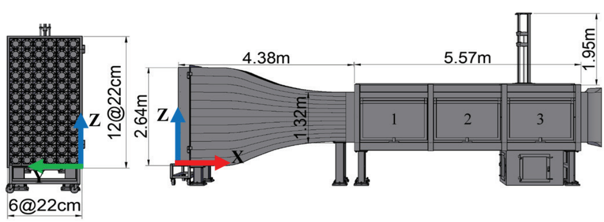

Figure 1. Multiple-fan wind tunnel at Tamkang University.

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* https://www.youtube.com/watch?v=g72AEW2kiQc&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=33

The primary design purpose of the MFWT-TKU is to generate various flow profiles; therefore, 72 fans were arranged in a 12 x 6 matrix, twelve fans per column, and six fans per row. Each fan has its independent ducting, with the internal walls of each also smooth. The contraction ratio is 2:1 from the dynamic section (72 fan-motor units) to the testing section. Such an arrangement allows generation of a finer resolution for vertical flow profiles than is possible with the fans alone. The secondary design purpose is to perform distinct accelerating or decelerating flows. The fan-motor unit consists of a self-designed fan, a servo motor, and a steel frame to fasten the fan and the motor. The AC Servo Motor SGM7J is adopted to provide high rapid rotation specification, and the fan is made to generate sufficient wind speed ranges for scaled-down wind tunnel tests. The reliable wind speed range in the testing section is 2 – 16 m/s. The instantaneous flow acceleration of an accelerating example can reach 8.5 m/s^2. However, due to the grid walls and flow mixing between the 72 fans, the inherent turbulent intensity of an empty wind tunnel condition is 3%, which has not been qualified to provide a practicable smooth flow. Figure 2 shows the target and measured mean wind speed profiles and turbulent intensity profiles in the along-wind direction for three example target profiles, uniform (UN) and two thunderstorms (TS1 and TS2) and the generated profiles in the MFWT-TKU. The elevation is normalized by the CAARC building model height, H.

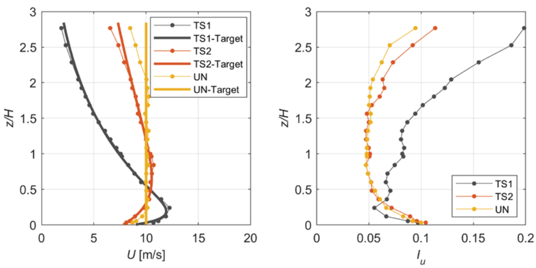

Figure 2. Target and measured U profiles (left) and Iu profiles (right) for the uniform (UN) and two thunderstorms (TS1 and TS2) test cases.

The MFWT-TKU was built in 2016 and was first put into practice in 2017 summer. So far, three series of wind tunnel tests have been conducted based on the MFWT-TKU during 2017-2020. They are systematic works on the accelerating and decelerating effects on the aerodynamic forces of two-dimensional prism models, the aerodynamic forces of a highrise building under various steady velocity profiles (Mason et al, 2020), and the transient effects of the aerodynamic forces of a highrise building when one flow profile suddenly changing to another one within few laboratory-scaled seconds (Mason and Lo, 2019; Lo and Mason, 2019). Figure 3 shows an accelerating flow case of a uniform flow.

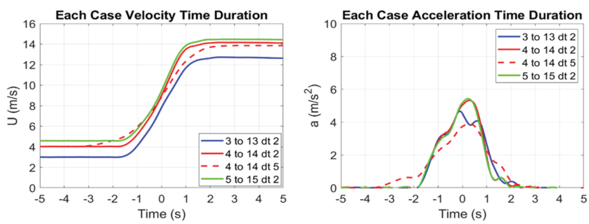

Figure 3. Ensemble averaged wind speeds (left) and accelerations (right) of four different accelerating conditions.

