

STRUCTURAL ARCHITECTURE OF WIDE SPAN ENCLOSURES: UNCERTAINTIES IN RELIABILITY ASSESMENT

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Key words: *structural architecture, wide span structures , reliability, experimental analysis, monitoring.*

1. ABSTRACT

Long span roof are today widely applied for sport, social, industrial, ecological and other activities. The experience collected in last decades identified structural typologies as space structures, cable structures, membrane structures and new - under tension - efficient materials which combination deals with lightweight structural systems, as the state of art on long span structural design. Many novel projects of long span structures attempt to extend the "state of the art". New forms of construction and design techniques, adopted in actual conceptual design methodology, generate phenomenological uncertainties about any aspect of the possible behavior of the structure under construction service and extreme conditions. Other factors as human errors, negligence, neglected loadings and/or poor workmanship are most often involved in malfunction, failures and collapses. In order to increase the reliability assessment of wide span structural systems a knowledge based synthetic conceptual design approach is recommended. Theoretical and experimental in scale analysis, combined with a monitoring control of the subsequent performance of the structural system, can calibrate mathematical modelling and evaluate long term sufficiency of design.

2. INTRODUCTION

Long span structures are today widely applied mainly for:

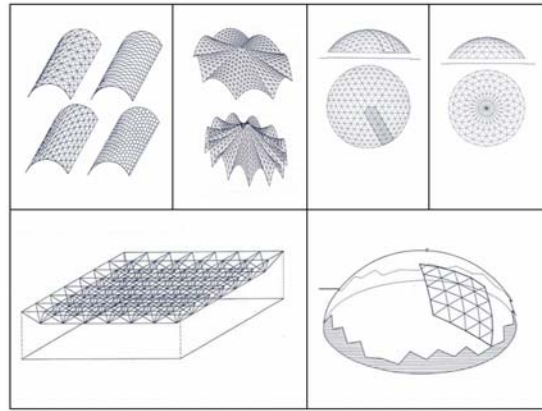
- | | | |
|--------------------------------|---------------------------|--------------------------|
| Sport buildings | Social buildings | Industrial buildings |
| - Stadia | - Fair pavillions | - Hangars |
| - Sport halls | - Congress halls | - Warehouses |
| - Olympic swimming pools | - Auditorium and theatres | - Airport terminals |
| - Ice tracks and skating rinks | - Open air activities | - Waste material storage |

2.1 The state of the art trend on widespan enclosures: the lightweight structures - from compression to tension.

According to the state of the art, the more frequently typologies and materials used for wide span enclosures are:

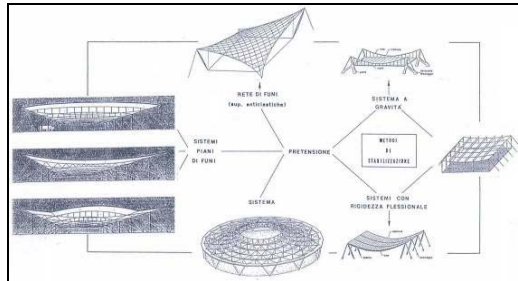
Space structures

- single layer grids
- double and multi layer grids
- single and double curvature space frames [1]



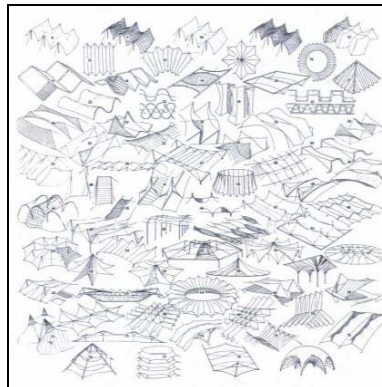
Cable structures

- cable stayed roofs
- suspended roofs
- cable trusses
- single and multilayer nets [2]



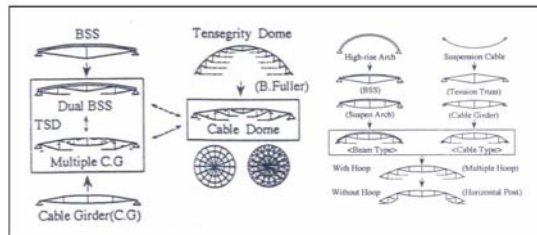
Membrane structures

- prestressed anticlastic membranes
- pneumatic membranes [3]



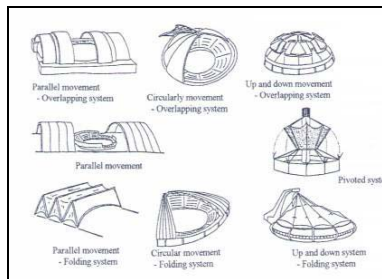
Hybrid structures

- tensegrity systems
- beam-cable systems [4]



Convertible roofs

- overlapping sliding system
- pivoted system
- folding system [5]



The historical trend in the design and construction process of wide span enclosures was and is the minimization of the dead weight of the structure and , consequently, the ratio between dead and live loads (DL/LL).

