Personal experiences in Structural Architecture: from form finding to free form design

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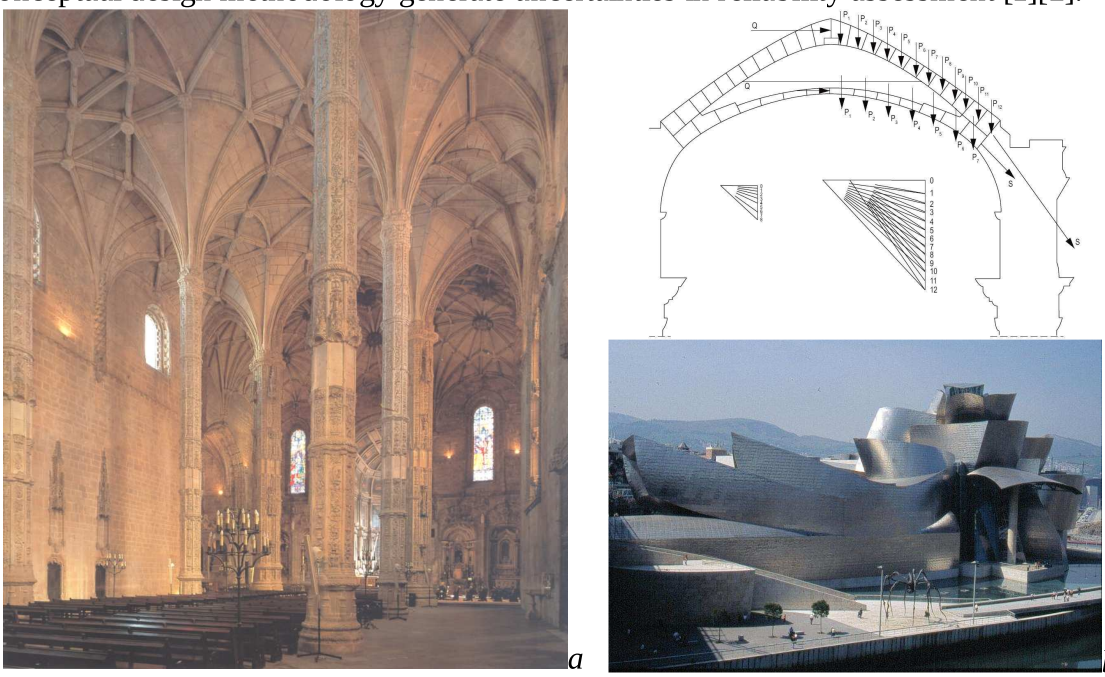
Abstract

The empirical method in structural form finding has achieved world-wide efficiency and recognition as massive building tradition has continued to expand in history. Through direct involvement of lithoid materials, working under unilateral state of stress, designers driven by “static intuitions” have largely succeeded in giving shape to complex constructions, stabilized by gravity acting on the structural dead load mass (Fig. 1a).Ever since the second industrial revolution, with the help of materials able to carry tensile stresses, still the form of the structures have nevertheless been conceived and found observing the laws of statics, as a guarantee of an aesthetic result achieved. For membrane and cable structures, where the morphology must satisfy equilibrium conditions under an initial state of stress, finding the form of the structure is a “must” and, hence, a form finding procedure is required to identify the initial geometry.

Nowadays, architects and engineers alike are immerged in a new challenge: the Free Form Design (FFD); a new fashion with the prevalence of aesthetics over static rationality where the role played by the structures is merely to support the architectural design Fig.1-b). Many novel projects attempt to extend the “state of the art” but, according to personal experiences, new structural morphologies adopted in actual conceptual design methodology generate uncertainties in reliability assessment [1][2].



a *b*

Fig. 1: a)A Gothic Architecture (1517); b) The Bilbao effect

Keywords: structural architecture, wide span structures, reliability, experimental analysis, monitoring.

1 Introduction

I have a debt to settle with IASS. As a student, in 1969, during the IASS Congress held in Madrid, I was truly impressed by spatial structures' design and the research that led to them. Lightweight structures strongly influenced my personal academic investigations and design activities. As a matter of fact, form finding and non linear behavior of cables, membranes and pneumatic structures were the subjects I focused on, at first, as an engineer and then as an assistant professor in College (University of Bologna). An interactive graphic software was developed on main frames in the early 70's, that was then extended to mini and personal computers, as a natural consequence of those early studies [3][4][5][6].

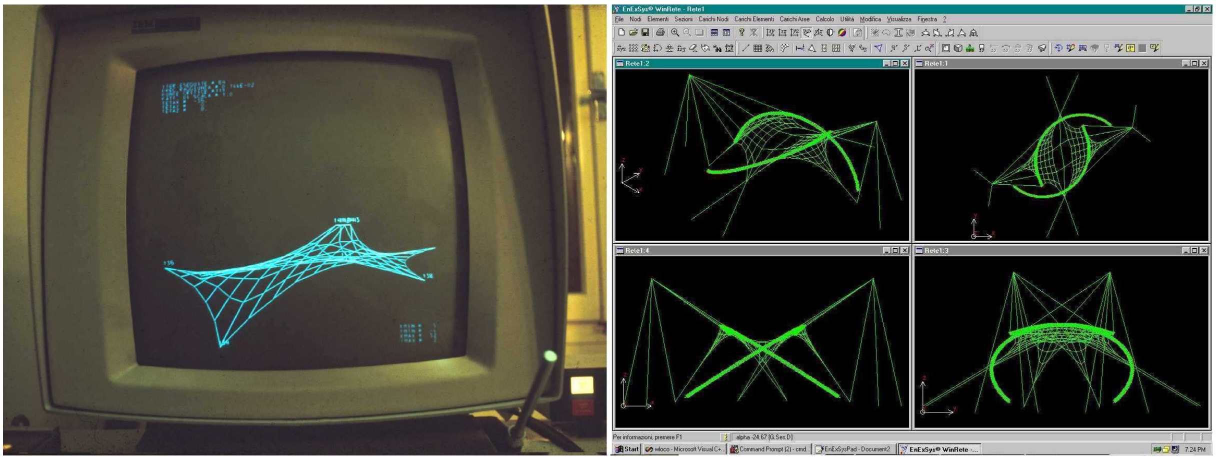


Fig. 2: 1973 IBM 2250 - 2010 PC Windows XP

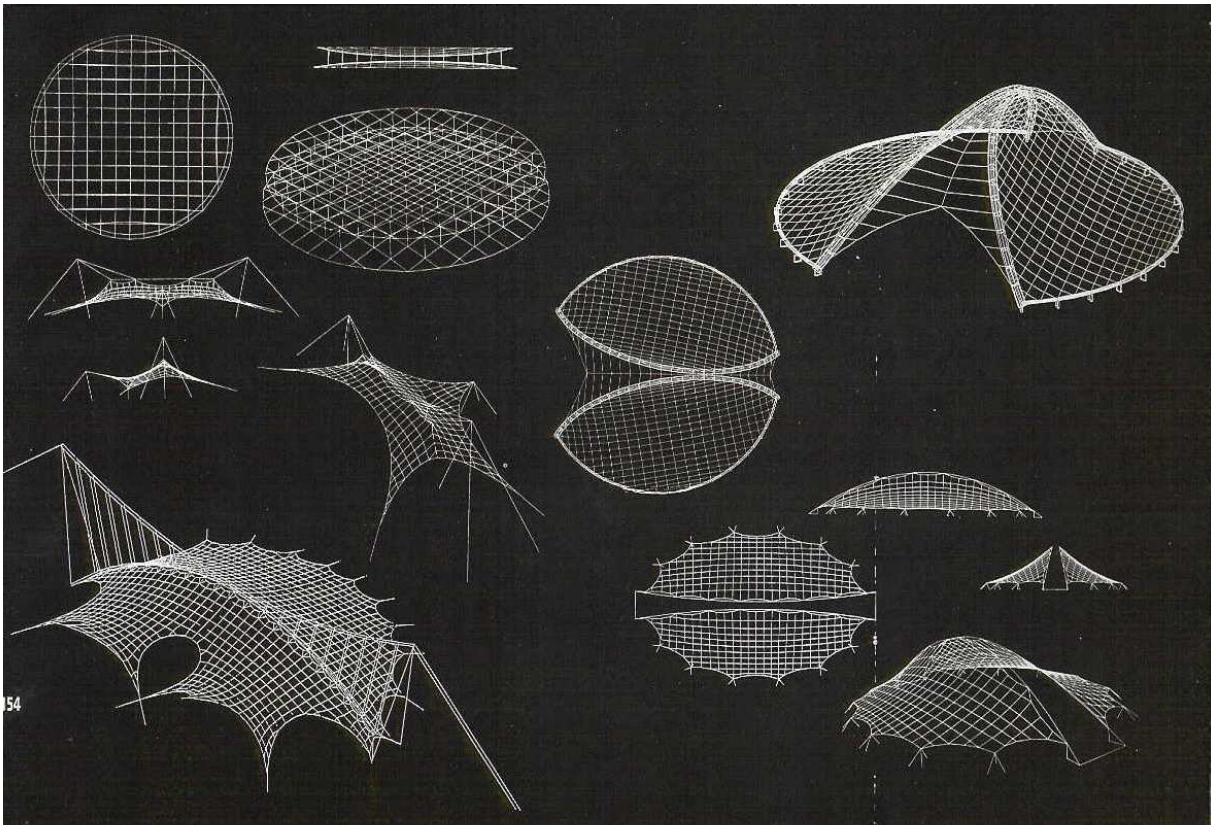


Fig. 3: Form Finding for cable and membrane structures

For this particular orientation I have already been honored with the Pioneer Award by the Space Structures Research Centre, UK, during the 5th International Conference on Space Structures, held in 2002. However, I feel indeed truly privileged as I gratefully and proudly receive the Torroja Medal from IASS and celebrate forty years of devoted career with such a wide circle of outstanding colleagues.
If it's my pleasant task to salute all those making this outstanding achievement possible, then it's again my pleasure to underline just how very important the research is by providing the Congress with a paper illustrating some personal research activities in theoretical and experimental structural analysis, followed by the subsequent conceptual synthesis in structural- architecture design of space structures.

2 The IASS tradition: morphology and structural analysis

Of course, the information technology revolution has influenced structural engineering as well. During the 50s and the 60s the design methodology of the structural engineer has been remarkably influenced by two major developments: the harmonization of the various theories of structural mechanics and the introduction of electronic processors accompanied by symbolic and matrix languages and finite element methods.
My generation bridged the era between approximated methods of analysis and the advent of FEM automatic analysis but, from the point of view of the conceptual design we get an inheritance from Eiffel, Gaudì, Torroja, Nervi, Maillart and others (Fig. 4); all using a common “structural language” as stated by Musmeci :“Through its form, the structure immediately reveals the flow of internal forces that cross it, which is not enclosed and hidden within the volume of an abstractly conceived morphology, prone to esthetic and static prejudice, in which most part of matter and space is superfluous”.

