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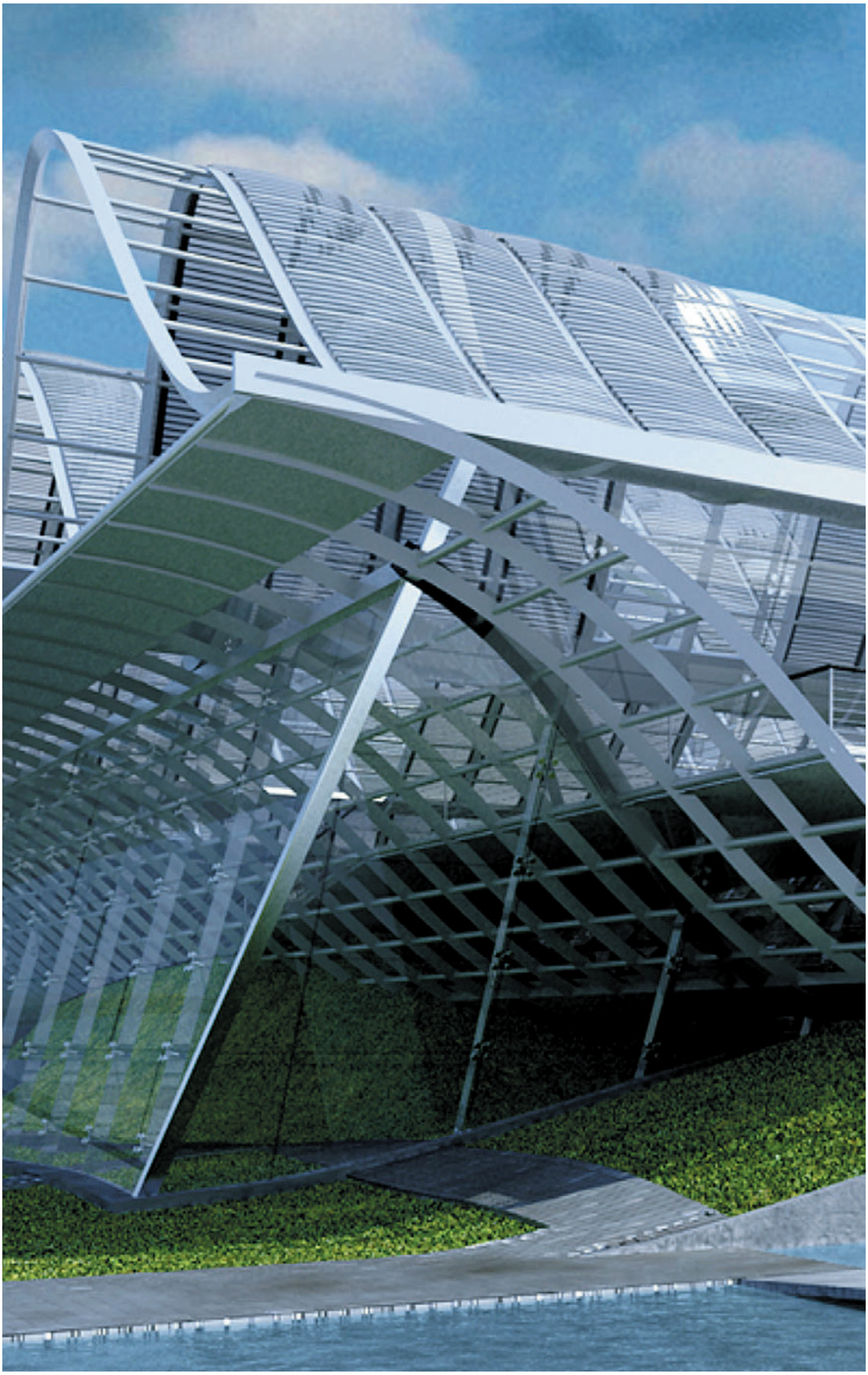

Ernst & Sohn
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The Free Form Design (FFD) in steel structural architecture – aesthetic values and reliability

Today the influence of surface and solid geometrical modelling powerful algorithms allows an unprecedented morphology freedom (FFD) that nobody could have barely imagined in the world of architectural conceptual design. The fast FFD's dissemination and the associated applications: the Free Form Buildings (FFB), some of them representative of a new trend for the actual history of architecture, has brought an "innovation concern" in the traditional design methodology of structural engineering, generating process uncertainties in reliability assessment in general and structural safety warnings in particular.
On the other hand, imitation and originality at any cost, achievable thanks to FFD's user-friendly facilities, lead to ethical problems of sustainability in the technical, cultural and economical fields. The FAST (Function Analysis System Technique) may help to obtain the best value index design solution.

1 Architecture and technology: the influence of IT

The technological innovation of the last few decades, related to new materials and structural typologies, has had an impact on architecture starting up a process of innovation and exerting such a great influence on it to earn the name "hi-tech architecture". Actually, we are currently experiencing a metamorphosis of the language of design brought about by information technology (IT) and computer aided design techniques.

In the process of conceptual architectural design the information technology component, through the employment of geometrical algorithms for the elaboration of surfaces and solids (Rhino, Catia, Maya, etc. Fig. 1) and software stemming from the field of industrial design, has become dominant: the "architectural form" can be "unbuilt" with unimaginable formal and compositional freedom. The result is that the architectural profile of gens, inhabiting a specific time and place and representative of a broader cultural context of belonging with all its corresponding traditions and customs that give rise to authentic architectural sensations, may be quickly homogenized by a globalizing information technology process.

Many of these new "architectural objects" have amazed us and in the name of the definition of the term architecture itself, i. e. a technical/mental activity aimed at modifying the physical environment according to the connected life needs, they have been largely appreciated. We cannot deny that some constructions reach the level of architectural-sculptural art and that the structure becomes merely a body that holds the object of "architectural design". These new architectural creations, based primarily on individual artistic capacity (such as the Sydney Opera House of *Utzon*, 1957–1973 and Bilbao's Guggenheim Museum, 1991–1997 of *Gehry* Fig. 2) might, on the other hand, be viewed as didactic deviations and lead to design imitations that, starting from Aspera could, without reaching Astra, stop at Mediocritas and introduce dangerous "acrobatics" in the structural field. Moreover, the artistic morphological aggregations of some projects inspired by the so-called "Bilbao effect" might lead to considering every building of prismatic configuration as out of fashion.

