International Forum on
Sports Installations Programming, Designing, Construction and Management

Turin, October 20, 21 and 22 2005

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DESIGNING AND CONSTRUCTING GREAT SPANS FOR SPORTS INSTALLTIONS[1]

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[1] **Only text version available.**

DESIGNING AND CONSTRUCTING GREAT SPANS FOR SPORTS INSTALLATIONS

Two prevailing and quite often contrasting architectural trends are typical in great sports installation roof design reflecting the static and constructional concept of bearing structures: function and symbol, that is to say installation functional polyvalence and the symbolical value of its architectural image.

The structural project is a basic part of the decisions made based on these two trends and corresponds to them, sometimes supporting but more often interpreting them at the very origins of the architectural project and de facto identifying with it.

The vast array of static schemes, mechanical concepts and calculation methods, structural forms and construction technologies structural engineering can be used today for sports installation roofs with high quality applications and a powerful stimulation to development.

1. Shows and Functional Polyvalence

The form and structural features of great sports installation roofs have always been mostly regulated by the function sports have as a show. The peculiar features of sports activities held inside installations, with few exceptions such as the compressed air roofs over tennis fields for instance, have never played a very influencing role.

Exception made for constraint on main plan and elevation measurements, one cannot generally acknowledge a specific nature for these elements as sports installation roofs, even less so for specific sports activities; stadiums with a natural grass playing ground, where roofs only cover the grandstands, are for the show but are generally harmful to the playing ground, are a case in point.

This definition of sports installations as show places was re-launched some twenty years ago at a much more general level: not just different type and level sports shows but theatrical and musical events as well, or even altogether different ones such as exhibitions or great public gatherings.

This functional polyvalence at first just involved Sports Palaces, but more and more stadiums now; it satisfies economic, quality and continued use needs, thereby requiring full-time use buildings and other complementary buildings and structures needed today for qualifying any great show container.

A special though recurrent case is that of installations built for specific sports events, such as the Olympic games or World Soccer Championships that quite certainly will not occur again during their life but involve basic project parameters such as capacity.

After the event, there comes the issue of transforming the installation into a generally reduced capacity but highly flexible building.

The design for the Sydney Olympic Stadium for instance already had provisions for transforming it by reducing its capacity by 30,000 seats, after the 2000 Olympic games **(Figures 1 and 2)**. The two 296 metre span grid arches had been designed to support any increased load due to possible roof extension and their foundations were also adequately proportioned to bear any future mobile roof.

The possible future installation of further sliding modules for complete stadium coverage was also taken into consideration in the project for the Wembley arch and parallel beam roof diagram **(Figures 3 and 4)**.

Transformations could be even greater, however.

Tenders were called for the design of an 80,000-spectator stadium for the Stockholm 2004 Olympic games, to be later transformed into a completely covered-up poly-functional Arena accommodating 20,000 spectators The project by Nicholas Grimshaw and Partners **(Figure 5)** included a flower-like internally collapsible bleacher upper ring, a surprising hypothesis when thinking of the different loads and stresses on grandstands and roofs, but typical of today’s issues and their involvement in great bearing structures.

In this same perspective already somehow perceivable in recent projects there might very well be the same distinction between sports Stadiums and Palaces, that for Arenas it might decrease in the future by using mobile roofs, mobile grandstand systems, artificial or transferable grass fields already provided for some stadiums, or progressively lead to conceiving single highly flexible containers.

Great roof structures can be involved in various ways and at different levels in this general trend towards sports installations functional polyvalence:

- the structure can remain unaltered for different ordinary uses but is designed to enhance any possible transformation. This is the prevalent approach nowadays and was very clearly applied in the new Turin Palahockey, for instance **(Figure 6)**;
- the structure itself can be used as a machine in ordinary installation transformations, as in the case of variable shape roofs, opening covers particularly. Some large size opening roofs have been built for the Cardiff installation, for instance, with rectangular shaped mobile panels supported by parallel beams **(Figures 7 and 8)**; for the Fukuoka one, with

a round cupola mobile sectors **(Figures 9 and 10)**; and for the Toyota City one, with accordion layout mobile elements coupled with inflatable cushions **(Figures 11 and 12)**;

- type and size structure design can also provide for possible structural changes or integrations enhancing great future changes, such as in the case of the Sydney Olympic stadium mentioned above.

The following roof structural items are important for polyvalence:

- **Surrounding constraint structure overall dimensions and layout**.

