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Education and dissemination in wind science and engineering

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ABSTRACT

An adequate education in a discipline as vast and articulated as wind science and engineering cannot fail to recognize its origins, developments, fundamentals, advancements and prospects. This paper analyses and discusses the actual state of education by identifying its limits, gaps and strengths, as well as the hard core of knowledge that should constitute the common basis for a mature and modern discipline capable of generating figures endowed with broad views and specialized skills. Pursuing this vision in a rational and homogeneous framework, it also points out the role of new strategies aiming to exploit technological evolution and communication systems, to rationalize co-operative educational programs on broad territorial scales, to involve different competences as in-depth as they are varied in the wind science and engineering community. Meanwhile, it highlights the necessity of reaching those who need to establish and consolidate this culture, but do not have the opportunity to personally experience the manifold initiatives in the discipline, to seize the interest of people towards wind science and engineering, to disseminate its culture and know-how into everyday life and society.

1. Introduction

Writing a paper on education in wind science and engineering is a daunting task even for an author who has dedicated his entire life to this discipline, and has always given priority to the dissemination of knowledge towards the young generation, perceiving the academic role and the possibility to live among students motivated and eager to learn as a rare privilege. Certainly, the author considers this task much more difficult than discussing the state of the art of a familiar topic, or even more than presenting the results and prospects of a project to which the author himself and his research group are continuously working (Fig. 1).

The difficulty of treating the education in wind science and engineering in a critical and rational way comes first of all from the fact that this discipline, in its whole, can still be considered as relatively young. It first devoted its efforts to the scientific and technical development of arguments that span an exceptionally broad field, perhaps as in no other sector, and only later, and thus quite recently, has given growing space to education and dissemination. This has been done first in a rather uneven way, almost always linked to local realities where research activities were carried out, then, little by little, in a more systematic and capillary way. Accordingly, gathering and disseminating this information is not easy as there is still a limited tradition to refer to.

Well beyond this problem, which remains essential, the author would avoid the risk of debasing and trivializing this treatment in an attempt to collect and systematize the almost inextricable web of what is happening worldwide - with the certainty of describing only a limited part of it and not to give credit to highly appreciable initiatives of which he does not know the existence - losing sight of the opportunity to seize this moment as a reflection upon the entire matter. On the other hand, by transposing the objectives of this article on this plan, the difficulty of dealing with this subject in an organic and comprehensive way is strengthened.

Trying to put order in his own thoughts, and aiming to organize them more broadly, the author believes that an education of adequate level, even more so in a discipline as vast and articulated as wind science and engineering, cannot fail to recognize first of all the origins, developments, fundamentals, advancements and prospects of the discipline itself. However, this cannot be limited to a simple historical and perspective reconstruction, but should grasp the cultural and interdisciplinary matrix that generated the matter and constitutes its imprint.

From this approach it emerges the vision that such a retrospective view can and must enhance a clear collection and a critical classification of the current state of education in wind engineering, aiming to identify its limits, gaps and strengths, the hard core of knowledge that should constitute the common basis for consolidating a mature and modern discipline, and the curricular paths that can radiate from this vision, giving rise, according to circumstances and opportunities, to figures endowed with broad visions and specialized skills.

Equally, a vision can and shall take shape, which may enhance advanced strategies for exploiting technological evolution and communication systems, rationalizing co-operative educational programs on

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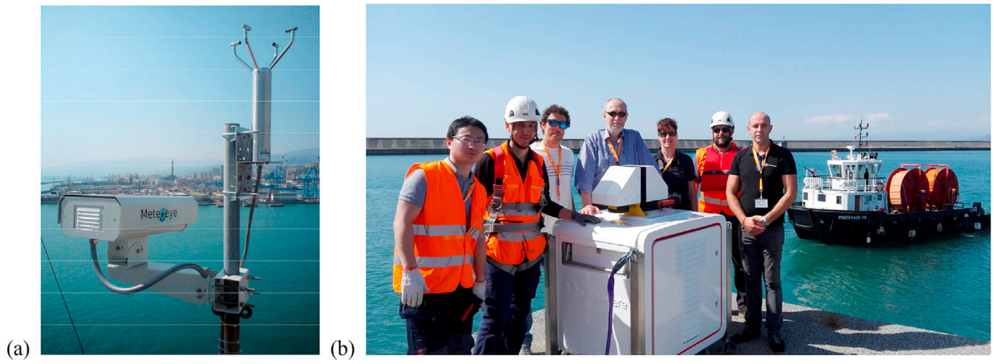

Fig. 1. ERC THUNDERR Project monitoring network: (a) ultra-sonic anemometer; (b) LiDAR scanner.

wide territorial scales, involving different competences as in-depth as they are varied in the wind science and engineering community, reaching those who need to establish and consolidate this culture, but do not have the opportunity to personally experience the multiple initiatives in the discipline, seizing the interest of planetary community towards the themes of wind science and engineering, spreading its culture and knowledge even outside the scientific and technical context, to the point of bringing it into everyday life and into society.

Retracing these considerations, three distinct but at the same time linked moments emerge that represent the core of the topics addressed in the three following sections: a retrospective look at the past (Section 2), a critical and proactive acknowledgment of the present (Section 3), and a view projected into the future (Section 4).

2. A retrospective viewpoint

Few natural phenomena are as ethereal, indefinable and mysterious as the wind. Few natural phenomena produce effects so visible, tangible and varied as the wind does. Few natural phenomena have been the object of speculation, observations, experiences and research as abundant as those carried out about the wind. Few natural phenomena have received so much attention as to cause scientific and technological progress in several sectors of science and engineering as the wind has done. Few natural phenomena still have so many unexplored aspects that require research as the wind needs (Solari, 2019).

These aspects are mostly due to the unique property of dualism of the wind. The wind is evil, or Devil, when it destroys buildings and territories, producing more fatalities and damage than any other natural event; when it whips men, houses and settlements with cold or hot air; when it makes urban areas uncomfortable; when it destroys crops and exposes transport to risks; when it erodes the soil up to make lands deserts; when it drifts snow, burying roads and buildings; when it is a tool for air pollution and for the aggression of monumental heritage. On the other hand, the wind is good, or God, because, as the engine of atmospheric circulation, life on the Earth would not exist without the wind; when it powers windmills and wind turbines, producing clean energy;

Fig. 2. (a) Fujin; (b) Letter of Toledo (1185); (c) Persian windmill (7th century); (d) Kingsbridge Cathedral (1170) (Follet, 1989); (e) Leonardo da Vinci Atlantic Code (Anderson, 1998).

