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Keynote Address

Conception design in the reliability of long-span lightweight structure systems: observations concerning retractable roofs

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Abstract

Long span structures 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, whose combination deals with lightweight structural systems. In order to increase the reliability assessment of long span lightweight structural system, a knowledge based on a synthetically conceptual design approach is recommended. The uncertainties related to the large dimension and the eventual movable and/or retractable functions must be considered with special attention during design process.

1 Introduction

Long span structures, fixed and movable, are today widely applied for:

Sport buildings
- Stadiums
- Sport halls
- Olympic swimming pools
- Ice tracks and skating rinks
- Indoor athletics

Social buildings
- Fair pavilions
- Congress halls
- Auditorium and theatres
- Open air activities

Industrial buildings
- Hangars
- Warehouses
- Airport terminals

Ecology buildings
- waste material storage
- pollution isolation

According to the state of the art, the lightweight structural typologies and materials more frequently used for long span structural systems are:

Space structures
- single layer
- double layer
- double curvature
- single curvature

Cable structures
- cable stayed roofs
- suspended roofs
- cable trustees
- single layer nets

Membrane structures
- double curvature prestressed membrane
- pneumatic membrane

Hybrid structures (materials)
- steel and aluminium
- structural glass
- carbon fibres
- fibre glass and PTFE
- aramidic fibres (KEVLAR)
- ceramic materials
- smart materials

Hybrid structures (typology)
- tensegrity system
- beam-cable system

1.1 Special aspects of conceptual design decisions on long span structures

Due to the different scale of long span structures several special design aspects arise as:

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

- the wind pressure distribution on large areas considering theoretical and experimental power spectral densities or correlated time history;
- rigid and aeroelastic response of large structures under the action of cross-correlated random wind action considering static, quasi-static and resonant contributions;
- the time dependent effect of coactive indirect actions as pre-stressing, short and long term creeping and temperature effects;
- the local and global structural instability;
- the non linear geometric and material behaviour;
- reliability and safety factors of new hi-tech composite materials;
- the necessity to avoid and short-circuit progressive collapse of the structural system due to local secondary structural element and detail failure;
- the compatibility of detail design with the modelling hypothesis;
- 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.

In case of designing retractable roof, special loads must be considered:

- statistical evaluation of live loads during transitory retractable operations;
- horizontal load during opening and closing;
- inertia and bracking forces
- impact forces;
- loads on shock absorbers.

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 retractable roof of the Montreal Olympic Stadium due to wind excitations of the membrane roof (1988), the Minnesota Metrodome (1983) air supported structure that deflated under water pounding, etc. Those cases are lessons to be learned from the structural failure mechanism in order to identify the design and construction uncertainties in reliability assessment.

Many novel projects of long span structures attempt to extend the "state of the art". New forms of construction and design techniques (as movable and retractable roofs) generate phenomenological uncertainties about any aspect of the possible behavior of the structure under construction service and extreme conditions.

Fortunately, structures rarely fail in a serious manner, but when they do it is often due to causes not directly related to the predicted nominal loading or strength probability distributions. Other factors as human error, negligence, poor workmanship or neglected loadings are most often involved [1]. Uncertainties related to the design process are also identified in structural modelling which represents the ratio between the actual and the foreseen model's response.

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 and movable structures involving often something "unusual" and clearly have an influence affecting human interaction.

In Table 1, the prime cause of failure gives 43% probability (Walker, 1981) to inadequate appreciation of loading conditions or structural behaviour.

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 (Matousek & Schneider, 1976).

Performance and serviceability limit states violation are also directly related to structural reliability. Expertise in structural detail design, which is normally considered as a

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micro task in conventional design, have an important role in special long span structures: reducing the model and physical uncertainties and avoiding chain failures of the structural system.

Table 1. Prime causes of failure. Adapted from Walker (1981).

Cause	%
Inadequate appreciation of loading conditions or structural behaviour	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

According to the author, knowledge and experience are the main human intervention factors to filter gross and statistical errors in the normal processes of design, documentation, construction and use of structures.

The reliability of the design process in the field of special structures must be checked in the following three principal phases: the conceptual design, analysis, and working design phases.

2 Knowledge based conceptual design and reliability level

The conceptual design (Fig 1) 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 errors. Gross errors may be removed, also informally, as a result of the observation: "something is wrong" [1].