From ancient massive structures (DL/LL>>1) to modern lightweight structures (DL/LL<<1), the DD/LL ratio was reduced more than 100 times due to the most effective exploitation of the properties of special high-strength materials, in combination with structural systems where tensile stresses are dominant (Tension structures). Due to the inherent stability of tension against compression, tension structures leads naturally to optimization of the system energy against structures which are subjected to bending moments or are stressed axially with the possibility of reversal from tension to compression, as is the case with grids and framed structures. Therefore, the actual trend on lightweight structural typologies is to combine, as far as possible, a dominant tension mechanical system and hi-strength materials.

In Table 1, is possible to observe the exceptionally efficiency of conventional and HS steels and hi-tech materials observing the strength to weight ratio ($K=\sigma/\gamma$) in tension (K_t). Considering also the cost/weight ratio and the inherent reliability, steel remain the reference construction material for long span structures.

The different mechanical behaviour of compression and tension structures can be illustrated by Fig.1 where, starting from a thin parabolic arch under uniform distributed load , it is possible to observe, during incremental loading, the following phases of the load displacement curve:

- Phase A: unloaded structure.
- Phase AB: compression phase; geometric softening; decrease of tangential stiffness, reduction in the positive value of the secondary term of the total potential energy $\delta^2\pi$.
- Phase BCE: unstable phase; dynamic displacement from B to E with liberation of kinetic energy (cross hatched area). Here, the secondary term of total potential energy is negative ($\delta^2\pi < 0$).
- Phase DEF: tension phase; geometric hardening increase in the tangent stiffness, branch of stable equilibrium with increasing value of secondary term of the total potential energy ($\delta^2\pi > 0$). Phase DEF is characteristic of the behaviour of tension structures. The non-linear geometric hardening results in a less than proportional increase of stresses in relation to increase external loads. This provides an increased nominal safety factor evaluated at ultimate limit state (β safety index).

MATERIALS	σ_t^R N/mm ²	σ_c^R N/mm ²	γ_k N/m ³ 10 ³	K_t m	K_c m
Bricks		3	18		166
Wood	85	37.5	5	21.250	9.375
Concrete		30	25		1.200
S 355	520		79.5	6.664	----
S 460	640		79.5	8.050	
S 690	860		79.5	10.080	
S 850	1050		79.5	13.376	----
Titanium	900		45	20.000	----

Table1. Mechanical properties of construction materials

MATERIALS	σ_t^R N/mm ²	σ_c^R N/m m ²	γ_k N/m ³ 10 ³	K_t m	K_c m
Unidir. Carbon fibres	1400		15.5	90.000	
Textile carbon fibres	800		15.5	52.000	---
Unidir. Aramid ic fibres	1600		13	123.000	---
Textile aramidic fibres (Kevlar)	750		13	58.000	---
Unidir. Glass fibres	1100		20	55.000	---
Textile glass fibres	450		20	22.500	---

Table 2. Composite hi-tech materials

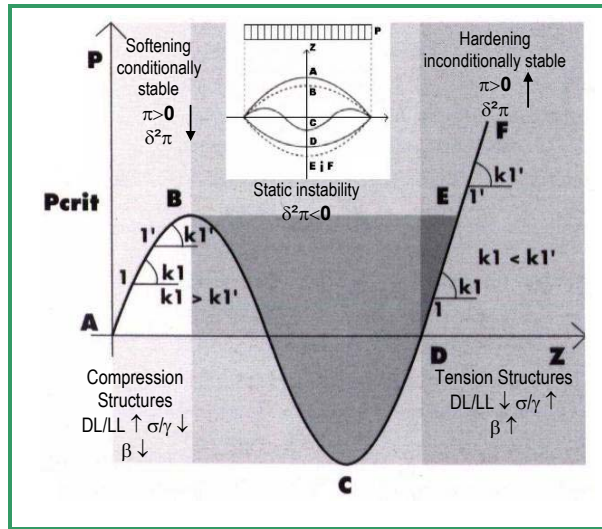


Fig.1: Mechanical behaviour from arch to cable

Several steel long span enclosures, designed by the author according the above mentioned structural typologies, are shown in Appendix 1.

3. UNCERTAINTIES IN RELIABILITY ASSESMENT

3.1 OBSERVED LIMIT STATE VIOLATIONS IN LONG SPAN STRUCTURES

From the observations of the in service performance, damages and collapses of all or part of structural systems, we have received many informations and teachings regarding the design and verification under the action of ultimate and serviceability limit states. Limit state violation for engineered structures have lead to spectacular collapses as the Tay (1879) and Tacoma bridges (1940). Sometimes an apparently "unimaginable" phenomenon occurs to cause structural failure. The Tacoma Narrows Bridge previously cited was apparently one such a case. It was also a design which departed considerably from earlier suspension bridge design.