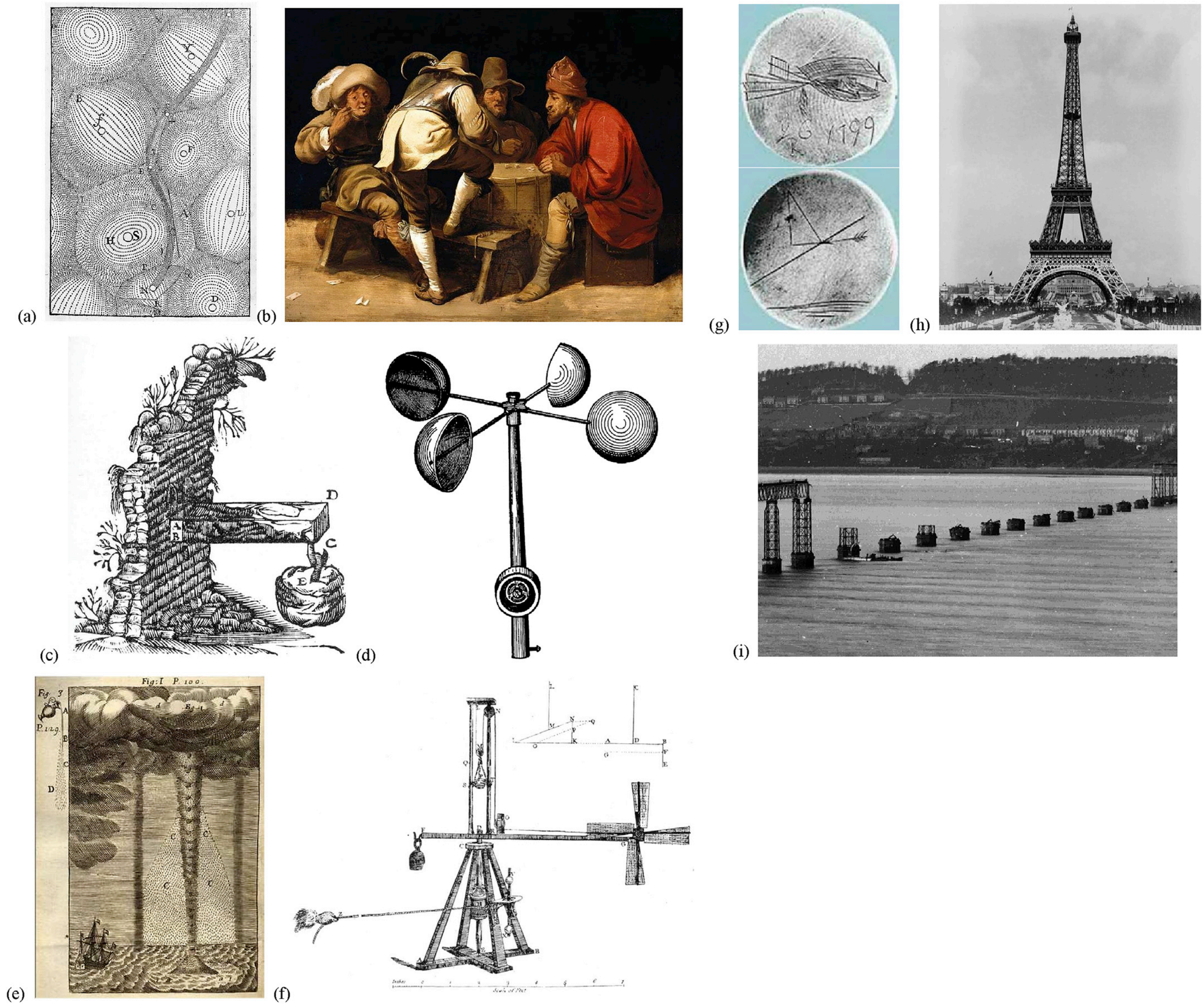

Fig. 3. (a) Descartes's theory of vortices (1634); (b) Chevalier de Méré and gambling (1654); (c) Galilei's problem (1638) (Solari, 2019; Benvenuto, 1981); (d) Robinson cup anemometer (1856) (Robinson, 1850); (e) Montanari's tornado (1694) (Solari, 2019; Montanari, 1694); (f) Smeaton's whirling arm (1759) (Solari, 2019; Smeaton, 1759); (g) Cayley's coin (1799) (Cayley, 1809); (h) Eiffel Tower (1889); (i) Tay Bridge collapse (1879) (Smith, 1976).

when it favours the circulation of fresh air inside buildings or along the arteries of the urban fabric; when it offers breath to the populations that live in deserts or in lands dried up by the sun; when it disperses pollutants and smog clouds away from populated areas and urban islands.

The evolution of wind knowledge and mankind's ability to exploit its beneficial aspects and to protect itself from the harmful ones has developed throughout four periods (Solari, 2019; Cermak, 1975; Baker, 2007): from the dawn of history to Renaissance (Section 2.1); from Renaissance to the end of the nineteenth century (Section 2.2); from the end of the nineteenth century to the mid-twentieth century (Section 2.3); and, from the mid-twentieth century to the third millennium (Section 2.4).

2.1. Origins: From the dawn of history to the Renaissance

The period that goes from the dawn of history to the Renaissance (Solari, 2019) was dominated by the will of men to know the wind, exploit its beneficial aspects and protect themselves from its harmful effects. At first men elaborated a mythological view that emphasized the dualism between the wind as a source of life and the wind as a means of death (Fig. 2a). Later, with the advent of Greek civilization, a naturalistic speculation was born inspired by observation. In parallel, the first scientific concepts and prodromes of experience, mainly related to mathematical, mechanical and astronomical problems, established themselves. From this reality, the innate interest of man emerged for weather knowledge and forecast: this gave rise to two disciplines, meteorology and astrology, destined to attract and repel throughout all history (Fig. 2b). At the same time, man learnt to exploit the wind power as an energy source, equipping his boat with sails, supporting the flying of kites, driving the blades of the first windmills for multiple forms of work (Fig. 2c). Man also developed the first experiences aiming at improving the life conditions of his settlements and homes, by blocking the path to the coldest winds or by creating pleasant streams of air where the heat was more oppressive. On the other hand he noted, usually with feelings of resignation and inevitability, the destruction caused to the territory and the built environment by windstorms (Fig. 2d) (Follet, 1989). Finally, with the advent of the Renaissance, the world was pervaded by a fervour of activity and innovation to which Leonardo da Vinci provided extraordinary contributions to many topics affecting wind culture, in

