1 Introduction

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1.1 SUMMARY

This Introduction aims to give an overall outline on the contents and main outcomes of the WINDERFUL project (acronym for "Wind and INfrastructures: Dominating Eolian Risk For Utilities and Lifelines"), run from Nov. 2001 until Nov. 2003 amongst the Research Projects of National Interest (PRIN) of the Italian Ministry of Education, University and Research (MIUR). To properly introduce the reader into the project, Sect. 1.2 will first describe the overall objectives and project structure, with the allocation of tasks amongst the different research teams, based upon the available resources; the organization and project management will be dealt with, which will be followed by a last Sect. devoted to national and international links with other similar activities. Sect. 1.3 introduces an overview on the main activities and results, with some transversal information about the structure of the final report and synthesis reports from the teams; it will also present an overall outline of the following Chapters of this final report/book of the project. Sections 1.4 & 1.5 will shortly introduce the dissemination activities and performances, including some future perspectives through follow-up projects.

1.2 PROJECT STRUCTURE AND DESCRIPTION

1.2.1 Project summary

In a country that is still considered a region with "well behaving climate", atmospheric wind and its effects on utilities & infrastructures are not yet considered as a priority hazard. As a matter of fact, according to the insurers' total claims from natural disaster, windstorms are by far 1st with about 70% of the claims, while earthquakes account for about 18%, flood 6% and other 6% relates to forest fire and volcanic eruptions.

In the recent past, two previous national research Projects (PRIN) have already focused on: a) establishment of research facilities and laboratories and definition of analysis tasks (RESACIV, 1997-99; 6 research teams) and b) the evaluation of eolian risk and the measures for its control and investigation (ACME CUE, 1999-2001; 10 research teams).

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The WINDERFUL project has mainly focused the target of avoiding “major fatalities” occurring to engineering facilities and main infrastructures: i.e. to guarantee quality of life and of the society after & during a major natural phenomena, like a heavy windstorm. This was the declared target in the application proposal, very well in line with a keyword of the 6th Framework Programme of the EU (quality of life and sustainable development), whose concepts were in preparation and discussion at that time (summer 1999). To focus more suitably the aim of the present proposal, one could shortly synthesize like following: “To keep a city running and ensuring quality services during & after a major windstorms”.

WINDERFUL has developed along two main lines: L 1, i.e. evidencing the “wind vulnerable” networks of infrastructures & facilities, whose reduced (or annulled) service ability would induce temporary or permanent failures in the entire network, and L 2: producing a kind of “white book” on the reliability/vulnerability of networks and complex systems to wind effects, containing useful & synthetic criteria for a “good practice”. In addition to these main two lines, WINDERFUL has interacted also with other activities in the field of environmental engineering (which is part of a research project on the study of pollutants dispersion on complex terrains), in order to ensure the interdisciplinary character of the concerned field (across the disciplines of structural engineering, fluid dynamics, physics of the atmosphere, networks & complex systems, etc.). As a matter of fact, WINDERFUL reflects only a part of a wide range of activities carried out by partners involved and focuses on the purely “structural engineering & quality of life” aspects, while the above mentioned research project mainly deals with “environmental and sustainability” aspects.

The project has been carried out, partly, as the Italian contribution to the wide COST[1] C14 Action in the domain “Urban Civil Engineering” on “Impact of wind and storms on city life and built environment”, grouping 16 European countries and chaired by the same coordinating Institution as the WINDERFUL one. As, notably, COST finances exclusively the coordination & the dissemination costs, it is important that nationally funded projects guarantee the continuity of the research activity. This has revealed as a good synergy effect and follows the principle of subsidiarity in research amongst the EU and the other associated countries.

1.2.2 Research objectives

Damages induced by windstorms have been very severe in the last years, so that both local Authorities as well as financial and economic operators have had to face with huge costs. The increase of losses caused by windstorms can be only partially ascribed to climatological aspects (changes in environmental climatology), but it can be due to increasing complexity and vulnerability of buildings and structures which have been built in the last years; more specifically, one of the most vulnerable structural category is represented by those necessary for the correct functioning of infra-structural lines (life-lines) such as roads, highways, airport sites, electricity and transmission lines, and so on.

The major part of losses is often due to elements directly related to life-lines, such as components of electrical power-plants (cooling towers, pylons, chimneys), components of transmission lines (towers and cables), and components of road and highway lines (mainly bridges). But it is to be remarked that the huge level of costs is mainly due to “indirect” costs, such as those deriving from temporary stops on life-lines functionality (such as black-outs induced by a collapse of some branches of electrical lines). Eight severe windstorms hit at least 10 different European Countries only in 1990. In December 1999 the two windstorms Lothar and Martin hit South-West Europe, from Denmark to France, causing more than one hundred victims and estimated losses of about 14 Billion Euros. Moreover, extended black-outs have been experienced in several big cities. It is

[1] European Cooperation in the field of Scientific and Technical Research programme

then evident the growing interest in the field of "eolian risk" showed by economists and researchers; the research is then not only addressed to assess wind effects on structures, but mainly to investigate real effects on the city life and on the whole built environment.

Among other research programmes, the recently established European COST Action C14 (entitled "Impact of wind and storms on city life and built environment", Sept. 2000 - May 2004) has to be recalled here; the action has been promoted (and it is at present chaired) by the proposer of this project and, till today, 13 different European Countries joined it, offering the support of several different researchers. The main objective of the COST Action is the investigation of new techniques and planning activities aimed to mitigate wind effects during severe windstorms, in order to ensure a correct working of the built environment. The WINDERFUL project was thought as inserted within this general framework. According to the above sketched research lines, the research project developed on two different scales: the first scale is related to the evaluation of the eolian risk connected to the "direct" damaging of elements being part of life-lines; the second scale has considered the influence that the damaging or the collapse of a certain component can have on a complex network, such as the life-lines system of a city (so analyzing the reliability of the whole system under severe windstorm conditions). From the viewpoint of the correct working of a complex life-lines system, not only the collapse of one component can lead to some stops, but also other circumstances could lead to serious effects: as an example, severe wind induced oscillations could lead a suspended bridge to be closed to traffic, as well as strong winds could lead to excessive oscillations in cables of electrical lines so that the power-supply must be stopped. Accordingly to these considerations, the project has split into two parts:

1. *singling out of all the life-lines connected to urban environment* and, within these, characterization of wind-sensitive elements, which, due to a reduced functionality, can lead to reductions as well as temporary (or final) stops of supply of some services (transport, electricity, etc.);
2. *evaluation of results from several wind researches from the viewpoint of the estimation of the risk* and reliability of life-lines and other complex systems.