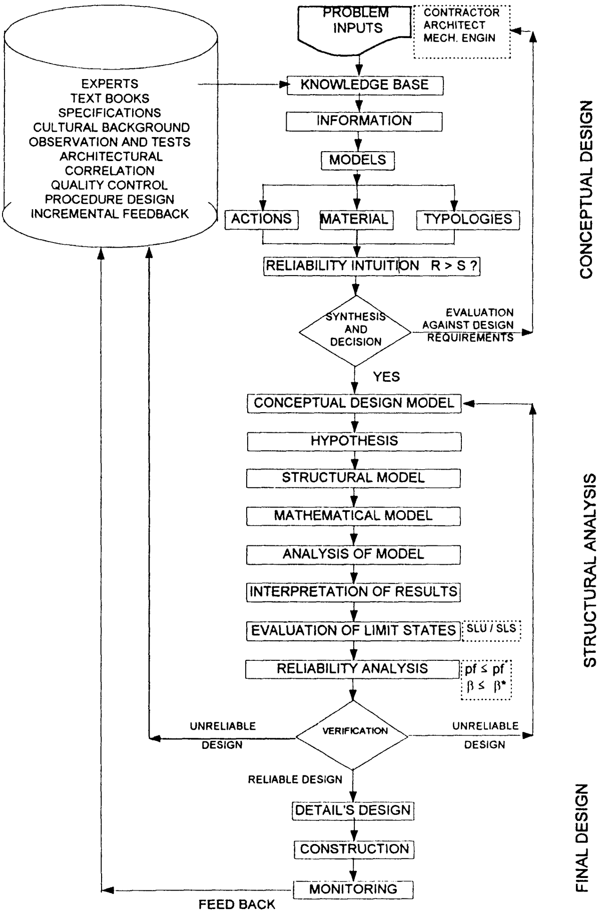

Figure 1: Conceptual design and analysis of structural systems.

In the conceptual design phase the structural expert contributes in finding a design solution together with other specialized professionals (architects, project managers, mechanical engineers, etc.). According to the design requirements the conceptual design is defined by a knowledged expert synthetical approach based on a reliability intuition of the selected model which has to be confirmed by the results of the analysis phase. The conceptual design phase directly depends on the skills and abilities of the design team members.

This concept is 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 is intended 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.

Formalized methods of 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.

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 case of movable structures the knowledge base concerns mainly the moving cranes and the related conceptual design process which 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 no. 16 prepared a state of the art report on retractable roof structures [2] including recommendations for structural design based on observations of malfunction and failures. Examples of causes and failures of moving cranes are included in Table 2.

Table 2. Example of failures of moving cranes from 230 observations [3].

	%		
Mechanical failure	51.3	Design failure	4
Electrical failure:		Manufacture failure	31
Motor	48.7	Material failure	40
Controller	52.0	Poor handling	45
Resistor	5.0	Service life and wearing	192
Wiring	2.0		
Contractor	25.0	Electrical failure	80
Others	8.0	Gust or collision	43

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Architects/engineers should pay attention to these malfunctions and failures of retractable roof structures in their design, with consideration given to the above-described examples of malfunctions (Table 3).

Table 3. Malfunctions and failures expected in retractable roof structures [3].

Unit	Expected malfunctions and failures
Running unit	- Falling from rail or cable, floating, brake trouble, insufficient locking device, failure in speed control, swinging, obstacle, failure of mechanical unit, wearing, etc. - Overrunning or collision due to operating failure. - Power failure, electric leakage, disconnection, etc. - Failure of synchronization, zigzag running, falling object due to swinging. - Trouble of suspension rope, cut-off rope, etc. - Improper running due to unequal settlement. - Loosening and falling of bolt due to vibration during running.
Control	- Synchronization control: difference in length of running between left and right. - Zigzag control: left and right deviation.
Roof surface	- Flapping of retractable membrane due to wind during opening and closing. - Slipping of cable.

3 Some observations on retractable roofs and movable structures

3.1 A retractable roof over a swimming pool in Rome. Design: M. Majowiecki

This covering system, designed in 1987, consists in circular shaped roof panels of 25 m span and 5 m wide realized in composite wood, covered by a polyester and PVC membrane.

The six panels move in longitudinal direction on rails, independently, by a motor driving mechanism. No structural problem has been detected at the moment. Only practical cleaning of the rails and ordinary maintenance were produced.

External and internal view are shown in Fig 2.