Long span coverings were subjected to partial and global failures as that of the Hartford Coliseum (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 (Fig. 2-8).

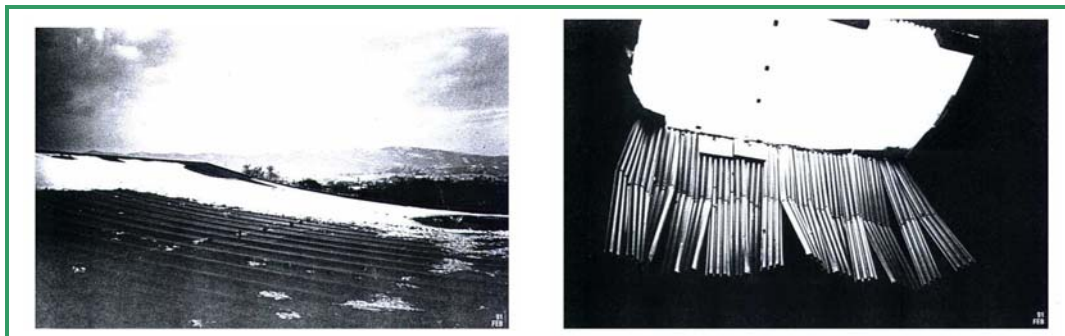


Fig.2 Sport hall Arezzo- Partial collapse by local Ponding (1980)

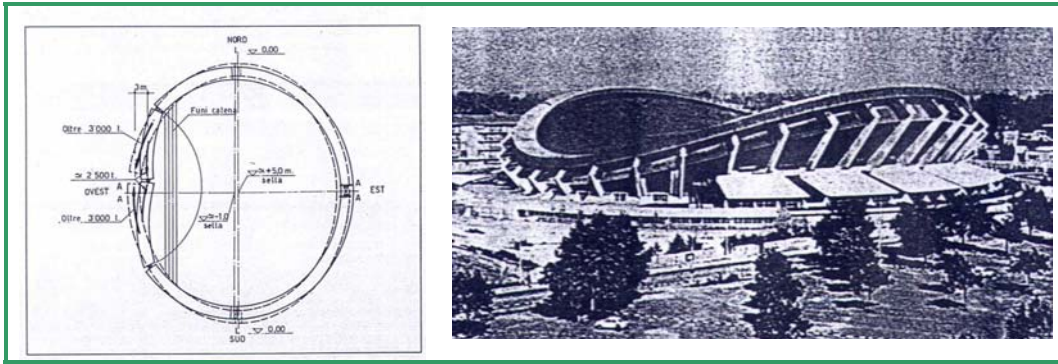


Fig.3 Milan Sport Hall – Roof collapse by snow load (1980)



Fig.4 Olympic Stadium Montreal – Roof failure under wind action (1988)

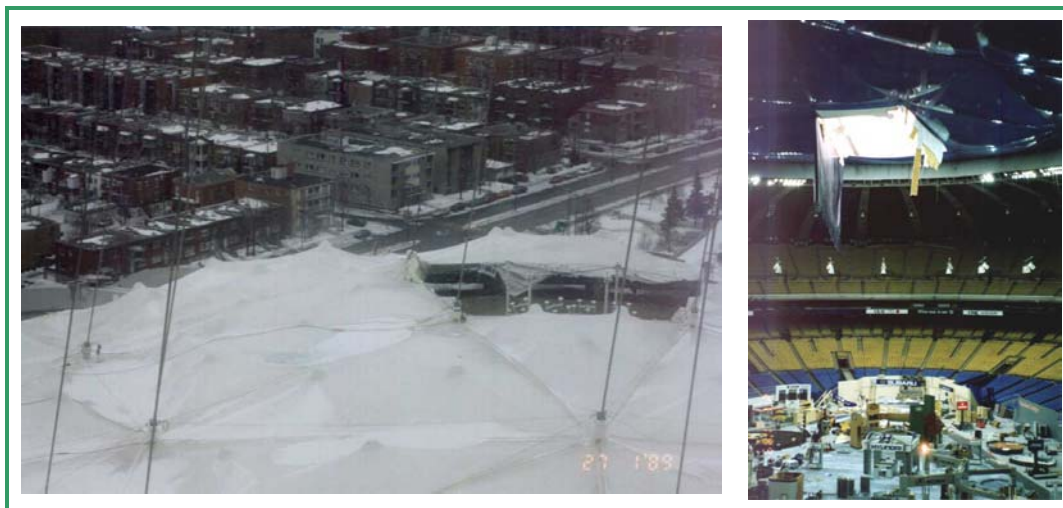


Fig.5 Olympic Stadium Montreal – Partial roof collapse by snow accumulation (1995)