The final objective of WINDERFUL is intended as the assessment of the "eolian risk" with a specific reference to life-lines, by analyzing both single components as well as the system as a whole.

The strong interdisciplinary approach of the project, involving network management experts and experts in several other research fields (fluid-dynamics, atmospheric physics, structural engineering), is very innovative for the field concerned. Among all aspects analyzed within the research activity, those which are more specifically connected with structural aspects have been taken into account, so aiming at two different objectives: 1. definition of "eolian risk" for specific structural elements from both the ultimate limit state (collapse) and the serviceability limit state (large oscillations), evaluating their instability thresholds; for some of these elements, an investigation on monitoring and mitigating devices (by using active, passive and semi-active control systems) has been performed, in order to evaluate a possible increase in the performances of such elements under strong wind loading; 2. evaluation of the vulnerability of certain life-lines as a function of the vulnerability of single components, in order to assess the whole "eolian risk" for a built environment on for the quality of city lifes.

1.2.3 Project structure, research teams & allocation of tasks

The project WINDERFUL has dealt with definition and reduction of "eolian risk", with a specific reference to life-lines, i.e. lines for transport and supply serving a built environment. Each single component of life-lines has been analyzed, relating its performances in networking with those of the other elements of the whole life-lines system.

Both theoretical and experimental methods are used to analyze the problems related with the research programme. Main research topics can be assembled into two different themes:

1. *vulnerability evaluation of some specific component of life-lines* under severe wind loading conditions. Specific reference has been intended to structural elements and components which are part of a life-line (as described in the following) and to elements which constitutes the so called “street architecture” (such as bill-boards, traffic signs and traffic lights, lighting poles, news-stands, bus stop shelters), which often suffer huge damage from windstorms;

2. *vulnerability evaluation of the whole life-lines system* under severe wind loading conditions. The research results have contributed to ensure the possibility of the correct working of these systems even during and after windstorms, especially for those of primary relevance with respect to the life of cities and built environments.

Experimental tests will be mainly carried out at Boundary Layer Wind Tunnel located in Prato, managed by CRIACIV (Inter-University Research Centre on Building Aerodynamics and Wind Engineering), i.e. the co-ordination Unit of the present project. Within these two research themes several sub-themes were singled out and allocated to the 10 research teams (Units) participating into the project, namely

Unit #1: Univ. of Roma “La Sapienza”, Dipartimento di Ingegneria Strutturale e Geotecnica (Coord.: Prof. G. Augusti)

Unit #2: Univ. of Firenze, CRIACIV, c/o Dipartimento di Ingegneria Civile (Coord.: Prof. C. Borri, Project Coordinator)

Unit #3: Univ. “Mediterranea” of Reggio Calabria, Dipartimento di Meccanica e Materiali (Coord.: Prof. F. Ricciardelli/Ing. E. D’Amore)

Unit #4: Univ. of Chieti-Pescara “G. D’Annunzio”, Dipartimento di Progettazione, Riabilitazione e Controllo delle Strutture Architettoniche (Coord.: Prof. P. D’Asdia)

Unit #5: Univ. of Perugia, Dipartimento di Ingegneria Civile ed Ambientale (Coord.: Prof. V. Gusella)

Unit #6: Univ. of Bologna, Dipartimento di Ingegneria delle Strutture, Trasporti, Acque, Rilevamento del Territorio (Coord.: Prof. M Majowiecki/ G. Matildi)

Unit #7: Univ. of Trieste, Dipartimento di Ingegneria Civile (Coord.: Prof. S. Noè)

Unit #8: Univ. of Firenze DET, Dipartimento di Elettronica e Telecomunicazioni (Coord.: Ing. M. Pieraccini)

Unit #9: Univ. of Napoli “Federico II”, Dipartimento di Analisi e Progettazione Strutturale (Coord.: Prof. G. Serino)

Unit #10: Univ. of Firenze DIC, Dipartimento di Ingegneria Civile (Coord.: Prof. P. Spinelli)

In the following, each one of the research themes is listed, together with all Units involved on the specific topic.

Theme 1 – Reliability of specific structural life-lines elements under severe wind conditions

1.1 – *Vertical structures*

Theme 1.1 groups all the structural elements which are parts of lifelines and that, for their particular conformation, result as highly sensitive to wind actions. These can be elements directly belonging to life-lines (such as bridge pylons, electricity lines pylons) or located into important plants or systems (such as chimneys and cooling towers in power plants, airport control towers). Within all the vertical elements belonging to life-lines, three different typologies have been singled out: chimneys (vertical slender cylindrical elements), cooling towers and antennas (mainly broadcasting ones).

The study of chimneys (which will be performed by the Units of Trieste, Chieti-Pescara and CRIACIV) is focused to the evaluation of actions which, in the lock-in range, can arise due to alternate vortex shedding. The analysis covers both theoretical aspects (tuning of the numerical model worked out by the Unit of Trieste), experimental "full-scale" tests (monitoring of the oscillations of the chimney of the new waste treatment plant: the new measurement system set-up by the Firenze-DET Unit within this project could be employed together with the GPS system already in use) and experimental wind tunnel tests (performed by the Units of Trieste and CRIACIV).

Natural draft cooling towers represent systems whose shape and thickness make them very sensible to wind actions. The study, performed by the Units of Firenze-DIC and CRIACIV, consists in experimental studies and numerical studies, these latter performed both in a linear-elastic range and in a non-linear one, leading, f.e., to define reliable "design loads" for these structures, as well as to estimate the actual vulnerability and safety level under different severe load conditions.

As last point included in Theme 1.1, the study of vertical antennas has been performed by the unit Perugia. A full-scale experimental antenna (built some years ago) will be used as specimen to be tested: full-scale measurements and numerical simulation will be performed in order to assess a reliable active or passive control system, in order to minimize the wind response of these structural elements. Radar techniques set up by the Unit Firenze-DET were usefully employed during the experimental tests.

