ARCHITECTURE & STRUCTURES: ETHICS IN FREE-FORM DESIGN (FFD)

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1. Introduction

Nowadays, the influence of powerful algorithms in geometrical modelling allows an unprecedented freedom (FFD), a freedom that could have been barely imagined in the world of architectural design. The fast pace of FFD's growth and the related applications (Free-Form Buildings), some of which are extremely important in the history of architecture, have brought innovation to the traditional scheme of structural engineering, and posed problems in terms of process and design reliability in general, and safety problems in particular.

On the other hand, the search for originality at any cost, made possible through FFD's user-friendly facilities, lead to ethical problems of sustainability in the technical, cultural and economical fields. The value analysis methodology (VA) may help obtain the best-fitting design solution.

2. Architecture & technology: the influence of IT

The technological innovation of the last few decades had an impact on architecture as well, starting up an innovation process and exerting such a great influence on it to earn the name "computerization of architecture". As a matter of fact, this process can be deemed to be a new, historical, scientific synthesis, obtained through the incorporation of technological contents, especially owing to new building materials and their association with adequate building types and methodologies (called hi-tech).

We are currently experiencing a metamorphosis of the language of design caused by information technology (IT) and computer-aided design (CAD) techniques.

In the process of conceptual architectural design the information technology component, through the use of geometrical algorithms for the production of surfaces and solids (RHINO, CATIA, etc.), and software stemming from the field of industrial design has become dominant: the "architectural form" can be "unbuilt" with unimaginable morphology freedom and combination of shapes. Hence, the architectural profile of a *gens*, living in a specific time and place and representative of a broader cultural context, with all its traditions and customs that give rise to authentic architectural sensations, may be quickly homogenized by a globalizing information technology process.

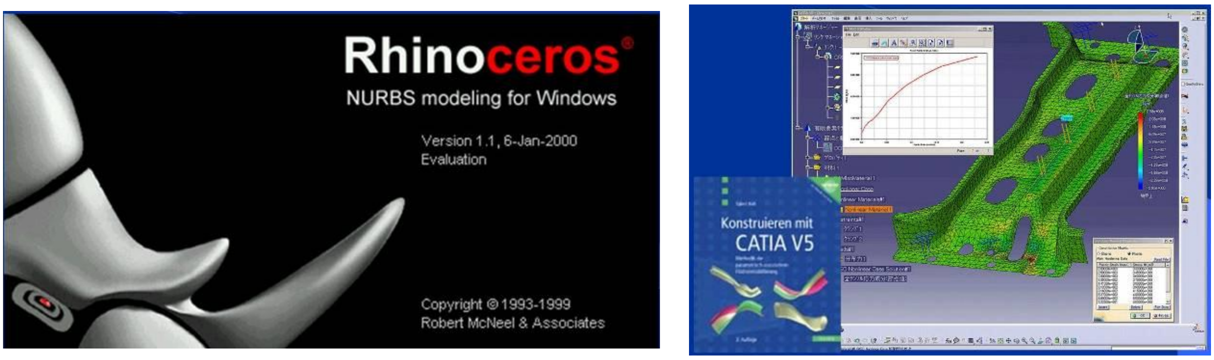


Fig.1 IT resources for FFB

Freedom of expressiveness now creates "architectural objects" featuring a shape that, in most cases, has nothing to do with structural principles.

Many of these new "architectural objects" 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 life needs, they have been vastly praised. It cannot be denied 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. Ultimately, they might 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 traditional configuration as "out of fashion".

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

3. Engineering & technology : The standardization of structural mechanics theories and automatic analysis

Of course, the information technology revolution has influenced structural engineering as well. During the ‘50s and the ‘60s design methodology used by structural engineers 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.

Looking at the historical development of building science, it is apparent that the process of unitary synthesis of the various theories of elastic bodies mechanics, which took place only in the second half of the last century, mainly owing to the energy methods, would have been possible much earlier, because the solution patterns preserved the general scheme that 19th century scientists had already envisaged (Pozzati, 1992, [1]): in fact, the physical model has remained unchanged since the time of Cauchy (1828); the force method initially developed by Navier (1826) was completed by Maxwell (1864), Mùller-Breslau (1886) and O. Mohr (1892); the displacement method was applied by A. Clebsh (1862) to specific problems and its great potential was rediscovered after ninety years due to Navier’s work, and after another twenty years by Mohr, A. Bendixen (1914) and A. Ostenfeld (1926) who incorporated the displacement method into the current practice of engineers. The methods based on evaluations of energy balance, usually referred to as “strain” methods, made their appearance with Menabrea (1875), Castigliano (1873) and Maxwell (1864).

The process of reconciliation with 19th century theory and harmonization of the various theories has nonetheless been troubled; such process was made possible by the increasingly intense contribution of symbolic language and, above all, by the huge impact of processors, using matrix language and discretization methods, especially finite elements methods (FEM, BEM, etc.).

TEORIA GENERALE - 1800

MODELLO FISICO-MATEMATICO	METODI E MEZZI DI ANALISI NUMERICA
METODO DELLE FORZE	GAUSS (1810)
METODO DEGLI SPOSTAMENTI	
METODI ENERGETICI	
NAVIER (1826)	METODO DEI DETERMINANTI
CAUCHY (1828)	(LEIBNITZ -1678 , CRAMER - 1750)
SAINT VENANT (1848)	
CLEBSH (1862)	
MAXWELL (1864)	SEIDEL (1874)
CASTIGLIANO (1873)	
MENABREA (1875)	
MULLER-BRESLAU (1886)	
MOHR (1892)	
BENEDIXEN (1914)	
OSTENFELD (1926)	

METODI APPROSSIMATI - 1900

MODELLO FISICO-MATEMATICO	METODI E MEZZI DI ANALISI NUMERICA
EMPIRISMO SCIENTIFICO	GAUSS-SEIDEL
metodo associato all'oggetto di analisi:	SVILUPPO IN SERIE
serbatoi, scale, telai, ecc.	DIFFERENZE FINITE
CROSS (1930)	
GRINTER (1937)	
SOUTHWELL (1946)	

SINTESI UNITARIA - 1950

MODELLO FISICO-MATEMATICO	METODI E MEZZI DI ANALISI NUMERICA
ARGYRIS (1954)	CALCOLO AUTOMATICO
MARTIN (1956)	LINGUAGGIO SIMBOLICO
TURNER (1956)	F.E.M.
	B.E.M.

Tab.1 Theory of structures & numerical modeling

This is the «language metamorphosis» era, as E. Benvenuto called it in his recent “history of building science”: symbolic language and mathematical formalism have gone beyond the mechanics of structures, which now serves automatic calculus. Therefore, the “mentality” on which scientific empiricism was based radically changed.

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 20 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 for the employment of such theories were still under development. One inevitably had to use approximative schemes and resort to indications derived from numerous tests and confirmations. Today, it is broadly acknowledged 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, producing the false impression that men can be outshined by machines and the logic by the automation.

In light of the current development of sophisticated automatic processors and common electronic programs, created for architectural and structural design, the ideal interaction between men and machines ought to be found in modern "graphic interaction" techniques.

Interaction between men and machines calls for both parties' best efforts, and might allow the simultaneous achievement of the following goals:

Excellent relation for the ANALYSIS phase (an operation entrusted to the processor, using its power, performance capabilities and calculus speed);

Excellent relation for SYNTHESIS (an operation entrusted to the designer who is responsible for data validity control and results analysis).