  Installation polyvalence firstly requires being susceptible of simple and fast modifying ground layout and any grandstand extension or layout with mobile elements. This requires ample access, handling and deposit areas are

  Constraint structures condition covered space inside to outside relationships leading to great span structures with constraints if at all possible independent of grandstand structures spaced along the hall or building perimeter.

- **System suspended load bearing capacity and type**.

  A polyvalent installation should offer good cover use margins as constraints for new equipment, plant, maintenance gangways, mobile walls and the like.

  The roof intrados shape, structural reticule, construction type and its local, mainly secondary structure, bearing capacity are involved in this need for suitability in achieving new constraints and especially bearing reactions on reasonably small deformation axes.

The guiding concept of functional polyvalence thus seems to go towards great span roof structures of apparently simple shape, such as a horizontal intrados or slightly arched reticule plate, with a square rather than round contour, organised into dense secondary link mobile compartments, supported by or suspended from a small number of constraining points possibly perimetral versus the entire structure.

So, a relatively heavy and complex roof structure that could look rather commonplace were there no covering materials, as so often happens, or great support tower or arch and stay suspension mega structure constraints typifying it architecture.

2. The Symbolical Value of Architectural Images

The roofs of great sports installations – similarly to the cathedral cupolas or the vaults of the great railways station and first universal exhibitions of past times – stand out with their size inside the urban landscape and take on symbolical values.

These symbols are present both in the feeling of belonging of athletes and the supporters of a team or sport or the dwellers of a town, and in showing the building skills or more generally the economic and cultural potential of a town or country.

An essential identity condition however for these two symbolical roles to become real is that the architectural image unique and therefore new for each great installation aspiring to play them.

This image can be supported by surface quality and new building materials and systems expressing advanced technological skills, but the primary role is still played by shape.

A new and unique shape as for the tallest skyscrapers that stands out in its urban context and from others in other towns and countries.

Structure becomes the project’s essential first actor here.

As building size grows because of material resistance and deformation compatibility issues, so architectural shape is increasingly conditioned by the structure. In many cases it can indeed be acknowledged that the construction’s structural conception is the original architectural shape inspirer.

Two very recent references can be used to exemplify the foregoing.

The Wembley Stadium white brickwork towers had to be torn down 70 years after their construction to move the new stadium further north and extend its capacity and improving access. How to replace that symbol?

The new stadium roof anyhow needed a great structure and a four-stayed pennon suspended solution was first designed. This would however have repeated the solution for already built installations such as all-new Cardiff Millennium **(Figure 7)**, so the idea was discarded

The great span double arch solution had already been adopted first at Sydney **(Figure 1)**, and later at Athens **(Figure 30)**.

The final idea was a single 315-metre span, 135-metre height vertically inclined arch **(Figure 3)** that the media turned into a symbol even before it was erected **(Figure 13)**.

The case of the 1936 Berlin Olympiastadion is nearly the opposite; the objective of its restructuring project for the 2006 World Games was to revamp its original architectural image and classical look **(Figure 14)**.

No new structure outside the columns would have been tolerable; nor stays or arches beyond its summit – not even a reticular ring as at the Rome Olympic Stadium to attach the new roof to.

To maintain the value of that architectural image, resort was made to an elementary solution consisting of radial reticular shelving installed offset by a pair of constraints, an outside stay and an internal column **(Figure 15)**.

The accepted outcome was thus the setting of 20 columns on the grandstands in the public's midst, as was customary for cantilever roofs in the first decades of last century. The external edge of the covering ring above the stadium's perimetral columns features a reduced and sharp section that no other bearing system could ever have had.

3. Static Systems

The theory structural design is based on for overall conception of a great roof structure is firstly the structural morphology of great spans.

It is a complex of static and constructional systems supported by mechanical concepts and their calculation methods, which started accumulating in the second half of the 19th Century with the first great bridges, rollway station roofs, winter gardens and universal exhibitions, and continued growing until our times.

Because of the various identity reasons already mentioned and dependency on specific construction conditions of the terrain and constraints, local materials and traditions, means and timing for implementation, the static system of great roofs always presents unique features whereby belonging to a construction or class must be referred not so much to a specific static and construction system as to the main mechanical principle the system design is based on.

3.1 Elementary Shapes

Arches, beams and ropes with their respective extensions to vaults, cupolas, beam structures and plates, rope systems and membranes are the elementary compression, bending and traction mechanical shapes and parameters at the basis of great span roof design **(Figure 16)**.