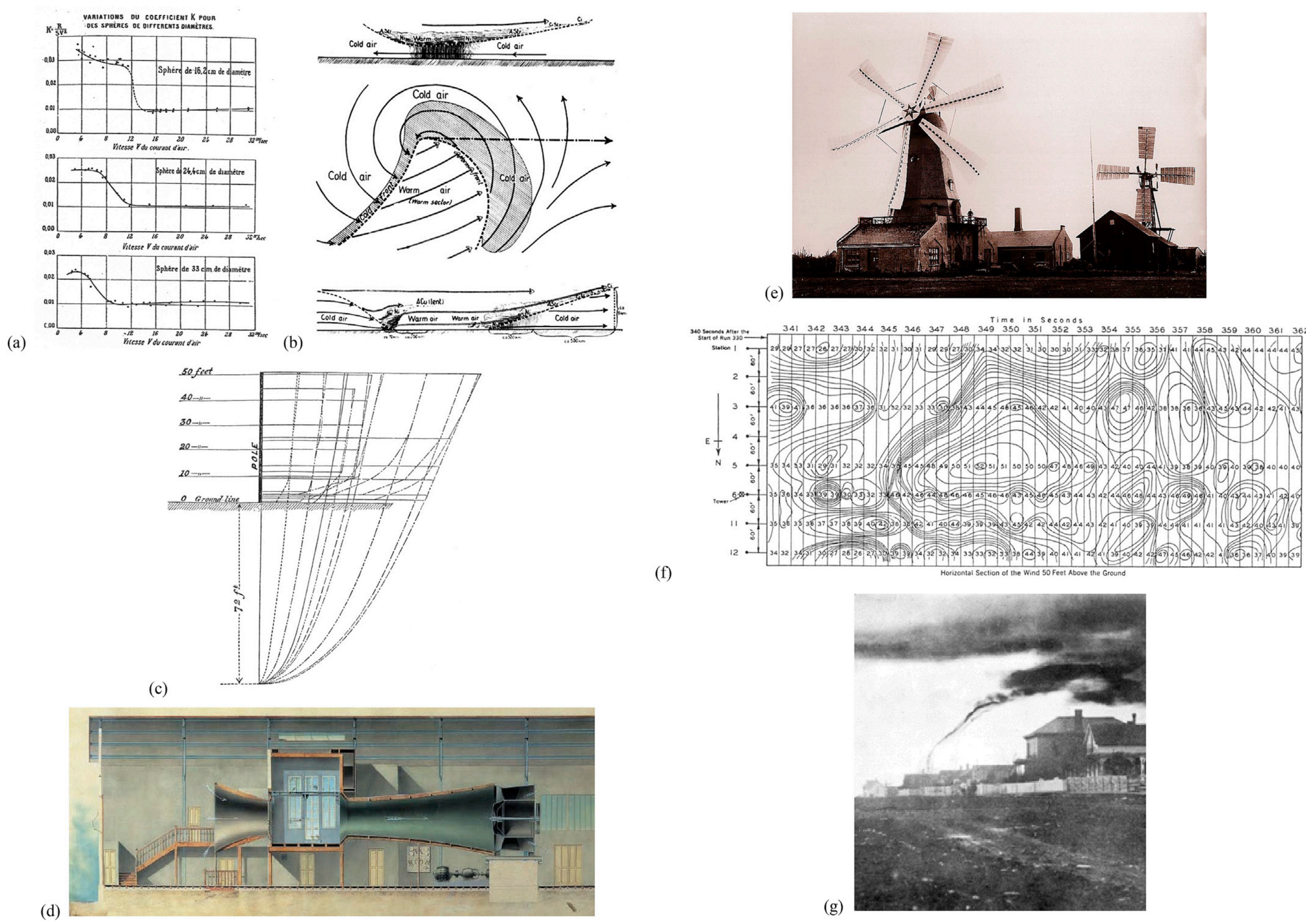

Fig. 4. (a) Eiffel's drag of a sphere (1912) (Solari, 2019; Eiffel, 1912); (b) Bjerknes and Solberg polar front theory (1922) (Solari, 2019; Bjerknes and Solberg, 1922); (c) Stevenson's power law profile (1880) (Solari, 2019; Stevenson, 1880); (d) Eiffel's wind tunnel (1912); (e) Lacour's experimental mills (1891) (La Cour, 1905); (f) Sherlock's isovelocity map (1937) (Solari, 2019; Sherlock and Stout, 1937); (g) first photograph of a tornado (1884) (Solari, 2019; Snow, 1984).

particular fluid and solid mechanics, meteorological instruments, aerodynamics (Fig. 2e) (Anderson, 1998) and human flight. There emerged the picture of a reality where the study of wind struggled to take on clear contours and autonomy of thought. In other words, the culture of this phenomenon remained an integral and often hidden part of broader and more general themes.

2.2. Developments: From the Renaissance to the end of the nineteenth century

In the second period, from the Renaissance to the end of the nineteenth century (Solari, 2019), a form of knowledge based on experience developed, science, supplanting the role of speculation and observation (Fig. 3a). The knowledge of the wind availed itself of this progress, drawing on principles from the basic disciplines that were born and developed in this period, especially physics, mathematics, probability theory (Fig. 3b), mechanics, fluid dynamics, thermodynamics, the gas kinetic theory, structural mechanics (Fig. 3c) (Benvenuto, 1981) and vibration theory. Thanks to this progress and the advances made in the fields of sailing and flight the wind culture received significant stimuli from the appearance and diffusion of weather instruments and measurements that fathomed the secrets of atmosphere (Fig. 3d) (Robinson, 1850). Accordingly, new and firm foundations were born to rationally approach the study of meteorology (Fig. 3e) (Montanari, 1694) and weather forecasting, to inspect the resistance of bodies in the air (Fig. 3f) (Smeaton, 1759), to adopt scales that may quantify the intensity of wind and its effects. Humanity made use of the renewed knowledge of the wind to better exploit this phenomenon as a means of propulsion for vessels. The links between wind and flight grew (Fig. 3g) (Cayley, 1809), in a context aimed towards scientific research. Technological evolution improved the efficiency of windmills and favoured their diffusion. Man also became aware of the risks faced by the boldest constructions (Fig. 3h) seeing the collapse, due to the wind, especially of many bridges (Fig. 3i) (Smith, 1976) that were the pride of the engineering of that time. As a whole, the culture about the wind was by then deeply ingrained in humankind and increasingly attracted scientific interest under many perspectives. The conditions that would lead, in the first half of the twentieth century, to the foundation of scientific disciplines aimed at dealing with specific issues related to wind had arisen.

2.3. Fundamentals: From the late nineteenth century to the mid-twentieth century

In the third period, from the late nineteenth to the mid-twentieth century (Solari, 2019), the maturation of the basic disciplines relevant to wind engineering was completed, especially fluid mechanics (Fig. 4a) (Eiffel, 1912) and probability theory; it is also worth mentioning the advent of the computer and its key link with meteorological forecasts. At the same time, new research lines were developed about wind, aerodynamics, wind actions and effects on environment and structures, wind hazard, vulnerability and risk. The knowledge of the wind phenomena took impetus from the evolution of ground-level instruments and remote

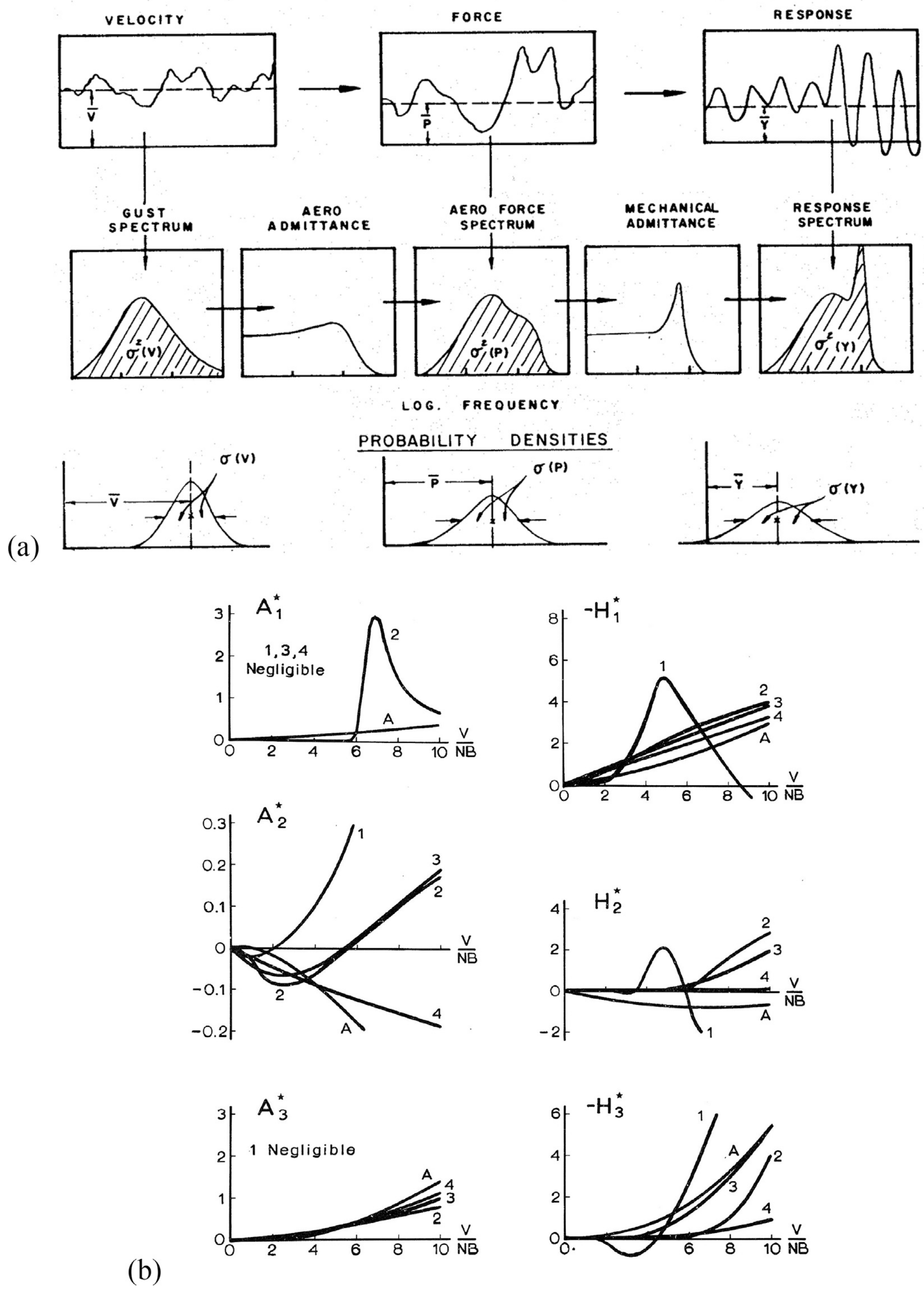

Fig. 5. (a) Davenport chain (1964) (Solari, 2019; Davenport, 1964); (b) Scanlan's flutter derivatives (1971) (Solari, 2019; Scanlan and Tomko, 1971).