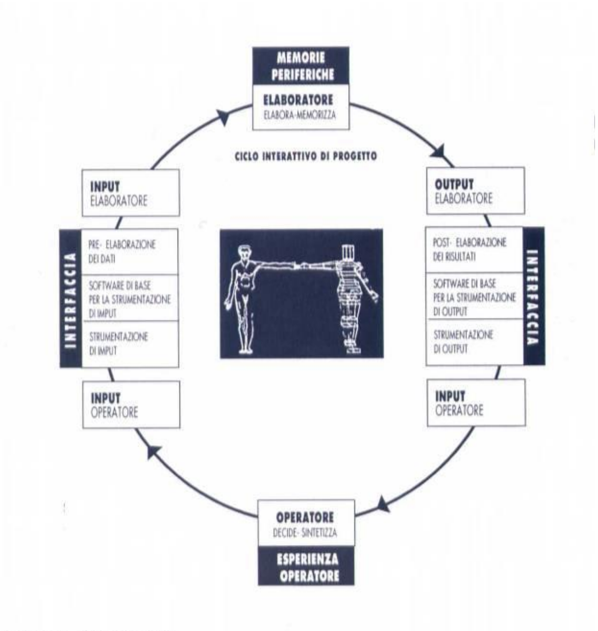


Fig.3 Interactive design process

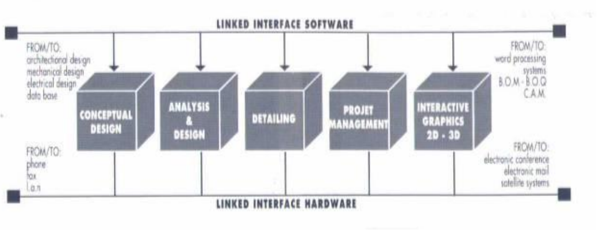


Fig.4 Hardware and software network

Interaction between designer and computer - which in our case involves well-known acronyms such as CG (computer graphics), CAD (computer-aided design), CAAD (computer-aided architectural design), CASD (computer-aided structural design), CAM (computer-aided manufacturing) - has revolutionized the design methodology and, implicitly, the language and media of design documentation. Design elaboration is interfaced through interactive hardware and software. The topological and geometrical media of the architectural project and of the structures become necessarily integrated.

4. Architecture & structures

In light of this third remarkable technological revolution (**I**nformation **T**echnology), the evolution of the interaction between architecture and structural engineering is worth being discussed. Luckily enough, many of the first pioneers in the field of structural architecture are Italian: Pier Luigi NERVI, Riccardo MORANDI and Sergio MUSMECI.

Nervi has no doubts: “Design is the basic element of a building work. Broadly, it is the invention and study of the tools needed to achieve a precise goal with maximum convenience.” And more:

“The development of a resistant system is a creative action, which is based on scientific principles only in part. The static sensibility that determines it, though a necessary consequence of the study of equilibrium and material resistance, remains, like aesthetic sensibility, a purely personal skill. Even in the case of static design, a clear vision of the aim to be attained and the serene independence of the soul from solutions already adopted in similar cases, are the necessary pre-conditions for success. Independence does not mean originality for originality’ sake”

Morandi warns against the danger of “plagiarism” in case of an automatic analysis of the structures during the design process in relation to the power of physical/intuitive synthesis. In fact he said:

“An average familiarity with design is enough to know that it is always possible, at least to some extent, to solve a problem in more than one way, and that these solutions may be perfectly equivalent from a functional, static and economical point-of-view. At this point, the choice of one among the many equivalent solutions and the special attention to formal detail (which is almost always independent from calculus restraints) go beyond the purely technical aspect and, either intentionally or unconsciously, participates in artistic creation.”

Morandi began to challenge any validity both of technology for technology’ sake and of formal preconception, preferring a clear architectural design, committed to the ideal of (uncompromising) balance between functionality of setup, strictness of the structural solution and quality of the final image.

The conscious building choices that shape the final identity stem from the explicit adoption of “simple and easily controllable static schemes, also in relation to an always imperfect execution, in which the arrangement and the shape of the various frames clearly express the static function: ultimately, their reason for existence.” Then observe:

“Calculus, this mysterious word for the uninitiated and in the name of which many executions of wonderful subjects have been wasted and continue to be wasted, could it ever be considered as an absolute factor of determination of a structure’ shape, when it has been proven that this is based on the conscious sensibility of the designer, be it an architect or an engineer?”

With Sergio Musmeci the conceptual setup of Nervi and Morandi, that requires the structure to feature an expressive “language” in terms of static functionality, is supported by mathematical demonstrations. Musmeci introduces the concept of the search for “structural form” associated with material minimization to contrast the potential energy of a system of external forces.

“The search for the structural form is not triggered by intuition or whimsy, but by a process that investigates the necessary configuration of matter in space, capable of carrying out a specific structural task by employing the minimum amount of resources”.

“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”.

Musmeci believes there is only one minimum quantity of a certain material with which every structure can be created, once the system of external forces has been defined. This invariant is directly associated with the concept of structural minimum.

It is form that, with a minimum employment of a certain material, occupies the minimum volume in space.

He says “I amused myself in determining the arch limit shape...

$y=\log \cos X$

an equation that seeks to asymptotically represent a column of uniform resistance whose asymptote is the limit span for the material.

The result is simply: $K=\sigma/\gamma$

Where σ is the limit tension of the material and γ the specific weight. Parameter K, dimensionally expressed by a length, synthesizes the material’s efficiency

Conventional materials	σ_t^R N/mm²	σ_c^R N/mm²	γ_k N/m^3 10^3	K_t m	Kc 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	----

Composite hi-tech materials	σ_t^R N/mm²	σ_c^R N/mm²	γ_k N/m^3 10^3	K_t m	Kc m
Unidir. carbon fibers	1400		15.5	90.000	----
Textile carbon fibers	800		15.5	52.000	----
Unidir. aramidic fibers	1600		13	123.000	----
Textile aramidic fibers (Kevlar)	750		13	58.000	----
Unidir. glass fibers	1100		20	55.000	----
Textile glass fibers	450		20	22.500	----

Table 2. Mechanical properties of construction materials

Physically, it is the length of a rod, of a given material, that makes the initial section break as a result of its weight: in compression (Kc) or in traction (Kt) (note that the influence of the equilibrium's instability makes the Kc limit for the most efficient materials meaningless).

4.1 **F**ree **F**orm **A**rchitecture (FFA), a new frontier for the state of the art?

Many contemporaries have the following views on the laws dictated by new design trends [2]:

- the prevalence of esthetics over static rationality;
- thorough search for structural efficiency to solve a more complex issue than reality and 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.

In present-day realizations, free- formal expressiveness creates architectural objects such as leaning and twisted towers, sculptured bridges, free-form enclosures and the like, the shape of which sometimes fails to have any connection whatsoever with structural principles.

According to the technical and scientific philosophy that inspired Eiffel, Torroja, Nervi and others, who designed bearing in mind first and foremost the construction, it is undisputed that compliance with static engineering laws would be seen, *per se*, as a guarantee of achieving esthetic results, in this view, FFB would be nothing more than structural forgeries. However, many of these new architectural objects are astounding; undeniably, some works do achieve the level of architectural and sculptural art, and structures are merely a medium for architectural design Fig.5.

Conversely, a structural forgerie and/or morphological sculptured shapes, which may end up making any traditional building look outdated, may induce students and professionals lacking a sufficient knowledge and expertise to elaborate imitations; such imitation might pose dangerous design uncertainties.

Il progetto si basa sull'idea di ridefinire il significato di divertimento per le nuove generazioni. Lo spazio di divertimento, da luogo di mero consumo viene trasformato in un luogo di dissertazione intellettuale. Questo obiettivo viene raggiunto dalla combinazione di diverse forme di divertimento e si basa sulla produzione e sul cambio di conoscenza.