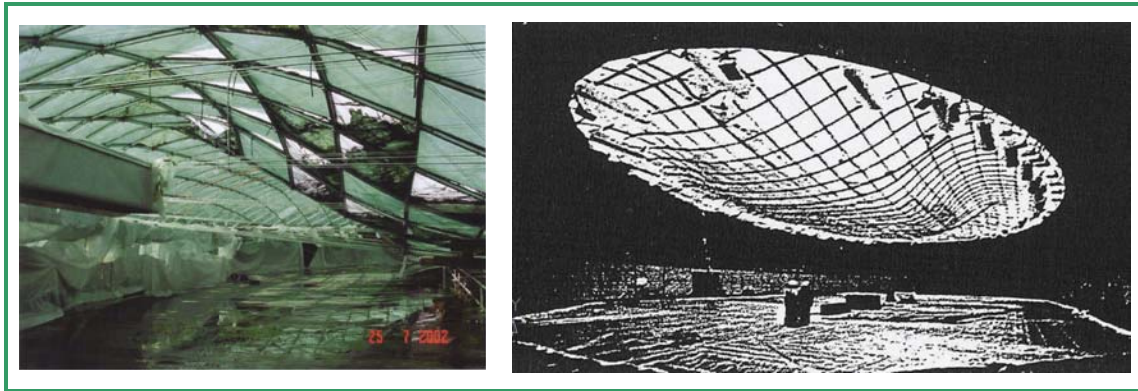


Fig.6 Sport Hall Halstenbeck – Global instability collapse (2002)



Fig.7 Acquapark and swimming hall Moscow – Roof collapse (2004)



Fig.8 Terminal Roissy Airport Paris – Shell collapse (2004)

Those cases are lessons to be learned from the structural failure mechanism in order to identify the design and construction uncertainties in reliability assessment.

According to Pugsley (1973), the main factors which may affect "proneness to structural accidents" are:

- new or unusual materials;
- new or unusual methods of construction;
- new or unusual types of structure;
- experience and organization of design and construction teams;
- research and development background;
- financial climate;
- industrial climate;
- political climate.

All these factors fit very well in the field of long span structures often involving something "unusual" and clearly have an influence affecting human interaction.

In Table 3, the prime cause of failure gives 43% probability (Walker, 1981) to inadequate appreciation of loading conditions or structural behaviour (Table3).

Cause	%
Inadequate appreciation of loading conditions or structural behavior	43
Mistakes in drawings or calculations	7
Inadequate information in contract documents or instructions	4
Contravention of requirements in contract documents or instructions	9
Inadequate execution of erection procedure	13
Unforeseeable misuse, abuse and/or sabotage, catastrophe, deterioration (partly "unimaginable"?)	7
Random variations in loading, structure, materials, workmanship, etc.	10
Others	7

Table 3. Prime causes of failure. Walker (1981).

Factor	%
Ignorance, carelessness, negligence	35
Forgetfulness, errors, mistakes	9
Reliance upon others without sufficient control	6
Underestimation of influences	13
Insufficient knowledge	25
Objectively unknown situations (unimaginable?)	4
Remaining	8

Table 4. Observed error factors. Matousek and Schneider (1976)

Apart from ignorance and negligence, it is possible to observe that the underestimation of influence and insufficient knowledge are the most probable factors in observed failure cases (Table4).

4. LONG SPAN STRUCTURES -DESIGN PROCESS UNCERTAINTIES EVALUATION

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 and the following types of uncertainties, in reliability assessment, have been identified [6] :

- phenomenological uncertainties.
- human factors;
- prediction uncertainties;
- physical uncertainties;
- modelling uncertainties.

4.1 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. 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. Many contemporaries observe the laws dictated by new design trends as [7] (Fig.9):

- 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.