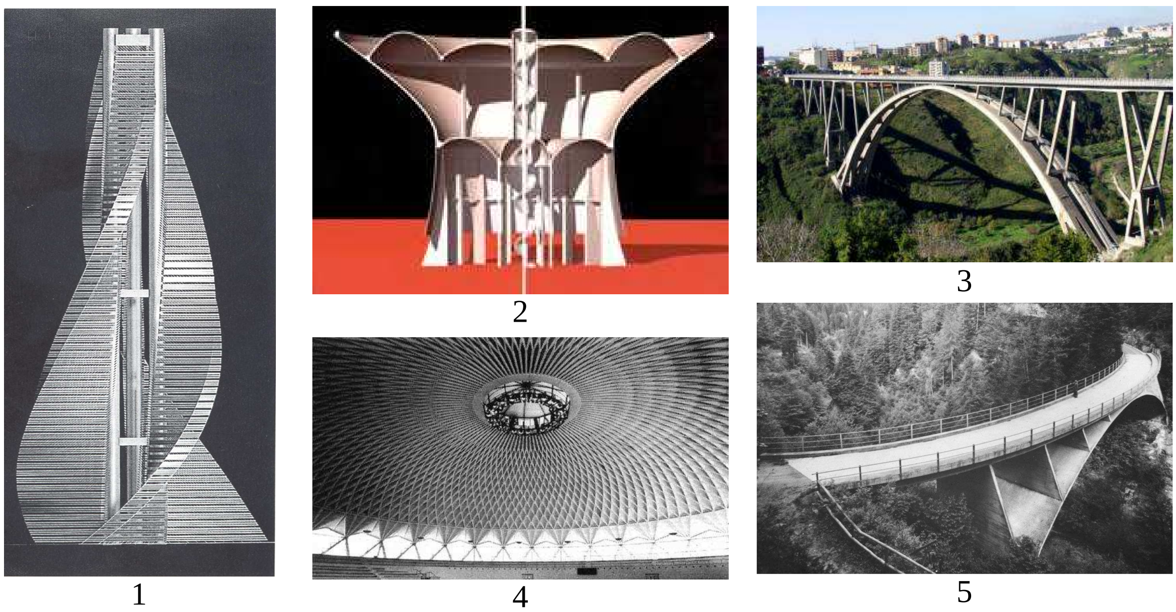


Fig. 4: The IASS Tradition (1-S.Musmeci, 2-E. Torroja, 3-R. Morandi, 4-P.L. Nervi, 5-R. Maillart)

Now we live in the era of «language metamorphosis», as it was called by E. Benvenuto in his recent “history of building science”, in which symbolic language and mathematical formalism have gone beyond the mechanics of structures putting it at the service of automatic calculus. Therefore the “mentality” on which scientific empiricism was based has changed radically.

J.T. Oden and K.J. Bathe see in this change the beginning of a new era of «computational empiricism». One of their interesting articles reads as follows:
«The engineers' community of 40 years ago was aware that the use of classical analytic methods offered limited tools for the study of mechanical behaviour and, as a consequence, the engineer had to enrich his analysis with a great deal of judgement and intuition achieved after many years of expertise. Empiricism played a crucial role in design: despite some general theories that were available, the methods to apply them were still under development and using approximate schemes and resorting to indications derived from numerous tests and confirmations was inevitable.
Today the common belief is that automatic calculus has put an end to this semi-empirical age of engineering: by now sophisticated mathematical models can be built on some of the most complicated physical phenomena and if the processor is sufficiently powerful, reliable numerical results can be obtained based on the response of the examined system».
The advantages brought by electronic processors may, on the other hand, create an uncontrollable exaltation of the automatic calculus and give the false impression that man can be outshined by machines and the logic by the automation [7][8].
The advantage offered by informatics and automation has been very important in the field of structural design in general and particularly significant in the case of special structural systems. It was possible to examine more rigorous theoretical models avoiding, on the one hand, excessive simplifications that deprive the theoretical model, like a schematic reduction of the reality, of all significance and, on the other hand, that exhausting calculations lead to the loss of facts with a true influence, thus discouraging designers from trying out different structural solutions.
Under such apparently favorable circumstances, many documented structural failures have been detected in which mistakes regarding the inadequate evaluation of structural behavior were caused by unreliable man/machine interaction and the illusion that computers, those powerful instruments of analysis, could replace conceptual design and the expert synthetic criticism of results.
Documented FEM modeling errors are illustrated in the First International Conference on computational Structures Technology [9] .

3 Some experiences in Theoretical & Experimental analysis of Spatial Structures

Due to the lack of space(see references for more information), with the intention to transmit some experiences that today may be part of the knowledge base, only some design and analysis illustrations of structural systems, where the author was directly involved, will be included in the present paper.
Considering the statistical results of the -in service- observed behaviour, the unusual typologies, the new materials and, specially, the “scale effect” of long span structures, several special design aspects arise. Uncertainties, in reliability assessment, principally due loading experimental identification and analytical modeling simulation of structural response, have been identified:

- the non linear geometric and material behavior under internal volume restraint fluid interaction and follower loading [10];

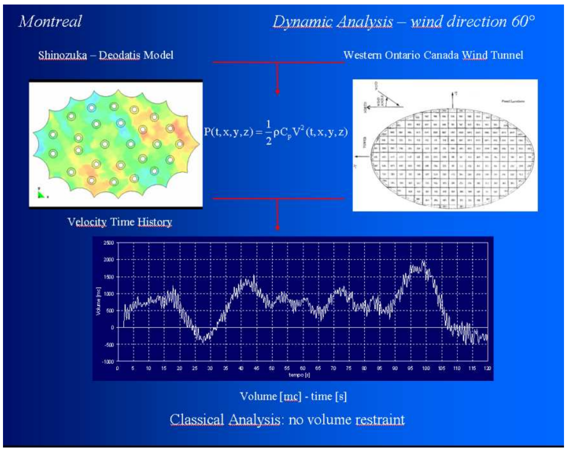


Fig. 5: Dynamic analysis in T domain

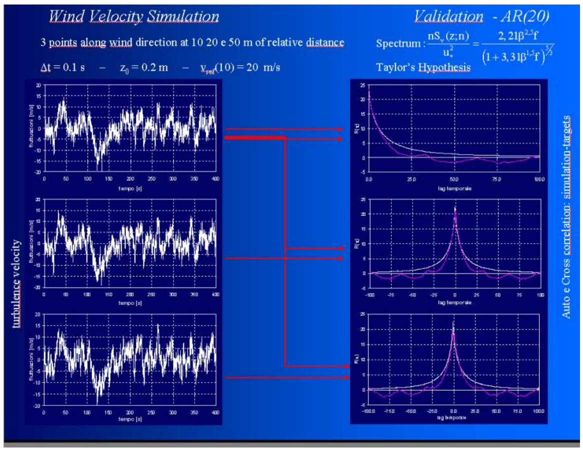


Fig. 6: Wind Velocity Simulation [18]

The wind induced response of the cable-membrane original supported stadium roof was analysed by a non linear model and a field of multi correlated artificial generated wind loading time histories [11] .Wind tunnel tests have been carried out at the BLWT Lab. of UWO on a model of 1:200.

- the snow distribution and accumulations on large covering areas in function of statistically correlated wind direction and intensity [12];

During the design of a new cable stayed steel roof for the Montreal Olympic Stadium (), a special analysis was made considering three roof geometries varying the sag of the roof from 10 m, 11.5 m and 13 m, in order to find a minimization of snow accumulation by wind interaction.

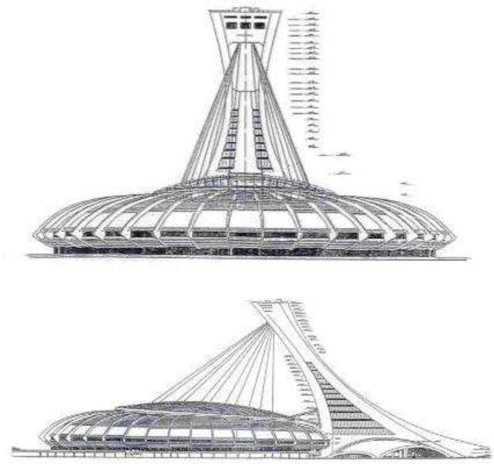


Fig. 7: Montreal Olympic Stadium. A cable stayed roof solution

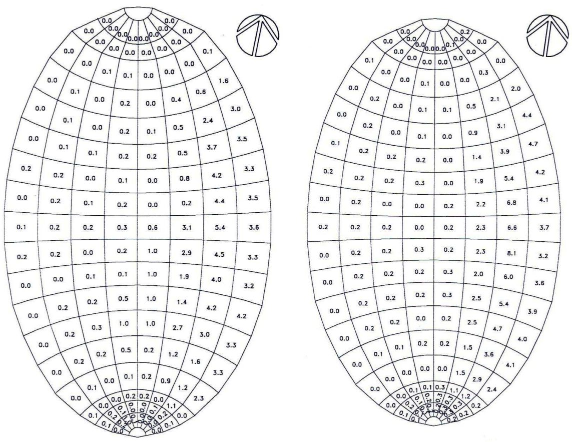


Fig. 8: Comparative analysis of snow loading distribution in function of roof shape (10-13m)

The experimental investigation was carried out by RWDI [13] to provide design snow according to FAE (Finite Area Element) method, representing up to day a state of the art on the matter.

- the parametric sensibility of the structural system depending on the type and degree of static indeterminacy and hybrid collaboration between hardening and softening behaviour of substructures.

The unusual suspended roof of the Montreal Stadium has been analyzed being sensitive to the tolerances in length of the cable stayed system.