Fig. 5 Some Actual Free Form Designs

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 esthetics is being very warmly received in many parts of the world. Even though Spinoza states that ethics change over the times owing to changes in our intellect's perception of substances, the introduction of architectural and structural ethical issues, according to the principle of ethical technological responsibility introduced by Hans Jonas[3], could prevent the success of some technological and structural stereotypes such as London's Millennium Bridge, where structural stability was sacrificed, for instance, to technological astonishment. Similarly, false conceptual design statements and didactic deviations are to be seen in the Seville Alamillo Bridge, where the successful design of what was meant to become a landmark was associated with the hypothesis that the bridge's tilted tower weight was enough to counterbalance the bridge deck with stays, while most of the material used for the bridge function was indeed structurally useless, and aimed instead at creating a sculpture. Ethics may foster obtaining more reliable information from designers and realization processes; consequently, ethics may prevent, at least, designs based on false statements.

5. Design uncertainties as a gap between Science (Know-why) and Technology (Know-how)

In an interesting essay of 1956, Francisco Vera stated that the development of science (know-why) and technology (know-how) in Western civilizations had no correlation in time, as it was the case with Eastern civilizations in relation to harmony and coherence.

In the 1st industrial revolution a phenomenon of technological acceleration, as opposed to the associated scientific sector, began. This dichotomy became more evident in modern times, when technological research and production are no more “filtered” or integrated through the parallel process of scientific synthesis. Technological discoveries that are not accompanied with scientific control often turn out to be counterproductive and “polluting”. Technological innovation seems discontinuous, takes the form of an industrial revolution, and features impulsive manners after having reached an inertial threshold represented by tradition and current scientific convention.

Since the last industrial revolution, technological progress has grown at a very fast pace, and examples thereof can be found in many fields. Over this time-span the speed of trains, for example, has gone from one hundred kilometers per hour to over three hundred kilometers, ships’ weight increased from eighty thousand tons to two million tons, propeller planes have surrendered to spacecraft and in the field of high-rise buildings we have gone beyond four hundred meter heights (for example, the Sears Tower of Chicago and the Petronas Towers of Kuala Lumpur), while huge structures of more than eight hundred meters are now taken into consideration. At the same time, the spans of reinforced cement bridges have risen from the one hundred eighty-seven meters of the arches of the Plougastel bridge (Brest) to three hundred and four meters with the Sydney Harbor Bridge, whereas in the field of metallic bridge spans of approximately two thousand meters are under construction in Japan, single span bridges of three thousand meters in the Strait of Messina and multi-span of 5,000 m. in the Strait of Gibraltar, are under design.

The History of technique deals with several “Hows” resulting from known “Whys”, in accordance with Bacon’s teachings, but the “Hows” often came before the “Whys”. There have also been some “Whats”, just like Watt’s steam engine, that worked for less than a century with a known “How” (the invention) and an unknown “Why” (revealed only when Sadi Carnot stated the 2° Principle of Thermodynamics).

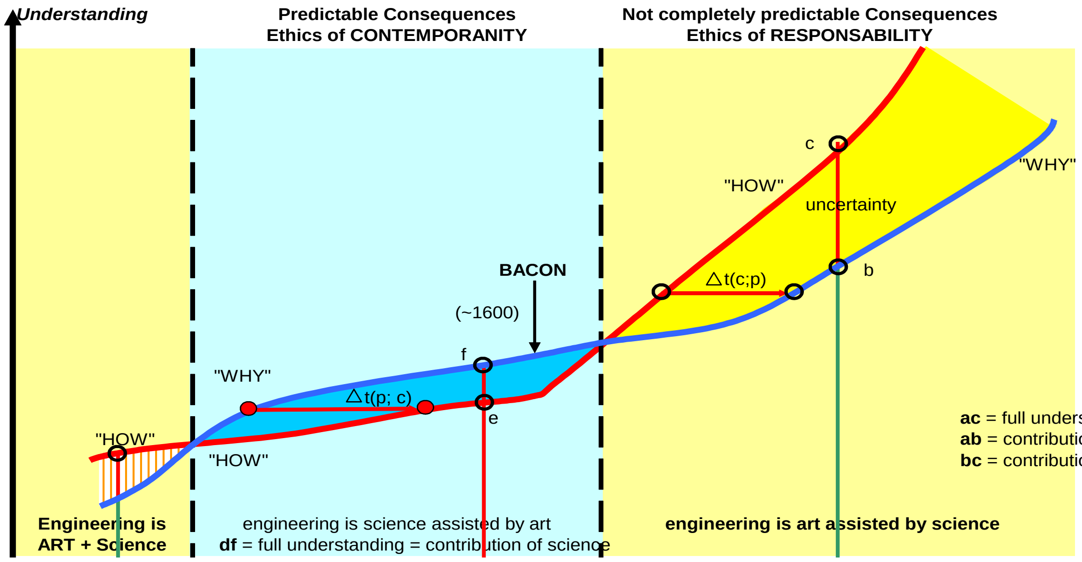


Figure 6. Growth of know-how and know-why in time

Sustainability ethics establishes progressively narrower limits in time until the Know-how exceeds the Know-why. The Know-how grows, in function of time, more rapidly than the Know-why, with the consequent increase of uncertainty *(fig.6)*; hence, it is not possible to foresee long-term consequences of an action, which one knows how to carry out, albeit it is unknown why the results thereof are originated and what the consequences thereof might be.

Some design errors caused by the lack of interaction between architecture and structural engineering under the new design trends, or by non-compliance with ethical standards in line with the principle of responsibility, have led in the past (and are still leading) to terribly unsuccessful designs, giving rise to legal proceedings, structural malfunctioning and even collapses. Considering that modern design is a complex, holistic, multi-cross and inter-disciplinary process that must achieve a required reliability level and observe generally accepted principles and feasibility constraints, Structural Architecture (SA) steps forward as a methodology, a thoughtful knowledge producing adequate design approaches within the framework of technological civil responsibility ethics, in order to reduce phenomenological structural uncertainties.

5.1 Observed limit-state violations in unusual constructions: a structural safety problem

The separate analysis of design variables leads to a lack of conceptual correlation, a later maturation, and normally to an overall lower quality. Some design errors, originated by a lack of architectural and structural interaction or by a failure to comply with the ethics of responsibility (sustainability), have been and still are the cause of design flops, legal proceedings, damages and sometimes malfunctioning and structural collapse of new buildings (which have increased in the last few years).

The observation of in-service performance, damages and collapses of whole or part of structural systems supplied us with plenty of information and teachings on designing and verification under the action of ultimate and serviceability limit states. Limit-state violations for engineered structures led to spectacular collapses like the Tay (1879), Quebec (1907) and Tacoma (1940) bridges. Sometimes structural failure is the result of an apparently "unforeseeable" phenomenon. The above mentioned Tacoma Narrows Bridge was apparently one such 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 pounding, 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.7-12).

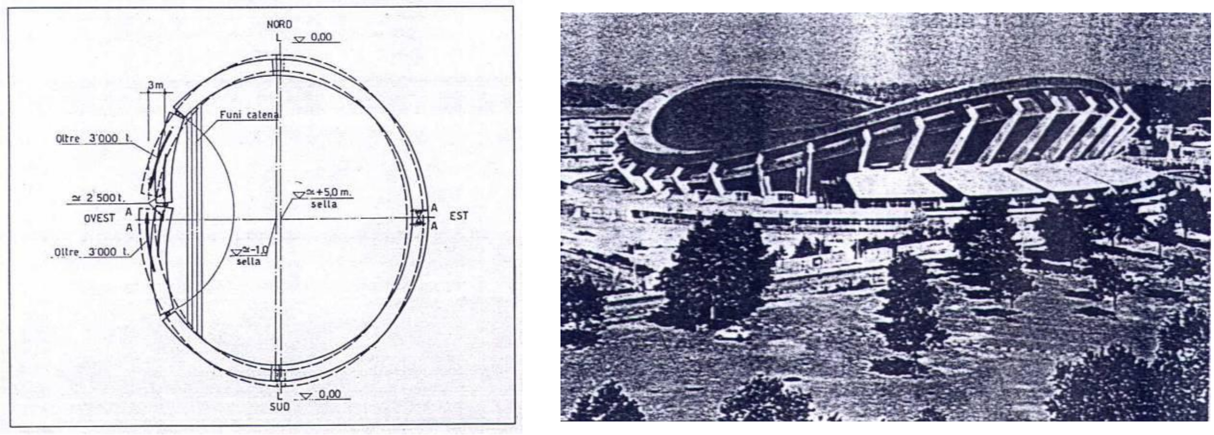


Fig.7 Milan Sport Hall – Roof collapse by snow load

Fig.8 Olympic Stadium Montreal – Partial roof collapse by snow accumulation (1995)