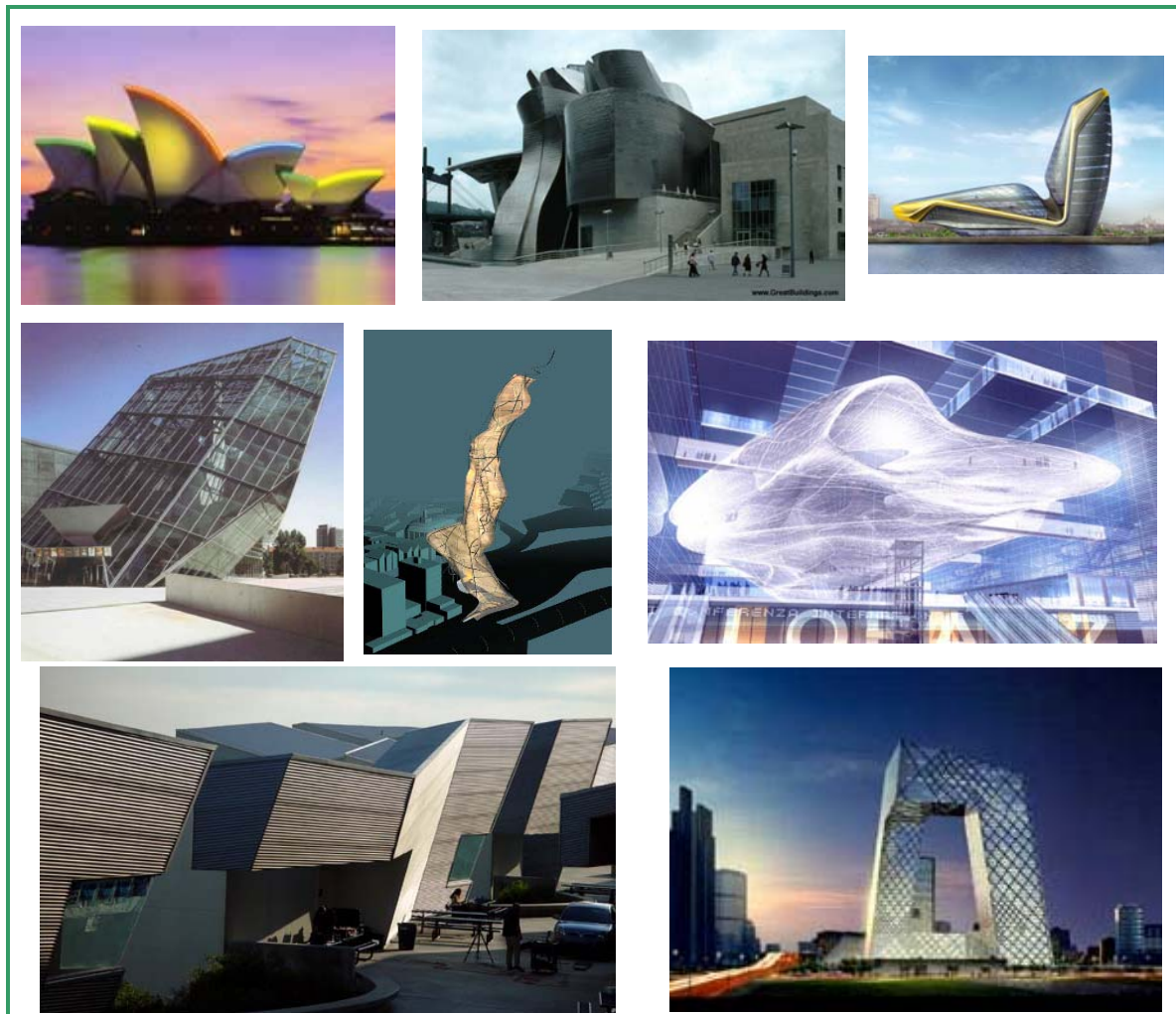


Fig. 9. New trends in architecture

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 marveled 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.

Conversely, these new architectural realities essentially based on individual artistic capabilities can be didactically deviant. A structural forgery may induce students and professionals to elaborate design imitations, with the introduction of dangerous unbalanced structural systems and/or morphological sculptured shapes making any prismatic configuration building look outdated.

The disciplinary correlation between architecture and structures, conceived as an integrated design language, may be stated as non-existent or false in many modern constructional realities affected by new painting and sculpture, scenic and cartoonist design variables. Modern examples of structural architecture are no longer correlated in disciplinary terms as in the past. Even though Spinoza states that ethics change in time because substances the intellect perceives obviously change, the introduction of architectural and structural ethical issues, according to the principle of technological ethical responsibility introduced by Hans Jonas[8], could prevent some technological and structural stereotypes, such as London's Millennium Bridge where structural stability was sacrificed to generating technological astonishment for instance, as well as false conceptual design statements, didactically deviating, such the Seville Alamillo Bridge, where successful design as a landmark was associated with the hypothesis that the bridge inclined tower weight was enough to counterbalance the bridge deck with stays, while most of the material used for the bridge function was, in actual fact, structurally useless but addressed to obtain a sculpture. Ethics may help to obtain a more reliable information from design actors and realizations process and, consequently, prevent, at least, design imitations based on false statements.

Ethics must also not be considered as a limit to creativity in searching for a design idea .In particular, according to Bignoli[9], 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.10).