1.2 – *Horizontal & sub-horizontal structures*

Within the framework of WINDERFUL project, the behaviour of some horizontal structures that are part of lifelines (such as viaducts or suspended and stayed bridges) were investigated. The research aimed to deepen the study of their safety, mainly on the side of the aerodynamic stability; the study took into account the control and mitigation of their oscillations under strong winds. The research involved four different Units with the aim of: 1) defining the "structure" of aeroelastic and aerodynamic forces acting on the deck sections of large suspended bridges, by wind tunnel model tests (Units of Reggio Calabria and CRIACIV); 2) improving the available numerical tools to predict the structural response of large bridges under severe wind conditions (Units of Roma "La Sapienza" and Chieti-Pescara); 3) evaluating the efficiency of some possible upgrading measures aimed to reduce the oscillatory regime during the life of the structure (Units of Roma "La Sapienza", Chieti-Pescara and Reggio Calabria).

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1.3 – Suspended structural elements (cables and stays)

The structural elements within this research theme are of particular importance: either they directly constitute parts of life-lines (transmission of and electrical lines) or they to have to carry other main structures composing life-lines (such as bridge hangers or stays). These structural elements were studied with the aim of controlling and mitigating their possible oscillations under strong winds as well as with the aim of evaluating their safety level against aeroelastic instability. In details, following research themes were addressed: 1) data collecting and set-up of a data-base about the whole Italian high and medium voltage electric network aimed to a further eolian risk analysis (Unit at Napoli); 2) experimental and numerical analysis of some actual cable configurations with respect to vortex shedding and galloping instability (units of Bologna and CRIACIV); 3) experimental and numerical analysis aimed to single out the most suitable protection devices and to define suitable design strategies (units of Bologna and Napoli).

1.4 – "Street architecture" elements

This research theme groups a series of "secondary" elements that normally result as the most suffering when severe windstorms hit built environments. Reference are made to a series of elements (such as bill-boards, traffic signs and traffic lights, lighting poles, news-stands, bus stop shelters) which are often seriously damaged by winds (then leading to high economic losses) but they are seldom studied and investigated.

In this research Theme, the Units Reggio Calabria and Roma "La Sapienza" have dealt with following problems: 1) the characterization of wind fields in the lower atmospheric layer (i.e. the one closest to the ground), which is often completely different with respect to the one adopted in usual structural calculations; 2) the aerodynamic characterization of the most usual elements; 3) the assessment of suitable techniques aimed to define their structural response; 4) the definition of some guidelines and interventions intended to mitigate wind effects on them.

The field of "street architecture" also includes some aspects dealt with by the Unit at Univ. of Bologna, aimed to reduce the risk connected to the joint action of several atmospheric events. The snow-wind interaction has been object of a series of theoretical studies performed in the framework of a previous research program. These results were integrated by wind-tunnel experimental tests on either some typical roofing elements and some simple reference cases. This part of the research programme, which is often completely neglected when dealing with wind engineering studies, has contributed to a more accurate definition of design criteria for the investigated structural elements.

Theme 2 – Reliability of life-lines under severe wind conditions

The topic addressed by the second research Theme was related to the observation that most of the losses caused by windstorms are not only represented by "direct" costs (i.e. due to failures or collapses of structures, structural elements and buildings) but mainly by "indirect" costs (i.e. due to stops or breakdowns of some essential life-lines). As an example, reference can be made to all the induced damages caused by black-outs, by the poor performances of transmission lines, by the interruption of roadways, highways and railways.

In the second part, the project developed tools and proper procedures to enable the maintaining of a correct working level of life-lines even during and after the windstorm event. The research has analysed the vulnerability of several life-lines (transport, electrical lines, communication networks), taking into consideration the interaction between different networks. Starting from well-assessed procedures developed by the researchers of the Unit at Roma “La Sapienza” in the field of the evaluation of network performances under seismic events, the research aimed to develope the most suitable preventive upgrading operations on vulnerable components of the network, in order to increase their performances according to some “objective functions”.

More specifically, following aspects were taken into account: the reliability of the network system (probability that the connections between a source node and a destination node will remain still active under a wind storm of given intensity); the expected value of the out-of-service time of the network determined by the occurrence of a windstorm; the expected value of the flow (i.e., the electrical power) between the source and the destination nodes in the emergency period that follows the storm. Analyses performed within the above mentioned research Theme 1. were used to give information on the vulnerability of each single component of the life-line, in order to obtain a correct estimation of the reliability level of the whole network.

Moreover, some data-base information on life-lines (such as the one that will be developed by the Unit of Napoli on the whole Italian high and medium voltage electric network) allowed to analyze the “eolian risk” in some particular Italian situations.

Summarizing, following allocation of tasks has been set amongst the project partners:

Theme 1. Reliability of specific structural life-lines elements under severe wind conditions

Theme 1.1: vertical structures. Units involved in the project: CRIACIV, Chieti-Pescara, Perugia, Trieste, FI-DET, FI-DIC

Theme 1.2: horizontal structures. Units involved in the project: CRIACIV, Chieti-Pescara, Roma “LS”, Reggio Calabria

Theme 1.3: suspended structural elements (cables and stays). Units involved in the project: CRIACIV, Napoli, Bologna

Theme 1.4: “street architecture” elements. Units involved in the project: CRIACIV, Chieti-Pescara, Roma “LS”, Bologna

Theme 2. Reliability of life-lines under severe wind conditions

Units involved in the project: Roma “LS”, Napoli, FI-DIC

(List of abbreviations: Roma “LS”: Roma “La Sapienza”, FI-DIC: Firenze, Dipartimento di Ingegneria Civile, FI-DET: Firenze, Dipartimento di Elettronica e Telecomunicazioni)

1.2.4 National & International activities & participation

As already mentioned before, the WINDERFUL project has been carried out, partly, as the Italian contribution to the wide COST[2] C14 Action in the domain “Urban Civil Engineering” on “Impact of wind and storms on city life and built environment”, grouping 16 European countries and chaired by the same coordinating Institution as the WINDERFUL one. The project has also acted as potential “Center of Excellence” in the field of “Risk Management”, being involved in the higher post-graduate education, amongst others, within:

[2] European Cooperation in the field of Scientific and Technical Research programme

- the International Doctoral Course on "Risk Management in the built Environment" and Graduiertenkolleg 802 of the DFG, between the Univ. di Firenze and the TU "Carolo Wilhelemina" Braunschweig (Germany);
- within a Master course in "Emergency Engineering", Univ. di Roma "La Sapienza" especially on eolian risk and its reduction.