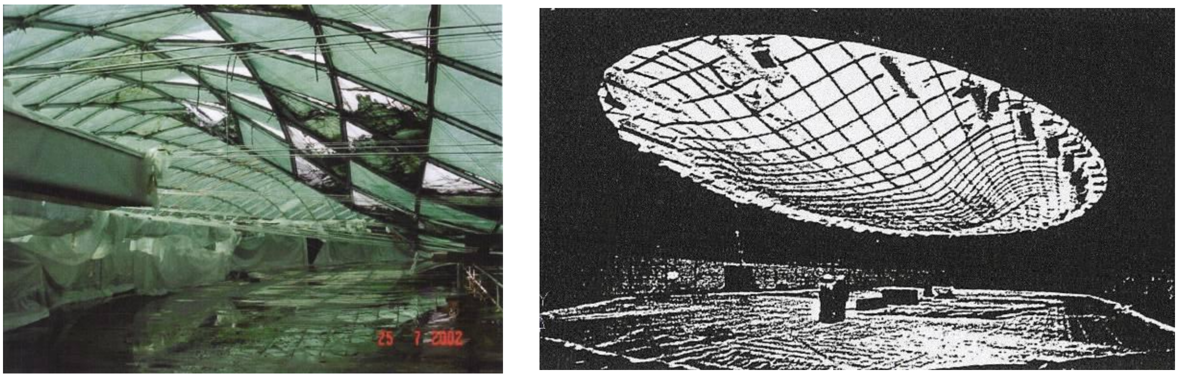


Fig.10 Sport Hall Halstenbeck – Global instability collapse (2002)

Fig.11 Acquapark and swimming hall Moscow – Roof collapse (2004)

Fig.12 Terminal Roissy Airport Paris – Shell collapse (2004)

These cases of failure of the structural mechanism can help 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 in dimension and morphology;
- experience and organization of design and construction teams;
- research and development background;
- financial situation;
- industrial situation;
- political situation.

All these factors fit very well in structures often involving something "unusual", and clearly have an influence affecting human interaction.

As evidenced in Table 3, in 43% of the cases (Walker, 1981) the main cause of failures is due to inadequate appreciation of loading conditions or structural behavior.

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 "unforeseeable"?)	7
Random variations in loading, structure, materials, workmanship, etc.	10

Table 3. Main causes of failure. Adapted from 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 (unforeseeable?)	4
Other	8

Table 4 – Error factors in observed failure cases *(Adapted from Matousek and Schneider*[4] *)*

Besides ignorance and negligence, the underestimation of influence and insufficient knowledge can be considered as the most probable factors in observed failure cases (Table 4).

6. FFB Architecture : uncertainties in reliability assessment

Many recent projects of long span and high-rise structures attempt to stretch the "state of the art". New shapes of construction and design techniques, used in today's conceptual design methodology, generate phenomenological uncertainties on any aspect of the possible behaviour of the structure under construction, in-service or subject to extreme conditions.

Other factors like human errors, negligence, neglected loadings and/or poor workmanship are most often involved in malfunction, failures and collapses.

Fortunately, structures rarely collapse in a serious manner, but when they do it is often due to causes not directly related to the predicted nominal loading or the probable distribution of material strength.

Through the statistical results of the perusal of in-service behaviors, unusual typologies, new materials and, especially, the "scale effect" of large dimensions, several special design aspects come to attention and the following types of uncertainties in reliability assessment have been identified [4] Fig.13 :

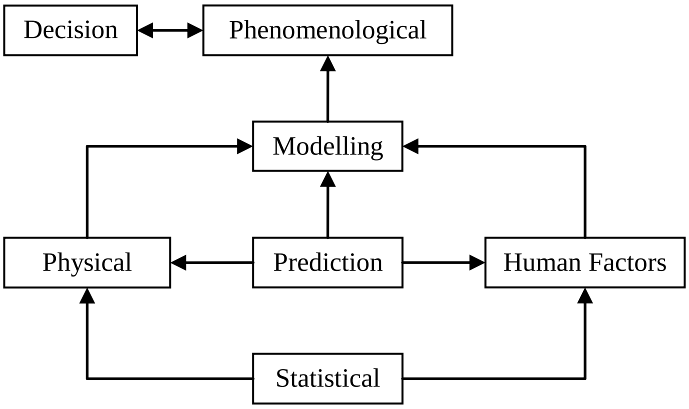


Fig.13 Uncertainties in reliability assessment according to Melchers (1987)

- phenomenological uncertainty;
- decision uncertainty;
- human factors;
- prediction uncertainty;
- physical uncertainty;
- modeling uncertainty;

6.1 Phenomenological uncertainties

Phenomenological uncertainty comes when the shape of the construction or the design technique generates uncertainty on any aspect of the possible behaviour of the structure, be it under construction, in-service and/or under extreme conditions.

Those uncertainties appear in designs which attempt to stretch the « state of the art », featuring new concepts and technologies, and leaving room for creativity when searching for a design idea.

When a new “**what**”, created by men’s fantasy and imagination, seemed to serve humanity, the challenge was “**how**” to accomplish it and learn “**why**” it accomplished its predicted function: the “**what for**”.

In particular, human mind’s faculties like knowledge, understanding, wisdom, imagination and intuition participate in the design process; therein fantasy introduces a level of phenomenological uncertainty that stretches creativity results in creating a new “state of the art” *(fig.14)*.

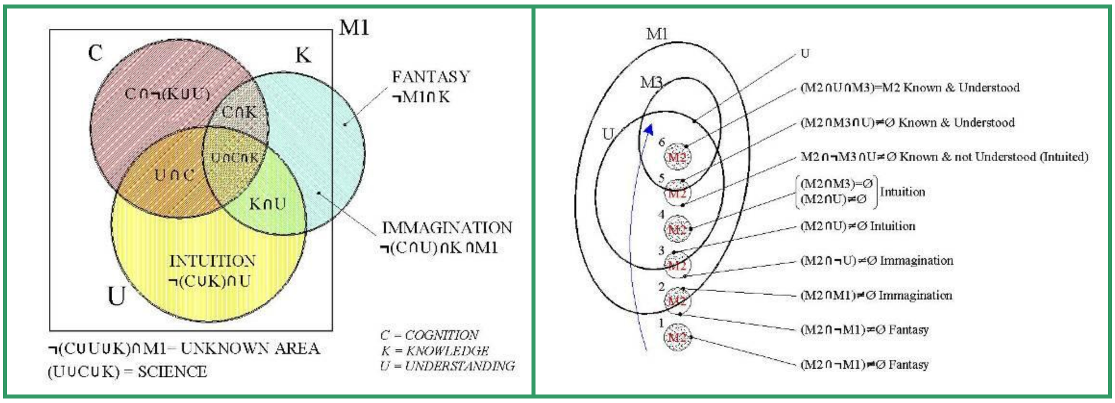


Figure 14. Creativity – stretching Knowledge

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 broadening knowledge. A divergent design solution has to be considered as a “design failure”.

With regard to interaction between architecture and ethics, it is important to consider that “failure” is defined as “performance that is not consistent with expectations” [5]. This implies that expectations of success must be realistic and that they take into account 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 users patiently excuse its gross inadequacies: despite its astonishing exterior, it never functioned properly as an opera house. Today, on the contrary, the challenge is, first of all, to obtain a spectacular and impressive shape like architectural free-form design objects such as: blobs, tilted and twisted high-rise buildings, landmark bridge icons, etc. An interesting contribution regarding the architecture trend after the “Bilbao effect” is by Martin Filler [6] 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.