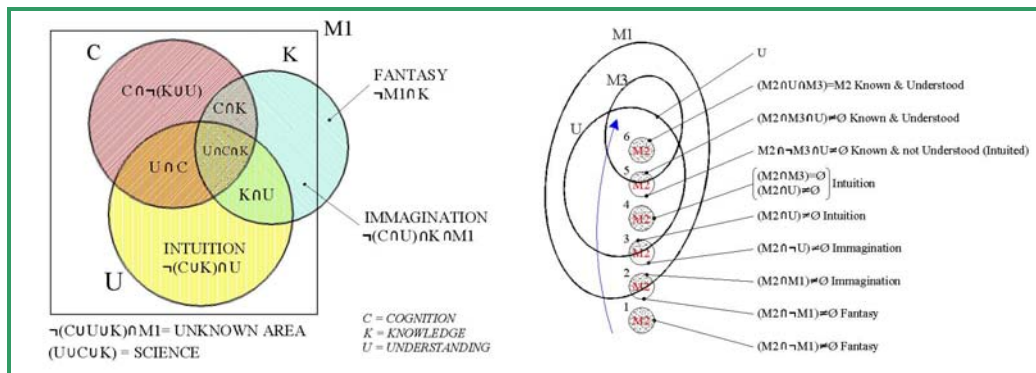


Figure 10. Creativity – extending the Knowledge

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. Considering that modern designing is a complex, holistic, trans-multi and interdisciplinary process, that 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.

4.2 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 [10], the numerical model, and the working design phases.

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" (Table5).

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 <i>not</i> 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

Table 5. Classification of human errors: Adapted from Baker and Wyatt (1979)

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).fig.11-12

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.

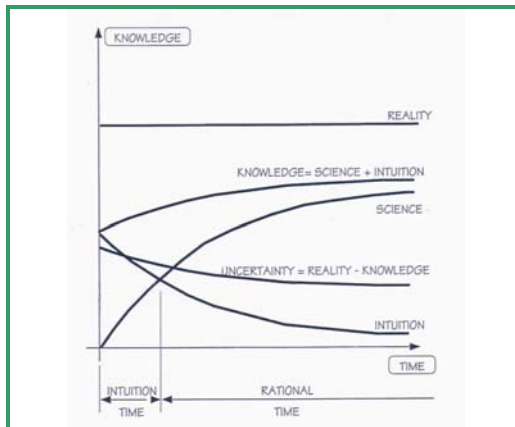


Fig. 11. Knowledge reducing uncertainties in design process

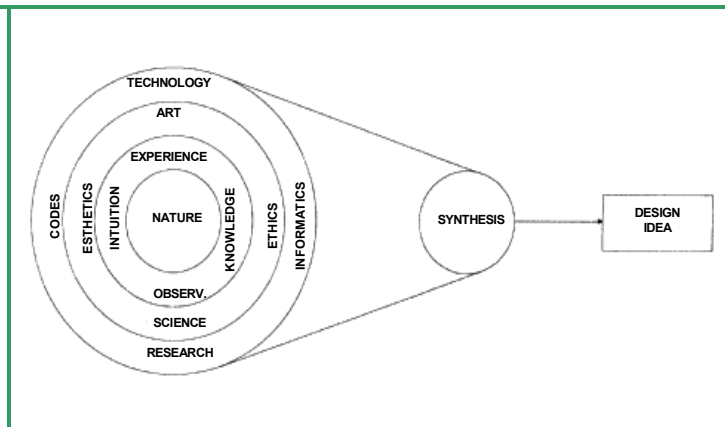


Fig.12 Holistic design approach

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 no. 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 consider the need to achieve, by the institution of a "safety plan", the requirements of structural safety, serviceability and durability.

QA procedures include:

- a) proper definition of functions;
- b) definition of tasks, responsibilities, duties;
- c) adequate information flow;
- d) control plans and check lists;
- e) documentation of accepted risks and supervision plan;
- f) inspection and maintenance plan;
- g) user instructions.

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 phenomena is given by Carper (1996) in (Construction Pathology in the United States) [11]: "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 [12].

4.3 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 writer, reduction of uncertainties in designing special structures may be obtained considering [13]. :

- the necessity to avoid and short-circuit progressive collapse of the structural system due to local secondary structural element and detail accidental failure;
- the compatibility of internal and external restrains and detail design, with the modeling 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 [5] including recommendations for structural design based on observations of malfunction and failures.

4.4 Physical uncertainties

Physical uncertainties are related to loading and material.

Concerning wide covering surfaces loading uncertainties may be reduced considering[14-18].:

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

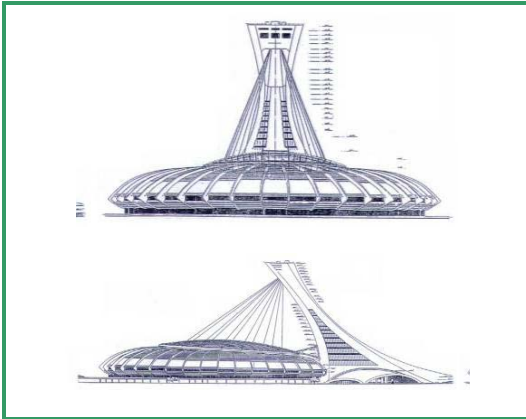


Figure 13. Montreal Olympic Stadium.
A cable stayed roof solution

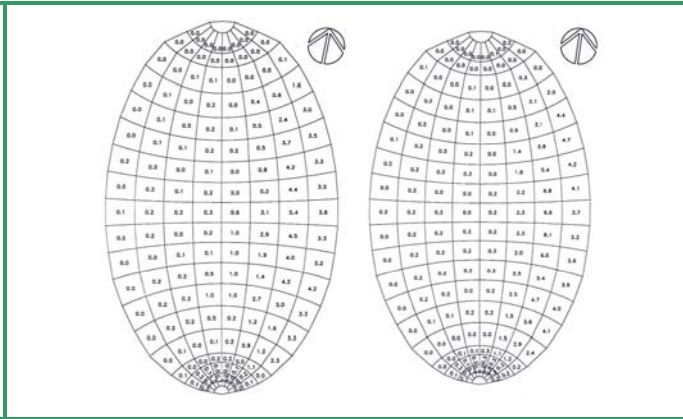


Figure 14. Comparative analysis of snow loading distribution in function of roof shape (10-13m) [7]

- the wind pressure distribution on large areas considering theoretical and experimental correlated power spectral densities or time histories (Fig. 15-16) [19];
- the time dependent effect of coactive indirect actions as pre-stressing, short and long term creeping and temperature effects.



Figure 15.3D rendering of the Olympiakos Stadium in Athens

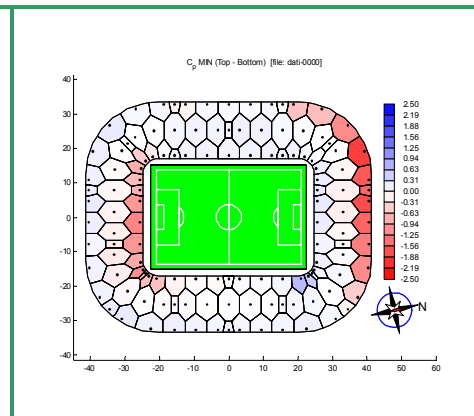


Figure 16. Maximum and minimum values of net pressure coefficients (wind direction: 0°) [19].

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 light-weight constructions, increase considerably the statistical uncertainties. For instance, the fragility of membrane fabric materials to initial tear propagation is incompatible with possibilities 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.

4.5 Model uncertainties

Modelling uncertainties concern the structural and numerical modelling.

The advantages offered by the informatic and automation has been very important in the field of structural design in general and particularly essential in the case of long span lightweight structural systems. It was possible to examine more rigorous theoretical models avoiding, on the one hand, excessive simplifications that deprive the theoretical model, as a schematic reduction of the reality, of all significance and, on the other, that exhausting calculations lead to the loss of facts with a true influence, with the consequent discouragement of the designer from making efforts towards trying out different structural solutions.

Under those apparently favorable 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 [20] . Documented. FEM modeling errors are illustrated in the First International Conference on computational Structures Technology [21].

The interactive software for analysis and design of special structural systems[22]., as normally involved in wide span enclosures requires in order to reduce modeling 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.17);

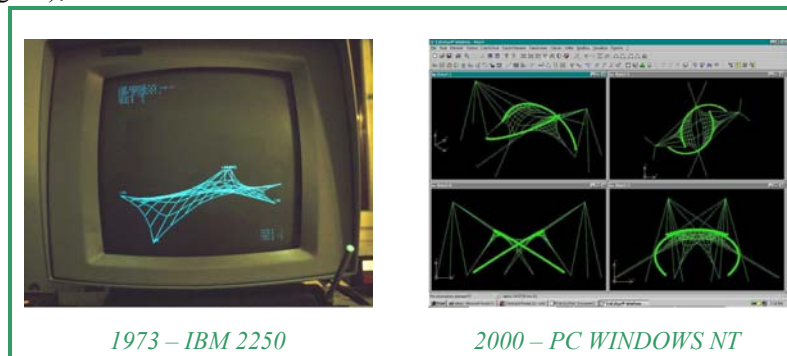


Fig. 17 Hardware and software evolution [22]

- non linear material analysis for elastic, anelastic and plasticity including short and long term creeping;