The project participants have been actively participating in all main scientific events (conference, workshops, etc.) in Europe and world-wide. It is worth to mention here the participation at the 11th International Conference on Wind Engineering, Lubbock, Texas, June 2003; 3rd East European Conference on Wind Engineering, Kiev, Ukraine, May 2002; 3rd World Conf. on Structural Control, Como, Italy, April 2002; 7th Convegno Nazionale di Ingegneria del Vento IN-VENTO-2002, Milan, September 2002; 16th Congress of Associazione Italiana di Meccanica Teorica e Applicata AIMETA'03, Ferrara, Italy, September 2003; 5th European Conference on Structural Dynamics Eurodyn 2002, Munich, Germany, September 2002; **"**Alan G. Davenport" Wind Engineering Symposium, London, Canada, June 2002; Final Conference of COST Action C14 "Urban Wind Engineering & Building Aerodynamics", Von Karmán Institute, Belgium, May 2004; 12th European Conference on Earthquake Engineering, London, U.K., September 2002; 2nd International Conference on Structural and Construction Engineering ISEC-02, Rome, Italy, September 2003; 5th International Symposium on Cable Dynamics, Santa Margherita Ligure, Italy, September 2003.

At the next IN-VENTO-04 (8th Italian Conference on Wind Engineering, Reggio Calabria, June 2004), a special session devoted to the dissemination of the results of WINDERFUL project is also scheduled.

1.3 ACTIVITIES AND RESULTS

1.3.1 The final report: outline

WINDERFUL, i.e. "Wind and INfrastructures: Dominating Eolian Risk For Utilities and Lifelines": one can surely state that the assigned topic has been well pursued and the main targets have been totally matched. The description of the research activity and general results are presented in the following together with the major contributions of the teams/Units involved. At a very overall level it can be said that the project was fully satisfactory, from both points of view: the cooperation amongst the different Units and the realization of a common objective.

It is evident, in fact, that the synergy effect created by sharing the resources of a common laboratory of excellence makes impossible to waste energies and efforts amongst the research groups. On the contrary, all contributions actually converge to the same target.

The WINDERFUL project had a wide resonance, both nationally as well as internationally: entire sessions within scientific conferences and workshops (IN-VENTO-2002, Milan; IN-VENTO-2004, Reggio Calabria; 11th ICWE, Lubbock; 3rd EACWE, Eindhoven; Workshop of COST Action C14 in "Urban Civil Engineering", Nantes) have reported on progresses and advances in the research activities, achieved by the project teams. Future activities within 6th European Framework Programme of RTD, like ERA-NET (Network of project nationally funded) are still in progress at the present.

To summarize the results, some overall figures appear very significant and give a precise dimension of the workload carried out: about 600 man $\times$ months is the global involvement of human resources entirely devoted to the project, which produced some 25 scientific papers published in international journals, 40 presentations at international and national conferences, about 90 participations to workshops and congresses and 10 other products.

1.3.2 Reports by the research Units

The research program of the **Unit #1 (at Roma "La Sapienza")** has been devoted to the assessment of reliability of large structures (in particular long span bridges) and elements of "street architecture" under the action of wind loads. The investigation of this topic has been integrated with an accurate theoretical-experimental analysis of the urban boundary-layer wind structure.

1 – ASSESSMENT OF RELIABILITY OF LARGE STRUCTURES (IN PARTICULAR LONG-SPAN BRIDGES). The attention has been focused on the detuning of large amplitude oscillations induced by vortex shedding in long span bridges. A first analysis, in combined effort with the Unit at Chieti-Pescara, as a conclusion of the previous PRIN works, has been addressed to the investigation of large vibrations with relative cables-deck motion, with lacking of suspension systems: a paper on this subject has been published on an international journal. A second report has been developed on TMD (Tuned Mass Dampers) system for the mitigation of the elastic oscillations of an existing suspended pedestrian bridge of 252 m span. The time-domain response has been evaluated within the framework of a finite-element model, able to account the second-order effects in terms of displacements. The correlated results are detailed in some papers and in a Degree Thesis.

2 – ELEMENTS OF "STREET ARCHITECTURE" UNDER THE ACTION OF WIND LOADS. About the aspect of the impact of wind effects on urban environments, some experimental work has been done on elements of "street architecture". Pertaining to this subject, a consistent description of the vertical wind profile in urban surroundings has been proposed, after measuring the boundary layer characteristics in three different landscapes identified by different roughness. A further test campaign has been dedicated to the identification of the wind action on a model of a framed signboard. Two cases have been analyzed: the first model was an isolated one, while a second model was immersed in a regular group of buildings with different incoming wind directions. These experimental tests have been the subject of a Ph. D. thesis and of some papers.

The Unit at Roma "La Sapienza" has also carried out some complementary work, i.e.: (i) a compound study of methodologies for the risk reduction in highway networks, with different vulnerability elements; the results have been summarized in a short cycle of lessons hold by the Responsible of the Unit in an important international Institution; (ii) a multimedia presentation, very useful to display the activity of the group, has been realized by the Responsible of the Unit, thanks to the experience achieved within a Master course in "Emergency Engineering", especially on eolian risk and its reduction.

The **Unit #2** (**at Firenze-CRIACIV**) has actively cooperated within all research activities, besides its own projects, especially by arranging different experiments in the wind tunnel managed by CRIACIV. In particular, the unit has technically supported the work and given all the assistance to the model design, following the experimental tests and analyzing the obtained results. Within the Unit Firenze-CRIACIV following specific research activities have been carried out:

1 – EVALUATION OF THE EOLIAN RISK ON COOLING TOWERS. Several efforts of the research Unit have been devoted to the study of the dynamic behavior of an isolated cooling tower immersed in a typical boundary layer of a suburban area, to obtain an estimate of the design static-equivalent wind loads. The pressure field on such tower has been measured: the complexity of the fluid-structure interaction phenomenon requires experimental investigations, to put in evidence the pressure distribution around the body due to the incoming turbulent wind field. Such experimental analyses are strongly suggested also by technical standards, considering that a large variability of wind loads need to be accounted for in different structural solutions.

2 – EVALUATION OF THE EOLIAN RISK ON CABLES AND SUSPENDED BRIDGES. The evaluation of the eolian risk on suspended bridges has been pursued by carrying on a wide

parametric analysis on different bridges. The goal has been achieved through a complete wind tunnel experimental campaign conducted on a set of aeroelastic section models to examine the flutter mechanisms for long span suspended bridges.