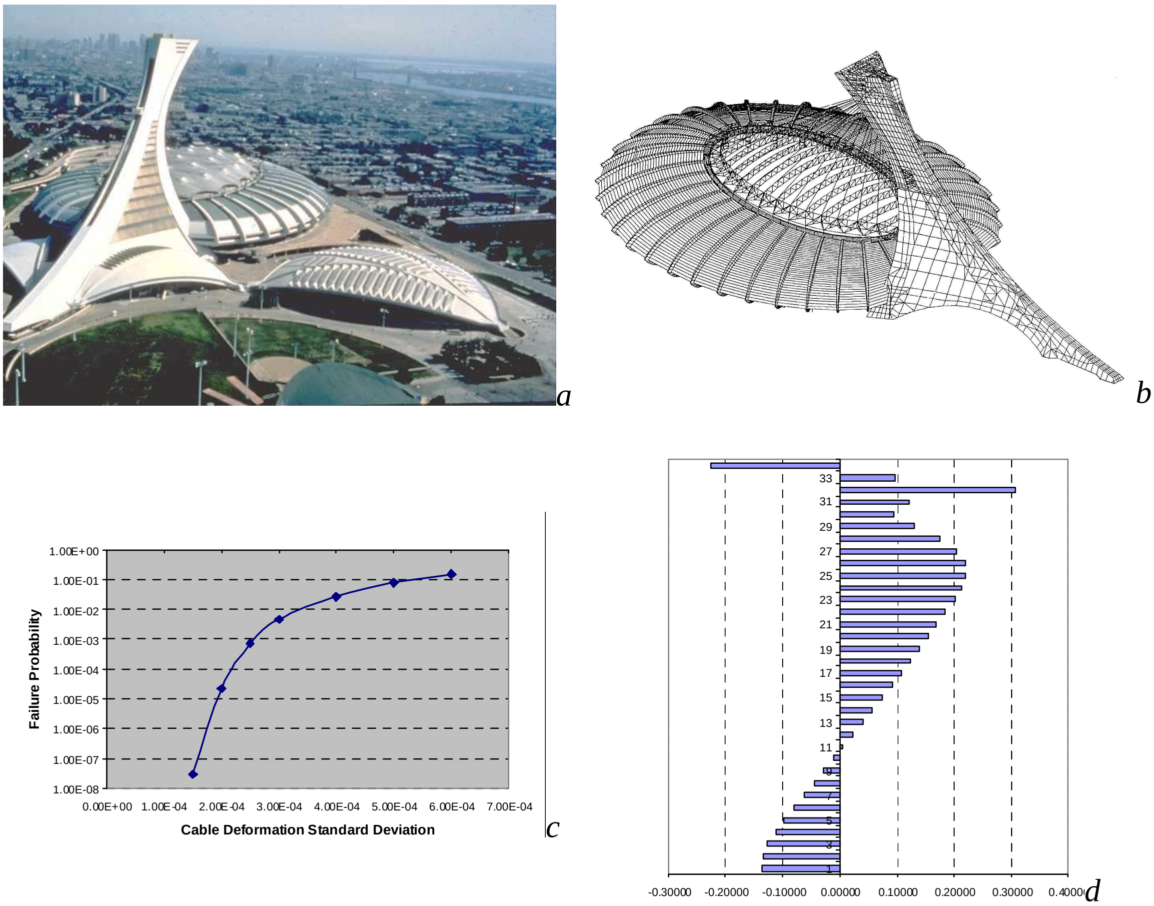


Fig. 9: Montreal stadium: a) external view; b) Numerical model of new roof; c) Failure probability in function of cable deformation standard deviation; d) Most probable $\Delta\varepsilon$ in each cable at failure for load comb. 7

- the wind pressure distribution on large areas considering theoretical and experimental correlated power spectral densities or time histories[14];

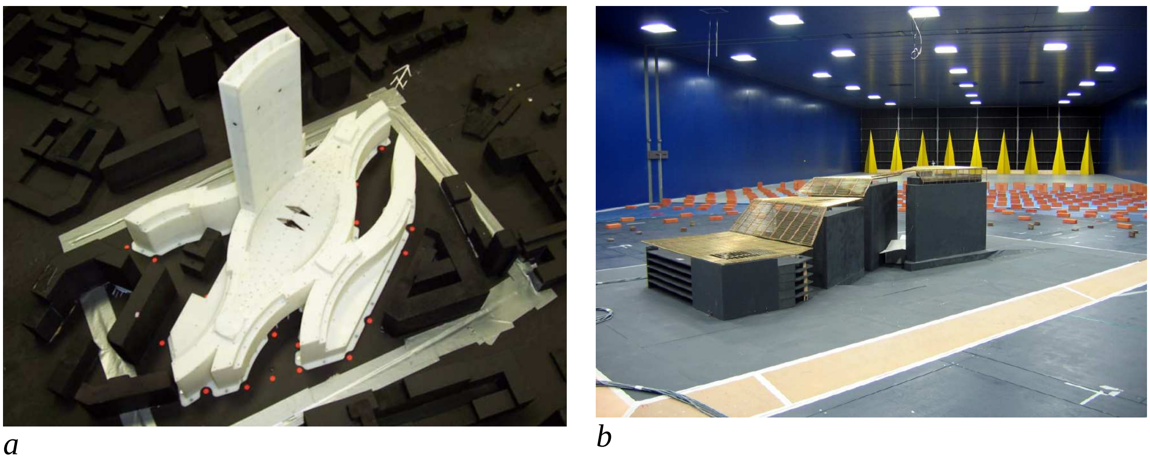


Fig. 10: The new center of the region Lombardia (a) and the new Town hall in Bologna (b)

Results and specifications:

1. pressure coefficients (maxima, minima and average) for every 10° of incoming direction;
2. peak pressures and global forces are given as a "final" design value;
3. time histories of the local pressures for every 10° of incoming flow direction; the maximum, minimum and average values of the wind pressure have then been evaluated, as well as the root mean square of its fluctuating part;
4. Aerodynamic pressure measurements;
5. Measurement of global forces by dynamometric balance;
6. Evaluation of pressures and flow within the double skin façade.

And some problems detected during global forces measurements:

1. the fluctuating part was completely different ;
2. the balance results seem to be "fuzzy";
3. as it is shown by the correlation loci between the force Fx (in the global structure reference system) and the corresponding base moment Mz.

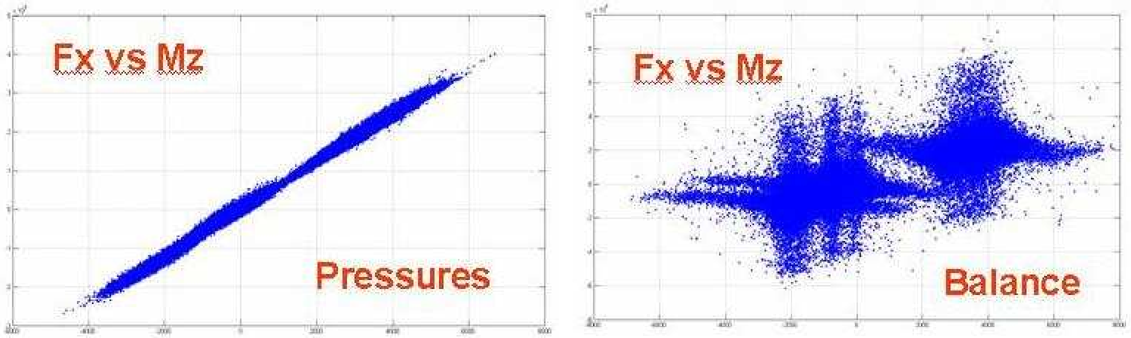


Fig. 11: Insufficient correlation between the force Fx and the corresponding base moment Mz.

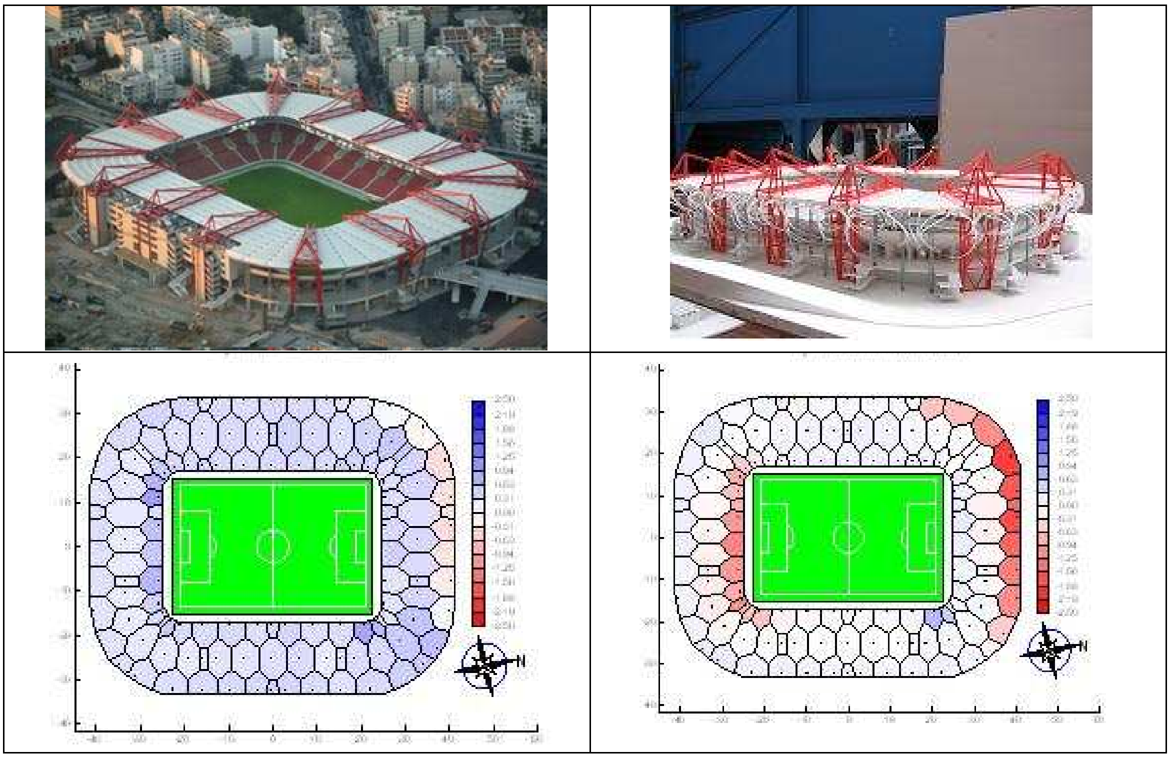


Fig. 12: Karaiskakis Stadium (Athens) wind tunnel tests - Maximum and minimum values of net pressure coefficients (wind direction: 0°)

- auto and cross-spectra of the fluctuating pressure (averaged on every single panel) .