On the other hand, the structural challenge associated with the formal revolution evidently increases the uncertainties in reliability assessment and, therefore, makes architecture’s need for a responsibility (sustainability) ethic even more impelling: the so-called “Archethic”.

6.1.1 Realizations: What-Why-How or What-How-Why ?

David I. Blockley said “To do you must know, and to know you must do”. If we applied this to the contents of this paper, we would say: To accomplish the “Hows” you must know the “Whys” and to know the “Whys” you must have accomplished many “Hows” (expertise). We have seen that “Hows” may come earlier than “Whys”, just as it has already happened. Therefore, the previous expression is pure wishful thinking or an ideal situation, difficult to implement in reality, impossible for just one man but possible for the next generations of caring, diligent architects and engineers.

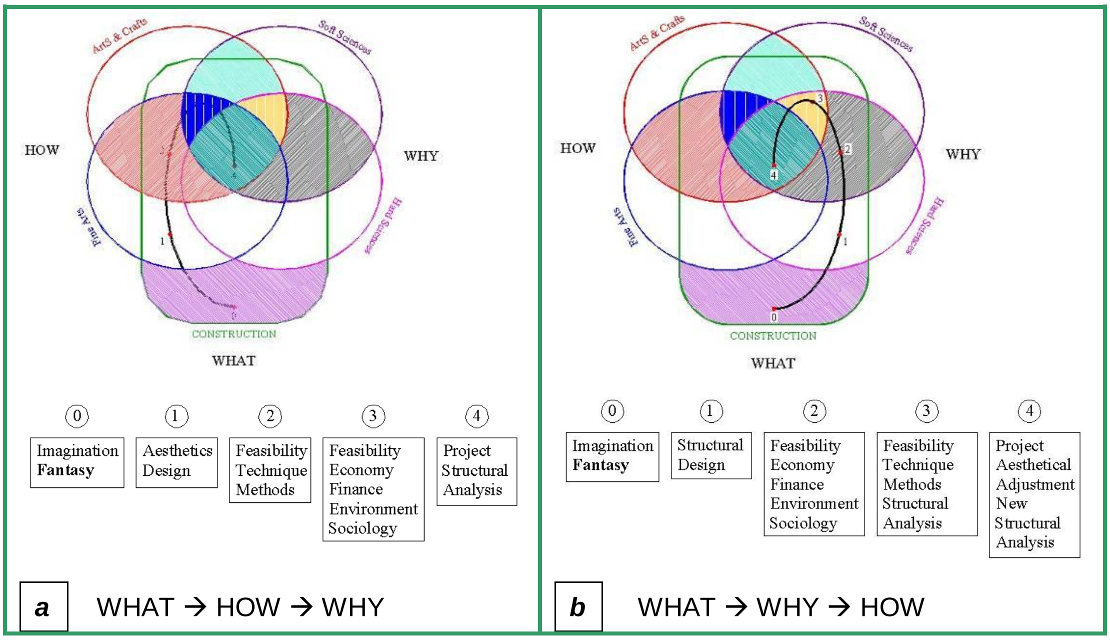


Figure 15.***a***_SA is Art (technique) assisted by Science;
15.***b***_SA is Science assisted by Art (technique).

Besides the two above-mentioned ways to reach the "perfect design solution" Q∩C∩P (point 4), to simultaneously achieve **the know how and the know why** is a privilege of wise, experienced architects and engineers *(Fig.13)*. Architects who set trends mainly based on modern powerful know how, tend to dramatize and mystify the physics of structure to increase the sculptural effect of "What" according to the "**a**" method**;** on the contrary, the **"b"** method is typical of engineering as it considers the design discipline more as a science than as an art, as less a sort of magic (*Fig.15*).

6.1.2 Sustainability ethics in structural architecture

As far as the classical ethics of the contemporary times are concerned, it is worth discussing the ethics of sustainability (which Hans Jonas calls the "ethics of responsibility") and the consensus ethics, based on statistics (which is in fact a lack of Ethics), broadly acknowledged to be non-ethics.
Classical engineering is a Possession (P) and a State (S) where State means "state of art in time t_0 = S(t_0) (*Fig.16-17*), [7].

Possession means everything engineering includes (knowing and doing) = E (t0) at the same time t0

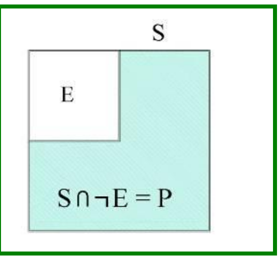


Figure 16. The object is S = E. To be up to date with engineering (almost constant in time)
Progress:
P = S ∩ ¬E until S ∩ ¬E becomes ∅.

2° "Modern Engineering is an enterprise and a process".

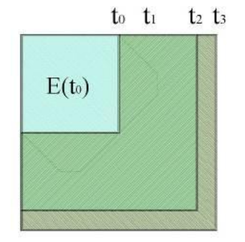


Figure17. The enterprise is to carry out the process:
E(t0) ⊆ E (t1) ⊆ E (t2)…The object is the continuous progress (inevitable according to Jonas):
Pi = Ei ∩ ¬Ei – 1 ≠ ∅ when i = 1; 2; 3..

SA interacts with ethics through the scientific+technological contents of the components: structural engineering + architecture *(Fig.18)*.

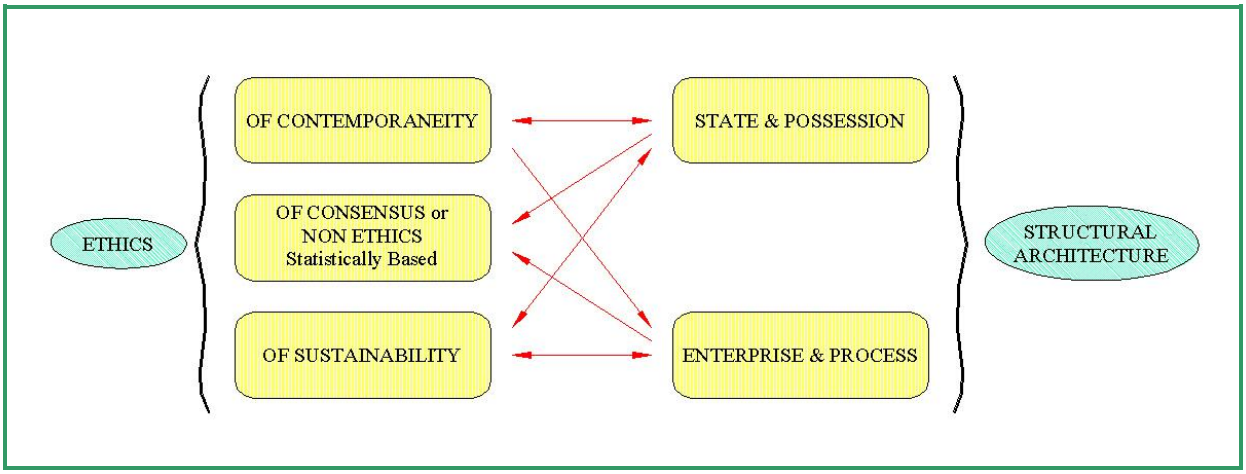


Figure 18. Interactions between SA and ethics

If actual progressive engineering is an enterprise that accomplishes a process and such process means that "possession" and "state" grow in function of time, then this process might change the ethics of sustainability, making the same ethics increasingly complex to accomplish in the event of the state growing larger than possession, which is also possible. However, it is fairly easy to predict that the growth of possession P (t) implies the possibility of changes that would generate new actionswhich Sustainability Ethics would probably consider as ethically unacceptable *(Fig.19).*