The issue is sports installations, and today there seems to be no reason for the general superiority of one class over another, which might lead to some preconceived preference. The three bearing systems, though quite different in historical development, mechanical behaviour and architectural and constructional implications, are all at the same quality level and only general layout conditions of individual processes should justify preference of one system rather than another.

This preference is not necessarily generalised over the entire project but articulated according to the overall organisation of the structure into different components as to hierarchical position, building type and static role.

Stress structures offer an instructive example in this connection.

The quest for lightweight and transparent works that was typical of so many projects starting from the 1970s later produced remarkable development of all stressed bearing structure types, with a great success – nearly a fashion – of contrasting rope stress structures, rope systems and fibre reinforced membranes, as well as compressed air structures.

However, some typical features of these structures, such as the architectural and constructional size of constraining elements, the necessarily curved line surface, generally high deformability, sensitivity to dynamic wind effects, specific and costly maintenance, sometimes appeared unfavourable, which led to their appreciably reduced use.

The season of great over 10-metre span hyperbolic parabolic rope web roofs that were made resort to between 1975 and 1985 was that of construction of the Milan Sports Palace, the Calgary Ice Stadium and the Athens Sports Palace. All that is over today and transfused membrane stress structures are increasingly used as covering materials, though structurally limited to secondary elements.

Beside the case of light ring roofs for stadium grandstands, the use of contrasting rope or rope web stress structures as the main bearing system of a great roof is quite rare today.

The stadium just completed at Munich for the 2006 Soccer World Championship, the Allianz Arena **(Figure 17)**, features a very conventional rigid roof bearing structure, with great reticular shelving recalling the first hangars built at Orly and Athens in the Sixties **(Figure 18)**. This is in obvious contrast with the Olympic Stadium stress structure that was Munich's most important 1972 experience in using stress structures for sports installations.

On the other hand, the entire Allianz Arena lining consists of EFTE translucid cushion membranes constrained by 4-metre high rhomb frames **(Figures 19 and 20)**.

3.2 Structure Hierarchy

Any great roof structure is mostly organised according to a hierarchy of bearing systems, and distinguishing between main and secondary bearing systems is very important in this connection.

The fact that both systems can be strongly integrated into the project, with the latter performing stabilisation functions essential to the former, just as the fact that putting all structures together in the same calculation model is quite common today given the services offered by modern computers, does not make this distinction senseless as it is essentially constructional and mechanical: the secondary system is more repetitive and has constraints anchored to the main system while those of the primary system are independent of the secondary system.

Many great roofs have been built without a hierarchy, such as double curvature vaults with a continuous reinforced concrete structure, or continuous space steel grids in the shape of vaults of cupolas, for instance. The Stockholm Globe Arena, built in 1989, is quite a recent example of a continuous roof polyfunction installation **(Figures 21 and 22)**: it is a 110-metre diameter double layer spatial grid sphere, recalling projects by Buckminster Fuller.

Today's trend, however, that is also associated to the preference for steel construction, is to separate the two main and secondary systems, as this distinction generally offers mpre flexible construction organisation, such as in making prefabs for instance; a separation of component roles consistent with different component life, more limited distribution of ground constraints, greater suitability to polyvalent building use and possible future transformations.

Nor could one for instance imagine a great opening roof structure not underscoring the prevalent role played by the bearing system mobile components slide on. The 10 Cardiff Stadium mobile roof panels weighing 1,200 tons overall slide as on a travelling conveyor on two 220-metre span stayed beams that thus become the primary structure of the whole roof structure organisation **(Figures 23 and 24)**.

Another reason for differentiating primary and secondary structures is constraint distribution.

Markedly discontinuous distribution induces corresponding static discontinuity on the structure, inevitably destined to reflect in the prevalent structural elements and zones channelling the highest stresses.

The structure must therefore be internally differentiated, which is what also occurs when the project maintains its architectural and continuous construction consistency.

So for instance in the roof of the new Turin Palahockey, the great ice slab is a continuous structure also from the mechanical standpoint, but the structure layers that correspond to pylon longitudinal and transversal alignments take on a main bearing function versus the remainder of the plate that reflects markedly in structural project development and the constructional system adopted **(Figures 6 and 25)**.