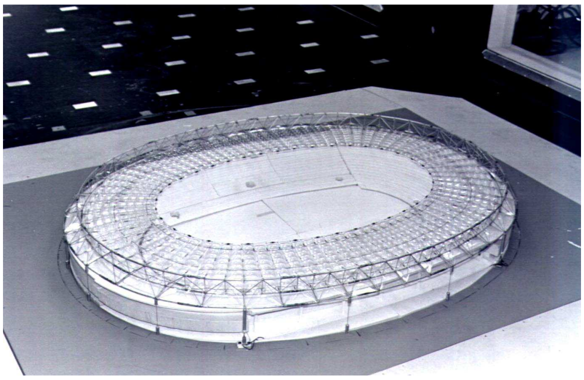


Fig. 13: Aeroelastic model for Rome Olympic Stadium

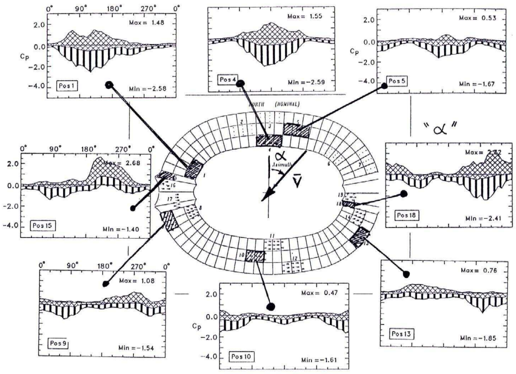


Fig. 14: Aeroelastic model for the Stadium of the Alpes-Panel's pressure

The aerodynamic behaviour shows a clear shedding phenomenon [15] [16]. The external border of the structure, constituted of the trussed compression ring with triangular section and tubular elements and by the roofing of the upper part of the stands, disturbs the incoming horizontal flow in such a way so that vortex shedding is built up. This causes the roofing structure to be subjected to a set of vortices with a characteristic frequency. This is confirmed by the resulting Power Spectra Density Function of the fluctuating pressures, which shows a peak at about 0.15 Hz even if the values rapidly decrease with increasing distance (Fig. 15).

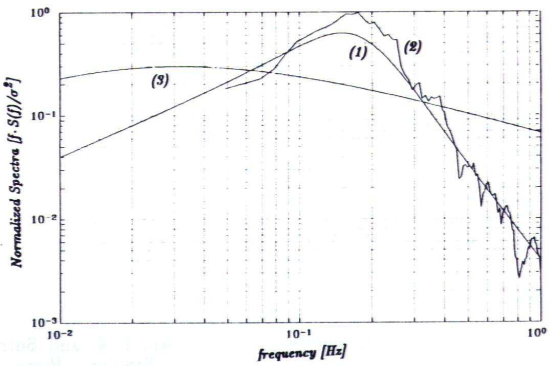


Fig. 15: Target (1), simulated (2) and Kaimal's (3) normalized spectra of wind velocity

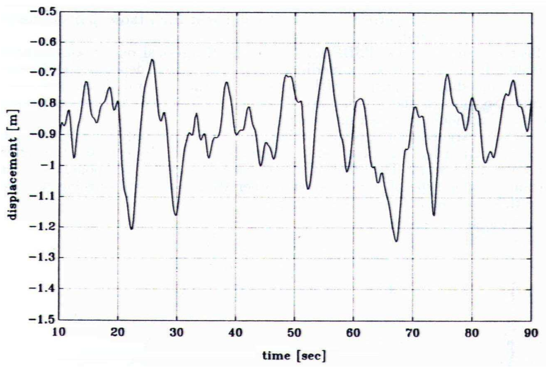


Fig. 16: Time History of the displacement (leeward side at tension ring, run #2)

- rigid and aeroelastic response of large structures under the action of cross-correlated random wind action considering static, quasi-static and resonant contributions;

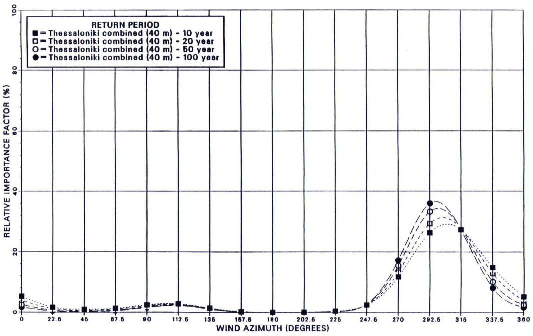


Fig. 17: Relative contribution of Azimuthal Direction to the exceedance probability of various return period wind speeds for Thermi, Thessaloniki, Greece

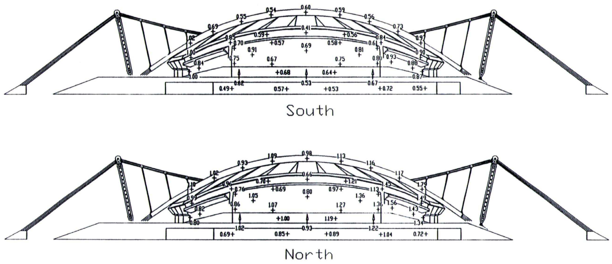


Fig. 18: Taps location

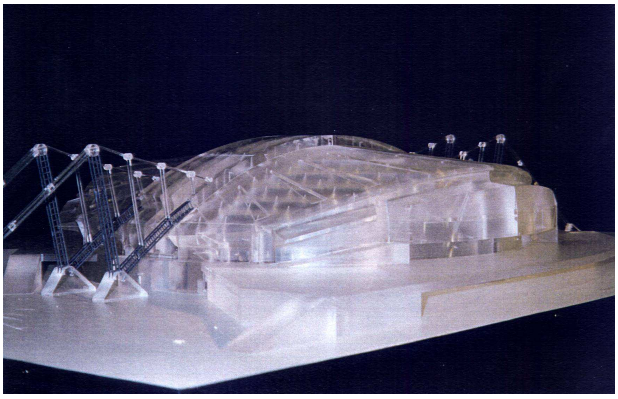


Fig. 19: Views of pressure model

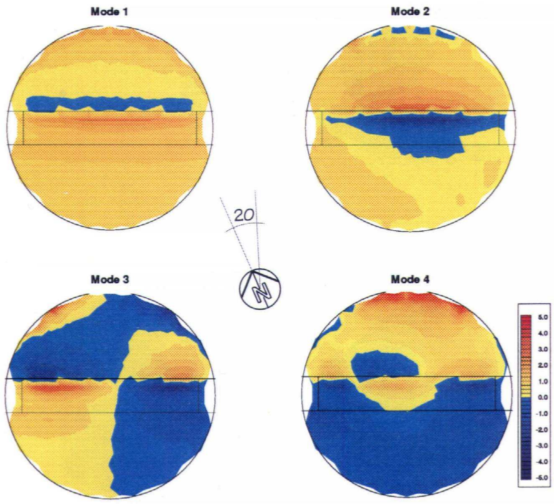


Fig. 20: POD - Proper Orthogonal decomposition of pressure mode shapes

- the local and global structural static and dynamic stability;

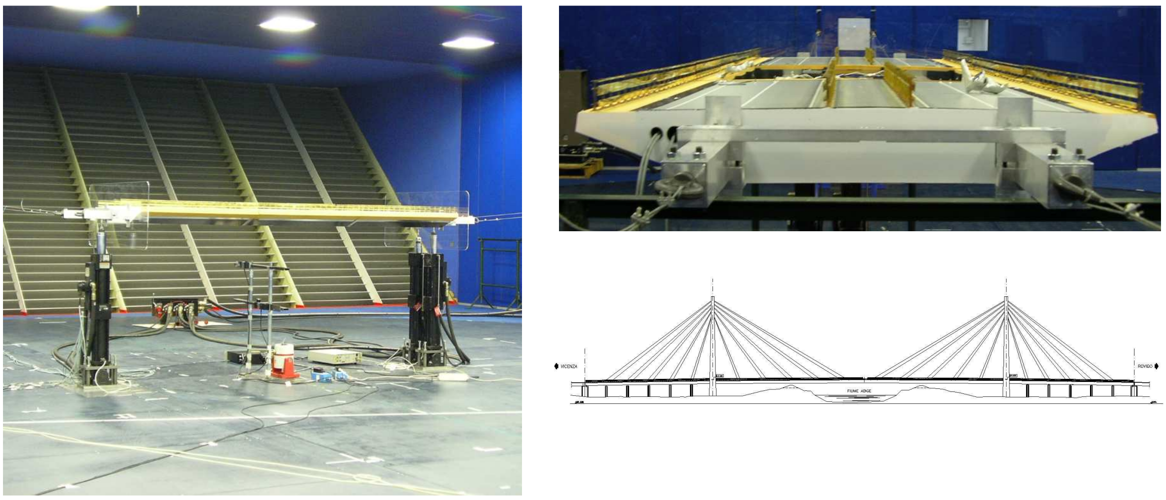


Fig. 21: Experimental deck model (Adige River Bridge- 330m central span)

The aeroelastic behaviour was investigated by both a direct and an inverse method [17]. The direct method consists in measuring the wind induced forces on the deck under an externally imposed 1-DOF motion. This allows defining and changing a-priori the (mean) angle of attack; it also allows a large reproducibility of the tests. On the other hand, the inverse method consist in measuring the forces on the deck during a free motion. This procedure allows to investigate the vortex shedding mechanism and flutter derivatives.

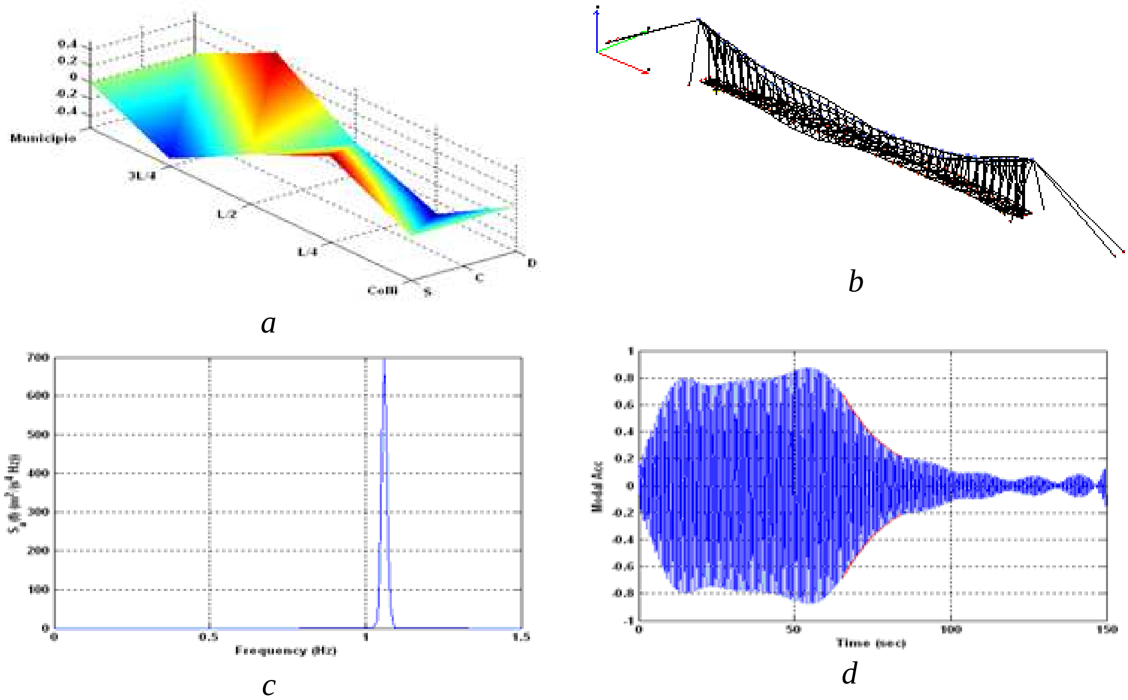


Fig. 22: Dynamic identification of a suspended footbridge under crowd anthropic loading: a) eigenvector of the asymmetrical first torsional mode, POD experimental data; b) asymmetrical first torsional mode, numerical model; c) spectral density and d) time history of the asymmetrical first torsional mode f=1,06 Hz, ξ=0,93%.