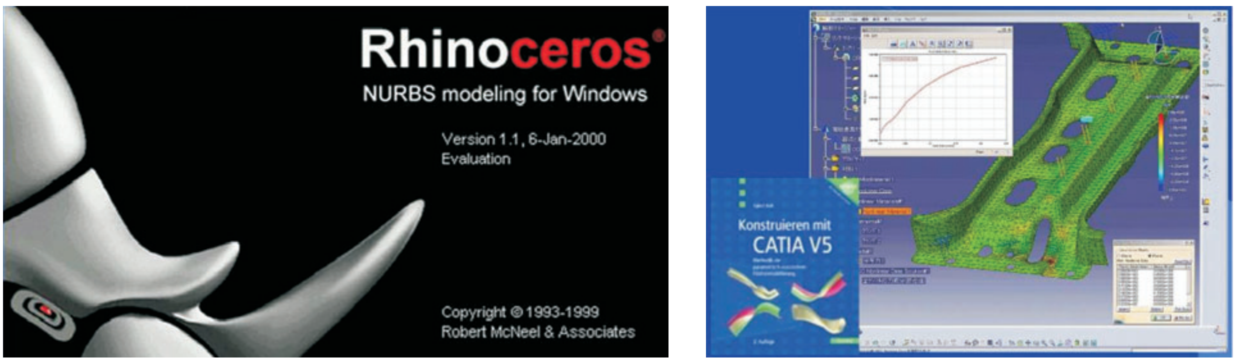

Fig. 1. IT resources for FFB

Fig. 2. FFB: The Sydney Opera House and the Bilbao Guggenheim Museum

2 Structural design uncertainties detected extending the state of the art: a gap between "know why" and "know how"

2.1 Free Form Design (FFD), a challenge for structural engineering?

In present-day realizations free formal expressiveness gives rise to architectural objects such as leaning and twisted towers, sculptured bridges, free-form enclosures and the like whose shape sometimes has no connection whatsoever with structural principles.

As regards discipline, modern examples of structural architecture are no longer correlated as in the past; in the meantime, spectacular architecture has become an international vogue and theatrical aesthetics is being so warmly received in many parts of the world. Even though *Spinoza* states that ethics change in time because substances perceived by the intellect obviously change. The introduction of architectural and structural ethical issues according to the principle of ethical technological responsibility introduced by *Jonas* [1] could prevent some technological and structural stereotypes such as London's Millennium Bridge where structural stability was sacrificed, for instance, to technological astonishment, as well as false conceptual design statements and didactic deviations like the Seville Alamillo Bridge, where the successful design of the landmark was associated with the hypothesis that the bridge inclined tower weight was enough to counterbalance the bridge deck with stays. Most of the material used for the bridge function was in actual fact structurally useless and aimed, instead obtaining a sculpture. Ethics may help obtain more reliable information from designers and realization processes and consequently prevent, at least, designs based on false statements.

The separate analysis of design variables leads to the lack of conceptual correlation, deferred maturation as regards time and as a rule to an overall lower quality. Some design errors, born of the lack of architectural and structural interaction or the non-observation of the ethics of responsibility (sustainability) have been and still are the cause of design flops, legal proceedings, damages and in some cases malfunction and structural collapse of new buildings (which have increased in the last few years).

Considering the statistical results of the "in service" observed behaviour, the unusual typologies, the new materials and, specially, the "scale effect" of wide enclosures and high rise buildings, several special design aspects arise and the following types of uncertainties, in reliability, assessment have been identified [2]:
– phenomenological uncertainties
– decision uncertainties
– human factors
– prediction uncertainties
– physical uncertainties
– modelling uncertainties.

2.2 Phenomenological uncertainties

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. When a new trend produced by the fantasy and imagination of man seem to serve humanity, the challenge is how to accomplish it and learn why it accomplishes its predicted function: the what for.

In actual realizations of free-form architectural objects, whose shape sometimes has no connection whatsoever with structural principles, phenomenological design uncertainties play a very important role. In fact, many contemporaries observe the laws dictated by new design trends as [3] (Fig. 3):
– the prevalence of aesthetics over static rationality
– stringent search for structural efficiency to solve a more complex issue than reality, in order to achieve an original solution
– the categorical rhetoric of structural actions that translate into design languages
– the structure as a sculpture
– mechanistic impressionism
– the metaphorical transposition, into architecture, of nature and other foreign elements
– the rhythmic and monotonous repetition of an architectural motif
– the emphatic representation of a typical element's details, to identify the overall scale
– the introduction of auxiliary IT resources.

According to the design philosophy inherited from *Eiffel. Torroja, Nervi* and others, who designed by looking first and foremost at the construction, quite sure that observing the

Fig. 3. New trends in architecture

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 marveled us and are appreciated in the name of the very definition of the word architecture, as an intellectual and technical challenge 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 Free Form Design.

Conversely, these new architectural realities can be didactically deviant. A structural forgery may induce students and professionals to elaborate design imitations with the introduction of dangerous unbalanced structural systems in morphological sculptured shapes.

Considering that modern designing is a complex, holistic, trans-multi and inter-disciplinary process, which must achieve a required reliability level observing general hypotheses and feasibility constraints, Structural Architecture (SA) presents as a methodology. A reflective knowledge, productive of proper design approaches, within the framework of technological civilization responsibility ethics, in order to reduce phenomenological structural uncertainties.

Ethics must also not be considered as a limit to creativity in searching for a design idea. In particular, according to *Bignoli* [4], the power of human mind as knowledge, understanding, wisdom, fantasy, imagination and intuition allow a phenomenological uncertainty level where to extend creativity matches up with creating a new state of the art (Fig. 4 and Fig. 5).

Some design errors originating from the lack of interaction between architecture and structural engineering under the new design trends and circumstances, or non-compliance with ethical standards according to the principle of responsibility, have been in the past and still are today the cause of serious unsuccessful design ensuing legal proceedings as well as structural malfunctioning and even collapse.

In several cases of actual FFD architecture, many disagreements and a remarkable amount of litigation over the construction resulted from unrealistic expectations, especially in relation to the degree of perfection achievable within a given budget.

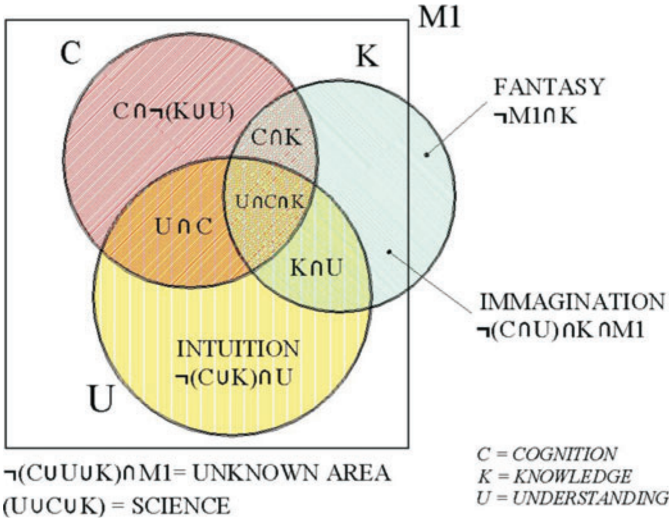

Fig. 4. *Creativity – extending the knowledge*

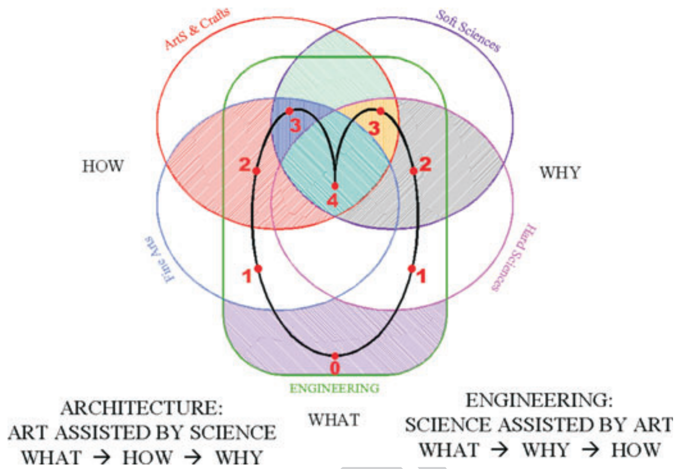

Fig. 5. *Design road map*

Like all iterative processes, the step by step elaboration of the design will generate a reliable solution if the phenomenological uncertainties introduced by fantasy (still belonging to the unknown area) converge to a known and understood area thus increasing knowledge. A divergent design solution has to be considered as a "design failure". With regard to interaction between architecture, structural engineering and ethics, it is important to consider that "failure" is defined as "performance that is not consistent with expectations" [3]. This implies that expectations of success must be realistic and that they take into account also the available resources.