The MFWT-TKU is a versatile tool for producing bespoke non-traditional boundary layer profiles and accelerating or decelerating flows. However, it can still be improved in many ways. It is always worth developing advanced technologies or facilities to help understand the various countenances of natural winds.

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Wind and structural monitoring system for a telecommunication lattice tower – from setup to data analysis*

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Many wind monitoring campaigns have been conducted around the world with the purpose of better understanding wind and its effects on structures (Fujita, 1985; Levitan et. al., 1990; Solari et. al, 2015; Vallis et. al, 2019). However, in Romania research on thunderstorm winds and their effects on structures is very limited even if the country has been identified as having among the highest thunderstorm activities in Europe (Taszarek et. al, 2019).

Based on a cooperation agreement between the University of Genoa, Italy and the Technical University of Civil Engineering Bucharest, Romania, a wind and structural monitoring system was installed on a telecommunication lattice tower located in Romania with the joint purpose of detecting and analysing thunderstorms and performing experimental analysis of the structural response of the antennae tower to the action induced by downburst winds. The tower was equipped with wind and structural monitoring sensors such as an ultrasonic anemometer, a tem-

* https://www.youtube.com/watch?v=no7yLtOsaS0&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=34

perature sensor, two triaxial accelerometers, six strain gauges, a data acquisition system and a video surveillance system to capture the cloud formation during thunderstorms. The monitored tower is located in Sânnicolau Mare (Figure 1a), a city that has been affected by thunderstorm damage several times in recent years. The location was chosen based on previous studies which showed that the western part of the country is the most affected by thunderstorms (Calotescu, 2019).

The structure is a 50m high triangular telecommunication lattice tower, the tower geometry being one of the most commonly used geometries for antennae towers in Romania (Figure 1b). The distance between leg members is 12.0m at the base and 2.30m at the top. The tower is divided into 10 sections and is tapered up to 39.40m with a 3.72deg inclination with respect to the vertical. From 39.40m up to 50m the tower has parallel legs. Along the height there are two resting platforms at 15m, 27.5m and two working platforms at 40m and 47.5m. All members are made with circular hollow cross-sections.

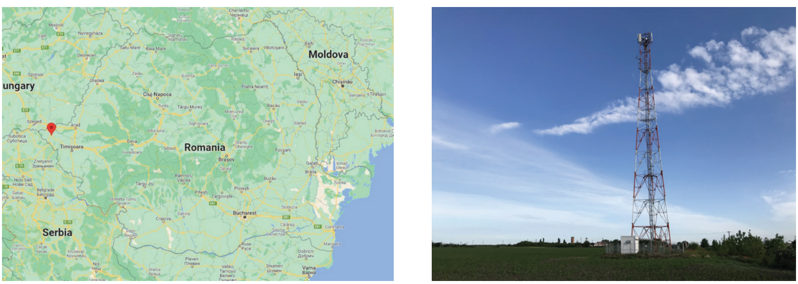

Figure 1. a) Tower location: Sânnicolau Mare, Romania and b) the monitored tower.

The monitoring system has been in use since January 2021. Wind data is analysed in order to identify, extract and classify events based on a methodology elaborated by De Gaetano et. al (2015). Throughout the duration of the 2021 thunderstorm season (May-August), approximately twelve possible thunderstorms have been recorded, the most noteworthy event being a thunderstorm that has occurred on June 25th, 2021 with wind velocities reaching 40.9m/s. Due to this storm, both wind and hail damage has been induced to hundreds of houses in Sânnicolau Mare. The high resolution simultaneous wind velocity, acceleration and strain records allow a deep inspection of non-stationary wind events and structural response.

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Evolutionary spectral model for thunderstorm outflows and application to the alongwind dynamic response of SDOF systems*

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The study of thunderstorms and their impact on structures has received increasing attention from the wind engineering community in the last decades. Despite the great amount of research, civil engineers still miss a robust model to predict the wind-excited response of structures subjected to these mesoscale phenomena, mainly due to the nonstationary nature of the phenomenon and the lack of wind velocity records on which studies can be based on. In this framework, this study is focused on the prediction of the dynamic response of SDOF systems to thunderstorm outflows and the derivation of its maximum value starting from an Evolutionary Power Spectral Density (EPSD) model of the thunderstorm wind velocity based on full scale records.