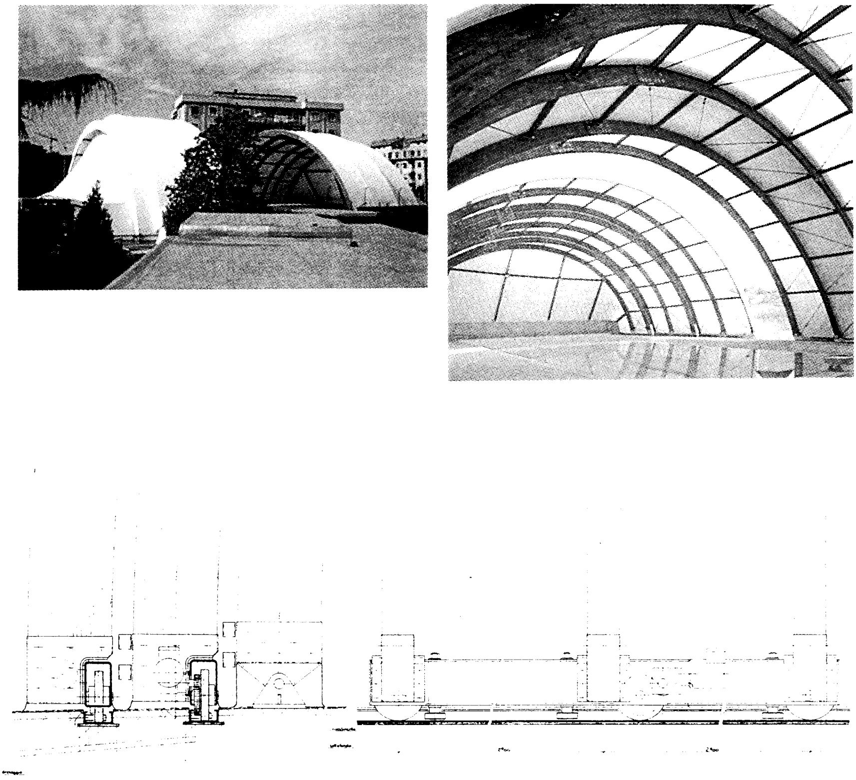

Figure 2: Wood and membrane covering under opening operations. Wheels, rail and motor driving mechanism.

3.2 Retractable roof over an Olympic swimming pool-Ravenna. Design: M. Majowiecki & L. Marchetti

An existing Olympic sized swimming-pool has been covered by a retractable roof during 1986, for the city of Ravenna (Fig 3).

The main structure consists in 10 cable stayed frames of 36 m span placed every 6.30 m. The roof is formed by a part over the grand stands and two movable panels of 10.9 x 6.3 m, obtaining globally an openable roof surface of 1250 m^2. The roof panels are formed by a sandwich of steel metal sheets with internal insulation supported by Teflon wheels.

The translational movement of the panels is produced by two synchronized motors connected with the panels by a steel reinforced Teflon during belt. The roof is displaced in 15 min.

The construction is also equipped by 9 wall steel framed

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elements cladded with polyester and PVC membrane, electrically movable, with horizontal end position used as solar screen.

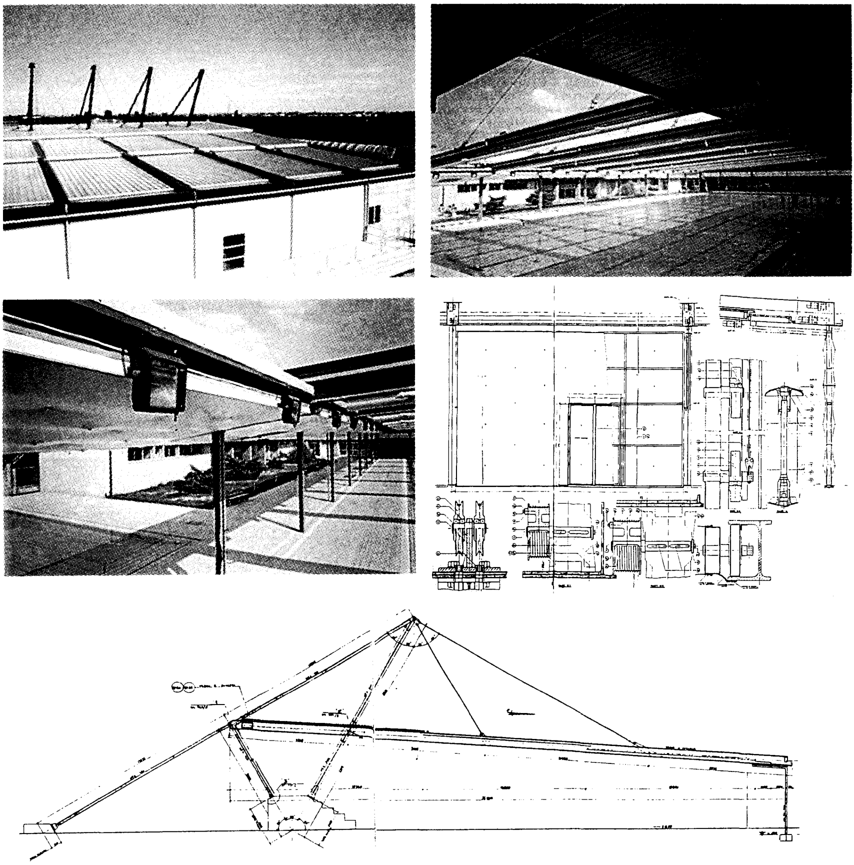

Figure 3: External view of panel covering and movable wall; open situation of covering; open situation for wall-screen; section of the structure; mechanism of the openable wall.

3.3 The Milan Fair convertible roof. Design: M. Majowiecki

The main structure is a rope truss formed principally of an upper carrying rope, a lower stabilizing rope and two A-shaped columns (Fig 4).

The upper rope is anchored to pile foundations at a relative distance of 205 m, have a span of 125 m, and a sag of 13 m. It is made of four spiral zinc-coated (B class) cable 42 diameter formed with 127 wires of 3.2 mm of 1600 N/mm^2 breaking strength. The lower cable is anchored directly to the ground with a span of 105 m and 22 m sag. The cable data are the same as the upper rope.