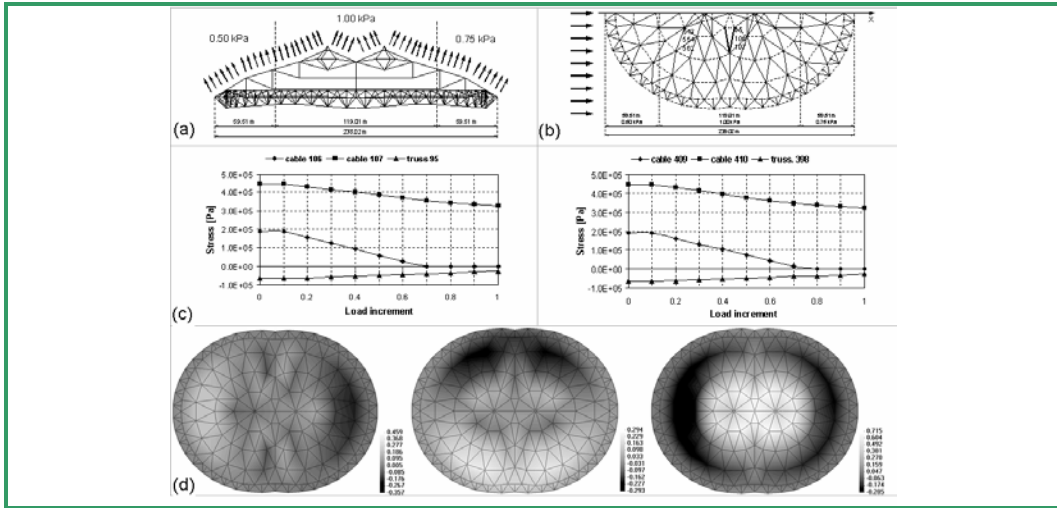


Fig. 18. La Plata Stadium validation analysis. Wind in X direction: (a) load configuration; (b) null cable stresses; (c) stress diagrams and (d) displacements along X- direction, Y-direction and Z-direction [23].

- 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 internal and external pressures on large enclosures (Fig. 19-20);

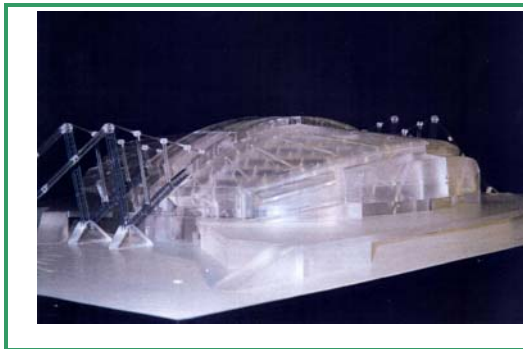


Figure 19. Views of pressure model of Thermis Sport Hall

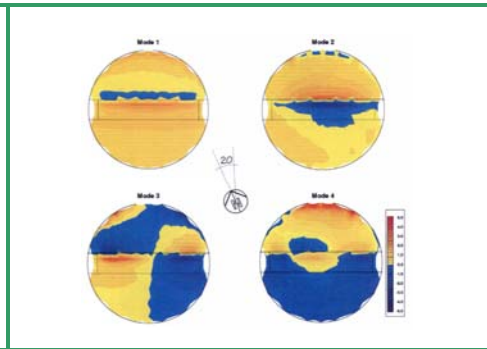


Figure 20. Orthogonal decomposition: pressure mode shapes

- 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.21-22) [23] ;

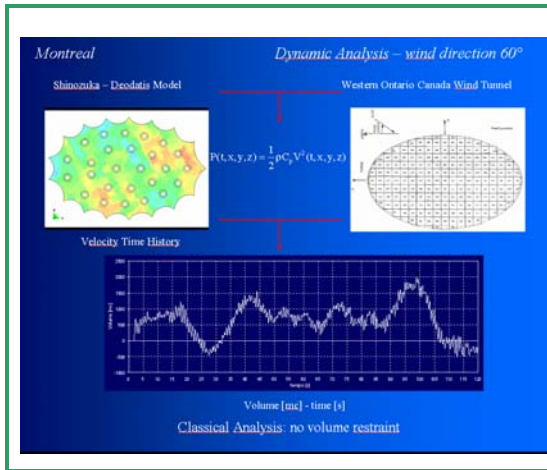


Fig. 21. Dynamic analysis

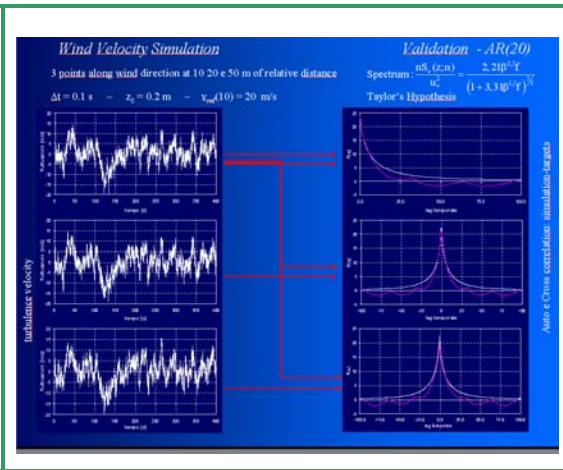


Fig 22. Wind Velocity Simulation [18]

- application of the optimization techniques to the structural design [24];
- parametric stochastic sensibility & reliability analysis[25] (Fig. 23-24).



Figure 23. The new suspended cable roof of Braga Stadium (Portugal)

Figure 24. β -Safety Index distribution, evidencing SLU sensibility on black region ($\beta=3.798$) [25]

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APPENDIX 1