Also in this case, the complete research program has been developed in different steps, described in details in the final report to the Ministry.

At the **Unit #3 (at Reggio Calabria),** the definition of the aerodynamic loads on the bridge decks has been performed following the classical approaches in time and frequency domains as the Proper Orthogonal Decomposition technique. The analyses in time and frequency domain have been carried out on experimental data obtained from wind tunnel tests by using both a system constituted of load cells, laser displacement transducers, accelerometers and a set of pressure taps. This latter system allowed the evaluation of the pressure distribution along the transversal axis of the bridge deck section.

Through the Orthogonal Decomposition method, the excitation frequencies have been evidenced, and for each of them, a component in-phase of the wind force and one out-of-phase have been identified, by using only a relatively small number of vibration modes.

Moreover, a carbon fiber bridge model with rectangular section has been designed and built, with the purpose of analyzing aerodynamic and aeroelastic wind loads on a simple and well-documented section. The effect of turbulence on the vibrating model will be investigated within such new experimental campaign. The wind action on elements of “street architecture” has been investigated with two different experimental models, in order to characterize the flow field in urban areas, in terms of turbulence and gust factors. With the first set of experiments, a qualitative flow behavior and a first estimate of the Reynolds stress have been obtained: in particular it has been attained that the leeward Reynolds stress can overpass by three times the same amount measured windward.

At the **Unit # 4 (at Chieti-Pescara),** following four themes have been considered, of which only the first two were originally scheduled:

1 – THEORETICAL MODELS AND EXPERIMENTAL TESTS IN WIND TUNNEL MODEL FOR VIBRATION CONTROL OF LONG-SPAN BRIDGES. The problem of control and mitigation of aerodynamic and aeroelastic vibrations of cable-stayed and suspended bridges has been addressed; in fact, comfort and traffic capacity problems can arise due to the unexpected vibrations, even if the collapse of the structure can be excluded. In cooperation with researchers of the Unit at Trieste and Roma "La Sapienza”, a wide set of experimental tests have been set up. In parallel, a finite-element code (TENSO), developed in the last ten years, has been employed. This program is able to simulate not only the various aspects of geometrical and mechanical nonlinearity, but also the different significant types of fluid-structure interactions (aerodynamic and aeroelastic forces, vortex shedding, etc.) acting contemporary on structural members. In particular the role of wind turbulence has been investigated, through a comparison of the structural response with different combinations of power spectral densities and correlation functions proposed in scientific literature. Moreover, the theme of the passive control of the vibrations induced by the vortex shedding on bridge decks has been followed. Different active, semi-active and passive control disposals for bridges and pedestrian bridges have been analyzed and compared, considering their range of applicability. In particular classical Tuned Mass Dampers (TMD) have been compared with multiple disposals of the same kind (MTMD), able to mitigate the induced vibrations in a wider frequency range of the acting forces.

2 – THEORETICAL MODELS AND NUMERICAL PROCEDURES FOR THE EVALUATION OF THE EFFECTS OF VORTEX SHEDDING ON SLENDER STRUCTURES. Wind tunnel tests have allowed a detailed description of the synchronization phenomenon and of its effects on the wind load acting on the structure. In collaboration with the Trieste unit, an accurate

study of the experimental results obtained in the experimental campaign carried out with the model built at the Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, has been performed, in particular focusing attention on the variating ratio among the main parameters of the lock-in phenomenon. The experiments with a second model have been continued at the CRIACIV wind tunnel. Free vibration tests have been carried out, in laminar and turbulent flow, with different turbulence intensities. With the Unit at Trieste, a new numerical formulation of the aeroelastic loads due to vortex-shedding has been proposed for the lock-in condition, both for slender structures and bridge decks. This formulation completes the numerical model built in these last years with the use of experimental observations.

3 – STRUCTURAL IDENTIFICATION: Beside the described topics, a research activity on structural identification has been carried with the contribution of researchers of the Units Roma "La Sapienza" and Napoli. In this case the main goal of the activity has been the setting of a robust structural identification system for actions not directly or non completely measurable, as it happens often for wind-induced loads. This topic is strictly related to the others, especially to the aspects of structural control.

4 – STREET ARCHITECTURE: Lastly, during the first two years of PRIN, several studies on the wind effects on elements of street architecture have been performed. In particular, some measurements of the wind field in urban areas have been carried out on a scale model of a signboard at the CRIACIV wind tunnel in Prato.

The research activity at **Unit #5 (at Perugia)** has dealt with the design, the construction and the application of active control systems to full-scale structures under the wind action, with particular attention to systems for telecommunication networks. The results obtained are related to different aspects of the problem of correct estimating the eolian risk. As a first step, the structural vulnerability has been evaluated, for support structures devoted to transmission and/or telecommunication systems (antennas, etc.). The estimation of the reliability of such structures under the action of extreme wind loads, has been investigated in wind tunnel tests with model built with full-scale elements, with regard to the safety of the structure itself, to its efficiency and maintenance. Aerodynamic loads and drag and lift coefficients variable with the system configuration and with the wind direction have been evaluated through these experiments. Considering the eolian vulnerability, the identification of the stochastic characters of the wind pressures and the simulation of the corresponding loads has been performed. These analyses have been carried out on industrial building roofs that can evidence strong sensitivity to the wind action. An interesting comparison among the recommendations of different standards has been made. Experimental wind tunnel data have been analyzed, to characterize statistically the time histories for the calibration of a probabilistic model for the numerical simulation of pressure histories. Finally, a first experimental campaign on cables has been carried out at the CRIACIV wind tunnel, to obtain a first load estimate. Considering the structural response, the numerical simulation methods have been utilized within a Database-Assisted-Design, to investigate the stochastic characters of the response of a typical small building under the action of wind flow. Moreover, a procedure for the evaluation of the peak response of strong non-linear systems has been developed. Using previous results, the problem of the mitigation of the structural response has been addressed, using active control systems. For this purpose, a prototype antenna has been designed by the Unit, and an experimental campaign in situ has been carried out to evaluate the efficiency of proportional/ derivative control systems (PD). A second, cable-stayed & tubular, antenna has been realized, for the contemporary measures of the wind velocities. The efficiency of the procedure has been validated through a comparison of the structural response under the wind action in two different cases: a configuration with the control disposal, and a non-controlled one. The efficiency of the active PD system has been evidenced by the relevant decrease of the peaks in the fluctuating response component.