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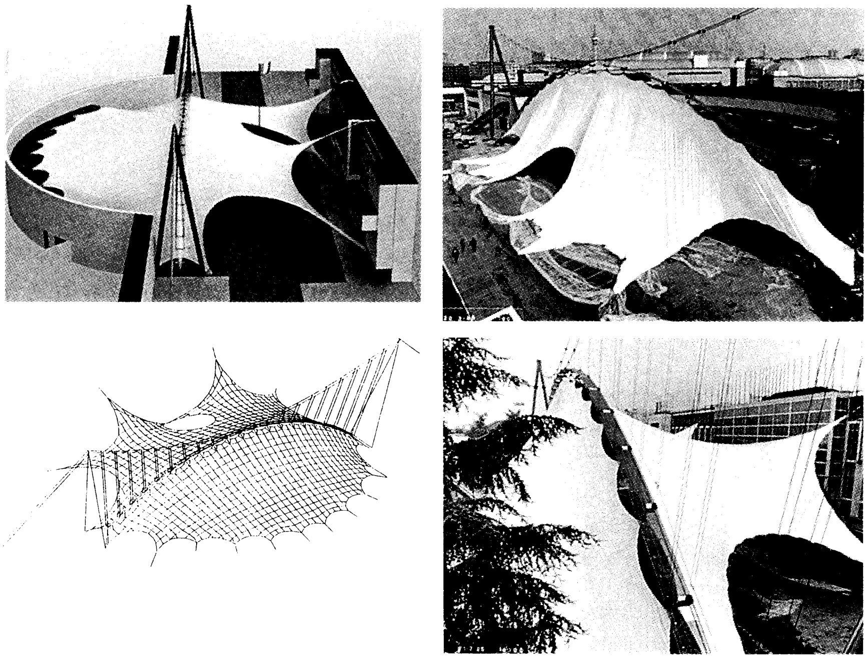

Figure 4: Membrane during yearly conversion and the mathematical model.

The connection between the upper and lower cable is made with 2+2 12 mm cables diagonally disposed. Diagonal stays are connected to upper and lower cables with steel cable fittings. High strength tightened bolts assure transmission of tangential forces and prevent slipping with a friction design coefficient of 7%. The columns are of Fe 510 B steel grade, 900 mm diameter and 12 mm thickness. At the top there is a saddle for the upper rope with a ratio of 20 between saddle radius to strand diameter. At the bottom of the A-shaped columns two spherical hinges are placed in order to permit erection and in-service rotations. At the same level is placed the lower rope anchorage (open bridge socket).

The membrane structure have a plan surface of about 6,000 m^2 and cover the main square of the Milan Fair (Piazza Italia).

The membrane structural system is oriented along the main axis of the roof surface with a span of 125 m. The cross section, in relation to the axis of symmetry, is of about 80 m, corresponding to the distance between two existing buildings. The membrane covering is suspended at the bottom of the main longitudinal structural system at a maximum height of 22 m, and is anchored at discrete points to the ground and on the existing buildings. The covering remains in place from spring time to autumn and is removed during winter time.

Design of details was very important for the success of the operations of convertibility. A cat-walk pulleys and anchorages on the ground permits the placement of the membrane covering in two days at the beginning of April (see Fig. 5).

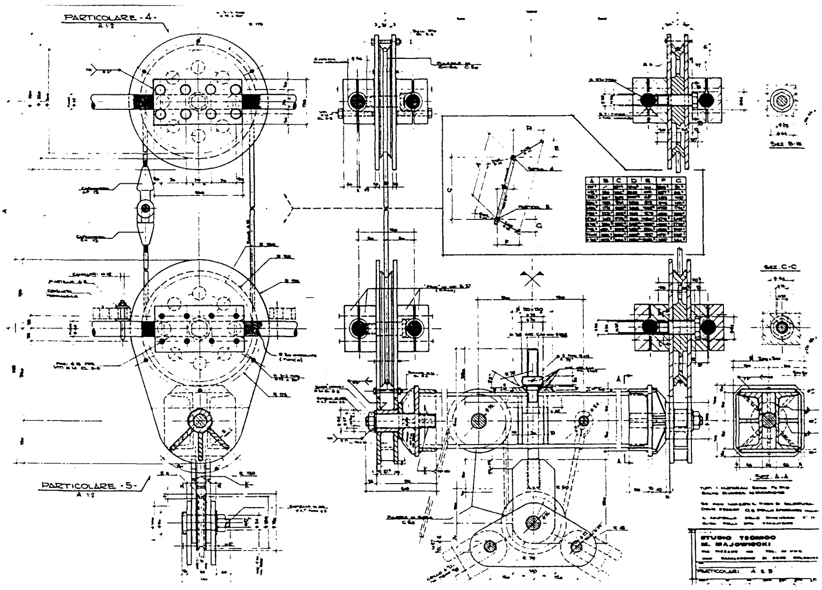

Figure 5: Central fixing mechanism of the membrane.