An interesting example, considered at that time to be a rare exception and probably the first example of Free Form Design, is the Sydney Opera House of 1957–1973. A building so beautiful that the users patiently compensate for its gross inadequacies: despite its astonishing exterior, it has never functioned properly as an opera house. Today, on the contrary, the exception becomes the rule. The challenge is, first of all, to obtain a spectacular and impressive form like architectural Free Form Design objects such as: blobs, inclined and twisted high-rise buildings, landmark bridge icons, etc. An interesting contribution regarding the architecture trend after the "Bilbao effect" is by *Filler* [5] who finely makes a distinction between FFB architecture and kitsch. With the same sensibility, the Financial Times (Jan. 2006) makes a distinction between creative residential architecture and sculptured architecture to the detriment of functionality.

A representative example of ethics applied to the evaluation of the resources employed for an aesthetic main design function is that of bridges and footbridges. An interesting research carried out by the Princeton University on the relation between building ethics and aesthetics, presented by *Woodruff* and *Billington* during the Footbridges International Symposium 2005 held in Venice, compares the costs of some footbridges (Fig. 6). Table 1 shows the remarkable difference between the costs of "conventional" and "innovative" footbridges. The question is: How much is too much? Ob-

Fig. 6. *Modern footbridges*

Table 1. Costs of recently built footbridges adapted from Woodruff and Billington [3]

Brigde	Built	Main Span, m	Total Lenght, m	Cost	Cost/m^2
1 London Millennium	2000	140	325	42.000.000	32.600
2 4° Bridge over Canal Grade	2006	83	90	9.400.000	19.580
3 Turtle Bay Sundial	2004	150	230	23.500.000	12.160
4 Solferino	1999	145	140	11.780.000	6.460
5 Casalecchio di Reno	2002	100	120	605.000	1.730
6 Bologna	2008	100	120	2.200.000	3.600

viously, the answer cannot be "the lowest cost" but, rather, the search for the "maximum value" obtainable through the available resources.

The value index is very useful in the decision-making activities, especially for public sector clients, as it allows assessing projects and executions in compliance with the ethics of responsibility (sustainability).

The balanced evaluation of the three functional components SF (service function) EF (esteem function or status symbol) and TF (technical specifications) determines the work's quality. Special attention to the SF component must be paid in the case of Free Form Architecture, something that clients often take for granted as they rely on the "Archistar" of the moment.

By attributing negative values to the evaluation function EF, the value analysis may, for example, prevent some projects that damage the environment ("genius loci" esteem function) as shown by Fig. 7: "…a tied arch bridge that does not respect its surrounding environment at all, next to a stone bridge that is proportionate and dates back to the Roman period" [5].

2.3 Decision uncertainties

Contractual and technical documents often show that the decision-making procedure has been influenced by contrasting objectives. On the one hand, there is the need to have a reliable solution and avoid experimental adventures. On the other hand, the effort to learn from past errors is considered as the contractual permission of allowing original concepts and/or technological "jumps" without sufficient scientific background.

Some owners accept the risk by introducing a higher level of decision uncertainties in the realization process, in view of the possibility to obtain an extra value from a very innovative design, for example: "This building is still today the biggest in the world. The realization come to the end of an ambitious project along a design and construction process plenty of difficulties due, from one side, to technological innovation and, from others, for certain characteristics of the original concept which make his realization very difficult. This construction may be considered a prototype where the observation of his – in service response – represents a precious source of information for the improvement of the concept or, eventually, his abandon".

This remarkable point of view, which allowed the scientific and technological advances in the field of lightweight structures, is very appropriate if correlated and carefully calibrated as an extension of the "state of the art" (see phenomenological uncertainties). On the other hand, the same document states that: "The reliability, durability and safety of the new roof is a priority objective. From this point of view all efforts will be addressed in order to minimize the experimental character of the design and building process".

Yet, in reliability analysis, decision uncertainties are also related to political and financial climates. Therefore, especially in the case of unusual realizations, political and financial decision-making must be supported by expert value analysis and quality control of the functions involved in the design solution. There is no doubt about the possibility of preventing "design failures" through the normal procedures of accurate validation analysis, assuming that necessary knowledge, experience and feedback is property of the client, designers and suppliers.

2.4 Human factors

The uncertainties resulting from human involvement in the design and construction building process can be considered in two categories: human errors and human intervention.

To assure a required reliability level in the field of special structures the design process must be checked in the following three principal phases: the conceptual design synthesis [6], the numerical model and the working design phases.

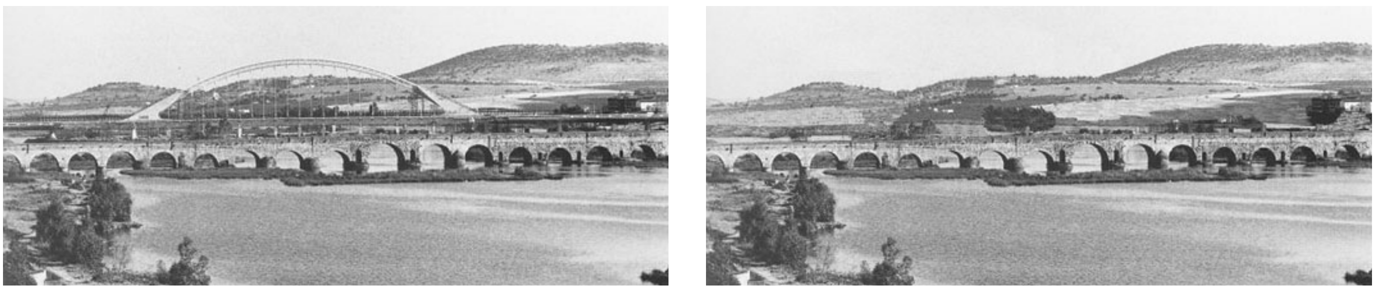

Fig. 7. Avoidable with the „genius loci" function associated with ambient value

The conceptual design is knowledge based and, basically, property of individual experts. Their involvement in early stages of design is equivalent from the reliability point of view to a human intervention strategy of checking and inspection and from a statistical point of view to a “filtering” action which can remove a significant part of “human errors” (Table 2).

A very powerful short-circuit of “gross human errors” may happen, also informally, by human intervention factors as may result from the observation that “something is wrong”; action that directly depends on the skills and abilities of the design team members.

Knowledge-based contribution may remove, from the very beginning, gross errors and reduce, drastically, statistic human errors. Therefore, it is recommendable that checking or validation procedures be activated in early holistic stages of design: the conceptual design phase, where the process is dominated by intuition and expertise (intuition time).