The problem of cables and cable structures under the wind action has been addressed at **Unit #6** (**at Bologna),** with particular attention to the response to aerodynamic action and interaction with suspended elements. ***Damping systems for stays***: the efficiency of distributed damping disposals for the ending part of a cable has been analyzed. Such systems are more effective in the mitigation of wide spectrum vibrations than the concentrated damping ones. ***Excitation of stays under the combined action of wind and rain***: a new experimental campaign has been launched at the wind tunnel CRIACIV in Prato, to definitely characterize a numerical predictive model (already published) with the calibration of some parameters affected by uncertainties. ***Large roofs supported by cables and cable systems***: an application of the recent techniques for the definition of the wind loads has been developed in the analysis of the roof of the Braga Stadium (Portugal). The eolian forces have been analyzed with the orthogonal decomposition of signals. The response has been numerically evaluated, with different techniques in the frequency domain and with a complete analysis in time domain; a monitoring system of pressures and wind velocities has been set up. ***Response to the wind action for roofs containing closed volumes:*** in the present research a simplified model for the interaction of structure and enclosed gas has been proposed. This model can be an useful tool for the simulation of the damping induced by the fluid on the structure. The model is based on two physical assumptions: (1) the motion of a portion of structure is damped by a local pressure variation; (2) the local pressure peaks are propagating in a finite time interval in the structural volume.

Unit #7 (**at Trieste)** has carried out the research activities as briefly pointed in the following sections:

1 – DETAILED DESCRIPTION, BY MEANS OF WIND-TUNNEL BASED MATH MODELS, OF THE PHENOMENON OF THE SYNCHRONIZATION AND ITS EFFECTS ON THE LOAD ACTING ON THE STRUCTURE. A detailed study of the results obtained from the tests executed in the BLWT Laboratory of the University of the Western Ontario has been carried out. Attention has been placed to the relationships between the main parameters of the phenomenon of lock-in. According to the second model, tests of free oscillation in conditions of laminar flow and with various values of the intensity of turbulence have been executed in the BLWT Laboratory of CRIACIV.

2 – COLLECTION OF THE EXPERIMENTAL DATA ON A REAL CHIMNEY. It has been continued the campaign of measures on the chimney of the new system of refusal burning plant of the province of Trieste.

3 – DEVELOPMENT OF THE NUMERICAL MODEL OF THE LOAD DUE TO THE VORTEX SHEDDING. It has been set up a new numerical formulation of the aerolastic load due to the separation in condition of lock-in. Both the amplitude of the lock-in band and the value of the lift coefficient depends on the oscillation amplitude, coherently to how much has been experimentally investigated.

4 – STUDY OF THE RESPONSE OF SLENDER STRUCTURES TO THE SEPARATION OF THE VORTICES. In collaboration with the Unit of Chieti-Pescara, it has been lead a wide parametric survey with TENSO code, taking into account the geometric and mechanical nonlinearity, including the unilateral behavior of hangers and the fluid-structure interactions (mean and aeroelastic actions, vortex shedding, etc).

Four main streamlines of research activity have been pursued at **Unit #8** (**at Firenze-DET**):

1 – VALIDATION, BY MEANS OF EXPERIMENTAL TESTS ON PROTOTYPE, OF THE INSTRUMENTATION ALREADY AVAILABLE AT DET, previously to the activities of this research project. In agreement with the partner, it a test-site suitable to the validation of the radar

technique has been selected. Therefore, in July 2002 an experimentation in-situ has been performed in the Department of Civil and Environmental Engineering of the University of Perugia, where a steel structure, 15 meters tall and instrumented by means of a hydraulic jack on the top. The dynamic behavior of the structure has been evaluated under the excitation of the hydraulic jack, and under a low-speed wind action. In both cases goods results, in terms of frequency and amplitude of oscillations have been carried out with an accuracy comparable to the conventional instrumentation. The measure without artificial excitation has been particularly meaningful: the system has been able to operate a distant measure the natural frequency of a structure movement in a few minutes. The applicative impact of such a technique is remarkable, as, for example, the possibility to monitor a large number of structures (quickly and non-destructively). Thanks to the rapidity and simplicity of the method, with a single instrumentation a lot of monitoring in a day could be executed controlling wide urban areas.

2 – DEVELOPMENT OF A SYSTEM RADAR WITH A SAMPLING TIME LOWER THAN 60 SECONDS. In the present project it has been completed a first prototype of radar not based on laboratory instrumentation, but entire realized with discrete members operating in X band (approximately 10 GHz). This prototype has the main scope to constitute a test bench for the technology and the know-how to be developed in the present project. The prototype is not directly applicable to monitor structures in dynamic conditions but happening like penetrating radar (GPR has been applied with: Ground Penetrating Radar). The adopted technological solutions and the experimental tests on a wall realized in laboratory have been object of a discussion in an international conference.

3 – DEVELOPMENT OF A SYSTEM WITH A SAMPLING TIME OF THE ORDER OF THE FRACTION OF A SECOND, able to follows the transitory phenomena induced by the wind. The most cumbersome activity in terms of resources and engagement has been the design and the realization of a prototype radar based on advanced technical solutions and technologies at the state of the art. The system operates in K_u band (approximately 17 GHz) with one bandwidth of 400 MHz. The architecture of such system is based on the direct digital synthesis (DDS: Direct Digital Synthesis) that constitutes a meaningful innovation in the field of the radar technology. Moreover the architecture of the communications between the devices is based on protocol USB, also this is one important innovation that allows high speeds of communication between the system and the Personal Computer. The realized system is currently able to log one single radio frequency in 10 microseconds, as also verified from laboratory measures. Since an image radar is constituted typically of 1000 radio frequencies, the system is able to acquire an image every 10 milliseconds. This speed is widely able to sample the transitory of the wind in the architectonic structures. About the accuracy of measure carried out from the laboratory tests on a target able to make calibrated movements, it turns out that the system can appreciate movements lower than one-tenth of millimeters as for distances of some hundred of meters.