3.4 Arts and sport hall in Ravenna. Movable grand stands. Design: M. Majowiecki & C.M. Sadich

The roof structure can be defined as a double layer space frame with an average geometrical surface of global elliptical curvature. The inner and outer layers are omothetic circular cylindrical surfaces of 54.602 m and 56.102 m, respectively. Those surfaces are disposed in a square plan of 54.06 m side, 25.09 m high with a ribbed connection along the diagonals.

A standard mesh of 3.90x3.90 m in correspondence of the outer surface define the base of the tetrahedral unit of the space frame lay-out. In the top of the vault a 7.80 m square grid, electrically movable permits the natural ventilation of the vault. The shell is supported, at 7.40 m from the play ground, by a reinforced concrete framed structure which takes the vertical components and the global drag forces due to wind an seismic action. The horizontal components due to arch behaviour is eliminated by a cable system placed horizontally at the

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level of supports. The cable is pre-stressed for dead load components.

The structural elements are tube profiles between Ø 76.1/3.2 to Ø 127/4 diameter and thickness of Fe 510 C steel. The elliptical diagonal arches have rectangular section formed by welded steel plates of 10 to 15 mm thickness.

The space frame, in order to facilitate the erection procedure has been produced by initial independent triangular section meridian arches, then connected by steel tube bars in the inner surface in order to complete the frame-work. According to this fabrication system, was possible to optimize the assembling in the work-shop and the procedure of erection. On the outer surface, corresponding to meridian lines, were placed neoprene pads for the linear contact of the covering pre-stressed membrane system realized with teflon coated fibre glass.

In this construction instead moving the roof, the grand stands are displaced out of the building electric motors and a driving mechanism on wheels and rails. After a run of 70 m in 10 min the sport hall is empty and available for a real multifunctionality. Externally the grand-stands are used for out-door sport and social events (Fig 6).

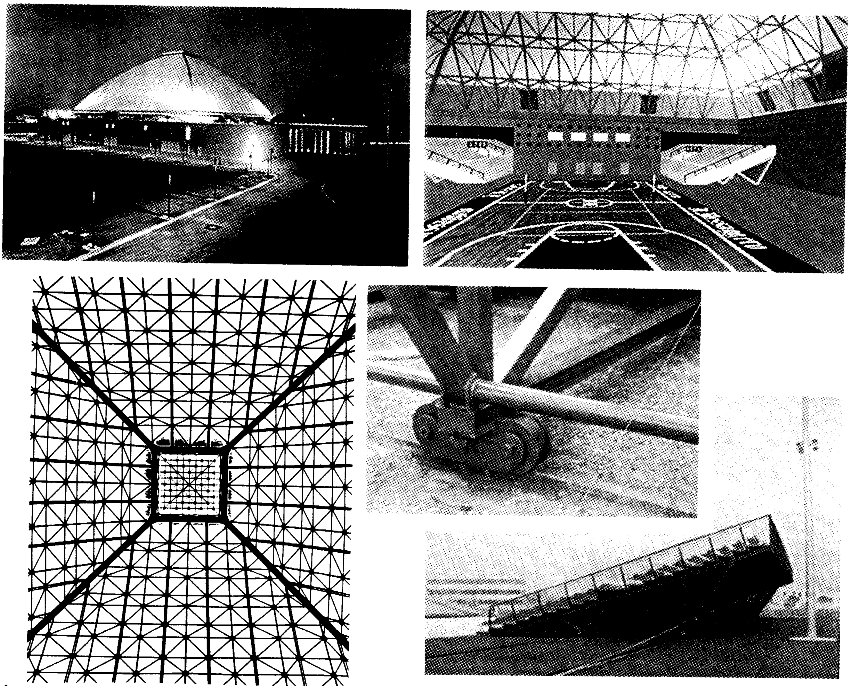

Figure 6: Outdoor and indoor view of the sport hall; computer simulation of grand stand translation; view of the stands on rails.

3.5 The Olympic Stadium in Roma. Design: Italprogetti & Studio Tecnico Majowiecki

The cable roofing system, used to cover the Olympic Stadium in Roma, is formed mainly of:

- a radial distribution of cable trusses;
- a polycentric inner tension cable ring;
- an outer anchorage system consisting of a space frame, reticular, polycentric ring;
- an easy to assemble membrane covering system.

The membrane covering is made of a strong fiberglass fabric with an orthotropic weave, covered on both sides with PTFE (polytetrafluoroethylene). The radial elements, with plan dimensions about 46x10 m, are erected and fixed indipendently each other in order to avoid chain collapse. Figure 7 shows the easy assembling and removing membrane panels.