- reliability and safety factors of new hi-tech composite materials;
- the necessity to avoid and short-circuit progressive collapse of the structural system due to local secondary structural element and detail accidental failure;

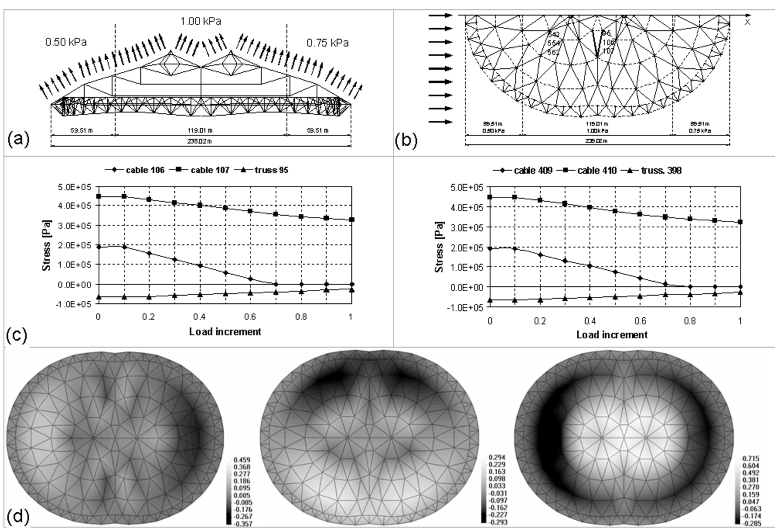


Fig. 23: La Plata Stadium validation analysis. Wind in X direction: (a) load configuration; (b) null cable stresses; (c) stress diagrams and (d) displacements along X- direction, Y-direction and Z-direction [23].

A fluid-interaction non linear analysis in time domain, made for the checking of La Plata stadium design [9] under simulated progressive collapse, shows a better agreement between theoretical model and experimental values.

- the compatibility of internal and external restrains and detail design, with the modelling hypothesis and real structural system response;

Special attention was dedicated to the analysis of main suspending joint of the new (under construction) Juventus Stadium in Torino. A dedicated 3D FEM mathematical model was implemented to analyze the stress distribution and peak concentrations.

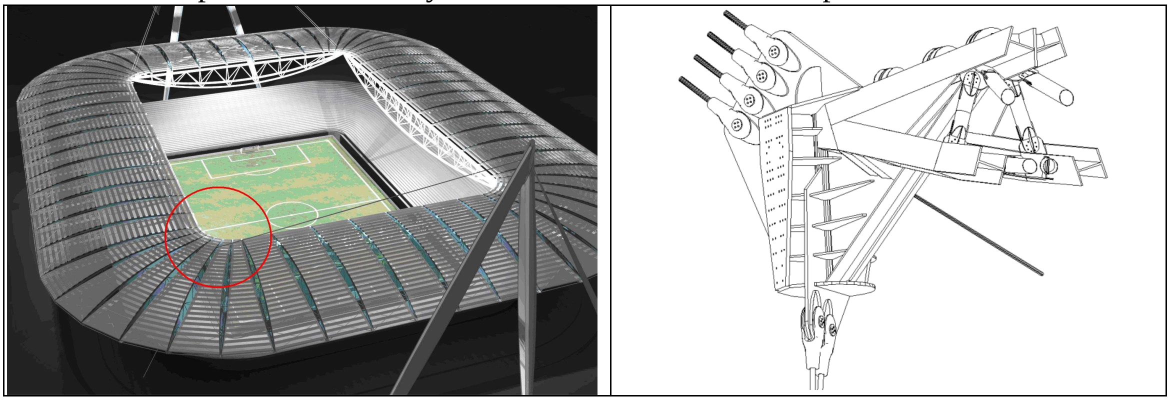


Fig. 24: New Juventus Stadium roof and solid view drawing of main suspension joint

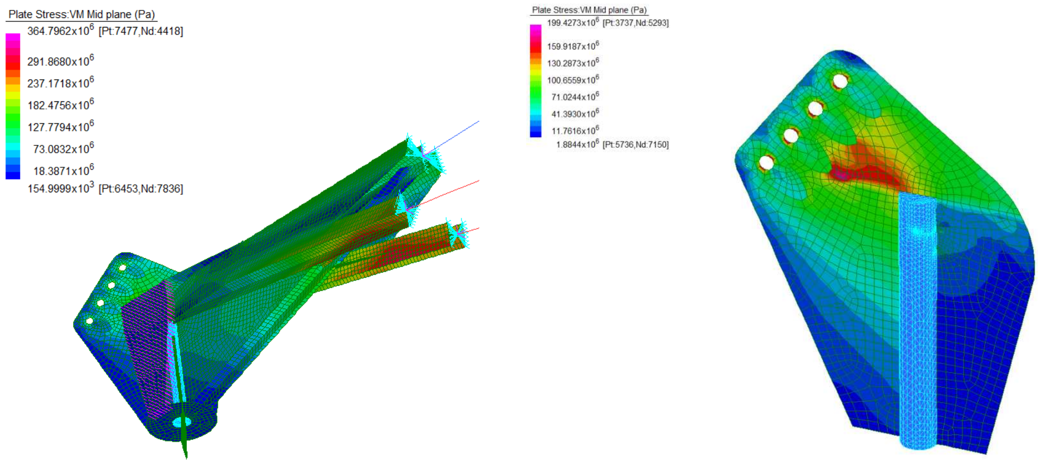


Fig. 25: Graphic representation of stresses

- In the case of movable structures, the knowledge base concerns mainly the moving cranes and the related conceptual design process have to consider existing observations, tests and specifications regarding the behaviour of similar structural systems. In order to fill the gap, the IASS working group n°16 prepared a state of the art report on retractable roof structures [24] including recommendations for structural design based on observations of malfunction and failure

4 Some experiences in Structural conceptual design and realizations

From the synergy between research and design, synthetically expressed by David I. Blockley as:"To do you must know, and to know you must do", some designs of structural architecture in the field of spatial structures are shown . They are collected according the typologies of the IASS tradition.

Space structures

- single layer grids
- double and multi layer grids
- single and double curvature space frames

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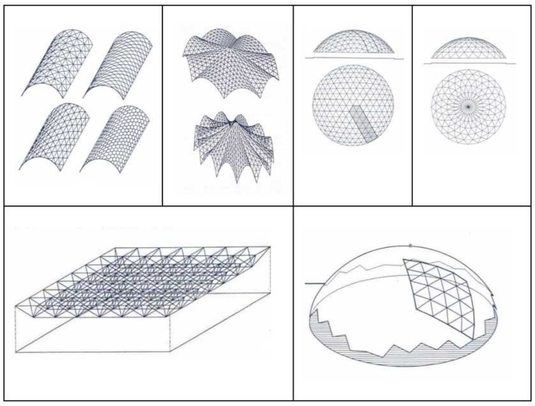

Some typical gridworks [18]

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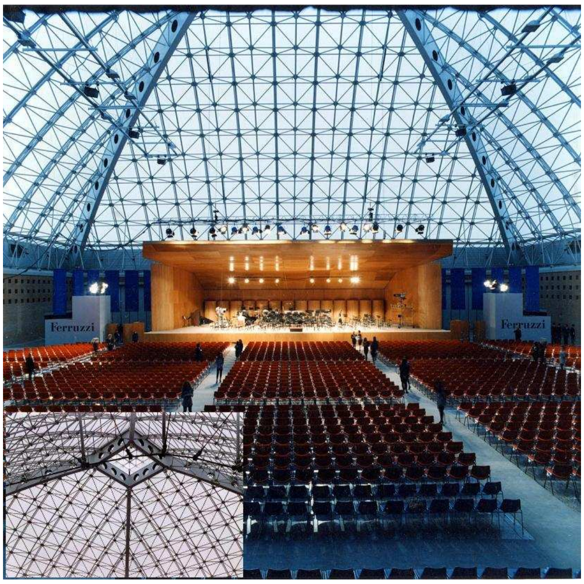

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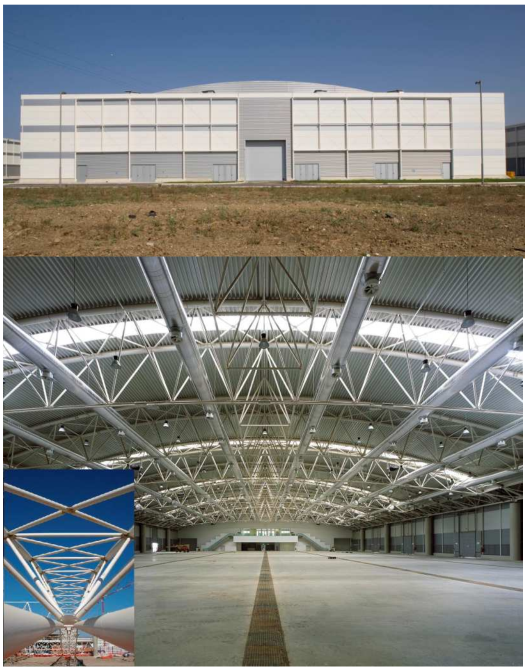