monitoring, the advancements of synoptic meteorology (Fig. 4b) (Bjerknes and Solberg, 1922) and the classification of wind events based on their time and space scales, the advent of micrometeorology (Fig. 4c) (Stevenson, 1880), the newborn theory of turbulence and the first climatological studies. Aerodynamics made huge progress in the experimental field thanks to full-scale and wind tunnel tests (Fig. 4d); this greatly contributed to the new culture that pervaded the fields of aeronautics and, consequently, shipping, road and rail transport. Environmental wind actions and effects were fertile fields to study wind energy and wind the turbines (Fig. 4e) (La Cour, 1905) that supplanted the old mills, the atmospheric dispersion of pollutants, soil erosion and snow drift, the protection of crops by means of barriers, urban and architectural design inspired by bioclimatic principles. The study of wind actions and effects on structures was strengthened by the proliferation of long-span bridges, tall and slender towers, and, more generally, a new generation of structures increasingly sensitive to wind loading (Fig. 4f) (Sherlock and Stout, 1937); a new culture also matured of the static, dynamic and aeroelastic wind actions on structures. Man understood that wind-induced disasters, mainly caused by tropical cyclones, tornadoes and thunderstorms, could be mitigated by manifold interventions to

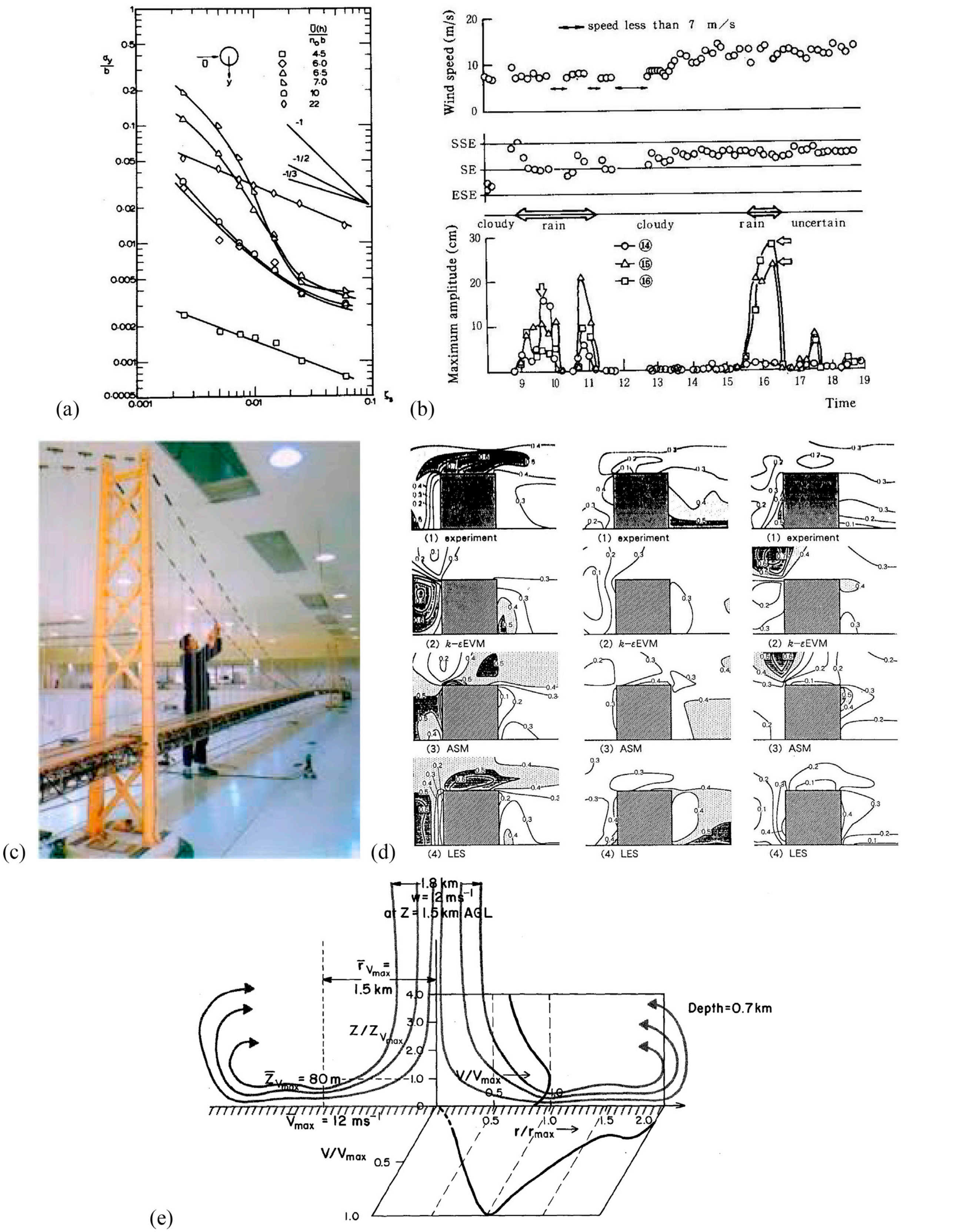

Fig. 6. (a) Vortex shedding and lock-in (Kwok and Melbourne, 1981) (Solari, 2019; Kwok and Melbourne, 1981); (b) rain galloping (Hikami and Shiraishi, 1988) (Hikami and Shiraishi, 1988); (c) Akasi-Kaikyo Bridge (Miyata et al., 1995) (Miyata et al., 1995); (d) CFD simulations (Murakami et al., 1992) (Murakami et al., 1992); (e) downburst flow field (Hjelmfelt, 1988) (Hjelmfelt, 1988).