One could ask what relationship there is or may be between a hierarchical position and a static system, and whether or not it is reasonable that the main bearing function be preferably assigned to the more mechanically efficient system in terms of the ratio between load carried and its weight, that is to say, the rope, the arch and the beam in that order.

Static systems and materials have always been traditionally classed by span in the bridge construction business; for steel bridges, the succession is broadly classed into full wall, reticular wall, reticular arch stayed system and suspended system. Except for the case of suspended bridges, that remain in their place, the entire history of bridges is however full of contradictions with the sequence indicated above, starting from 1850, when the 140-metre span Britannia full wall beam bridge over passed the then existing arch ones.

In the great roof business, it would be even more nonsensical to class static systems by span. Reticular beams have already gone beyond 200 metres in the San Siro roof **(Figure 62)** and in the more recent Leipzig Zentralstadion **(Figure 63)**.

A system of inflected reticular plates could be in secondary to a system consisting of arches or great isolated or stayed beams, as well as a complex of membrane or opposing rope stress structures could be secondary to a beam system.

To close, one might say that all bearing systems are useable and used indifferently and nearly independently today as main and secondary systems alike, only based on consistency with architectural design and project plant requirements.

4. Bearing System Features and Performance

Different constructional needs and behaviours affecting performance and use in great roof projects correspond to the three bearing system classes of arches and vaults, beams and plates, stretched membranes and ropes.

Dome general remarks and examples of applications can clarify these differences, with prevailing reference to main structures and related to project consistency with material mechanical and technological features and structure behaviour under variable load.

4.1. Project Consistency with Material Mechanical and Technological Features

Steel has markedly won over reinforced concrete for great span roofs over the past 30 years. Whatever the static system, steel also prevails in great cupolas where reinforced concrete once ruled supreme and is now more often made of simple or double layer grids, such as the 220-metre span Seibu Dome **(Figures 45 and 46)** or the Stockholm Globe Arena.

Marked material price variations and new building techniques, such as the over 70 N/mm^2 resistance concrete high level pumping system used in skyscraper building may re-launch reinforced concrete building works for great roofs, but the race is certainly won by steel nowadays.

Steel is favoured by its high resistance to weight ratio, adaptability to different construction techniques, crossing static schemes and stress conditions other than operating ones during assembly, fast prefab component junction with bolts or welds, easy structure changes with adaptations and reinforcements for installation use requirements occurring during of after construction other than those it was designed for, compatibility with a wide range of transparent or translucid roof materials thanks to the limited overall dimensions of steel members.

Over the past 20 years, steel has been greatly favoured by the development of NC machine tools in workshops and interfaced programmes for spatial geometry generation, computation and automatic structure design.

This meant being freed from the regular square shapes typical of steel construction, starting from steel works products, and enabled designing and buildings with complicated curved shape structures, the representation and workshop tracing if which would have otherwise been impossible. Two examples are illustrated here, related in particular to the Cardiff Stadium roof structure tube carpentry components **(Figure 26)** and the new Turin Oval Palasport **(Figure 27)**.

A special advantage of steel structures, made possible by their relative lightness and suitability for machining, is the possibility of making roof construction independent of the remaining building underneath it, by resorting to assembly with finished structure lifting or relocation. This means increasing jobsite safety and dramatic timesavings.

The 1997 Osaka Dome cupola with its over 130 metres diameter was built on the ground at the same time as construction of the building that was to bear its weight and thrust. At work completion, the cupola complete with its roof and plant and weighing 5,500 tons altogether was raised to its installation height of 45 metres above ground level **(Figures 28 and 29)**. Its perimetral ring that is compressed in the static scheme plays the role of ringing during the lifting operation with traction of 610 tons.

A similar procedure had already been used in 1990 for the reticular cupola roof of the Sant Jordi Sports Palace built for the Barcelona 1992 Olympic games.

An important relocation operation was completed very recently on the Athens Olympic Stadium two roof models **(Figures 30 and 31)**. Each module, featuring a 304-metre span, 80-metre height and 9,500-ton weight non-thrust main arch structure, was moved horizontally for over 70 metres. The two arch supports were fitted with hydraulic cylinder operated sledges for this operation, a technique conventionally used for opening steel beam bridges.