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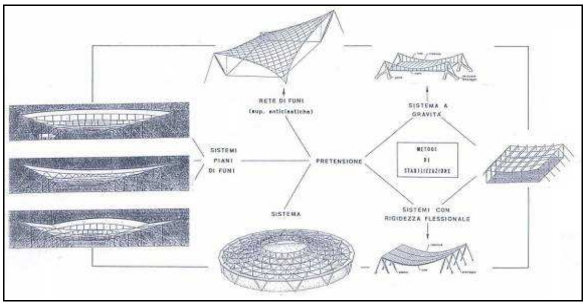
Tab. 1: *1)Hangar of Pratica di Mare; 2)-3)-4)High – Speed Train Statin Rome (under construction); 5)Ravenna Pala D'Andrè space shell; 6)Typical Pavillion of the new Roma Fair (80m. span).*

Cable structures

- cable stayed roofs
- suspended roofs
- cable trusses
- single and multilayer nets

1



Typologies of cable structures [19]

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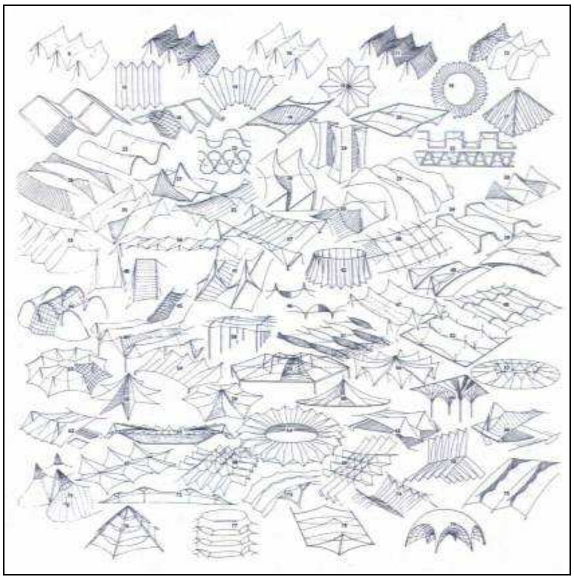
Tab. 2: *1)Athens Sport Hall; 2)Olympic Stadium Rome; 3)Stadium of the Alpes Torino; 4)Braga Stadium Portugal; 5)New Juventus Stadium Torino[20]; 6)Genova: bridge over the Polcevera river; 7)Market of Genova; 8)Footbridge over A-13 Highway* [21]; *9)Footbridge over Reno River Bologna.*

Membrane structures

Typologies of membrane structures [22]



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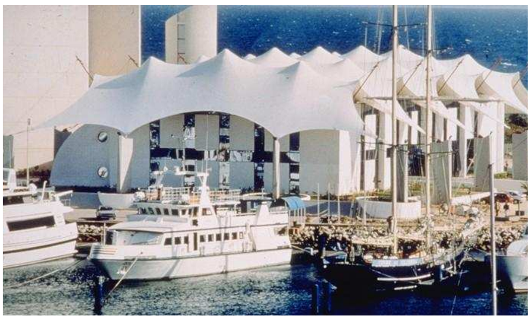

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Tab. 3: 1) Olympiakos Stadium F.C.; 2)Highway pay toll entrance; 3)Panathinaikos Stadium; 4)Stadium of the Alpes Torino; 5) Milano Fair [23]; 6)Inox steel membrane covering 1.8 Km long footbridge at Roma Fair[24]; 7) Membrane in Lisboa Harbor.

Hybrid structures

- tensegrity systems
- beam-cable systems [25]

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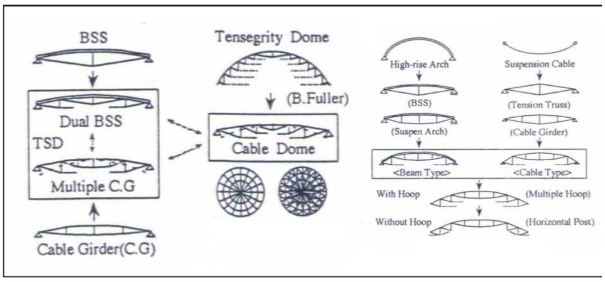

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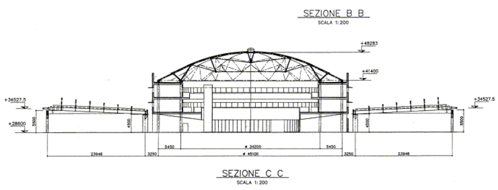

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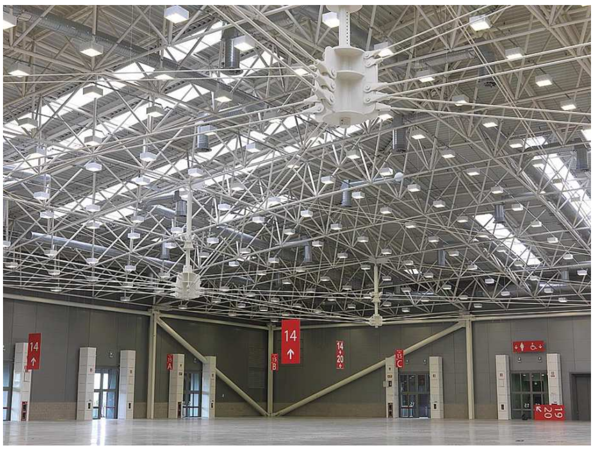

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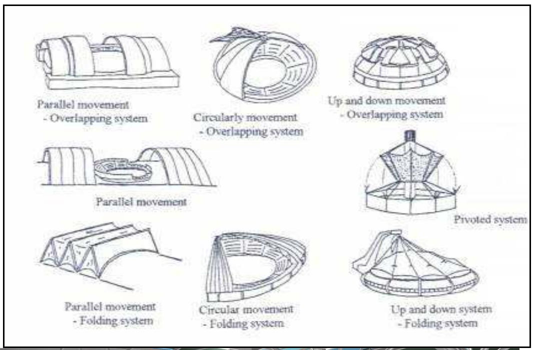
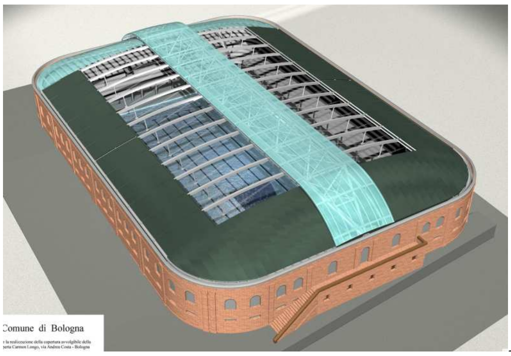
Tab. 4: 1)Pavillion 16-18 of Bologna Fair; 2)-3)Pavillion 19-20 of Bologna fair; 4)-5)-6)Cable string beam and details; 7)-8)Market of Rimini; 9) Pavillion 14-15 Cable supported space structure 100m span of Bologna Fair.

Convertible roofs [26]

- overlapping sliding system
- pivoted system

folding system





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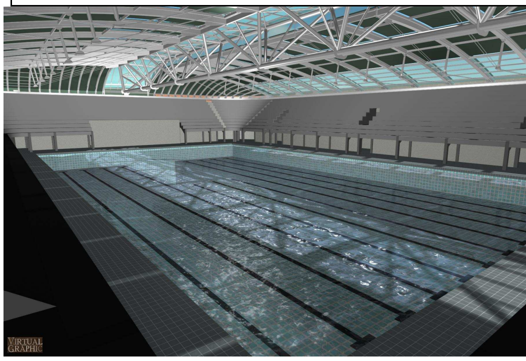
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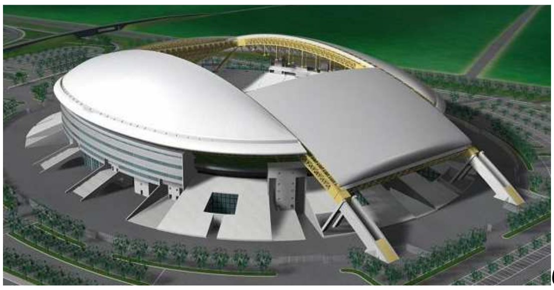
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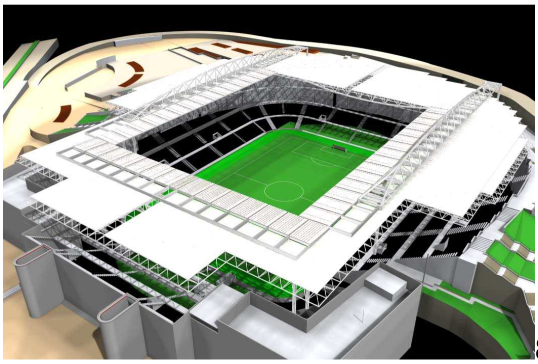
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Tab. 5: 1)-2)Retractable roof over a Swimming pool (Bologna); 3)-4)Ohita Stadium (Nikken Sekkei-Kajima Corp.); 5)-6) Marco Polo Stadium (Venice); 7)-8)Stadium of Messina

4 Actual trends in Structural Architecture: the Free Form Design

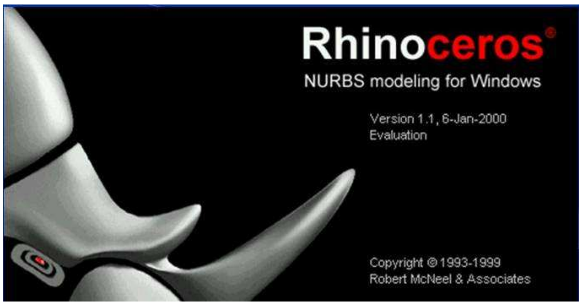
As written in the Divina Comedia:

"Halfway through the journey we are living
I found myself deep in a darkened forest,
For I had lost all trace of the straight path."

(Dante Alighieri, The Divine Comedy, Inferno, Canto I)

At this time, more than half way through my journey, I find myself in a "Wave Fashion" Comedy, with no accountable guides. I truly doubt that FFD, in architecture, shows the way to ascend into Heaven. Auxiliary IT (Informatics Technology) resources seem to overcome human reason, as "modern tendencies" diverge from the straight path [27] with:

1. the prevalence of aesthetics over static rationality;
2. stringent search for structural efficiency to solve a more complex issue than reality, in order to achieve an original solution;
3. the categorical rhetoric of structural actions that translate into design languages;
4. the structure as a sculpture;
5. mechanistic impressionism;
6. the metaphorical transposition, into architecture, of Nature and other foreign elements;
7. the rhythmic and monotonous repetition of an architectural motif;
8. the emphatic representation of a typical element's detail, to identify the overall scale;



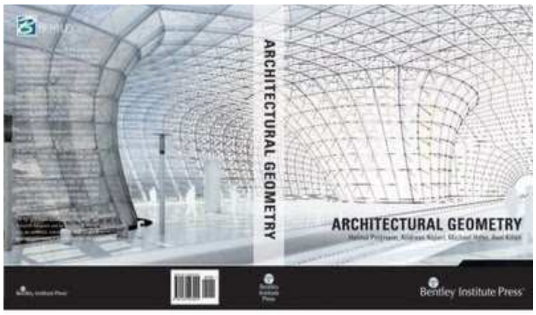


Fig. 26: IT(Informatics Technology) resources for FFD

Phenomenological uncertainty may be considered to arise whenever the form of construction or the design technique generates uncertainty about any aspect of the possible behaviour of the structure under construction, service and extreme conditions. Those uncertainties are introduced in designs which attempt to extend the "state of the art", including new concepts and technologies. In actual realizations, phenomenological design uncertainties play a very important role; today we see free formal expressiveness originating architectural objects such as leaning towers, sculptured bridges, free-form enclosures and the like, whose shape sometimes has no connection whatsoever with structural principles.