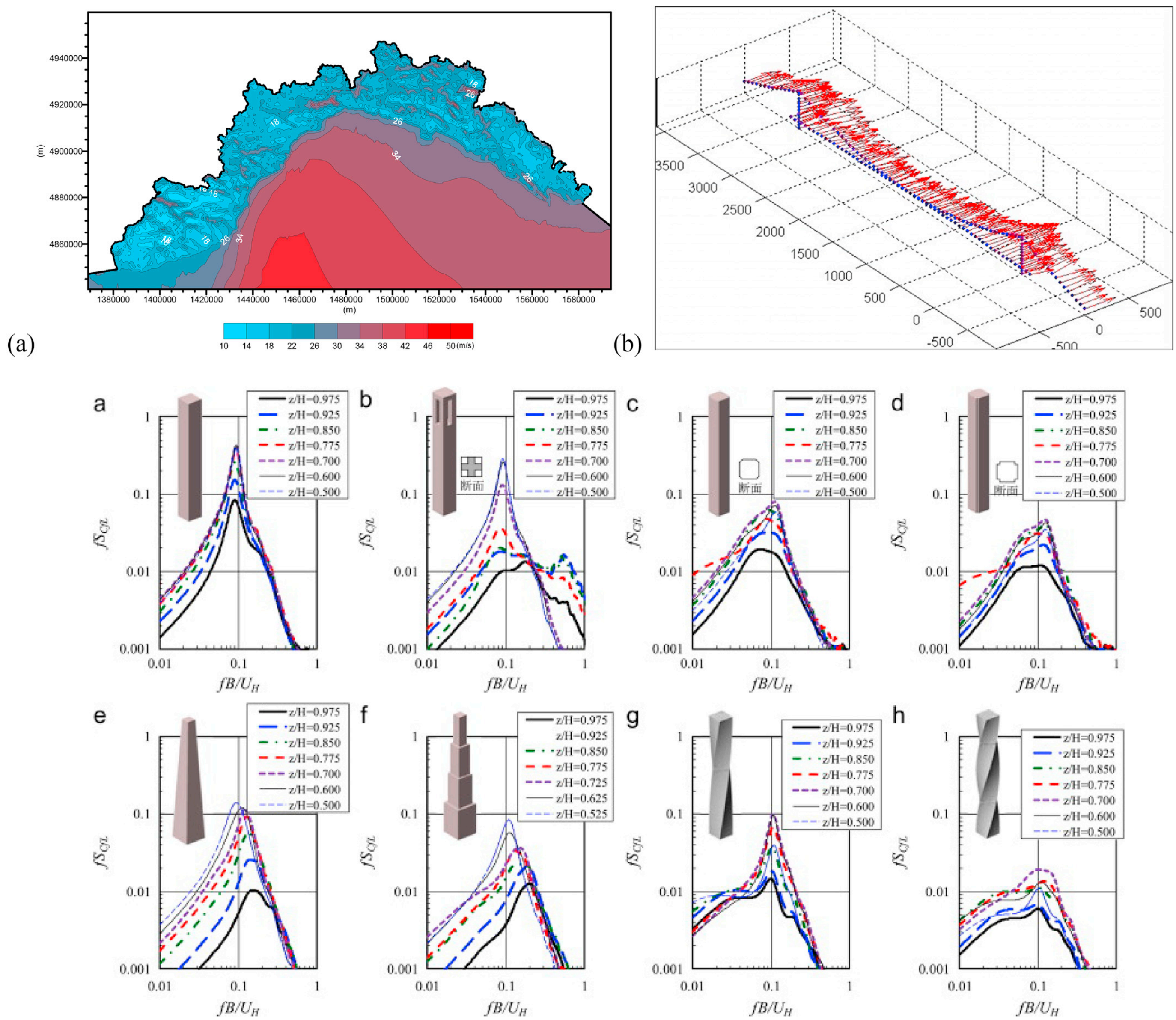

Fig. 7. (a) Micro-zonation map of Liguria Region: mean wind speed at 10 m height above ground with 50-year return period (Castino et al., 2003) (Castino et al., 2003); (b) Messina Strait Bridge: Monte Carlo simulation of the wind field (Carassale and Solari, 2006) (Carassale and Solari, 2006), (Burlando et al., 2007) (Burlando et al., 2007); (c) PSD of the crosswind loading of buildings with different shapes (Tanaka et al., 2012) (Tanaka et al., 2012).

which he devoted efforts and enthusiasm (Fig. 4g) (Snow, 1984). The whole range of these subjects highlights complex phenomena whose study calls for the joint use of advanced analytical, experimental and numerical tools. In this framework, they plant the seeds of the evolution that will take place from the second half of the twentieth century also thanks to the advent of the electronic computer. The grounds of these topics, however, are already present in this pioneering and founding age.

2.4. Advancements: From the mid-twentieth century to the third millennium

In the fourth and last period, from the mid-twentieth century to the third millennium (Solari, 2019), the many strands of the wind culture, until then generally cultivated as independent subjects, have come to be organized into an autonomous and homogeneous scientific framework.

In 1961 Davenport (1961) laid the bases of this transition by giving rise to the embryo of the namesake chain (Fig. 5a) (Davenport, 1964): it linked the fundamentals of wind, aerodynamics and mechanics, giving rise to the first framework for evaluating wind actions and effects on structures; this originated four international conferences on this subject, from 1963 to 1975, outlining the stages of the first phase of the new course (Fig. 5b) (Scanlan and Tomko, 1971).

During the last of these conferences, held in London, U.K., in 1975, the community involved realised how much this view was restrictive. Hence, the will arose to establish a wider community dealing, in its entirety, with the various issues related to wind actions and effects on construction, environment and territory. This gave rise to the advent of Wind Engineering, defined by Cermak in 1975 as “the rational treatment of the interactions between wind in the atmospheric boundary layer and man and his works on the surface of earth” (Cermak, 1975). With it, the International Association for Wind Engineering (IAWE) was born (Solari, 2007), aimed at coordinating the activities of the new sector, and a series of six namesake conferences, from 1979 to 1999, outlining the stages of the second phase of the new course (Fig. 6) (Kwok and Melbourne, 1981; Hikami and Shiraishi, 1988; Miyata et al., 1995; Murakami et al., 1992; Hjelmfelt, 1988).

In the last of these conferences, held in Copenhagen, Denmark, in 1999, the awareness matured that the wind had become crucial to many areas of science and technology and the number of people working in this sector was huge. Hence, the will arose to give the IAWE a more efficient organisation, able to play a proactive role for society. The following conferences gave testimony of the third phase of the new course (Fig. 7) (Castino et al., 2003; Carassale and Solari, 2006; Burlando et al., 2007; Tanaka et al., 2012), pointing out such a broad and complex framework as to make "wind engineering" an almost reductive definition (Solari, 2019). Hence a wider viewpoint has been emerging that projects this discipline into a more general scenario well-embraced by the definition "wind science and engineering" (Mehta, 2008).

3. A state of the art

In order to gather as much documentation as possible about the actual state of education in wind engineering, the author sent to colleagues from around 100 universities worldwide the request to provide him with a synthetic information about the activities carried out in their own university on wind engineering, and on matters related to it, also indicating the start date of these activities. The sending of this request concerned a sample, however representative, of those in the world who could carry out an educational activity in this field. The response to this request has been very broad but incomplete. Hence, the impossibility of providing in this section an exhaustive picture of previous, ongoing and future initiatives, a result to which, in any case, the author never aspired. Despite these remarks, an overall picture emerged which, although incomplete and subjective, makes it possible to provide an overview of this topic. This picture does not include educational tools such as books, magazines and facilities, for which the readers are addressed, by way of example, to (Solari, 2019; Mehta, 2008; Stathopoulos and Hajra, 2013). It also excludes specific initiatives in the field of wind energy.

In light of the information collected and author's personal knowledge, education in wind engineering can be traced back to three main activities, each of which is dealt with in the following three sub-sections: individual courses (Section 3.1), coordinated programs (Section 3.2), and independent schools (Section 3.3).

3.1. Individual courses

There is a very high number of individual university courses dedicated to wind engineering or to some of its specific aspects. Depending on circumstances, they are provided at under-graduate, graduate, master and/or doctoral level, dealing with arguments associated with structural and/or environmental aspects of wind engineering. The most characteristic element that most of these courses have in common is their close link with the teacher, even more than with the place where they are taught. This is evident from the title of the course or from its content, a fact that seems to be unavoidable: wind engineering is a subject so vast that it makes almost impossible to entrust its overall teaching to a single course given by a single lecturer.