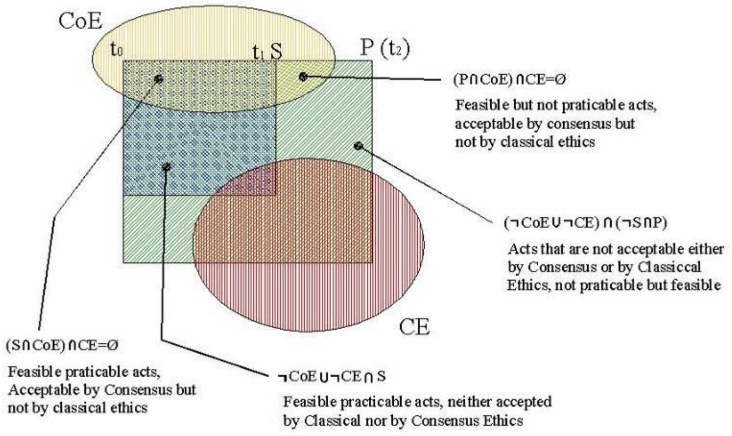


Figure 19.Realization & Ethic acceptability

This wouldn't be so if changes (the growth of the Know How) implied progress; in other words, if changes were always beneficial as they should be. Hence, known goals which have always been pursued, could be most likely achieved through the new techniques that these goals actually involve. However, events also occur in other ways, and basically every day new techniques might inspire, produce or even impose new goals, which were before unimaginable.

6.2 Decision uncertainties

Contractual and technical documents often show that the decision-making procedure has been influenced by conflicting targets. On the one hand, the need of reliable solutions, avoiding experimental adventures, is undisputable. On the other hand, the effort to learn from past errors is considered as the contractual allowance for original concepts and/or technological "jumps" to be part of the process, without simultaneous sufficient scientific background.

Some clients may take the risk by introducing a higher level of decision uncertainties in the realization process, in light of the possible extra value which might be performed by a very innovative design; for instance: "Ce toit reste toujours, en 1995, le plus grand toit au monde dans la catégorie des toits en toile rétractables. Son installation a constitué l'aboutissement d'un projet très ambitieux le long d'une voie très étroite semée d'embûches, posées les unes par un saut technologique important et les autres par certaines caractéristiques du concept original qui en rendaient la réalisation très difficile. Ce toit constitue donc un prototype dont l'observation représente une source d'information sans égale pour l'amélioration future du concept, ou éventuellement, son abandon".

This remarkable point of view, which allowed the scientific and technological advances in the field of lightweight structures, is very adequate if correlated and carefully balanced as an extension of the "state of the art" (return to phenomenological uncertainties for further reference). Though, the same document states that: "La fiabilitè, la durabilitè et la securitè du nouveau toit representent des objectifs prioritaires. De ce point de vue, on s'efforcerà, dans toute la mesure du possible, de minimiser le caractère experimental de la nouvelle toiture".

Yet, in reliability analysis, decision uncertainties are also relating to political and financial situations. Therefore, especially in case of unusual realizations, political and financial decision-making ought to be supported by expert value analysis and quality control of the functions involved in the design solution.

There shall be no doubt about the possibility of preventing such a situation through the ordinary procedures' application of accurate validation analysis, always attended that all the necessary knowledge, experience and feedback is property of the client, designers and suppliers.

6.3 Human factors

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

To ensure the required reliability level in the field of "unusual" structures, the design process must be validated by the following three primary phases: the conceptual design [8], the analytical model, and the working design phases, as shown in Fig. 20 .

Conceptual design is knowledge-based and, mainly, intellectual property of individual experts. Their involvement in the early stages of design is equivalent, from the reliability point of view, to a human intervention strategy of checking and inspectioning and, from a statistical point of view, to a "filtering" action which can remove a significant part of "human errors" (Table 5).

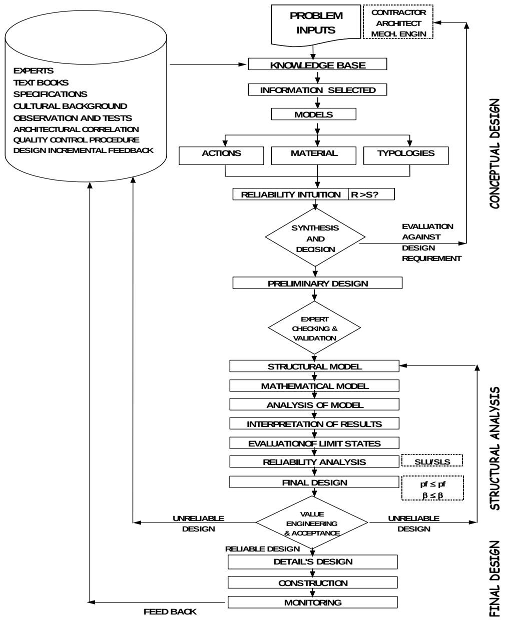


Figure 20. Conceptual design and analysis of structural systems.

Error type	Human variability V	Human error E	Gross human error G
Failure process	In a type of behavior according to which the structure was designed		In a type of behavior according to 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 behavior. Professional's ignorance of fundamental behavior
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 occur, also informally, owing to human intervention factors resulting from the observation that "something is wrong"; such an action is the direct consequence of the skills the design team members are capable of.

Knowledge-based contribution may remove gross errors right from the start and drastically reduce statistic human errors. Therefore, it is recommended that checking or validation procedures are activated in early holistic stages of design, such as the conceptual design phase, in which the process is dominated by intuition and expertise (intuition time)(*Fig.21-22*).

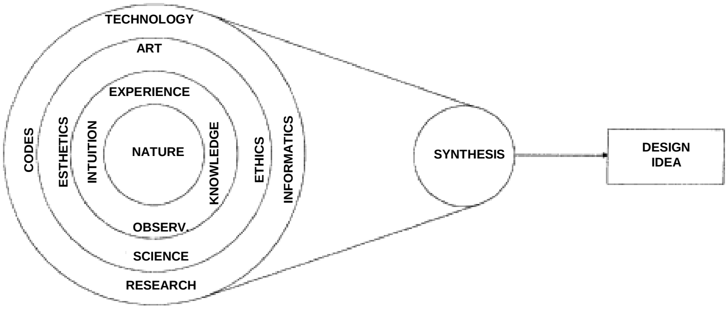
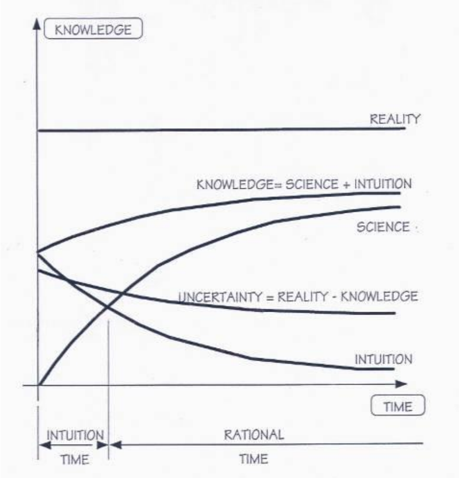
	

Fig.21 Holistic design approach	Fig. 22. Knowledge reducing uncertainties in design process

In line with the design methodology (work plan), conceptual design may be defined as an expert approach, based on knowledge and synthetic reliability intuition that allows the identification of the structural typology, the elaboration of a preliminary numerical model and the subsequent structural analysis and reliability verification.

The above-mentioned issues are now included in some national building codes, which normally are conceived only for conventional structural systems. As far as the **innovative design** is concerned, as for the most present-day free-form-buildings, only few comments can be passed on; for instance, the National Building Code of Canada (1990), at point A-4.2.4.1, states: "It is important that innovative designs be carried out by a person especially qualified in the specific method applied...".

Now therefore, statistic evidence shows that human errors in the fields of design and construction tend to increase remarkably when innovation is discontinuous and sudden, the progressive aid of scientific knowledge being omitted. The free structural morphology that stems from the current FFB trends is like a tsunami that makes havoc of 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 results, principally related to the deformation and stress states of the structures subject to gravity, wind and earthquake, obtained through sophisticated analysis carried out according to the finite elements method.