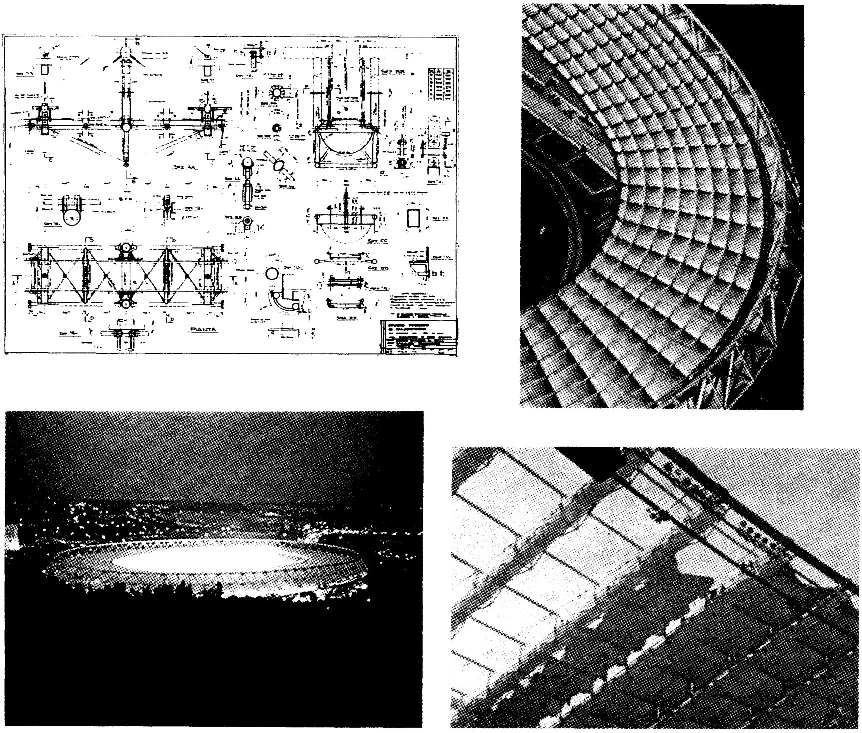

Figure 7: Aereal and internal view of the Olympic Stadium; membrane panels under assembling operations.

3.6 Ohita Stadium retractable roof. Design: Nikken Sekkei (Osaka, Arch. I. Hashimoto); Consultants: M. Majowieckj & Y. Watanabe

This design has been presented for the competition held in Ohita (Japan) in 1995. The main idea is to obtain an open athletic and football stadium which could be closed under adverse climatic conditions by a retractable roof.

According to this assumption the most probable situation, regarding retractability, is the open state.

The structural system is mainly formed by:

- two main longitudinal arches;
- two secondary longitudinal arches;
- two fixed covered grand stands;
- a central retractable roof with movable panels.

3.6.1 Main longitudinal arches

The longitudinal arches have a total length of around 300 m supported by struts and columns. The central part is supported by parabolic pre-stressed cable system in order to optimize stress distribution and minimize deformations induced by live loads. The section is formed by two rectangular boxed sections in steel Fe 510 grade C/D.

The stability out of plane is obtained by a lateral column and the fixed roof wind bracing effect. The two systems will be dimensioned in order to short circuit each other failure obtaining a double system working against wind and seismic actions.

3.6.2 Secondary longitudinal arches

The secondary longitudinal arches have the main rule of supporting the fixed stand roof in order to permit the independent construction of grand stand concrete construction.

The secondary arches are designed with the same typology of the main arches.

3.6.3 Covered grand stands

The grand stands of the longitudinal sides are covered by space trusses connected by secondary beams and covered with PTFE membrane.

The space trusses are formed by circular steel tubes. The transversal beams are made by rectangular hollow section.

All the steel structures of the roof form, by wind bracing, an in plane system able to stabilize, out of plane, the main and secondary arches in case of fault of the main structure.

3.6.4 Central retractable roof

The retractable roof consists of 27 movable standard units. Structurally, are simple supported beams of 106 m span formed by steel tubes according to a space frame typology (Fig 8).