Fig. 27: Some actual examples of Free-Form-Design

According to the technical and scientific philosophy taken from Eiffel. Torroja, Nervi and others, who designed by looking first and foremost at the construction, quite sure that observing the laws of static engineering would be seen, per se, as a guarantee of aesthetic results achieved, they are no more than structural forgeries.

On the contrary, many of these new architectural objects marvelled us and are appreciated in the name of the very definition of the word architecture, as an intellectual and technical exercise directed at adapting our physical environment to the needs of social life. It cannot be denied that some works achieve the level of architectural and sculptural art and the role played by structures is merely to support architectural design.

Under those circumstances Torroja anticipated, with an Ethic sentence, how to behave under the FFD which constitutes a new challenge for Architects and Engineers alike:

“If being creative simply stands for emerging driven by no sensible arguments, if creativity fails to happen as a direct result of reliable and accurate principles applied to new issues, then original ideas, torn between misrepresentation and inconsistent mannerism, move from genius to vanity, converting art into expediency. Innovation alone shall never take an instrumental role in promoting the artist; the skills of the artist should deserve respect and praise first and, eventually, focus the public interest on their innovatory potential" (Torroja, razon y ser de los tipos estructurales, cap.XVII).

At this point we have to say that from a statistical viewpoint, human errors in the fields of design and construction tend to increase remarkably when innovation is discontinuous and sudden and when it does not take place gradually with the aid of scientific knowledge [28][29]. The free structural morphology that stems from the current FFD trends represent, at the same time, challenge and anxiety in building science and technique, which are traditionally anchored to conventional typologies and geometries (frames, arches, shells, etc.). This entails a radical change in the civil structural engineer's forma mentis and methodology, especially with regard to the interpretative control of the structural response in terms of state of stress and deformation under the action of permanent and live loads, obtained through sophisticated analysis carried out according to the finite elements method.
Therefore, the FFD needs from structural engineering some new contributions as follows:

- As shown in Fig. 28, the use of conventional steel profiles, conceived to be connected mainly at 90°, are no more appropriate when the structural geometry is also involved into the FFD. A first International Colloquium of FFD, addressed to a new technologic contribute to facilitate production and construction process, was held at TU Delft in 2006 .

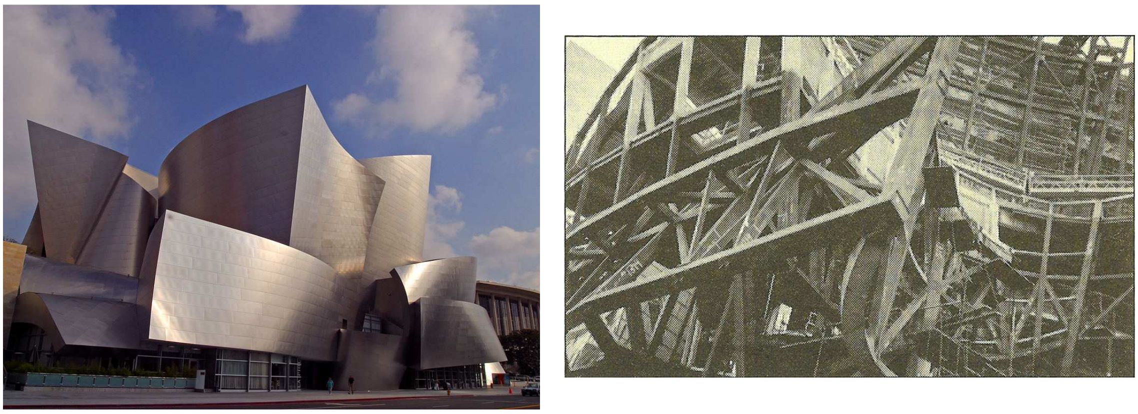


Fig. 28: External view and part of structures of the Walt Disney Concert Hall. Who is the column, who is the beam?

- An interesting contribute to generate structural composite steel plated elements able to follow a free form is shown in Fig. 29.

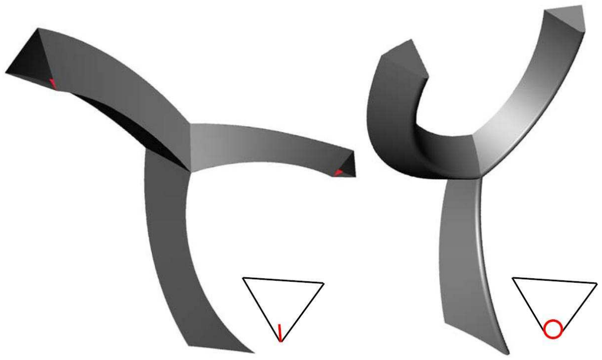


Fig. 29: Wetkamp Delta rib- system

Fig. 30: The new Pecking Olympic stadium

a *b*

Fig. 31: a) Variety of Delta Rib-shapes; b) Italian Pavillion for Shangai Expo 2010 (2ndPrice)

- ULS verification of free form member steel sections.

When using the plated box sections as in the under construction High Speed Train Station in Florence (originally designed by Foster and Arup, with final design for construction by STM), a special method of ULS verification of the steel members and sections named Reduced stress method is illustrated in [30] .

The method:
1) allows to take in account of direct stresses σx, shear stresses τ, stresses σz acting parallel to cross-section plane;
2) allows to define the acceptability of cross-section stresses distribution from the combined point of view of resistance and instability by means of the acceptability of stresses distribution of single cross-section plates;
3) allows to adopt as reference the stresses distribution derived from gross cross-section without iterative procedure and without additional eccentricity eN;
4) is the generalization of the previous effective cross-sections method.

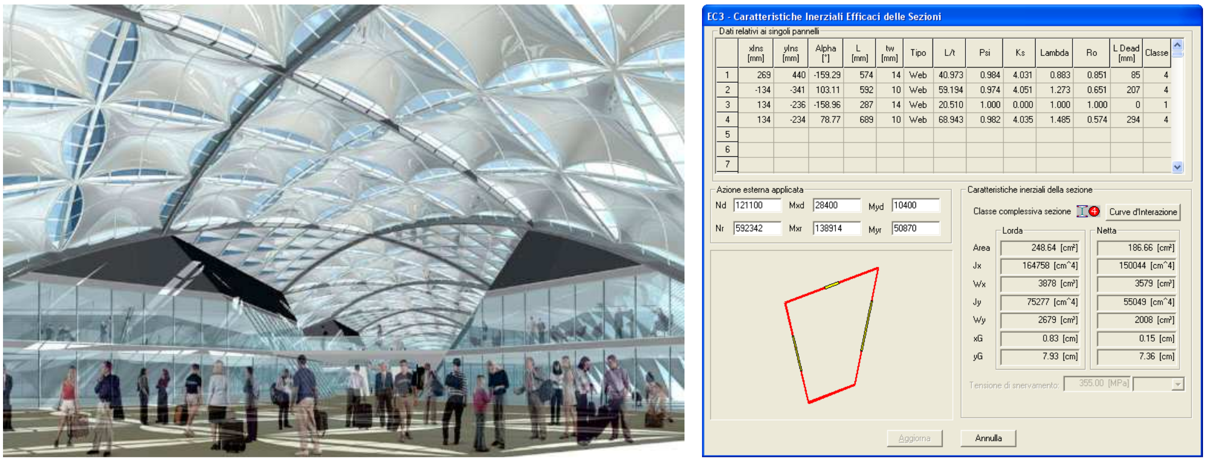


Fig. 32: Verification of the steel members of the roof of the new railway station of Florence

- Structural optimization methods to increase reliability in FFD. An optimization method based on genetic algorithm is presented in[31][32] Fig. 33.

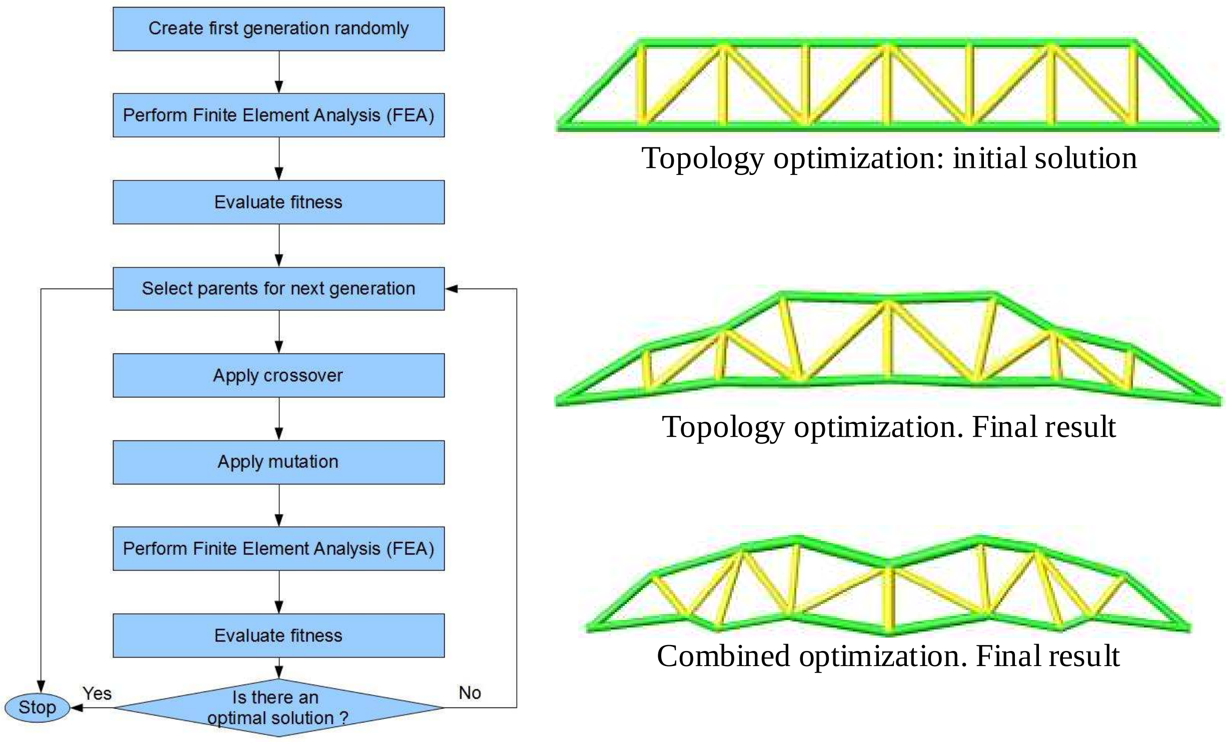


Fig. 33: Optimization method based on genetic algorithm

- Advanced methods of analysis for unconventional sensitive structural systems with uncertainties including construction tolerances.