To better illustrate these statements, seemingly general courses entitled as *Wind Engineering* are (were) given at the Politecnico di Milano by Giorgio Diana, at the University of Reggio Calabria by Francesco Ricciardelli (2001–2011), at the University of Florence by Claudio Borri and Claudio Mannini (from 2004), at the University of Glasgow, at the Bauhaus University Weimar by Guido Morgenthal, at the University of Illinois at Urbana-Champaign by Frank Lombardo (from 2017), at the Texas Tech University (1999–2007) and at the Rensselaer Polytechnic Institute (from 2011) by Chris Letchford, at the Florida International University (2005) and at the University of Florida (from 2008) by Forrest Masters, at the Johns Hopkins University by Emil Simiu and Donghun Yeo, at the Universidad Tecnológica de la Habana by Patricia Martin, at the National Central University Taiwan by Chia-Ren Chu, at the National Taiwan University by Tsang-Jung Chang, at the National Kaoshiung University, Taiwan by Chern-Hwa Chen, at the National Taiwan University of Science and Technology by Rwey-Hua Cherng, at the Hong Kong Polytechnic University, at the University of Sydney by Kenny Kwok, at the University of Queensland (1987–1999, by Chris Letchford, and from 2017, by Matthew Mason), at the University of Auckland by Richard Flay (since 1987).

Several other courses are offered at universities all over the world with denominations and purposes that reflect in more detail the lecturer's background. For instance, Bert Blocken teaches *Urban Physics* and *Sports & Building Aerodynamics* at the Technical University Eindhoven and at the KU Leuven, Luca Bruno teaches *Fluid Dynamics and Computational Wind Engineering* at the Turin Polytechnic (from 2010), having co-taught previously, still in Turin Polytechnic, *Wind Engineering/Statistics of random processes*" (2004–2010), Mark Sterling teaches *Atmospheric Engineering* and *Wind loads* at the University of Birmingham, Guido Morgenthal teaches *Numerical Wind Engineering* at the Bauhaus University Weimar, Chris Letchford taught *Bluff Body Flows* at the University of Queensland (in 1979) and in Oxford University (in 1985), Ted Stathopoulos teaches *Wind Engineering and Building Aerodynamics* at the Concordia University in Montreal (from 1980), Teng Wu teaches *Wind Engineering and Turbulent Flows* at the University of Buffalo, Bowen Yan teaches *Structural Wind Engineering* at the Chongqing University (from 2018), Takashi Maruyama and Kazuyoshi Nishijima teach *Wind Resistant Structures* and *Environmental Wind Engineering* at the Department of Architecture and Architectural Engineering of Kyoto University whereas the Civil Engineering Faculty of Kyoto University offers a course on *Earthquake and Wind Resistance of Structures, and Related Structural Design Principles*, taught by Kunitomo Sugiura, Yoshikazu Takahashi, Tomomi Yagi, Sumio Sawada and Kyohei Noguchi. Akashi Mochida teaches *Environmental Wind Engineering* at the Tohoku University.

There are also several courses of general character that dedicate more or less extensive cycles of lectures to wind engineering topics. This happens in the absence of specific wind engineering courses or to disseminate the fundamentals of this matter to a larger number of students. By way of example, the University of Auckland provides some lectures on wind engineering in a course called *Aerohydrodynamics* and in a course on *Civil Engineering Design*. John Macdonald provides lectures on wind engineering at the University of Bristol, during the courses on *Structural Dynamics*, *Earthquake Engineering and Infrastructural Resilience* and *Hazards and Infrastructure*; some wind engineering lectures are also delivered during the course on *Aerodynamics* at the Department of Aerospace Engineering. The Technical University of Civil Engineering in Bucharest provides wind engineering lectures inside the courses on *Structural Dynamics* from the early 1970s. Several lectures on the fundamental aspects of wind engineering are given by Yasushi Uematsu and his colleagues at the Department of Civil Engineering and Architecture of the Tohoku University. In India wind engineering is embedded into more general courses such as those devoted to bridges or tall buildings. The Civil Engineering Faculty of the Kyoto University offers a course on *Bridge Engineering*, taught by Kunitomo Sugiura, Tomomi Yagi, Yasuo Kitane and Kyohei Noguchi, containing lectures on wind engineering.

Finally, there are numerous courses, mostly short ones, offered by universities to other institutions such as professional associations; for example, the author has recently organized a course on *Wind Engineering* at the Institution of Chartered Engineers of the province of Genova. There are cases of centres with longstanding tradition in wind engineering that offer courses to universities where such courses are not delivered; for example, the CSTB of Nantes provides periodic courses in several French universities focused, depending on requests and hosting institutions, on structural or environmental issues. There are also courses held in the context of more extensive initiatives; for instance, in 2013 a training course on *Experimental Modeling of Wind Actions on Offshore Structures* was offered at the University of Florence within the European project Marinet-FP7-INFRA-2010; in 2018, the same university held a course on *Experimental Modeling of Wind Actions and Structural Response* in the framework of the European project Marinet 2.

(a) (b)

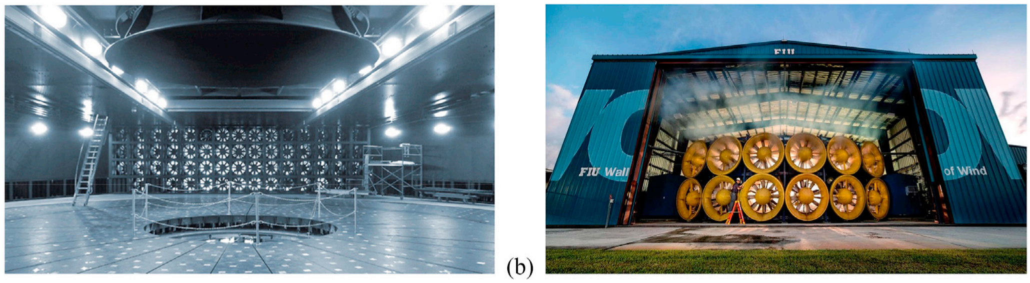

Fig. 8. Large scale laboratories: (a) WindEEE Dome at the University of Western Ontario; (b) Wall of the Wind at the Florida International University.

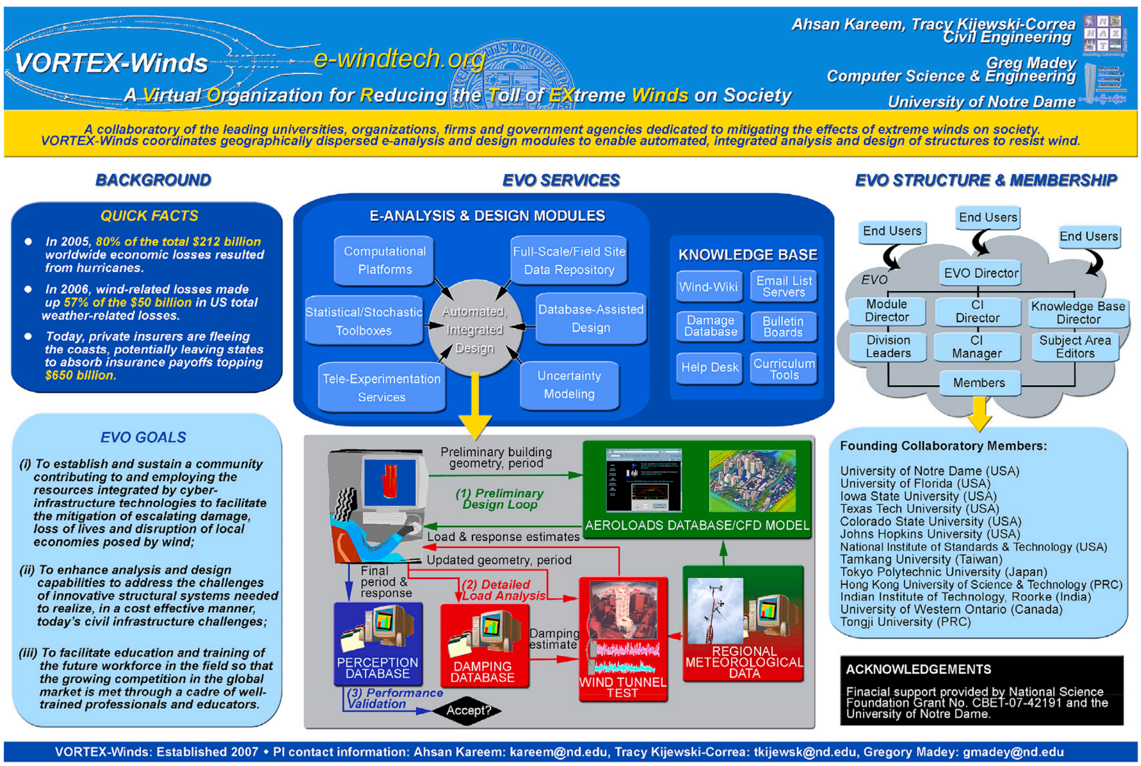

Fig. 9. Vortex-WINDS, University of Notre Dame.