4 – ADDITIONAL EXPERIMENTATIONS. The radar system developed according to the previous point, able to acquire an image in a fraction of a second, has been used on large viaduct near the city of Florence (the Indiano Bridge, a steel bridge 200 meters long over the Arno river). The driving surface is approximately at 10 meters elevation over the measurement level, and a pedestrian footbridge is hanging under the driving surface. The radar was installed on a river bank of the river in proximity of a pillar of the bridge and has been headed at the downstairs of the same bridge. The bridge was excited from wind and intensive traffic, and measured movements have been of approximately 2.5 cm in the central part and of fractions of millimeter near the pillars. The frequency of vibration of the natural mode was well characterized, like the dynamic deformation of the bridge: these are very original results, as currently, it does not exist anything

comparable to this system for the non-destructive/distant survey of the dynamic behavior of one large structure.

The research activities of the **Unit #9 (at Napoli "Federico II")** have concerned :

1 – THE DEVELOPMENT OF TECHNIQUES FOR REDUCING THE DYNAMICS RESPONSE OF THE ELEMENTS OF ELECTRICAL NETS AND INDUSTRIAL SYSTEMS. For the electrical nets, two arrangements of passive protection for a switch of 420 kV of one substation of transformation, have been proposed and analyzed (with determinist and probabilistic procedures). For the industrial systems, elements with prevailing vertical development (chimneys, cooling towers, etc) have been studied, with particular interest to the problem of vortex shedding, estimating the benefits derive from tuned masses with semi-active systems, also proposing a simplified design methodology.

2 – THE DEVELOPMENT OF ALGORITHMS BASED ON ENERGETIC CONSIDERATIONS FOR THE SEMI-ACTIVE CONTROL SYSTEMS. Some control algorithms based on energetic considerations have been proposed and characterized. These algorithms leads to a reduction of the response under eolian action up to the 50% of that would be possible in the case of systems based on traditional passive technologies. The obtained results have been applied also in the seismic field.

3 – THE DEVELOPMENT OF ANALYTICAL MODELS SIMULATING THE MECHANICAL BEHAVIOUR OF SEMI-ACTIVE MAGNETORHEOLOGIC-FLUID SYSTEMS, and their validation based on experimental tests. The study, first analytical and then experimental, of the mechanical and dynamic property of the dissipation devices based on the employment of magneto-rheologic fluids has lead to the development of analytical models subsequently applied to a steel test-model of a building tested on vibrating table.

4 – THE DEVELOPMENT AND THE IMPLEMENTATION OF CONTROL SYSTEMS OF THE DYNAMICS RESPONSE OF PEDESTRIAN BRIDGE INDUCED BY THE ACTION OF THE TRANSIT OF THE PEDESTRIANS. The advantages deriving from the substitution of the passive dampers of the tuned masses with semi-active systems have been demonstrated. These advantages consists in a greater total robustness of the system of control as for the variation of the characteristics of mass and rigidity of the structure and the content in frequency of acting loads.

At the **Unit #10 (at Firenze DIC)** two main research activities have been carried out on:

1 – EOLIAN RISK ANALYSIS OF COOLING TOWERS. Cooling towers are structures particularly sensitive to the action of the wind, and so they are critical points inside of the production- distribution chain of the electric power. Their particular sensibility to the eolian action derived from their dimensions and from the load conditions; actually, if the regular flow of the wind is disturbed from elements contiguous to the towers, the natural symmetry of the eolian pressure gets lost on the shell of the same tower and dangerous bending moments, removing the conditions of structural operation from the theoretical membrane condition, are generated in the structure. The research activities had been programmed according to five different steps, that is: 1 - execution of tests in wind tunnel, in collaboration with unit CRIACIV; 2 - non Gaussian pressure histories simulations; 3 - structural analyses; 4 – Eolian risk assessment of one or more cooling towers; 5 - definition of design wind loads on the single cooling tower. Experimental tests have been carried out in wind tunnel in collaboration with unit CRIACIV with the aim of measuring the wind pressures on towers surfaces varying the incidence direction of the wind as regards to the towers, theirs distance, their slenderness (defined like the relationship between their height and their base diameter), the average speed of the flow. In the CRIACIV boundary layer wind tunnel a test-model 1:300 scaled has been tested. A similar experimental campaign have been previously carried out on a model with a lower number of pressure taps. The pressure taps have been placed on 8 different levels equally spaced of 30°. A new software for the acquisition of pressure taps

have been implemented allowing to log data with a sampling frequency up to 1075 Hz. The wind pressure histories have been simulated by means of two approaches: the first one deals with Radial-Basis-Function Artificial-Neural-Networks (RBFANN) , developed in DIC improving the simulations methods based on parametric models; the second is based on the use of opportune transfer functions. Finite-Element models of the cooling tower have been implemented, and the equations of motion have been integrated with the pressure histories generated in the previous step. The models have been implemented with codes able of modelling at least the simplest characteristics of the reinforced-concrete, because the structural collapse heavy depend on the formation of cracks in the structure. An automatic code (MORE) for the assessing of the structural response with a strongly nonlinear behavior (like reinforced concrete structure in flexural regime) have been implemented. Such procedure is based on the decomposition of the field of structural motion on the space generated from the modal shapes of the actual structural system with a linearization around the mean deformed configuration The application of this procedure reduces the times of calculation being necessary for a dynamics analysis in flexural regime, drastically limiting the error in respect to the complete procedure, and simply leading to the next step of the research, which deals with the assessment of the eolian risk of one or more towers.

2 – DETERMINATION OF DESIGN WIND LOADS. Concerning the definition of design wind loads, the study has been organized as follows: Pressure coefficient have been carried out and characterized; Extend simulations of such coefficients have been carried out; Stresses induced in the structures from the wind pressures acting on the structural surface have been estimated; for this purpose: wind loads reproducing the worst stresses conditions have been computed by means of LRC method (load – response- correlation); Since the obtained design wind loads distributions are qualitatively very similar to the mean one, the internal stresses of the structure have been maximized (or minimized) by means of the GRF (Gust Response Factor) method which consists in multiplying the mean wind load by the GRF coefficient. In the present research value of GRF between 2 and 3 have been founded. The theoretical justification of such results are still in phase of elaboration, like the structural analysis.

1.4 DISSEMINATION EVENTS

Results have been disseminated, during the project life, within all main scientific conferences (in Italy, Europe and worldwide; s. 1.2.4): the present final publication will be officially presented during a special devoted session of the 8th Italian Congress of Wind Engineering, IN-VENTO-04, Reggio Calabria, June 2004.