The use of **laminated wood** in great spans was significantly enhanced by Norwegian Contractor works for the 1994 Lillehammer Winter Olympic games, where a high-bearing capacity reticular construction system featuring wall rods coplanar to the bridles was emplaced **(Figures 32 and 33)**. Junctions were 8-millimetre thick multiple metal plates and pins inserted into high-precision saw cut inserts in the rods parallel to wood fibres, forming a reduced overall dimension connection capable of bearing very high stress. The lower 56x57centimetre runners of Hamar Olympic Amphitheatre 71-metre span roof beams shown in **Figure 33** bear 7,500kN traction at the connections.

High material anisotropy is an important obstacle in laminar wood constructions for making two-dimensional or spatial static systems such as plates or vaults. This material is being increasingly used, nevertheless, for great span roofs, inside generally one-dimensional or reticular consistent bearing systems, such as beams, arches or portals located side-by-side. A particularly elegant modern work is the new Tazzoli Ice Palace at Turin **(Figure 34)**.

The use of different span arches located side-by-side of course simulates a double curvature vault, such as at the Lisbon Atlantico Palasport, a 114-metre span building featuring outstanding technological and architectural quality **(Figures 35 and 36)**.

Fibre-reinforced or not **plastic material** membranes are nearly exclusively used in the static scheme of negative double curvature stress structures, as rope webs. These structures are very lightweight and have no bending resistance so this saddle shape is a must to bear opposite sign pressure by snow and wind, to achieve a pre-stress condition capable of making the roof structure rigid and protect it from the dynamic effects of wind **(Figure 37)**.

Cupola shaped positive double curvature stretched membrane structures can only be made when pre-stressed by internal pressure such as compressed air **(Figure 38)** and air cushion ones **(Figure 20),** for instance.

After the success of the USA Pavilion at the Osaka EXPO 70**,** some outstanding compressed air structures were also completed for great sports installation roofs, always by assembling a rope web acting as a primary structure over the stretched membrane. The Pontiac, Michigan 1975 80,000-spectator capacity Silver Dome shown in **Figure 38** covers an area of 168 x 220 metres.

Diagonal rope layout on a square or rectangular plan with faired edges originally introduced by Geiger to limit membrane base perimetral ring stress is a general feature of these projects.

Structural safety dependency on internal pressure maintenance, functional limitations, management costs and several failures caused by membranes torn by vandals or wind and local snow accumulations in the areas in contact with ropes have led to relative abandonment of this type of approach.

Great success in sports installations is being achieved by the use of ETFE air cushion, a modified co-polymer sharing many positive features of PTFE Teflon that can be extruded into high resistance and chemical stability 0.1 to 0.2 millimetre thin sheets.

Cushions are constrained by smaller frames used as secondary structures and by covering and lining materials. They are highly appreciated for their new image, self-cleaning surfaces and good light and heat transmission properties. The new Water Cube Olympic swimming pool under construction at Peiping and assigned to be a future polyfunction installation with a 17,000 spectator capacity is completely lined with a complex air cushion aggregation **(Figure 39)**.

Plastic materials have a much shorter life than other structural materials, such as steel, reinforced concrete and wood and the air cushions used as secondary structures on independent removable frames consistently reflect this diversity.

4.2. Structure Behaviour under Variable Stress

Their load bearing capacity under normal stress makes static systems conceptually suitable to prevalently shape reacting structures, where load distribution is essentially stable in time. These shape reaction structures maximise their load bearing with lightweight construction solutions and minimised stress and deformation.

Snow and wind are however extremely time-variable events, especially for possible snow accumulations and wind directional changes, and cause the greatest effects on lightweight structures.

The thin arches and ropes used in their elementary static scheme for lightweight roofs thus expose the construction to the risk of major oscillation and deformation that are dangerous during use and can trigger off stability-induced collapse.

Beams are different, as grids and plates, systems that react very well to load distribution variations with easily controllable stress and minimum deformation.

The types of great span structures reflect this issue, by articulating into many different solutions that cannot be reviewed exhaustively here, so only the main design trends will be presented at this point.

Arch Structures

The conventional solution for arch structures regarding load variations and ensuing bending effects consists in creasing arch section rigidity by using a well-spaced bridle reticular structure.

This solution originally adopted on a vast scale in the cylindrical vault roof of London's Saint Pancras Railway Station in 1868 and repeated in many other stations, including the Milan Central, for instance is the same as the two unstressed arches of the 1996 Amsterdam Stadium, Europe's first great mobile roof installation **(Figure 40)**.