3.2. Coordinated programs

At present there is a limited but significant number of universities, generally with a longstanding tradition in wind engineering, where curricular courses dedicated to this discipline are developed. They are clearly marked by the local situation, tradition and territorial fabric in which these are carried out. Instead, they usually transcend the figure and the presence of the single lecturer, who is a contributor, however essential, to a wider, articulated and coordinated educational system. Very often they are associated to the local presence of large scale laboratories and facilities.

Just to cite some well-renown realities in this framework, the University of Western Ontario (Fig. 8a) provides one undergraduate course on *Wind Engineering: Modeling, Assessment and Mitigation* and eight graduate courses on *Wind Engineering*, *Computational Wind Engineering*, *Sustainable Building Design*, *Wind Effects on Building Components and Cladding*, *Wind Energy*, *Boundary Layer Meteorology*, *Bluff-Body Aerodynamics*, and *Wind-Excited and Aeroelastic Response of Structures*. In their whole, they are taught by Horia Hangan, Greg Kopp, Craig Miller, Girma Bitsuamlak and the author. In addition, Craig Miller, Ashraf El Damatty and Han-Ping Hong provide various courses on *Structural Dynamics* and *Random Processes*.

The Florida International University (Fig. 8b) organizes several educational activities about wind engineering under the Natural Hazard Engineering Resaerch Infrastructure(NHERI) Wall of the Wind (WOW) Experimental Facility (EF), with a special focus on hurricanes and wind damage mitigation. In this framework, courses on *Hurricane Engineering for Global Sustainability*, *Topics in Wind Engineering* and *Wind Effects on Structures* are delivered.

Extensive educational activities have been carried out at the Tokyo Polytechnic University Wind Engineering Research Center (WERC) from 2000 (Tamura, 2013). In 2003, it initiated the 21st Century Center Of Excellence (COE) Program on *Wind Effects on Buildings and Urban Environment*. It was followed, in 2008, by the Global Center Of Excellence (GCOE) Program on *New Frontier of Education and Research in Wind Engineering*. Through these programs, both directed by Yukio Tamura, an impressive effort was carried out to integrate activities in *Wind Resistant Design*, *Natural/Cross-Ventilation* and *Wind Environment/Air Pollution* as well as to implement, in co-operation with the University of Notre Dame, a Cyber-Based Data-Enabled Virtual Organization for Wind Load Effects on Civil Infrastructures (VORTEX-Winds) (Fig. 9) (Kareem and Kwon, 2017). In 2010, the name "School of Architecture, Tokyo Polytechnic University" was changed as "School of Architecture & Wind Engineering, Tokyo Polytechnic University": this was the first time the word "Wind

Fig. 10. Ph.D. program in Wind Science & Engineering, Texas Tech University.

Engineering" appeared in the name of a graduate school. In this framework, International Advanced Schools (IAS), intensive courses and open seminars were provided by several guest professors and offered to various level students. In 2013, the WERC was selected for the Joint Usage/Research Center (JURC) Program that currently involves a master course in *Wind Engineering* in Japanese and a Ph.D. course in *Wind Engineering* in English language. Both these courses involve two curricula, one in *Structural Engineering* and the other in *Environmental Engineering*.

The Texas Tech University opened a doctoral program curriculum on Wind Science and Engineering since 2006, under the chairmanship of Kishor Mehta (2008) (Fig. 10). The goal of this pioneering program is to develop individuals with an appreciation of, and the ability to execute and lead multidisciplinary wind-related analysis, design and risk management assessment including the mitigation of damage caused by extreme winds caused by hurricanes and tornadoes, the reduction of vibrations in tall buildings and long bridges, and the use of beneficial wind effects such as energy production and pollution dispersion. The curriculum includes six compulsory core courses (*Wind Science*, *Wind Engineering*, *Risk Management/Economics*, *Statistics*, *Time-Series Stochastic Processes*, and *Leadership/Ethics*), five additional courses selected by students (for instance *Atmospheric Measurements*, *Severe Storms*, *Wind Engineering Measurements*, *Wind Energy Systems*, *WindStorm Damage Analysis*), and an external internship.

The University of Genova offers a program of linked courses including, at the undergraduate level, *Probabilistic Methods in Civil Engineering*, and, at the graduate level, *Structural Dynamics I* and *II*, *Atmospheric Physics* and *Wind Engineering*; they are taught by the author, Giuseppe Piccardo, Federica Tubino and Massimiliano Burlando. Taking inspiration from Texas Tech, in 2018, the University of Genova also opened a doctoral curriculum in *Wind Science and Engineering*, which offers Ph.D. students, every year, a wide selection of courses provided by local lectures – for instance on *Thunderstorms*, *Wind-Induced Fatigue* and *Wind Tunnel Tests*, taught by author, Maria Pia Repetto and Andrea Freda, respectively – and by invited external lecturers – for instance *Bluff-Body Aerodynamics*, *Novel Developments in Wind Engineering* and *Probabilistic and Non-Probabilistic Methods for Evaluating Structural Safety*, taught by Guido Buresti, Horia Hangan and Giuseppe Muscolino, respectively.

Several universities in Taiwan provide articulated programs in wind engineering. Among these, the Tamkang University offers an undergraduate course on *Introduction to Wind Engineering* and three graduate courses on *Building Wind Engineering*, *Wind Resistant Analysis of Bridges* and *Computational Wind Engineering*, taught by Jenmu Wang, Cheng-Hsin Chang, Chung-Lin Fu and Yuan-Lung Lo; in addition, a *Wind Engineering Exhibition* and a *Summer Camp of Wind Engineering* for undergraduate students are organized every year. The National Chung-Hsing University offers three graduate courses on *Advanced Introduction of Wind Engineering*, *Studies in Prevention of Coastal Area Wind Damage* and *Special Topics in Wind Engineering* taught by Huh-Ming Fang and Long-Ming Huang. The National Taiwan Ocean University offers four graduate courses on *Wind Engineering*, *Turbulence in the Wind*, *Practice of Selected Wind Engineering Topics Study in Wind Tunnel*, and *Introduction to Theory and Applications in Wind Engineering*, taught by Bao-Shi Shiau and Yuan-Lung Lo.

Finally, it is worth mentioning the case of some university institutions that do not offer a specific wind engineering curriculum, but provide students with a broad spectrum of courses that cover, in their whole, the main topics of the discipline. The example of the University of Notre Dame is emblematic. Here, flexible programs are available with a focus on natural hazards including earthquake, wind and waves. In this framework, students can follow courses on *Advanced Fluid Dynamics*, *Fundamentals of Turbulence Theory*, *Turbulence*, *Atmospheric Modeling and Data*, *Environmental Fluid Dynamics*, *Experimental Methods in Structural Dynamics*, *Advanced Topics in Wind Effects on Structures*, *Wind Engineering*, *Applied Computational Probability: Uncertainty Quantification and Propagation*, *Topics in Advanced Structural Dynamics: Modeling, Simulation, and Random Vibration*, *Advanced Topics in Aerodynamics and Structural Dynamics*, *Structural Dynamics*, *Experimental Methods in Fluids*, *Digital Signal Processing and Analysis*, *Statistical Computing Methods for Scientists and Engineers*, *Bayesian Methods for Surrogate Modeling and Dimensionality Reduction*, and *CFD*. Several other courses in Mechanical and Aero-Engineering, Electrical and Computer Science, as well as in Applied Mathematics departments are relevant and available. Based on this system of lecturing the Natural Hazards (NatHaz) Laboratory led by Ahsan Kareem has produced in the course of the years a huge number of master graduates and research doctors.