In a situation like this, the influence of the above mentioned human errors can increase considerably.

Eurocode no. 1 intends to guarantee the level of safety and performance through a Quality Assurance (QA) strategy (point 2) and Quality Control procedures of the design process (point 8) so that human errors are minimized.

6.4 Prediction uncertainties

The estimate of structural reliability depends on the quality of the knowledge accessible to designers. As new knowledge on structures becomes available, the estimate becomes more sophisticated and reliable; hence, it is usually, but not necessarily, matched by a concomitant reduction of uncertainty. This is true in the conceptual design phase more than in any other phase of the process , since information about the effective strength of materials, new typologies, etc. become available and replace, in such phase, the estimates based on past performance and experience with similar structures. FFB are unusual and useful feedback is not available in technical literature yet.

According to the author’s direct experience, reduction of uncertainties in designing special structures may be achieved if the following issues are accurately perusaled [8]:

- the need to avoid and prevent the progressive collapse of the structural system, owing to local secondary structural element and detail accidental failure;

- the compatibility of internal and external restraints and detail design, along with 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 behavior 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 efficiency of the design can be evaluated.

In case of movable structures, the knowledge base mainly concerns the moving cranes; hence, the related conceptual design process shall be provided with existing observations, test and specifications relating to the behavior of similar structural systems. In order to fill the gap, the IASS working group n°16 drew up a state of the art report on retractable roof structures [9] including recommendations for structural design, based on observations of malfunction and failures.

6.5 Physical uncertainties

Physical uncertainties are related to loading and material.

In case of wide covering surfaces and high-rise buildings with unusual morphologies, loading uncertainties may be reduced if the following issues are accurately perusaled [10-14]:

- the snow distribution and accumulations in relation to statistically correlated wind direction and intensity;
- the wind pressure distribution considering theoretical and experimental correlated power spectral densities or time histories;
- 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), like experimental investigation in boundary layer wind tunnel scale models and monitoring of actual structures, play an important role in structural design of unusual structural systems.

As far as the material uncertainties are concerned, special care must be dedicated to the reliability and safety factors of new ceramics and smart materials and hi-tech composites of metallic matrix (MMC) or epoxy and polymeric (FRP) materials.

The uncertainties descending from the materials’ applicaton associated to very high ratios of live loads/dead weight, which are an evident characteristic of light-weight constructions, considerably increase the statistical uncertainties. For instance, the fragility of pre-stressed or pneumatic membrane fabric materials to initial tear propagation is incompatible with the ipothesis 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, plays an important role, in reducing modeling and physical uncertainties and preventing chain failures of the structural system in special structures.

6.6 Model uncertainties

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

Modelling uncertainties concern the structural and numerical modeling.

The advantage offered by informatics and automation has been vastly appreciated in the field of structural design in general and it is extremely significant in special structural systems. It has been possible to examine more rigorous theoretical models avoiding, on the one hand, excessive simplifications that deprive the theoretical model, like a schematic reduction of reality, of all significance and, on the other hand, exhausting calculations leading to the loss of facts, thus discouraging designers from trying out different structural solutions.

Under such apparently favorable circumstances, many documented structural failures have been detected whose causing errors, as a matter of fact, regards the inadequate evaluation of structural behavior, owing to 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. For this purpose, IABSE set up a special commission for the control of automation in structural design [15]. Documented FEM modeling errors are illustrated in the First International Conference on computational Structures Technology [16].

To reduce modeling uncertainty, the interactive software conceived for the analysis and design of special structural systems[17] requires, rather than general purpose programs, specific software that can provide the user with many aspects of theoretical analysis such as:

– state '0' form-finding analysis, for the shape-finding of cable, membrane and pneumatic structures;

- non linear analysis for elastic, inelastic and plastic materials including short and long-term creeping;
- 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 and seismic action considering static, quasi-static and resonant contributions, assisted by the experimental identification, on rigid scale models, of cross-correlated power spectral densities (PSD) of the internal and external pressures on large enclosures;
- 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[18].;
- application of optimization techniques to the structural design [19];
- parametric stochastic sensibility & reliability analysis[20]..

7. Increasing reliability in FFB design: The Archethic

Performance and serviceability limit states' violations are directly associated with structural reliability. Conceptual errors are very hard to remove in the subsequent phase of structural analysis and only human intervention strategies such as education, work environment, complexity reduction, self-checking and external checking may eliminate gross human errors (Table 6).

Facilitative measures	Control measures
Education Work environment Complexity reduction Personnel selection	Self-checking External checking and inspection Legal (or other) sanction

Table 6 – Human intervention strategies

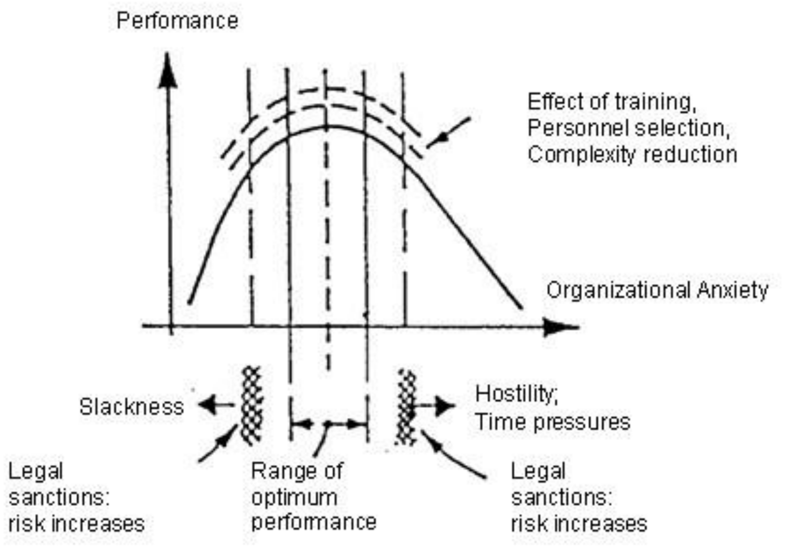
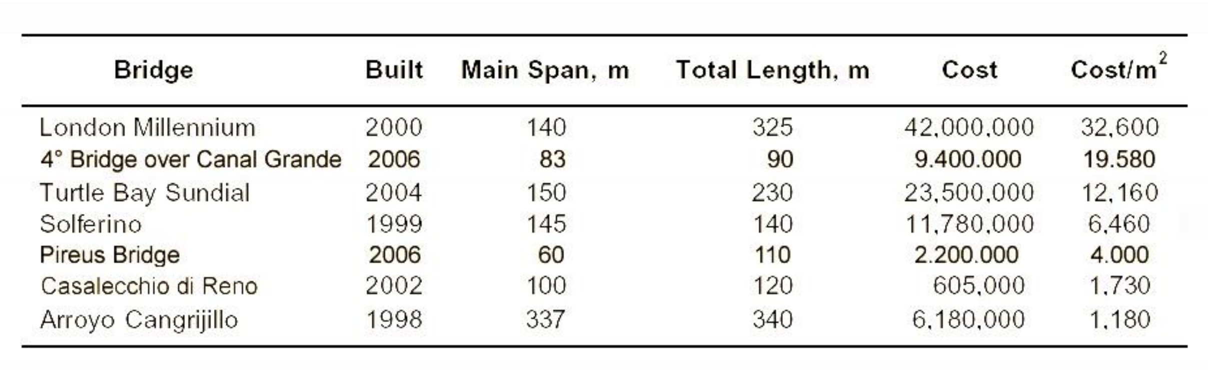


Fig.23 – Human performance function [Melchers, 1980]

Many controversies and a remarkable amount of litigations resulted from unrealistic expectations, especially in relation to the degree of perfection achievable on a determined budget bases.
A representative example of ethics applied to the evaluation of the resources employed for a main design function is the one identifing bridges and footbridges. An interesting research carried out by the Princeton University on the existing relation between building ethics and esthetics, presented by Woodruff and Billington during the Footbridges International Symposium 2005, compares the costs of some footbridges (Tab. 7).