The EPSD model has been derived from 129 full-scale thunderstorm wind velocity time-histories recorded in the ports of Genoa, La Spezia, Savona and Livorno. From each record, the slowly varying mean and standard deviation have been extracted and a test on the nonstationary turbulent fluctuations has been carried out to check if they can be delt with as a uniformly modulated process. An analytical model for the slowly-varying mean wind velocity and standard deviation has been proposed and pro-

* https://www.youtube.com/watch?v=vYVaKJ0lRO4&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=35

vided with parameters of physical meaning which describe the interaction between the thunderstorm and the background wind speed. Moreover, the error committed by assuming constant turbulence intensity has been verified to be small and the PSD of the stationary reduced fluctuations proved to be successfully modelled by means of the spectral models commonly adopted in wind engineering (Roncallo and Solari, 2020).

The wind loading on a point-like SDOF system is expressed, under the assumption of small turbulence, as the sum of a slowly-varying mean and a nonstationary fluctuating component characterized by a suitable EPSD model. The response to the mean part of the loading is assumed as the static response to the slowly-varying mean wind velocity. The EPSD of the wind loading is employed to calculate the evolutionary spectrum of the fluctuating part of the response. For this purpose, two methods have been investigated, namely the Simplified and the Rigorous Method. The former has already been proposed in the literature (Chen, 2008) and is based on the assumption of a long pulse duration for the modulating function of the mean velocity, the latter instead considers the effects of said modulating function through the so-called Evolutionary Frequency Response Function (EFRF) well known in seismic engineering (Muscolino and Alderucci, 2015). When the structure is sufficiently stiff and damped, the hypothesis of long pulse duration holds and the Simplified formulation is reliable. Once the EPSD of the dynamic response is calculated, the time-varying variance of the response is derived by its integration over the frequency domain. To estimate the mean value of the maximum fluctuating part of the response, the time-varying variance is employed to calculate suitable equivalent parameters, namely an equivalent standard deviation and an equivalent period (Michaelov *et al.,* 2001, Kwon and Kareem, 2019). By assuming the maxima of the mean and fluctuating part of the response as simultaneous, the mean value of the maximum response has been derived according to Davenport's formulation and the results compared with the numerical Thunderstorm Response Spectrum Technique, obtained by integrating the equation of motion in time domain using as loading condition the thunderstorms records available.

Results show that that the Simplified Method generally overestimates the Response Spectrum (RS), while it is reliable when the structure is stiff and highly damped. Both the Simplified and the Rigorous Methods overestimate the mean reduced RS from the data for the case flexible and lowly damped systems. This fact was found to be due to the Poisson approximation and it has been corrected by introducing a suitable effective rate through a methodology similar to the one proposed by Der Kiureghian (1980) in the seismic engineering field. The comparison between the corrected analytical RS and the numerical one is reported in Figure 1b. Although the comparison results particularly satisfying, recent results show that the choice of identifying the maximum response with its mean value may not be on the safe side for lowly damped structures due to the spread of its distribution. In this case the estimation provided by the model without the correction apported may give a suitable safety margin.

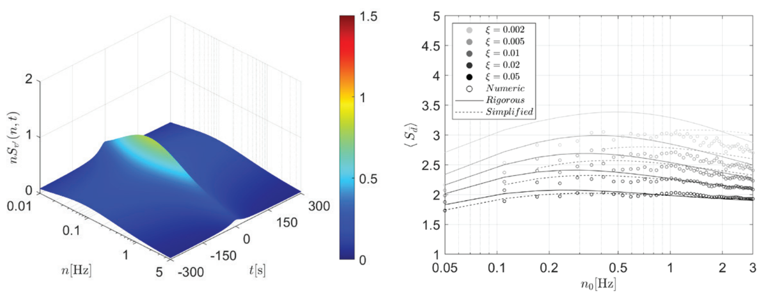

Figure 1. a) EPSD of the nonstationary turbulence; b) Comparison between the analytical and numerical TRST.