An arch rigidity system also effective in preventing off-level instability consists in constraining the arch at several sections with the same stays used to suspend the roof from. The great arches of the stadiums at Wembley **(Figure 3)**, Athens **(Figure 30)** and the Lisbon Da Luz stadium **(Figure 41)** use this same approach. The reduced overall dimensions of the several stays do not negatively affect the look of the arch that seems nearly isolated in space.

Efficient stiffening can be achieved in radial plan buildings by activating the contrasting function offered by the secondary roof structure, which causes a constraint to horizontal arch movement that is very favourable for asymmetrical load conditions. The Ruffini Park Sports Palace of Turin, recently restored, corresponds to this layout with a 100-metre span boxed structure 3-hinge arch structure **(Figure 42)**.

Spatial behaviour activated by secondary structures is also efficient in the case pf different span parallel arches, such as at the Lisbon Sports Palace **(Figure 35)** and the Oita, Japan Big Eye **(Figure 43)**. A transversal arch connected to them also ensures the stability of the parallel arches of this latter building, which proved support for mobile roof sliding.

Top quality, lightweight rigid roofs were achieved with double curvature structures made with crossed arch systems. Shape stiffness of these structures, increased when necessary by pre-stressed diagonal ropes in the quadrilateral fields defined by the arches, also enabled making them in a simple layer version with thin compressed membranes of glass featuring outstanding transparency, such as, or instance, at the 1988. Neckarsulm Aquatoll Dome shown in **Figure 44**.

An example of great architectural quality is the Seibu Dom built in Japan close to Lake Tama in 1998. It is a spherical surface lowered cupola surrounded by a 220-metre diameter perimetral ring resting in 12 V-shape suspended uprights and without any perimetral wall **(Figures 45 and 46)**. The central area of the cupola, covered by a translucid membrane, is made with a single layer arch grid; flange connections ensure arch bending continuity at crossings.

Rope Structures

The issue is radically different for rope structures, as an individual rope, unlike an arch, has no bending stiffness and cannot be always the bearer if its load.

This means that the rope changes shape at each load distribution change, with generally unacceptable movements and oscillations.

The system conventionally used to contrast this behaviour in suspended bridges is to couple the ropes to a stiffener beam that receives the load directly, distributes it along the rope and contrast oscillation with its stiffness.

The following two stiffening systems, sometimes also together, were preferably used in great roofs:

- limiting the arrow to span ratio and weighting the bearing rope with ballast to minimise the relative effects of variable loads (*suspended structures*);
- contrast the bearing rope with a drawing one, as shown in **Figure 47**, to impose a pre-stress state to the system (*stress structures*).

  The drawing rope can be located at the same level as the bearing one and connected to it with a screen of parallel or diagonal stays (*flat stress structures*); or orthogonally and connected to the bearing rope in direct contrast (*network stress structures*).

This rope bearing system articulation corresponds to very diverse constraint conditions and structural behaviour with outstanding repercussions on architectural shapes and structural overall dimensions.

Suspended Structures

This bearing system was used in the past for some round plan great roofs, typically placing the ropes in radial positions and anchoring them to a compressed perimetral ring. The capsized cupola-shaped structure generated in this fashion can also benefit from the membrane behaviour activated by the roof if it consists, as for instance the 1958 Montevideo Stadium, of a continuous reinforced concrete plate.

The case in which the surface generated by the ropes is cylindrical is different, as can be seen in rectangular plan buildings with side-by-side ropes anchored to two opposite plan sides, where stiffening comes from the chain stretched shape and ballast weight.

In buildings with no walls in the same parallel direction as ropes, a cylindrical surface also produces a very evocative architectural image given by membrane thinness referred to roof span and the unavoidably massive structure of the constraints used to support stretching. **Figure 48** of the Portuguese Pavilion for EXPO 98, is an example of thus effect.

Ballast is preferably made if prefabricated plates and reinforced concrete that complete the roof by transferring the load to rope axes. The reinforced concrete roof of the Braga Stadium in Portugal only covers the grandstands and is 24 centimetres thick, while the ropes continue through the stadium and are anchored to the top of the 202-metre span grandstands **(Figure 49)**. The stadium's shape shows the very high stretching exerted by ropes, corresponding to grandstand ballasts sloped outwards.

Flat Stress Structures

Drawing and bearing rope connection with diagonal stays makes up a sort of great link reticular structure (*rope beam*), where both ropes play the role of current rods while the wall rods are the diagonal stays. Pre-stressing generally imposed with cylinders located at drawing rope beginning induce enough stretching on all rods to prevent variable load-induced movements.