(a) (b)

Fig. 11. International Advanced School at: (a) Tokyo, Japan (2008); (b) Myanmar, Burma (2011).

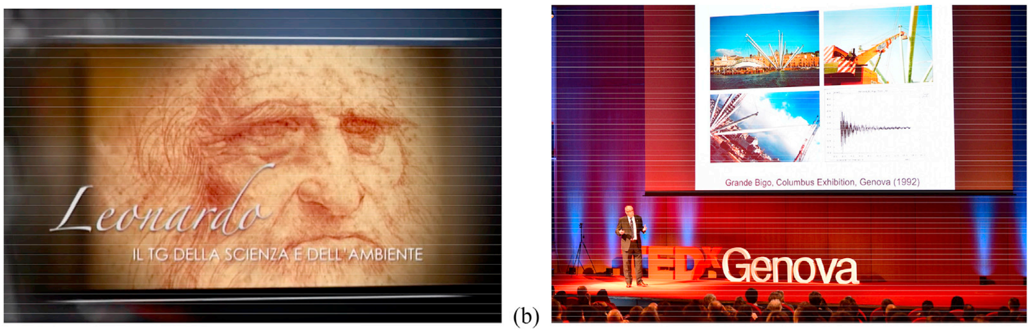

Fig. 12. (a) The Sir of Wind and Thunderstorms, TG Leonardo broadcasting, 24 May 2018; (b) the Wind Engineer, TEDxGenova, February 23, 2019.

3.3. Independent schools

Over the years, several schools have been organized, not necessarily linked to specific universities, which have transmitted the knowledge of wind engineering to entire generations of scholars and practitioners through general or specific teachings, with more or less periodic deadlines, in more or less fixed locations.

Among these schools, the author is particularly attached to the memory of the International Advanced School (IAS) on *Wind-Excited and Aeroeolastic Vibrations of Structures*, which he organized and chaired in Genova, in 2000, sharing the lecturing role with Guido Buresti, Ahsan Kareem, Masaru Matsumoto and Tetsuro Tamura. Re-reading today the list of the 71 students that came to Genova from all over Italy and the world is staggering: it included a long series of actual professors and engineers, at the maximum international level, that still focus their activity in wind engineering.

In the same spirit, Yukio Tamura has organized an impressive series of itinerant Advanced Schools on *Wind Engineering* over all the Far East. Initially, they have been carried out under the COE umbrella (2006–2007), then they were labeled as International (IAS, from 2007) and mostly developed under the GCOE umbrella (Fig. 11) (Tamura and Kareem, 2013). The last of these schools, IAS 17, has been held in Beijing just in correspondence of the 15 ICWE. Thanks also to a team of highly qualified lecturers from various countries, as a whole they have marked the initiation, training and advancement of legions of scholars in the wind engineering field.

Two courses organized in Udine by the International Center for Mechanical Sciences (CISM) also deserve a mention: *Wind-Excited Vibrations of Structures* (Sockel, 1994), in 1992, coordinated by Helmut Sockel, and *Wind Effects on Buildings and Design of Wind-Sensitive Structures* (Stathopoulos and Baniotopoulos, 2007), in 2006, coordinated by Ted Stathopoulos and Charalambos Baniotopoulos.

Equally noteworthy is the series of the Urban Physics Autumn Schools organized, from 2011, nearly every year, by the Eindhoven University of Technology in collaboration with the Swiss Federal Institute of Technology in Zurich and the University of Cyprus. They are designed especially for doctoral students and post-doctoral researchers, and intend to provide state-of-the-art knowledge in Urban Physics, focused on its multi-scale, multi-disciplinary and multi-phase character, including computational modeling, wind-tunnel testing and field experiments.

The Author is organizing an International Advanced School on Thunderstorm Outflows and their Impact on Structures, to be held in Genova in 2020, in the framework of the ERC Project THUNDERR (Solari et al., 2020).

4. A prospective viewpoint

Thinking about the perspectives of education in wind science and engineering, with special regard to coordinated programs, the author cannot avoid referring to the second level master course in *Wind Engineering* jointly organized by the Politecnico di Milano and the University of Genova, in the academic year 2003/2004, under the leadership of Giorgio Diana and the author himself. The course was structured according to three 4-month training periods. The first period established the fundamentals of the whole discipline through three compulsory courses – *Introduction to Wind Engineering*, *Atmospheric Physics*, and *Fluid Dynamics* – plus two courses chosen by students among four: *Structural Dynamics, Vibration and Control*, *Measurements*, *Structural Modelling*, and *Probability, Statistics and Simulation*. The second period was divided into two pathways concerning respectively *Structural Wind Engineering* and *Environmental Wind Engineering*. The students were free to shape their training in a flexible way, by choosing four courses among seven: *Aeroelasticity of Structures*, *Environmental Wind Actions*, *Wind Actions and Effects on Structures*, *Wind Energy*, *CFD*, *Wind Modelling and Climatology*, *Experimentations*. The third part of the course included the choice between a thesis and an internship. The course was successful and attracted a lot of candidates for a limited number of 25 fully funded scholarships. All the students who attended the course and obtained the second level master degree still work in public and private institutions, where they put to service what they learned on wind engineering. Despite this, the course lasted only one year and was not repeated due to the huge burden that fell on two very large and organized research groups, but nevertheless insufficient to support such a demanding impact, especially if added to the usual teaching activity of the various lecturers.

The principle of the educational offer, however, remains. It translates, at least at the conceptual level, most of what has been discussed in this paper, namely: 1) the delivery of a very general course aiming to provide a homogeneous know-how including a broad vision of the origins, developments, fundamentals, advancements and prospects of wind science and engineering; 2) the creation of a solid and unitary background in the basic disciplines, namely atmospheric sciences, fluid mechanics, bluff-body aerodynamics, structural mechanics, probability and statistics, hazard, vulnerability and risk, computational tools, and so on, completing the preparation of students in those matters in which they are weaker; 3) the offer of a specialized but flexible training about the two major subjects of structural and environmental wind engineering, leaving the students free to compose a personalized curricular pathway; and, 4) a targeted finalization to research, through a thesis, or to the insertion in the world of work, through an internship.

This commitment, which was in fact unmanageable by one or two universities, no matter how specialized and equipped they are in the field, is today probably conceivable as carried out in a different perspective, capable of exploiting the technological evolution and the potential of communication and dissemination systems.

In this context, it could be interesting to organize an educational system that, by involving the best international experts in the discipline, or even its specific aspects, can use remote educational tools implemented on a common international syllabus, as suggested by Mark Sterling, and based on Massive Open Online Courses (MOOC) of the type adopted, for instance, by Bert Blocken. The master and doctoral theses could be developed through co-tutoring agreements aimed at offering the new graduates degrees awarded by two or more universities. This approach could also open the door to reaching those scholars and engineers who need to establish and consolidate this culture, but do not have the opportunity to experience the multiple initiatives actuated in the discipline.

Beyond this vision, the author maintains it is essential to spread the knowledge of wind and its multiple phenomena towards a community not restricted to academics and practitioners working in this sector, but to open this culture to a wider public, bringing it into everyday life and society (Fig. 12).

The author hopes this paper may stimulate a wide discussion at it may give rise to remarks and proposals such as to correct, complete and improve this contribution, making its content perhaps transferable to a platform managed by the International Association for Wind Engineering through its Web page.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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