The observation of in-service performance, damages and collapses of whole or part of structural systems has supplied us with plenty information and teachings regarding the design and verification under the action of ultimate and serviceability limit states. Limit state violation for engineered structures has lead to spectacular collapses like the Tay (1879), Quebec (1907) and Tacoma bridges (1940). Sometimes structural failure is the result of an apparently “unforeseeable” phenomenon. The above mentioned Tacoma Narrows Bridge was apparently one of such a case. It was also a design which drew inspiration from earlier suspension bridge designs.

Long span coverings were subject to partial and global failures like that of the Hartford Colisseum (1978), the Pontiac Stadium (1982) and the Milan Sport Hall (1985) due to snow storms, the Montreal Olympic Stadium due to wind excitations of the membrane roof (1988) and snow accumulation (1995), the Minnesota Metrodome (1983) air supported structure that deflated under water ponding, the steel and glass shell sporthall in Halstenbeck (2002), the Acquapark in Moscow (2004), the Roissy air terminal 2E in Paris (2004) and many others. A typical service limit state design failure was detected during the inauguration of the Millennium Bridge in London (2000) (Fig. 8 and Fig. 9).

According to the design methodology (plan of work), the conceptual design may be defined as a knowledge expert approach based on synthetic reliability intuition allowing: a decision making identification of the structural typology, the elaboration of a preliminary numerical model and a subsequent structural analysis and reliability verifications.

The above mentioned concepts are now included in some national building codes, which are normally addressed only to conventional structural systems. As far as innovative designs are concerned, as in the case of most of the realized long span structures, only few comments are dedicated as for instance in the National Building Code of Canada (1990), point A-4.2.4.1: “It is important that innovative designs be carried out by a person especially qualified in the specific method applied…”.

Eurocode 1 intends to guarantee the level of safety and performance by a quality assurance (QA) strategy (point 2) and control procedures of the design process (point 8) in order to minimize human errors. Other human intervention factors addressed to reduce human errors are the formalized methods of Quality Assurance (QA). QA consider the need to achieve – by the institution of a “safety plan” – the

Table 2. Classification of human errors adapted from Baker and Wyatt (1979)

Error type	Human variability V	Human error E	Gross human error G
Failure process	in a mode of behaviour against which the structure was designed		in a mode of behaviour against which the structure was ***not*** designed
Mechanism of error	one or more errors during design, documentation construction and/or use of the structure		engineer’s ignorance or oversight of fundamental behaviour – profession’s ignorance of fundamental behaviour
Possibility of analytic representation	high	medium	low to negligible

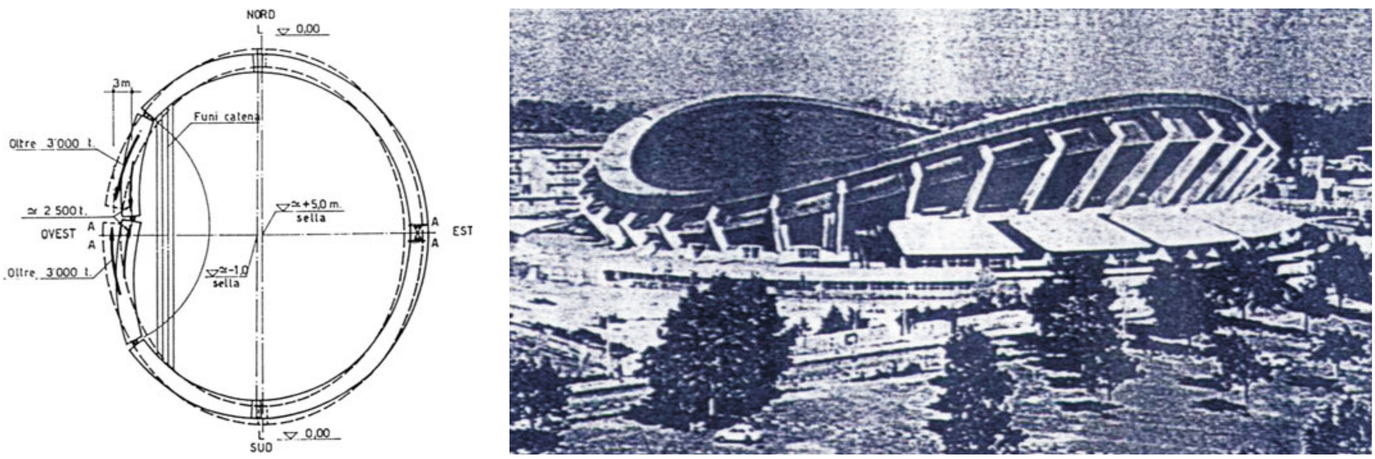

Fig. 8. Milan Sport Hall – roof collapse by snow load (1980)

Fig. 9. Terminal Roissy Airport Paris – shell collapse (2004)

requirements of structural safety, serviceability and durability.

A real danger is that excessive formalization of QA, born for tangible manufactured articles and not suitable for intangible conceptual control procedures could lead to unacceptable and self-defeating degeneration of the design process in a certain kind of *Kafkian* bureaucratic engineering and management. Notice about this phenomenon is given by *Carper* (1996) in (Construction Pathology in the United States) [7]: "many repetitive problems and accidents occur, not from a lack of technical information, but due to procedural errors and failure to communicate and use available information". An important contribution concerning the matter was given by the International Symposium on "Conceptual design of Structures" organized by IASS [8].

2.5 Prediction uncertainties

An estimate of structural reliability depends on the state of knowledge available to the designers. As new knowledge related to the structure becomes available, the estimate will become more refined with, usually but not necessarily, a concomitant reduction of the uncertainty. This applies particularly during the conceptual design phase, when information about actual strengths of materials, new typologies etc. becomes available to replace estimates based on past performances of, and experience with, similar structures.

From the direct experience of the author reduction of uncertainties in designing special structures may be obtained considering [9] and Fig. 10 to Fig. 15:

– compatibility of structural morphology with element shapes and detail design

– the necessity to avoid and short-circuit progressive collapse of the structural system due to local second-