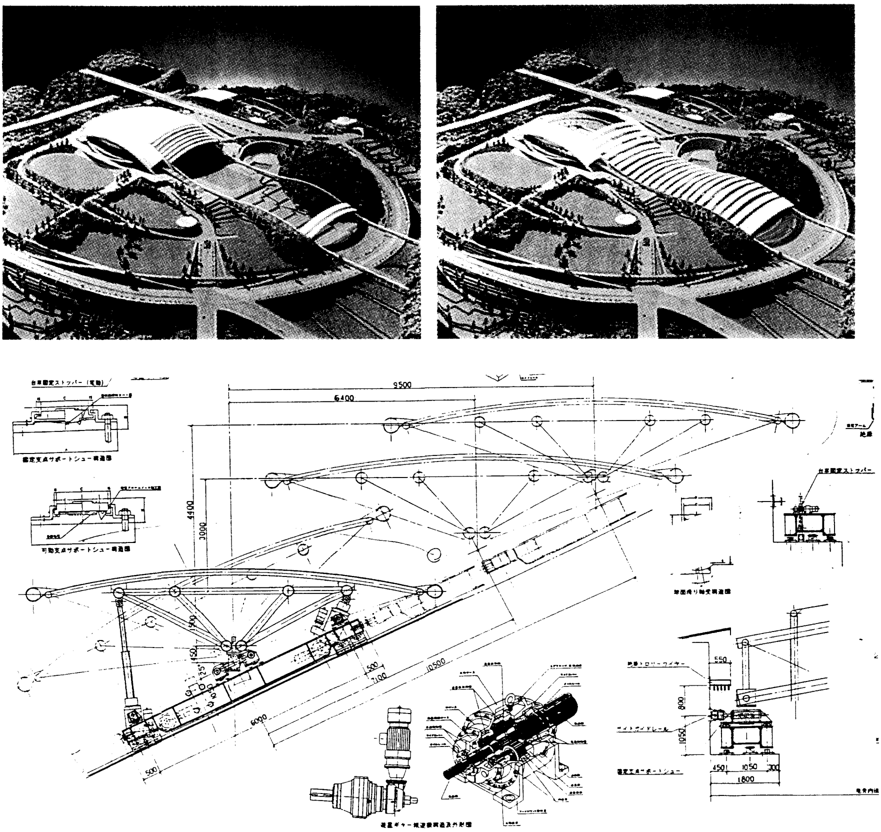

Figure 8: Open and closed position of central movable roof; driving mechanism of roof panels.

The driving mechanism is designed in order to permit thermal and static deformations and transmit horizontal dynamic forces due by wind and seismic actions.

The different phases of design and structural verifications will be based on the following step of analysis (considering the open, transitory and closed position of the roof):

Loading analysis:
- basic loading
- load conditions
- load combinations

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Mathematical model:
- open state (locked position)
- open transitory state (moving situation)
- closed state (locked position)

Structural analysis:
- Static analysis
  - open state
  - open transitory state
  - closed state
- Dynamic analysis
  - open state
  - open transitory state
  - closed state

Driving mechanism analysis and design:
- running devices
- driving devices
- locking devices
- tracks

Structural verifications of resistance and stability:
- allowable stress method
- ultimate limit state
- serviceability limit state

Maintenance book specifications:
- structural monitoring program
- driving mechanism monitoring system
- ordinary and extra-ordinary maintenance specifications for the structural system
- management specifications for durability under expected lifetime service (opening and closing procedures and control)
- management and maintenance of the driving mechanism

3.7 Bergisel Stadium. International ideas competition for a convertible roof. Jury Components: H. Rühle & M. Majowiecki

3.7.1 Description

The Bergisel stadium in Innsbruck is a large outdoor arena on a partially man-made hill with a 90 m ski jump. It is located in the immediate vicinity of the city, lies 80-200 vertical meters above the Inn valley, and was designed to hold nearly 60,000 standing spectators on the steep steps of the grandstand. The stadium is set apart first of all by its unique and particularly scenic location - with a panorama including the city of the foot of the hill against the magnificent mountain backdrop - and secondly by the size of the ski jump together with the impressive space in the stadium interior with its unity of form.

3.7.2 Main objectives

The objective of the competition was to develop a concept for the structural design and spatial organization of the Bergisel stadium which is to be redesigned as a covered, multifunctional center with the atmosphere of an open-air stadium for use year round.

The key element in the designing task is the proposal for a roof - preferably convertible - over the spectator area and the proposed stage complex. This roof may in no way whatsoever hamper the ski jumpers or block the spectators' view of the athletes when ski-jumping competitions are held in the stadium.

3.7.3 Main results of competition

The projects submitted reflect the international state of the art of roof structures with wide spans and large surfaces in a remarkably wide range, and in most cases they also meet the requirements of convertibility. Many authors base their projects on well-tried supporting structures which have already been implemented and which are now interpreted in the light of design concepts parts of which are new. With few exceptions innovative approaches are limited in concept if rich in detail. All common types of structures are represented in a relatively wide range of possible variations. There are domes, arches, steel spatial structures, membranes, and pneumatically stabilized structures. In most cases the materials used are employed in a suitable way and hybrid construction principles are shown with high-quality fabric roof membranes suggested in a number of projects. Most of the designs submitted have taken the problem of convertibility very seriously. If domes have already proved their reliability in practice, other techniques still require further development and testing.

It has become more and more obvious that the specific shape and situation of Bergisel stadium limit the possible use of structures and allow only those which offer weather protection but still permit an unobstructed view. For these reasons structures, which are typical for sport palaces, such as domes or arches, even if considered excellent solutions from the technical and the economic points of view, do not necessarily meet the requirements. In intensive discussions of the competition entries the question arises to which extent certain roof and stadium structures are compatible with the peculiarities of this very specific location. The Jury realized that a "perfect, omnifunctional sports hall" involves the danger of destroying the uniqueness of Bergisel.

In Fig 9 are illustrated the most interesting retractable roof systems.