Bridge	Built	Main Span, m	Total Length, m	Cost	Cost/m^2
London Millennium	2000	140	325	42,000,000	32,600
4° Bridge over Canal Grande	2006	83	90	9.400.000	19.580
Turtle Bay Sundial	2004	150	230	23,500,000	12,160
Solferino	1999	145	140	11,780,000	6,460
Pireus Bridge	2006	60	110	2.200.000	4.000
Casalecchio di Reno	2002	100	120	605,000	1,730
Arroyo Cangrijillo	1998	337	340	6,180,000	1,180

Tab. 7 Costs of recently built Footbridges - Adapted from S.Woodruff and D.Billington [21].

Table 7 shows the remarkable difference between the costs of “conventional” and “innovative” footbridges. The question is: How much is too much?
Obviously, the answer cannot be “the lowest cost”; the search for the “maximum value” obtainable through the available resources is substantial in approaching this issue.
The ethically sustainable value can be identified during the design stage through the value analysis method (VA).
VA features an operational technique that allows to estimate and quantify the satisfaction of the needs, both explicit and implicit, of the client/user.
The VA method includes the following features: universality of the object to be evaluated, defined entity = idea, project, product, service, organization or any combination of these; the approach is based on organized, interdisciplinary group activity, coordinated by a VA expert and carried out on behalf of the client by experts in various fields and non experts (users). The functional analysis and creativity (brain storming) that the five phases of the VA method involve, seek to simulate a behavioural approach that aims to achieve goals set in advance.

The introduction of the value analysis method can overcome the "design to cost" limits, i.e. the mere search for cost reduction that can lead to inadequate solutions which cannot grant the required service, and therefore cannot fulfill the needs of all players involved (stakeholders).

In terms of a public or private client’s economical satisfaction, the value of a project suggestion can be determined, roughly, when its function and quality level have been identified. What matters is that the function is satisfactory (meets the needs) and the production cost minimal. This allows to identify the Value Index (VI),

$$VI = \frac{Function\_worth}{Global\_\cos t}$$

a comprehensive numeric parameter that helps estimate and compare alternative design solutions produced during the creative phase.

The VI is the ratio between the function worth, the service that the design solution aims at providing in a given period of time (expected service life), in a specific place and under specific circumstances, estimated by the VA in terms of "commitment to pay" a certain amount of money for each function taken into account, at the established place and time and under the specific circumstances, and the global cost for the implementation of the functions themselves (function cost or function global cost).
This shows clearly that as for the VA, the product with the highest "value" is the one which carries out the needed functions at a minimal cost.
This also highlights VA’s pattern: first of all, an action hinged on the functions, which will be studied and critically examined, then an action hinged on costs, and finally the optimization of both factors. The concept of function, i.e. the reason for which the design was executed, determines what is necessary and sufficient.
Functions can be very subjective and clients may require remarkably different functions for the same design execution (a car for example may be considered essentially as a mean of transport or as a status symbol).
It is therefore advisable to divide functions into two categories:

- on the one hand, the functions related to service (those which directly meet the need of the user); within the service functions a further distinction is needed between:

  - service function (in the case of a bridge: allowing to go from A to B)

- esteem function (associated with quality: the fact that a bridge is a landmark or has an artistic added value);

- on the other hand, the technical function of the design's elements: groups, subgroups, elementary parts (lighting, production limitation, transport and assembly; median type, etc.).

The value index is very useful in the decision-making activities, especially for public sector clients, as it allows to estimate projects and executions in compliance with the ethics of responsibility (sustainability).
The balanced evaluation of the three functional components fs (service function) fe (esteem function) and ft (technical function) determines the work's quality.
Special attention to the ef component must be paid in 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 prevent some projects to damage the environment ("genius loci" evaluation function), as shown by fig.24: "..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" [22]; unfortunately this wise sentence was not part of a VA teamwork.

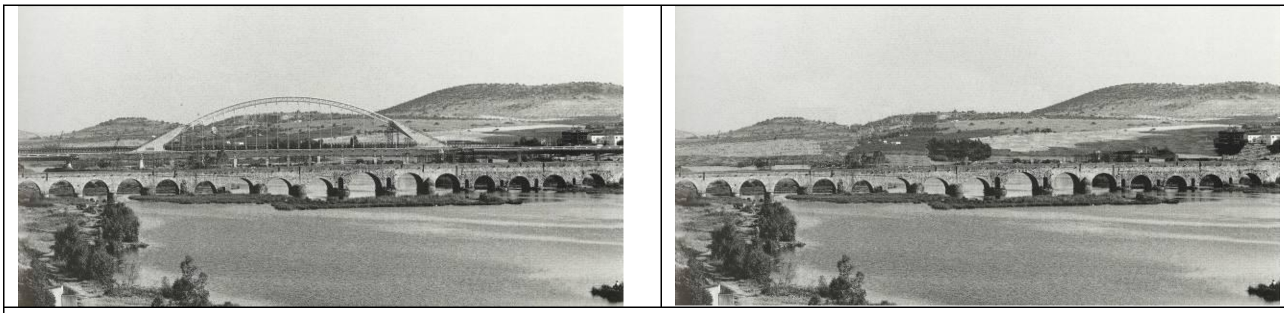


Fig.24 With or Without the "genius loci" function?

Other human intervention factors, aimed at reducing human errors regarding design and construction, are the formalized methods of Quality Assurance. QA is based on the need to meet, through the implementation 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 represented by the occurance of excessive formalization in QA; if applied to intangible conceptual control procedures, QA might lead to an undesirable and self-defeating degeneration of the design process to a sort of Kafkian bureaucratic engineering and management. These phenomena have been reported and documented by Carper (1996) in "Construction Pathology in the United States" [23]: "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 regarding this matter was given by the International Symposium on "Conceptual design of Structures" organized by IASS [24].

8. Conclusions

FFD is a challenge for architects and engineers as well but the first impressive realizations have been followed by the ethic and esthetic consequences of FFB's appeal on the social context. These consequential effects shall be carefully examined, to avoid a misleading interpretation of the term "innovation", which is not supposed to have a positive meaning, of any kind, **as positive merely because it is innovative** , in despite of effective credits and its contribution to Knowledge.
In order to guarantee the required reliability 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, so that most suitable and compatible solutions can be found in accordance with the expected function worth.

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Traduzione delle figure in italiano su cui non è stato possibile soprascrivere

Tab.1
Teoria generale= General theory
Modello fisico-matematico= Physical-mathematic model
Metodi e mezzi di analisi numerica= Numeric analysis methods and tools
Metodo delle forze= force method
Metodo degli spostamenti= displacement method
Metodi energetici= energy methods
Metodo dei determinanti= determinant method
Metodi approssimati= approximative methods
Empirismo scientifico= scientific empiricism
Sviluppo in serie= series development
Differenze finite= finite differences
Sintesi unitaria= unitary synthesis
Calcolo automatico= automatic calculus
Linguaggio simbolico= symbolic language

Fig. 3 Interactive design process

Memorie periferiche= peripheral memory
Elaboratore (elabora- sintetizza)= processor (processes-synthesizes)
Ciclo interattivo di progetto= design interactive cycle
Input/elaboratore= Processor/input
Pre-elaborazione dei dati= data pre-processing
Software di base per la strumentazione di input= Basic software for input instrumentation
Strumentazione di input= Input instrumentation
Input/operatore= Operator input
Interfaccia= interface
Operatore decide-sintetizza= Operator decides-synthesizes
Output elaboratore= processor output
Post-elaborazione dei dati= data post-processing