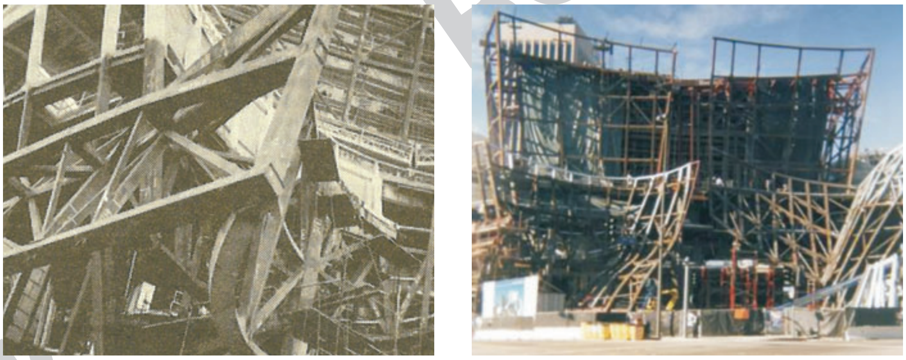

Fig. 10. Walt Disney Concert Hall – Los Angeles

Fig. 11. Couverdure Court Visconti – Louvre

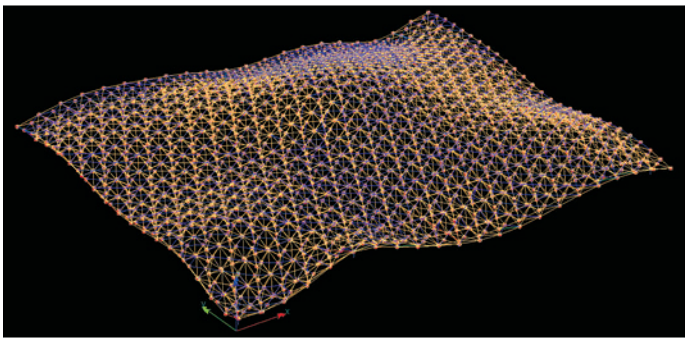

Fig. 12. Space frame structural system

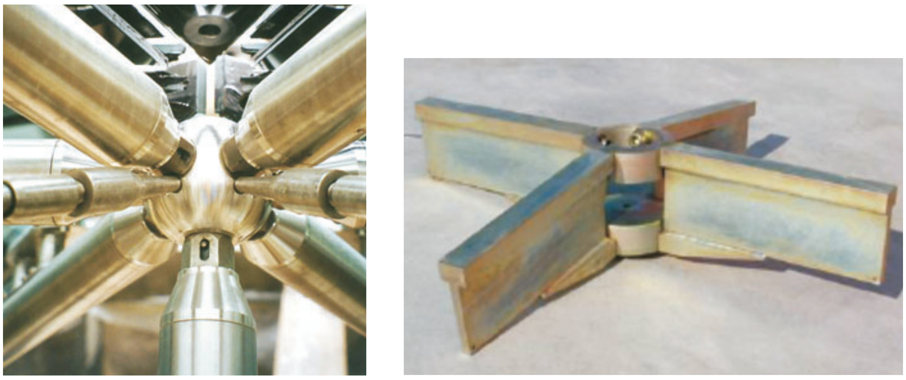

Fig. 13. Details for single and double layer FFD

Fig. 14. Italy – Eur Congress Centre

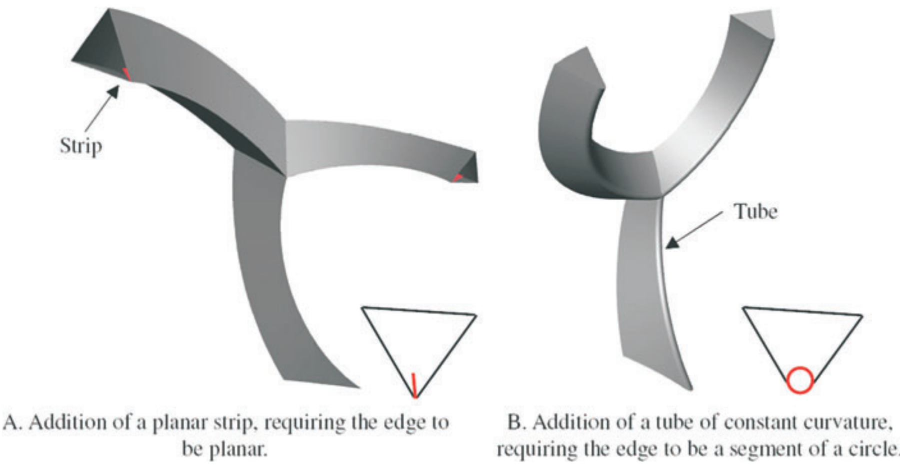

Fig. 15. Customisation of a Deltarib, demonstrated in two prototypes [Veltkamp, 2006]

ary structural element and detail accidental failure
– the compatibility of internal and external restrains with the modelling hypothesis and real structural system response
– 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.

Furthermore, 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.

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 [10] including recommendations for structural design based on observations of malfunction and failures.

2.6 Physical uncertainties

Physical uncertainties are related to loading and material. Concerning wide covering surfaces loading uncertainties may be reduced considering [11] to [15]
– the snow distribution and accumulations on large covering areas in function of statistically correlated wind direction and intensity (Fig. 16 and Fig. 17)
– the wind pressure distribution on large areas considering theoretical and experimental correlated power spectral densities or time histories (Fig. 18 to Fig. 21) [16]
– the time dependent effect of coactive indirect actions as pre-stressing, short and long term creeping and temperature effects.

Design assisted by testing (see Eurocode 3, point 8), as experimental investigation in boundary layer wind tunnel scale models and monitoring in actual structures, have an important role in structural design of wide enclosures. Regarding the material uncertainties, special care must be addressed to the reliability and safety factors of new hi-tech composite materials.

The uncertainties of the material, associated to the very high ratios between live loads/dead weight, which are an evident characteristic of lightweight constructions, increase considerably the statistical uncertainties. For instance, the fragility of membrane fabric materials to initial tear propagation is incompatible with possibili-

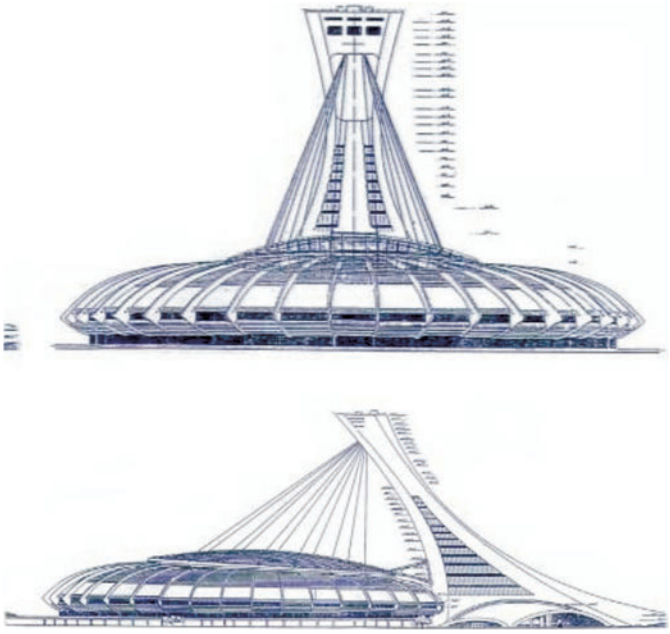

Fig. 16. Montreal Olympic Stadium – A cable stayed solution

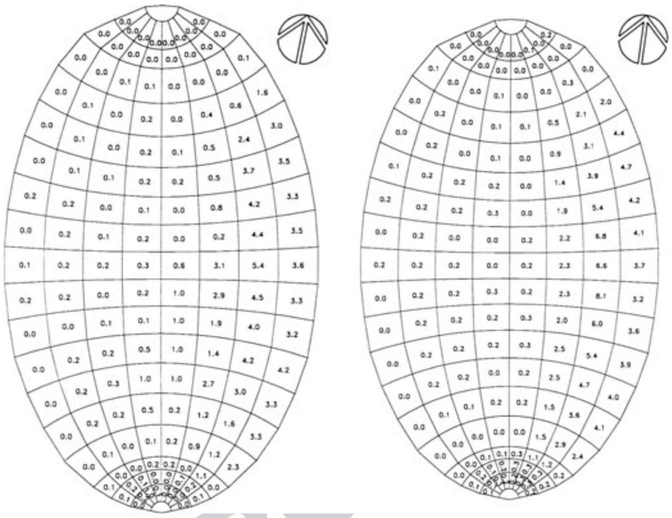

Fig. 17. Comparative analysis of snow loading distribution in function of roof shape (10 m to 13 m)