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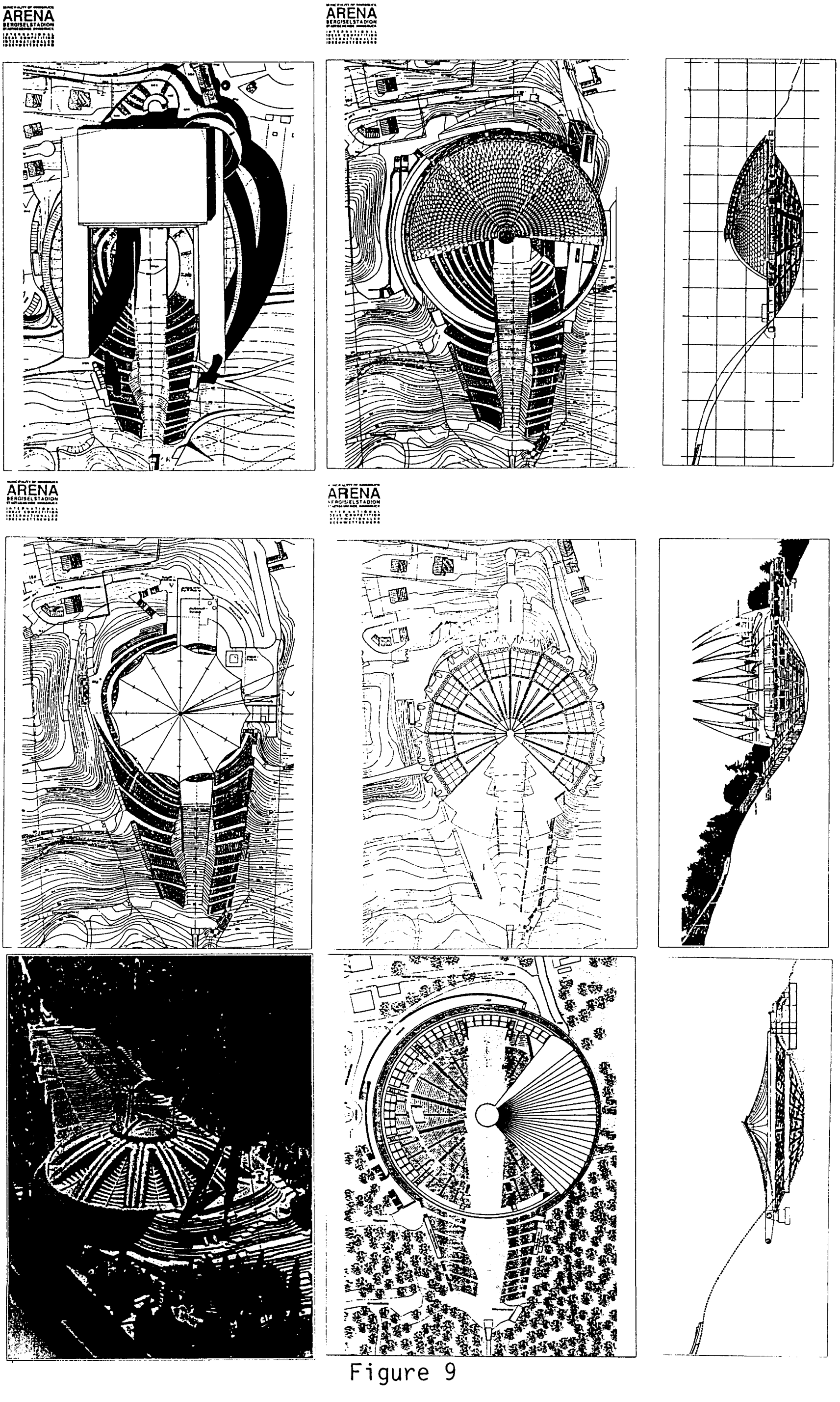

Figure 9

A review of the structures used shows some important general experiences [4]:

- Number of projects (from 40 countries)	184
- Not any or insufficient structural treatments	34
- No spatial structures	11
- Application of arches	46
pylons	37
fabric membranes	52
pneumatic structures	4
steel and steel spatial structures	65
cables	52
- Structural design (projects)	
domes	19
steel spatial structures (not including domes)	49
arch + cables + membranes	28
pylon + cables + membranes	18
cables + membranes	5
pylon + steel spatial structures + membranes	19
wood spatial structure + membrane	1
- Retractable systems	45

References

1. Melchers, R.E. Structural Reliability, Elley Horwood Ltd, 1987.

2. Ishii, K. (ed) Structural Design of Retractable Roof Structures, IASS Working Group no. 16, 1995.

3. Nagatsuka, G. & Honda, S. Practical Design Manual for Cranes, 2nd edition, Sangyo Tosho, 1990.

4. Rühle, H. Some results on development of structural design as result of international ideas competition Bergisel Stadium 1991, IASS-MSU International Symposium, Istanbul, Türkiye, May 24-28, 1993.

5. Majowiecki, M. Conceptual design, experimental and theoretical analysis, detailing and performance of long span lightweight structural systems, Lightweight structures in civil engineering, Warsaw, Poland, Setptember 25-29, 1995.