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On the dynamic response of slender structures subjected to thunderstorm outflows through the strip and quasi-steady theory*

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The strip and quasi-steady theory (Kawai, 1983) allows a direct relationship between the wind and the pressure and/or force fields to be established, and its applicability is robust when dealing with the action of synoptic winds. These have indeed steady characteristics in both wind speed and flow direction (e.g., Solari, 2019). On the other hand, the case of the thunderstorm outflows present features that strongly differ from the synoptic reference, being characterized by sudden variations of the wind speed and, often, of the flow direction as well (e.g., Holmes *et al.*, 2008). At present, the literature concerning the applicability of the strip and quasi-steady theory for unsteady flows is limited and fragmentary, being often associated with accelerations which are way too high to be considered as representative of thunderstorm outflow. For instance, this is the case of the pioneering work carried out by Sarpkaya (1963) by means of water tunnels.

The present work aims at proposing an analytical formulation for the prediction of the dynamic response of slender structures (whose structural axis is denoted as). In doing so, the strip and quasi-steady

* https://www.youtube.com/watch?v=Frd4vNM-bP4&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=36

theory is applied in a non-conventional way. In fact, the aerodynamic coefficients are considered as time-varying quantities, being linked with the time-varying values of the mean wind velocity and flow direction. The formulation is proposed for a slender structure, studied as a multi-degree of freedom system. Its cross-section is compact to avoid any sort of torsional effects. Vortex-shedding phenomenon is neglected. The equations of motion may be written as:

$$\tilde{M}P(t)+\tilde{C}\ddot{P}(t)+\tilde{K}\dot{P}(t)=\tilde{F}(t), \tag{1}$$

where $\tilde{M}$, $\tilde{C}$ and are the principal mass, structural damping stiffness matrices, respectively. P is the vector of the principal coordinates, and $\tilde{F}$ constitutes the vector of the principal wind actions. This is function of f, which is the vector of the wind actions per unit length. These can be framed in three different parts, according to their nature:

$$f(Z,t)=\bar{f}(Z,t)+f'(Z,t)+f_a(Z,t), \tag{2}$$

where $\bar{f}$ is the mean action and it is related to the mean wind field, f is relevant to the incoming turbulence, and f_a contains the motion-induced forces linked to fluid-structure interaction.

Focus is firstly given to the definition of an appropriate methodology for the aerodynamic forces ($\bar{f}$ and f'), neglecting any sort of fluid-structure interaction (f_a). The novelty of the proposed methodologies (Method 1, Method 2 and Method 3) lies on the possibility to retain the directionality effects typical of thunderstorm outflows. They differ amongst each other because of the required input data: Method 1 is fed with the data coming from the classical decomposition technique (e.g., Chen and Letchford, 2004) for signals linked with thunderstorm outflows, while Method 2 is based on a novel directional approach (Shi *et al.*, 2019). Moreover, it further enables the hypothesis of small turbulence (Method 3) to be made, in a complete analogy with the classical formulation, opening the doors to a robust comparison between synoptic winds and thunderstorm outflows.

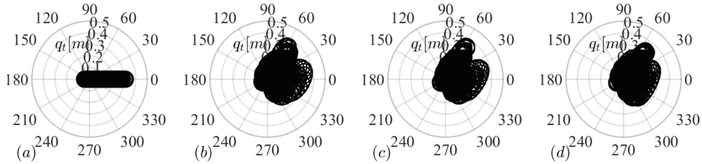

Figure 1. Polar plots of the dynamic response of the BEC: (a)/(b)/(c)/(d) non-directional Method 0/Method 1/2/3.