This section presents a reliability analysis of the roof of the Stadium of Braga under random wind loads [33][34]. The following results are obtained: a) the sensibility of the failure probability of the roof to the spatial random distribution of wind loads, b) the wind direction that drive the structure to fail with most probability (considering all wind direction with a uniform distribution), c) the points of the roof that will fail with most probability, and d) the spatial distribution of wind loads that drive the structure to fail with most probability.

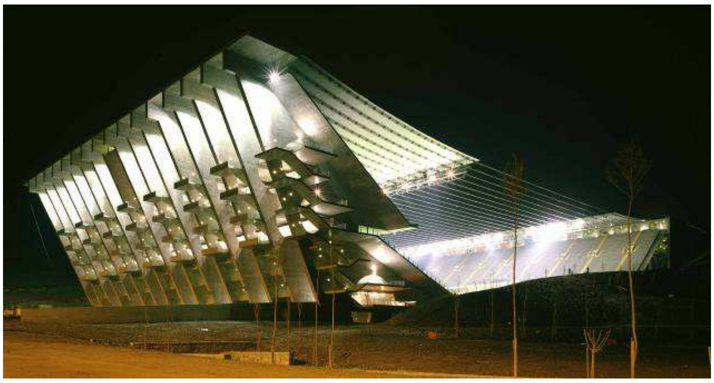
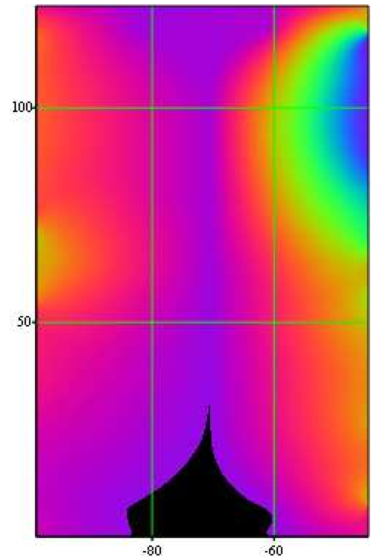


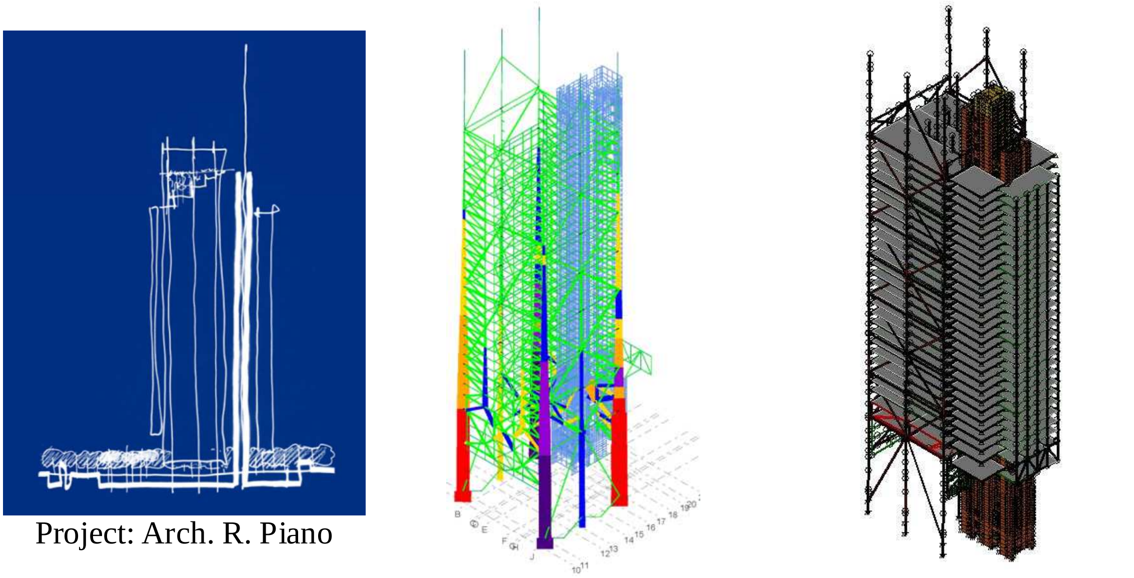
Fig. 34: The new suspended cable roof of Braga Stadium (Portugal)



$\left(x, y, Beta^{\langle 0 \rangle}\right)$

Fig. 35: β-Safety Index distribution, evidencing SLU sensibility on black region (β=3.798) [25]

- The time dependent effect of coactive indirect actions as pre-stressing, short and long term creeping and temperature effects; furthermore, when rheological uncertainties (as creep differential column shortening in high rise buildings or construction time history incremental state of deformation and stress, etc.) involve modelling uncertainties, it would be necessary to have adequate and systematic feedback on the response of the design by monitoring the subsequent performance of such structures so that the long term sufficiency of the design can be evaluated.



Project: Arch. R. Piano

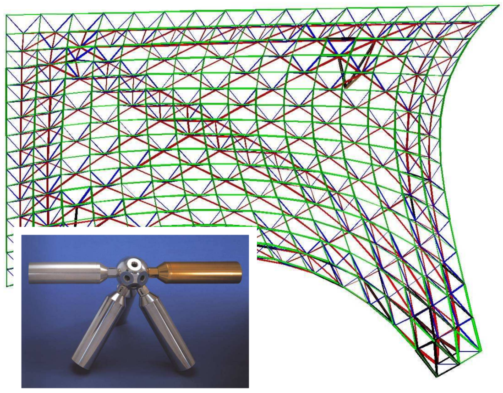
Fig. 36: the numerical model of the San Paolo Tower in Torino, this model takes into account the creep of the concrete structures during incremental construction.

Some actual, under construction, FFD designs elaborated under the structural consultancy of the author, are shown in the following figures:

Free form structures

- Reticular spatial structures
- Shaped and welded profiles

1



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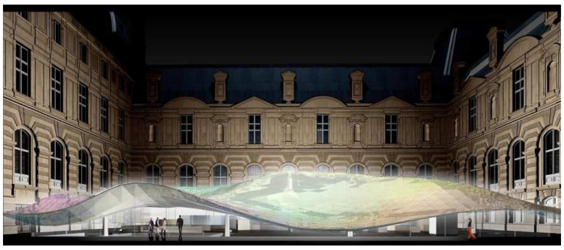

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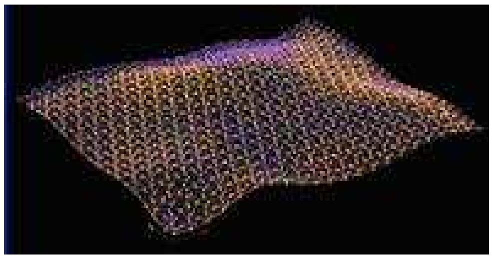

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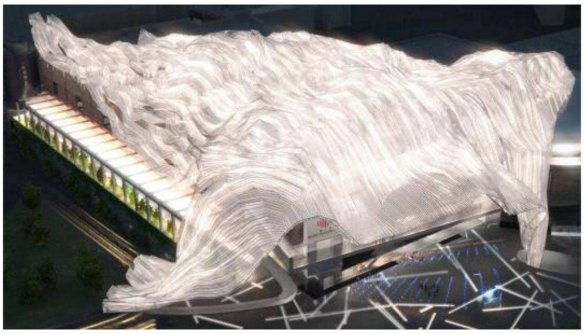

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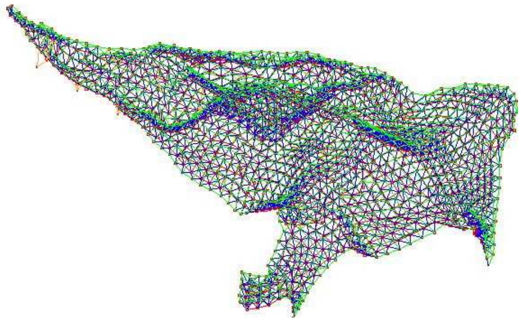

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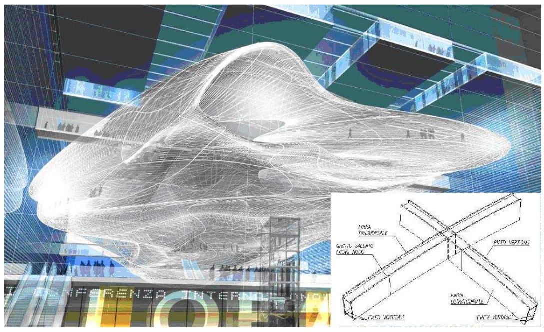

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Tab. 6: 1)-2) Vela over the Unipol Tower plazalin Bologna; 3)-4) Covering of Louvre Visconti square (Arch. Bellini and Ricciotti); 5)-6)"Cometa" Milano PortelloFair (Arch. Bellini); 7)-8)"The Cloud"New Congress Centrei EUR in Rome (Arch. Fuksas).

CONCLUSION

FFD is a challenge for architects and engineers alike but, after the first's impressive realizations, the ethic and aesthetic repercussions of FFD's appeal on the social context must be carefully considered, to avoid the inclination to view innovation, of any kind, as positive merely because it is innovative, irrespective of its real merits or its contribution to knowledge.
From the structural point of view, in order to guarantee the required reliability level, special expertise is needed in the design and construction of free structural morphologies involved in FFD. Considering that modern design & construction activities are part of a complex, holistic, trans-multi and inter-disciplinary process that must achieve a required reliability level a Value Analysis is also highly recommended, even in the preliminary design phase, in order to find the most suitable and compatible solution in accordance with the expected function worth , focusing from the "know-how" to the "know-why", in designing and constructing the "what" or – better - the "what for".

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