This is a simple, particular rigid and lightweight construction system with many applications, especially in sports installation roofs, starting form the great project by Finnish designer David Jawerth for the1962 83-metre span Stockholm Ice Palace **(Figure 50)**.

Parallel stay connection was typically applied as a radial shelf structure in ring stress structures for stadium grandstand roofs.

The drawing and bearing ropes are constrained to the stadium perimeter top and are joined together at the internal drawing ring that provides pre-stressing **(Figure 51)**. The two ropes of individual shelves on the external perimeter cam be connected to the ground as in the case of parallel rope beam roof or constrained to the upper and lower edges of a perimetral compressed ring. The roofs of the Turin Stadio delle Alpi and the Rome Olimpico are examples of this difference **(Figures 52 and 53)**.

The optimum geometrical condition for ring stress structures is a circular plan building as stress and deformations generally become more unfavourable when the internal and external rings present marked plan curvature variations.

An original rope layout for ring stress structures coupled to a translucid membrane of the bearing ropes was completed at Zaragoza in Spain, to reuse the old Arena as a general show installation **(Figure 54)**. The same rope layout was later used for the Abuja, Nigeria Stadium **(Figure 55)**, but with the roof constrained to stretching ropes.

In both cases, the two ropes are joined at the compressed outer ring and are constrained inside by two separate traction rings spaced by uprights. This solution +resents the advantage pf minimising structure overall dimensions for the outside perimetral constraint.

Network Stress Structures

The great span network stress structures made in the decade from 1975 to 1985 for hyperbolic parabolic sports installation roofs, as said earlier **Figures 56 and 57** refer for instance to the Milan Sports Palace **Figures 58 and 59** and the Calgary Ice Stadium.

The circular plan of these roofs, in both cases featuring some 130-metres diameter, is consistent with the need to minimise edge ring bending stress. In fact, considering the ring as just sitting on the building perimeter and therefore free to inflect horizontally, its circular shape essentially subtracts it from bending when draws distributed by the bearing and stretching ropes are the same.

A typical aspect if the structural project is therefore balancing ring bending around this neutral condition as loads change **(Figure 57)**. This balancing involves saddle point position, that is to say bearing and drawing arrow ratio, the original rope pre-stress level, and pre-stress control and recovery in time. This issue was the subject if investigations made after collapse of the Milan Sports Palace roof on January 17 1985 due to ring collapse under the snow.

Beam, Trellis or Plate Structures

Reticular plate, trellis or multiple parallel beam structures are the simplest, most consistent and functional solutions for typical Sports Palace roofs as proven by the three works already mentioned for Torino 2006, namely the Palahockey **(Figure 6)**, the Tazzoli Ice Palace **(Figure 34)** and the Oval Palasport **(Figure 60)**.

The 100-metres span tubular metal carpentry beams of the latter building feature an original design with a great architectural effect for their section reinforced with a pair of curved chains featuring the secondary beam arch bridles and the tall upset pyramids that typify support on the building entry side.

Movements consequent on the asymmetry of these great beams do not involve the perimetral glass walls as they are connected to the roof with compact and careful design spherical hinge rods **(Figure 61)**.

Reticular beam solutions have also been repeatedly applied to great stadium roofs: just two parallel beams intermediate to the structure and bearing on the greater span make up, for instance, the main structure of the1989 San Siro, 1998 Cardiff and 2003 Leipzig stadiums.

The load and span of these beams is reflected in design details directed at minimising stress levels. The 205-metre span San Siro beams are offset, beside the supports to balance bending diagrams with ballast **(Figure 62)**; a the 220-metre span Cardiff beams are supported in two intermediate section by stays transferring stress to the building outside **(Figure 7)**; the 202-metre Leipzig beams are on inclined parabolic shape levels at a maximum bridle spacing of 19 metres, the bridles being located across the roof and stabilised by stays **(Figures 63 and 64)**. The spans defined by the great main system isolated beams are generally solved as a secondary system, with parallel reticular beams or beam grids.

To close, it can be said that beams, grids and plates, structures that are generally heavier than arch and rope ones, are however very competitive even for great spans due to their typical advantages of load variation resistance; minimised overall dimensions of perimetral constraint structures already engaged by prevalently vertical reactions, greater consistency with installation and functional requirements typical of large size show buildings.