The formulation has been applied to estimate the dynamic response of the Brâncuși Endless Column (BEC) and a circular structure, subjected to the effects of ten 10-minute signals linked with thunderstorm outflows. These anemometric signals are converted into compatible vertical wind fields. The structures are considered as characterized by a linear elastic behavior, their natural frequencies are well-separated and the damping is small and proportional. Only the contribution of the first mode of vibration is considered in the analysis. The results (Figure 1) point out strong effects induced by directionality effects on the Brâncuși Endless Column, leading to an increase of the dynamic response.

The second phase of the work concerns the formulation of the motion-induced forces, f_a:

$$f_a(Z,t)=-\breve{C}_a(t)\dot{P}(Z,t)-D\beta(t)\breve{K}_a(t)P(Z,t), \quad (3)$$

where $\breve{C}_a$ is the time-varying principal aerodynamic damping matrix, and $\breve{K}_a$ is the time-varying principal stiffness matrix. $D\beta$ represents the temporal derivative of the flow direction.

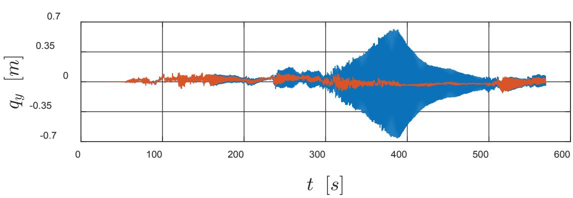

Figure 2. Crosswind response of the BEC considering aeroelastic terms (blue) and neglecting them (orange).

The formulation is applied considering the action of the same wind events as before, this time studying the BEC without modules and wrapped in a plastic sheet (typical of the restoration works carried out at the end of the Nineties). This configuration is much more exposed to aeroelastic phenomena. Taking the aeroelastic terms into account newly highlights the effect played by the flow direction. Indeed, its variation seems to prevent the building-up of large oscillations. Conversely, a sufficiently regular flow direction furnishes sufficient activation time to the fluid and the structure to synchronize (Figure 2).

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Toward the codification of thunderstorm/ downburst winds*

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Thunderstorm/downburst winds often exhibit rapid changes during a short period which may be accompanied by changes in direction. This introduces non-stationarity both in the mean and the standard deviation of wind fluctuations. Thus, design loads in these non-synoptic non-stationary winds obtained from conventional analysis frameworks included in codes and standards such as the gust loading factor approach may not be appropriate, calling for a careful examination of traditional design procedures. This study reviews a proposed design procedure for thunderstorm/downburst winds. Two major frameworks reported in the past literature such as the gust front factor and the thunderstorm response spectrum technique are examined to step toward the codification of gust front winds.

With the exemplary success of the gust loading factor (Davenport, 1967) in capturing the dynamic wind effects introduced by buffeting

* https://www.youtube.com/watch?v=cJRWSgwpDSY&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=37

action of winds and its popularity in design codes and standards worldwide, a gust front factor framework (Kwon and Kareem, 2009, 2013) was proposed along the lines of the gust loading/effect factor formulation existing in ASCE 7 (Solari and Kareem, 1998) that encapsulates critical features of gust front winds to capture their load effects. To accomplish this objective, the gust front factor (GFF, $G_{G\text{-}F}$) (Eq. 1) and its generalized version (G-GFF, $G_{G,G\text{-}F}$) (Eq. 2) were therefore introduced. The former was formulated for use in conjunction with the existing design codes and standards, e.g., ASCE 7, while the latter was for a more general case, akin to the conventional gust loading/effect factor, which best captures the dynamic effects of gust front winds. The design wind loads (equivalent static wind loads, ESWL) using the two factors in a gust front, F_{Design} and $F_{G,G\text{-}F}$, respectively, are then expressed by:

$$F_{Design}=F_{ASCE7}\cdot K_{z,G\text{-}F}\cdot G_{G\text{-}F}$$

$$G_{G\text{-}F}=I_1\cdot I_2\cdot I_3\cdot I_4 \tag{1}$$

$$F_{G,G\text{-}F}(z)=\bar{F}(z)\cdot G_{G,G\text{-}F}=\tfrac{1}{2}\rho\cdot A\cdot V^2_{G\text{-}F}(z)\cdot G_{G,G\text{-}F}\cdot C_{D,G\text{-}F}$$

$$G_{G,G\text{-}F}=I_2\cdot(I_3\cdot G_{GLF}) \tag{2}$$

where $F_{\text{ASCE 7}}$ represents the ESWL in ASCE 7, the $G_{G\text{-}F}$ is the GFF that relates F_{Design} in a gust front to the $F_{\text{ASCE 7}}$ recommendations in conventional boundary layer winds, and $K_{z,G\text{-}F}$ accounts for the velocity/pressure profile in a gust front as opposed to boundary layer winds in ASCE 7. The $G_{G\text{-}F}$ can be best captured in terms of four underlying factors (Kwon and Kareem 2009, 2013). In this format, the $G_{G\text{-}F}$ explicitly takes into account the following features: variation in the vertical profile of wind speed – kinematic effects factor (mean load effects), I_1; dynamic effects introduced by the sudden rise in wind speed - pulse dynamics factor (rise-time effects), I_2; non-stationarity of turbulence in gust front winds - structural dynamics factor (non-stationary turbulence effects), I_3; transient aerodynamics – potential load modification factor (transient aerodynamics effects), I_4 (Figure 1a).

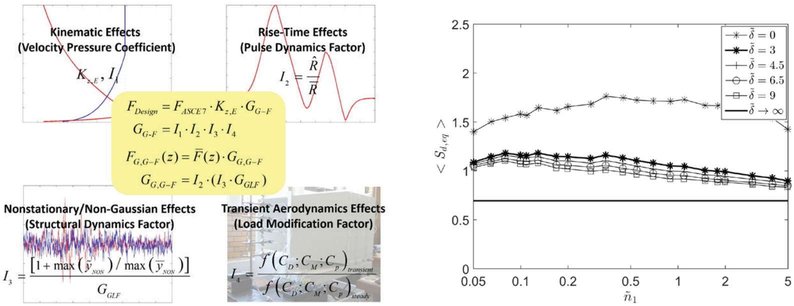

Figure 1. Schematic diagram of GFF/G-GFF and a thunderstorm response spectrum. (a) Gust front factor and its generalized version; (b) thunderstorm response spectrum (ERS).

Recently, Solari (2016) has introduced an alternative approach for the design of thunderstorms focusing on downburst events. It is referred to as the thunderstorm response spectrum technique (TRST), which has adopted the concept of the response spectrum being widely used in the field of earthquake engineering as well as blast design. For this reason, the TRST also demands several representative datasets to establish a reliable response spectrum, such datasets have been obtained through a wide range of full-scale wind monitoring networks, Wind, Ports, and Seas. Thus, this is a data-based approach while GFF/G-GFF is a model-based one.

The equivalent static wind loads (ESWL) in the TRST has the format similar to Eq. (2) used in the G-GFF framework, which is expressed as (Solari 2016):

$$f_{eq}(z)=\hat{f}(z)\cdot S_{d,eq}$$

$$\hat{f}(z)=½\rho V_{max}^2(h)\hat{G}^2(h)V_{G\text{-}F,sol}^2(z)A(z)C_D(z) \tag{3}$$

where, $\hat{f}(z)$ = peak static wind load by thunderstorm outflows; $S_{d,eq}$ = equivalent response spectrum (ERS) that is a graphical representation to choose a value for a non-dimensional parameters ($\tilde{n}_1$, $\tilde{\delta}$) (Figure 1b); $G^2(h)$ = gust velocity factor at a reference height, h.