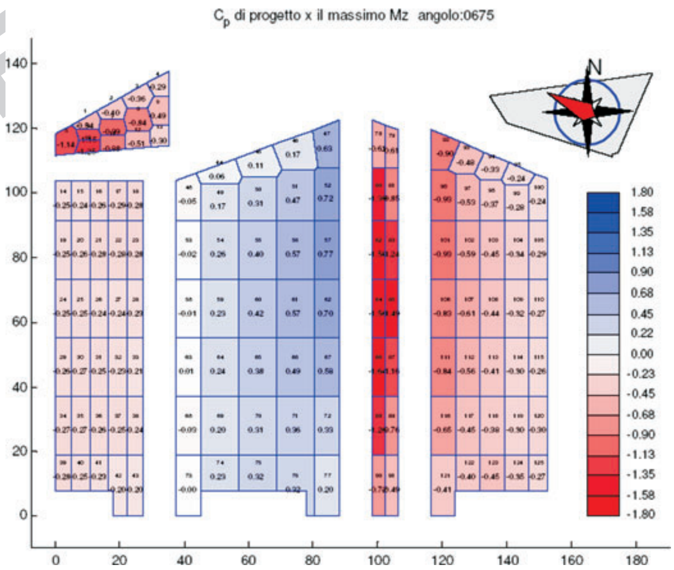

Fig. 18. Wind tunnel test for the Unipol Tower of Bologna

Fig. 19. Wind tunnel test on aeroelastic models for the new city hall of Bologna

Fig. 20. *An image of the Olympiakos Stadium in Athens*

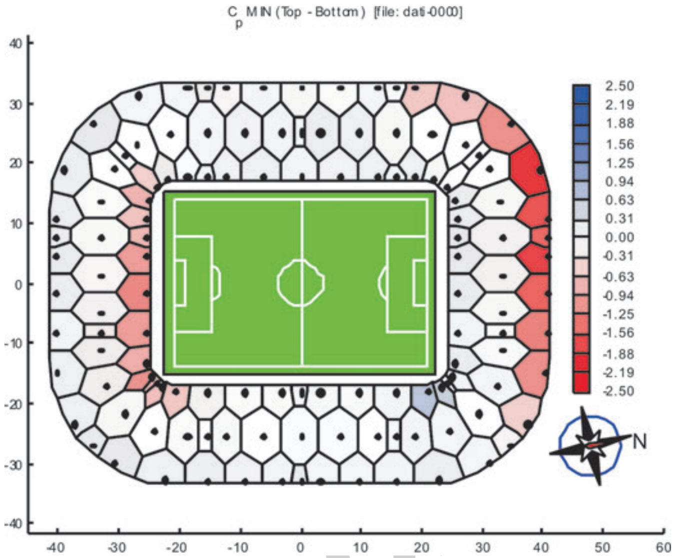

Fig. 21. *Maximum and minimum values of net pressure coefficients (wind direction: 0°)*

ties of ice sack formation (ponding effects) that could slide on and cut the membrane.

Expertise in structural detail design, which is normally considered as a micro task in conventional design, have an important role in special long span structures: reducing the model and physical uncertainties and preventing chain failures of the structural system.

2.7 Model uncertainties

Uncertainties related to the design process have been also identified in structural numerical modelling, which represents the ratio between the actual and the expected model's response.

The reconciliation with 19^{th}-century theory and the harmonization of the various theories has nonetheless been a laborious process, which was made possible by the increasingly intense contribution of symbolic language and, above all, by the huge impact of available software and hardware computer facilities, using matrix language and discretization methods, especially finite elements methods (FEM, BEM etc.) for the numerical analysis of continua.

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.

We live in the era of "language metamorphosis", as it was called by *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.

Oden and *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 30 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".

Under those apparently favourable circumstances, many documented structural failures has been detected where mistakes in the inadequate appreciation of structural behaviour was caused by unreliable man-machine interaction and the illusion that the computers, as powerful instrument of analysis could replace conceptual design. For this purpose, IABSE have set up a special commission for the control of automation in structural design [16]. FEM modelling errors are illustrated in the First International Conference on computational Structures Technology [17].

The interactive software for analysis and design of special structural systems [18], as normally involved in wide span enclosures requires in order reducing modelling uncertainties, more than general purpose programs, addressed software to assist on many aspects of theoretical analysis as:
– state "0" form-finding analysis for the shape-finding of cable, membrane and pneumatic structures (Fig. 22)
– non linear material analysis for elastic, inelastic and plasticity including short and long term creeping (Fig. 23 and Fig. 24)

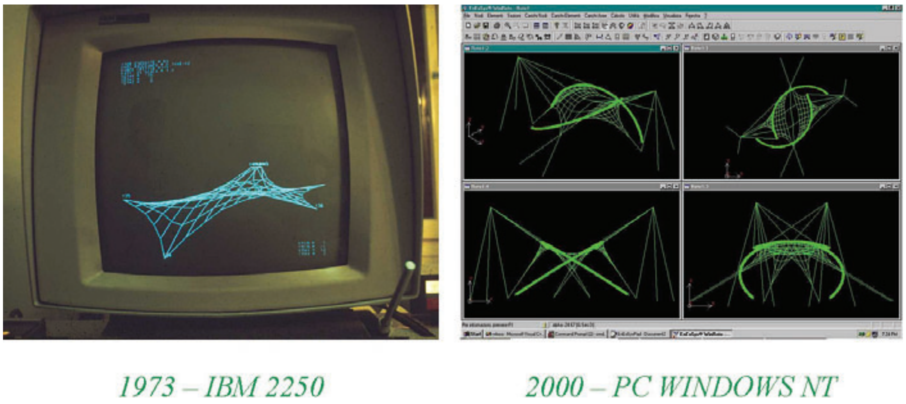

Fig. 22. Hardware and software evolution

– non linear geometrical analysis; for the static and dynamic analysis under large displacements
– incremental non linear analysis to detect local and global structural instability
– stochastic dynamic analysis in frequency domain for the buffeting response under the random wind action considering static, quasi-static and resonant contributions, assisted by the experimental identification on scale rigid models of cross-correlated power spectral densities (PSD) of the inter-

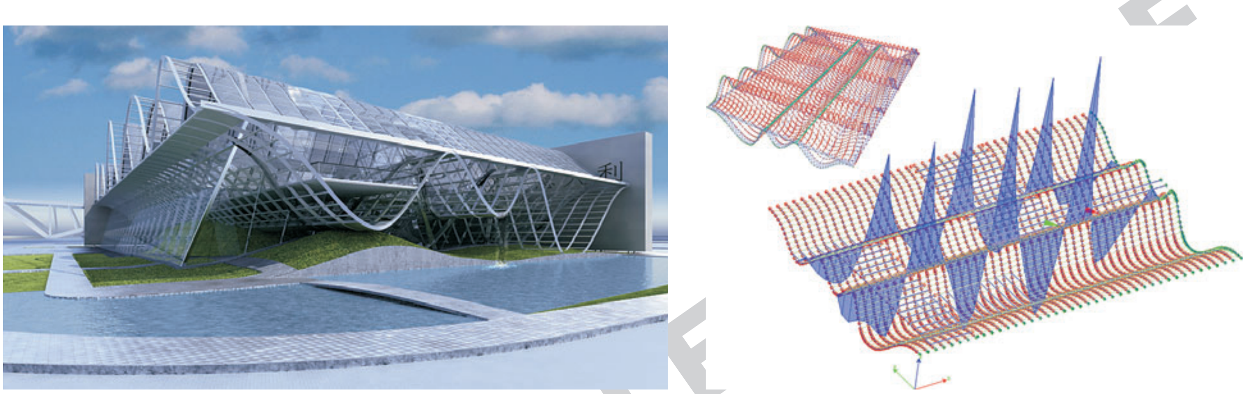

Fig. 23. 3D rendering and numerical model of the Italian stand for the Expo 2010 in Shanghai