1.5 FUTURE PERSPECTIVES

An immediate follow-up of the project has already started his activity and is lifely continuing some of the research streamlines initiated by WINDERFUL: this *follower* project, which has been approved and co-financed within the PRIN (Research Projects of National Interest) in Nov. 2003 for the two years 2003-2005, deals with: LIFE-CYCLE PERFORMANCE, INNOVATION AND DESIGN CRITERIA FOR STRUCTURES AND INFRASTRUCTURES FACING EOLIAN AND OTHER NATURAL HAZARDS, and aims to introduce a new “PERformance Based Approach to Construction Cost Optimization” (PERBACCO, which the new acronym of the project). Besides the great impact that WINDERFUL has had on the European developments in the field, and especially on the results of the COST action C14 in “Urban Civil Engineering”, it is likely that a new COST action will be launched in the immediate future, which will be based on this new approach. The heritage of WINDERFUL, both at National as well as European/international level, is therefore ensured.

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1.6 RESEARCH UNITS

Unit #1
Dipartimento di Ingegneria Strutturale e Geotecnica – Università degli Studi di Roma "La Sapienza"

Research Theme:	**Reliability under wind actions of (1) elements of transportation infrastructures (horizontal structures like viaducts and suspended or cable-stayed bridges, and "street architecture" components like roadway and railway signs, bus stops, etc.) and (2) lifeline networks, in order to keep utilities and cities running during and after windstorms**	
Coordinator:	Giuliano AUGUSTI	Full Professor
Components:	Marcello CIAMPOLI	Associate Professor
	Carlo PAULOTTO	PhD student
	Furio Lorenzo STAZI	PhD student

Unit #2
CRIACIV (Centro di Ricerca Interuniversitario di Aerodinamica delle Costruzioni ed Ingegneria del Vento) – Università degli Studi di Firenze

Research Theme:	**Evaluation of the eolian risk on cooling towers, cables and suspended bridges**	
Coordinator:	Claudio BORRI	Full Professor
Components:	Gianni BARTOLI	Associate Professor
	Serena CARTEI	Secretary
	Carlotta COSTA	PhD student
	Claudio MANNINI	PhD student
	Lorenzo PROCINO	Technician
	Michele RIGHI	PhD student

Unit #3 **Dipartimento di Meccanica e Materiali –** Università degli Studi di Reggio Calabria		
Research Theme:	**Evaluation of the response of wind sensitive structures and its reduction: from long-span bridges to street architecture**	
Coordinators:	Enzo D'AMORE	Assistant Professor
	Francesco RICCIARDELLI	Associate Professor
Components:	Enrico Tullio DE GRENET	PhD student
	Giulio NICOLOSI	Full Professor (Univ. of Napoli)
	A. David PIZZIMENTI	PhD student
	Raffaele PUCINOTTI	Technician
	Aldo RAITHEL	Full Professor (Univ. of Napoli)

Unit #4 **PRICOS** (Dipartimento di Progettazione Riabilitazione e Controllo delle Strutture Architettoniche) – Università degli Studi di Chieti-Pescara		
Research Theme:	**Analysis and control of the wind risk for infrastructures formed by flexible structures**	
Coordinator:	Piero D'ASDIA	Full Professor
Components:	Salim FATHI	PhD student
	Vincenzo SEPE	Associate Professor
	Massimo TARQUINI GUETTI	Consulting Engineer
	Alberto VISKOVIC	Assistant Professor

Unit #5 **Dipartimento di Ingegneria Civile ed Ambientale –** Università degli Studi di Perugia		
Research Theme:	**Wind hazard reduction for telecommunication networks by means of control systems**	
Coordinator:	Vittorio GUSELLA	Full Professor
Components:	Marco BRECCOLOTTI	PhD student
	Federico CLUNI	PhD student
	Massimilano GIOFFRÈ	PhD
	Annibale Luigi MATERAZZI	Full Professor

Unit #6 **Dipartimento di Ingegneria delle Strutture, Trasporti, Acque, Rilevamento del Territorio –** Università degli Studi di Bologna		
Research Theme:	**Dynamic behaviour of cables under wind actions: cable response and structural interaction**	
Coordinators:	Massimo MAJOWIECKI	Associate Professor
	Giuseppe MATILDI	Associate Professor
Components:	Nicola COSENTINO	PhD student
	Stefano PINARDI	Consulting Engineer
	Roberto TREVISAN	Consulting Engineer

Unit #7 **Dipartimento di Ingegneria Civile –** Università degli Studi di Trieste		
Research Theme:	**Vulnerability of slender structures to vortex shedding**	
Coordinator:	Salvatore NOÈ	Associate Professor
Components:	Boris SOSIC	Technician
	Franco TREVISAN	Technician
	Tatiana SLUGA	PhD
	Luca CARACOGLIA	Consulting Engineer

Unit #8 **DET** (Dipartimento di Elettronica e Telecomunicazioni) – Università degli Studi di Firenze		
Research Theme:	**Interferometric radar for remote monitoring of large structure vibrations caused by wind**	
Coordinator:	Massimiliano PIERACCINI	Assistant Professor
Components:	Davide LEVA	PhD student
	Linhsia NOFERINI	PhD student
	Paolo CLEMENTE	Researcher (ENEA)

Unit #9		
DAPS (Dipartimento di Analisi e Progettazione Strutturale) – Università degli Studi "Federico II" di Napoli		
Research Theme:	**Development of methodologies for the reduction of aeolic vulnerability of electric networks and industrial plants**	
Coordinator:	Giorgio SERINO	Full Professor
Components:	Carlo BAGGIO	Associate Professor
	Manuela DI DONNA	Consulting Engineer
	Renato GIANNINI	Full Professor
	Alessio LUPOI	PhD
	Fabrizio PAOLACCI	Technician
	Tommaso PUOPOLO	Consulting Engineer
	Lorena SGUERRI	PhD
	Maria Cristina SPIZZUOCO	PhD

Unit #10		
DIC (Dipartimento di Ingegneria Civile) – Università degli Studi di Firenze		
Research Theme:	**Eolian risk analysis for cooling towers and evaluation of design loads**	
Coordinator:	Paolo SPINELLI	Full Professor
Components:	Michele BETTI	PhD
	Luca FACCHINI	Associate Professor
	Maurizio ORLANDO	Assistant Professor
	Stefano PASTÒ	PhD student