A comparison is made between the two frameworks to assess the performance of the two approaches will be made. Also, a living codification concept through learning and updating invoking the emerging «Design Thinking» approach is discussed.

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Nonstationary winds: characterization, simulation and response analysis*

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* https://www.youtube.com/watch?v=6C0-H451VkM&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=38

Post-event survey and damage analysis of an intense thunderstorm in Sannicolau Mare, Romania*

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On 25 June 2021, an intense thunderstorm occurred in Sannicolau Mare, Romania, causing power and water supply cut-off to the city and producing damage to structures and vegetation. In this study, the nearby field records of wind are presented, and a post-event survey is conducted to collect over 200 building damage cases induced by both wind and hail. The surveyed area, approximately 8.5 km^2 in size, included almost the entire urban area of the city.

Field measurement data of the thunderstorm winds were collected by an ultra-sonic anemometer, which is installed 50 m above ground near the city to its southeast perimeter, at a sampling frequency of 4 Hz. The anemometric records showed that the instantaneous wind speed rapidly increased from 18:10 to 18:20 Coordinated Universal Time and gradually decreased afterwards. The maximum instantaneous and 30-s-mean wind speed reached 40.9 m/s and 35.8 m/s, respectively, demonstrating the remarkable intensity of the monitored event. Meanwhile, the wind direction shifted drastically from southwest (≈ 240°) to east (≈ 90°) and the temperature showed a sudden drop from 27 °C to 15 °C.

* https://www.youtube.com/watch?v=a6vz7vBcH7M&list=PL-bF0BXX_6CPKgfxrWeqmjfWcjqL2C9E1a&index=39

According to the survey, there were two major types of damage occurred to the buildings during the thunderstorm event, namely, the wind- and hail-induced damages. The damage cases are discussed in the following.

Figure 1 presents the wind-induced damages of a church. The most severe damage was the roof (about 500 m^2 in area) entirely uplifted as shown in Figure 1(a), which was subjected to the excessive suction induced by flow separation at the leading edge. The corner of the roof of the bell tower, shown in Figure 1(b), was also partially lifted, and it was caused by not only the negative external pressure but also the positive internal pressure boosted during the thunderstorm through the damaged window shown in Figure 1(c). Besides, multiple severe indentations caused by wind-borne debris, which originated from the displaced roof shown in Figure 1(a), were also found on the roof as presented in Figure 1(d).

Figure 1. Wind-induced damage of a church.

Hail-induced indentations were observed from over 200 buildings in the city, mostly on their west facades. For instance, more than 8000 indentations were identified on the west facade of a 10-m-tall residential building. Observations show that there were 100 to 400 indentations in each 1-m^2 square area on this facade and the distribution density increased with the height. Notably, the locations of hail indentation were highly sensitive to the wind direction, showing the feasibility of using them as an indicator of the outflow direction and therefore also of the thunderstorm path. Furthermore, statistical analysis from 198 hail damage cases indicates that the probability of a wall without a top coat being damaged by hail is about 8 times that of a wall with one.

Based on the wind records collected by the anemometer and the wind-induced roof damage of buildings observed by the survey, four widely adopted wind speed estimation scales are validated herein. The scales and their estimated wind speed are as follows: 32.6 – 50.1 m/s by the Fujita scale (Fujita, 1979), 28.6 – 43.4 m/s by the Enhanced Fujita (EF) scale (McDonald and Mehta, 2006), 27.8 – 43.1 m/s by the Canadian EF-scale (Environment Canada), and 25 – 55 m/s by the Japanese EF-scale (Japan Meteorological Agency). On the other hand, the measured maximum 3-s gust speed was 38.4 m/s, which can be converted to approximately 33.5 m/s at the reference height of the EF-scale (i.e., 10 m above ground) following Wood *et al.* (2001) and Hjelmfelt (1988). Such gust speed is within the ranges estimated by all the four scales, indicating that these scales can estimate the intensity of a thunderstorm with a sufficient accuracy.

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