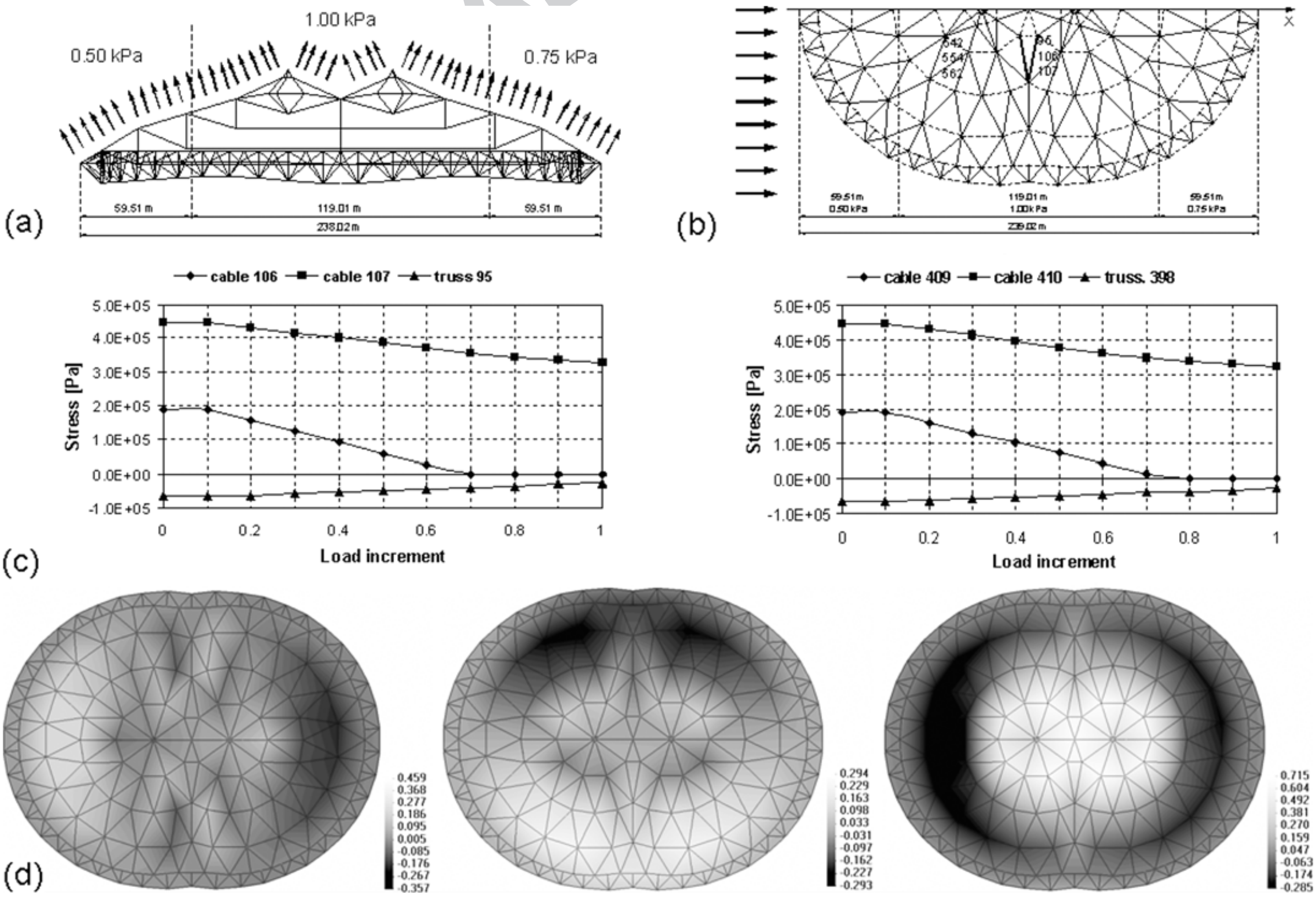

Fig. 24. La Plata Stadium validation analysis. Wind in X direction: (a) load configuration; (b) null cable stresses; (c) stress diagrams and (d) displacements along X, Y and Z direction.

nal and external pressures on large enclosures (Fig. 25 and Fig. 26)
– stochastic dynamic analysis in time domain for the control of the aerodynamic stability of wide and flexible structural systems under wind excitation, assisted by the experimental identification on aeroelastic scale models of the cross-correlated time histories, considering fluid interactions (Fig. 27 and Fig. 28)
– application of the optimization techniques to the structural design (Fig. 29)
– parametric stochastic sensibility & reliability analysis (Fig. 30 and Fig. 31).

3 Conclusions

FFD is a challenge for architects and engineers alike but, after the first's impressive realizations, the ethic and esthetic repercussions of FFB'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 reli-

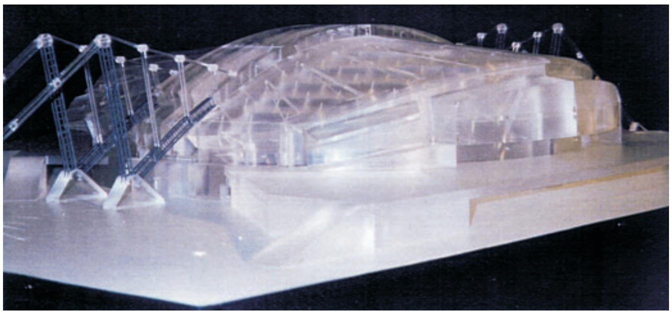

Fig. 25. Views of pressure model of Thermis Sport Hall

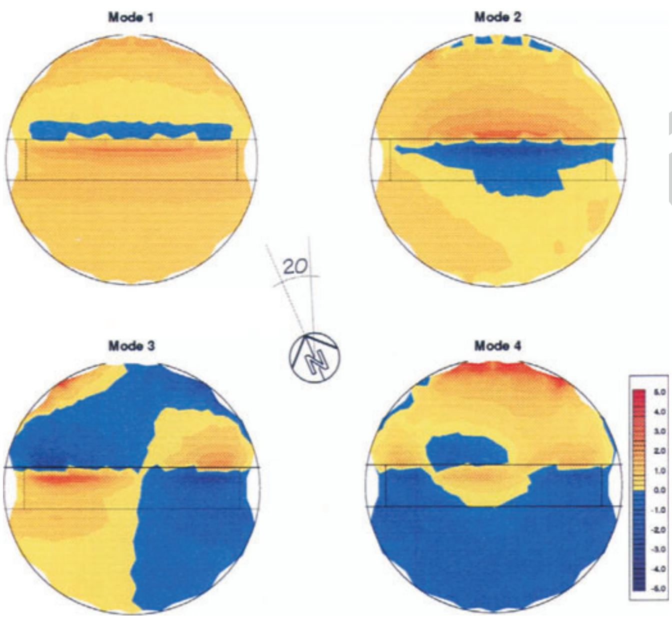

Fig. 26. Orthogonal decomposition: pressure mode shapes

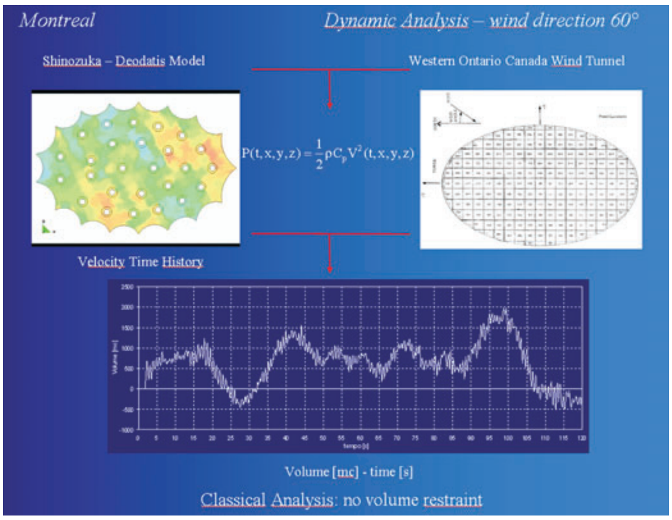

Fig. 27. Dynamic analysis

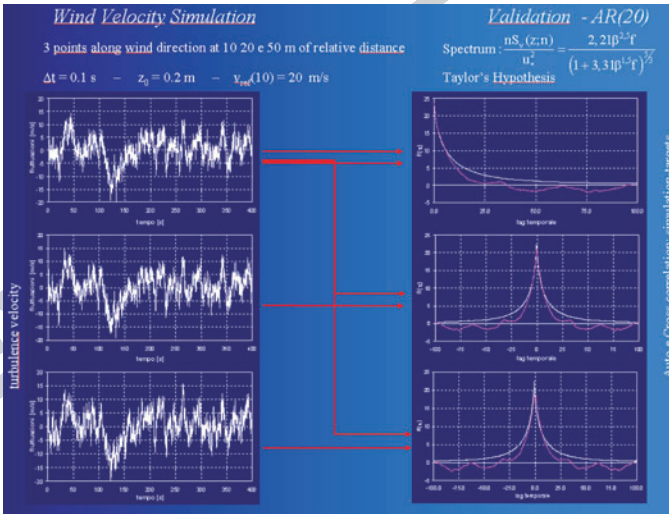

Fig. 28. Wind velocity simulation

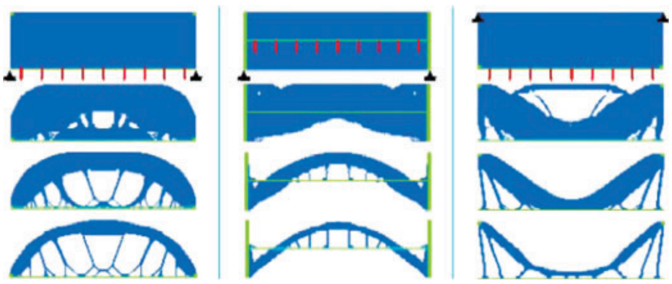

Fig. 29. Optimisation sequences [19]

Fig. 30. The new suspended cable roof of Braga Stadium (Portugal)

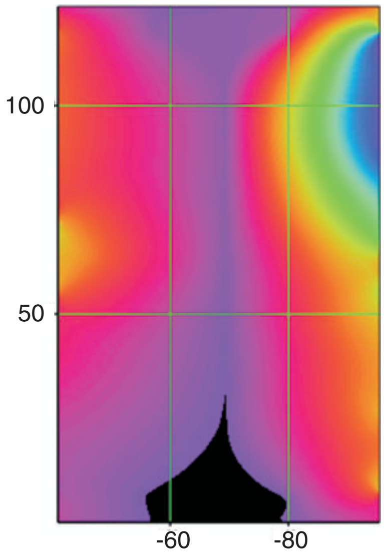

Fig. 31. β-Safety Index distribution, evidencing a limit state violation

ability level, special expertise is needed in the design and construction of free structural morphologies involved in FFB. 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.

References

[1] *Jonas, H.*: El principio de Responsabilidad. Herder, Barcellona, 1995.
[2] *Puppo, A. G., Bertero, R. D.*: Evaluation of Probabilities using Orientated Simulation. Journal of Structural Engineering 118 (1992), No. 6, pp. 1683–1704.
[3] *Woodruff, S., Billington, D.*: Aesthetics and Ethics in pedestrian bridge design. Footbridge 2005, 2nd International Conference, Venice, Italy, 6–8 December 2005.
[4] *Bignoli, A. J.*: Interaction between ethics and engineering. The Plan. Architecture & Technologies in Detail 3 (2003), pp. 13–20.
[5] *Filler, M.*: The New York Review of books. Vol. 52, No. 20, December 2005.
[6] *Samartin, A.*: Application of optimization techniques to structural design. Lightweight structures in civil engineering, Warsaw, Poland, September 1995.
[7] *Carper, K.*: Lessons architects can learn from failures. Structural Failures and Reliability of Civil Structures, Venice, Italy, 6–7 December 2001.
[8] *Vickery, B. J.*: Wind loads on the Olympic Stadium – Orthogonal decomposition and dynamic (resonant) effects. BLWT-SS28A, 1993.
[9] *Majowiecki, M.*: Snow and wind experimental analysis in the design of long span sub-horizontal structures. Journal of Wind Engineering and Industrial Aerodynamics 74 (1998), pp. 795–807.
[10] Structural Design of Retractable Roof Structures. IASS working group n°16, WIT Press, 2000.
[11] RWDI: Roof snow loading study-roof re-design Olympic Stadium Montreal, Quebec. Report 93-187F-15, 1993.
[12] *Vickery, B. J., Majowiecki, M.*: Wind induced response of a cable supported stadium roof. Journal of Wind Engineering and Industrial Aerodynamics 41–44 (1992), pp. 1447–1458.
[13] First International Conference on Computational Structures Technology, Heriot-Watt University, Edinburgh, U.K., August 1991.
[14] *Majowiecki, M., Trevisan, R.*: A graphic interactive software for structural modelling analysis and design. Space Structures 4. London: Thomas Telford 1993.
[15] *Lazzari, M., Majowiecki, M., Saetta, A., Vitaliani, R.*: Analisi dinamica non lineare di sistemi strutturali leggeri suborizzontali soggetti all'azione del vento. 5° Convegno Nazionale di Ingegneria del vento, ANIV, Perugia, Italy, 1998.
[16] Working Commission V: Using computers in the design of structures. IABSE proceedings.
[17] First International Conference on Computational Structures Technology. Heriot-Watt University, Edinburgh, U.K., August 1991.
[18] *Dietrich, R. J.*: Faszination Brücken. München: Callwey Verlag 1998.
[19] *Baker, W. F., Novak, L. C., Jajich, D., Beghini, A.*: Optimisation tools for the conceptual design of structures, IASS, Venice, Italy, 2007.

Key words: Free Form Design (FFD), design methodology, structural morphology, reliability assessment

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