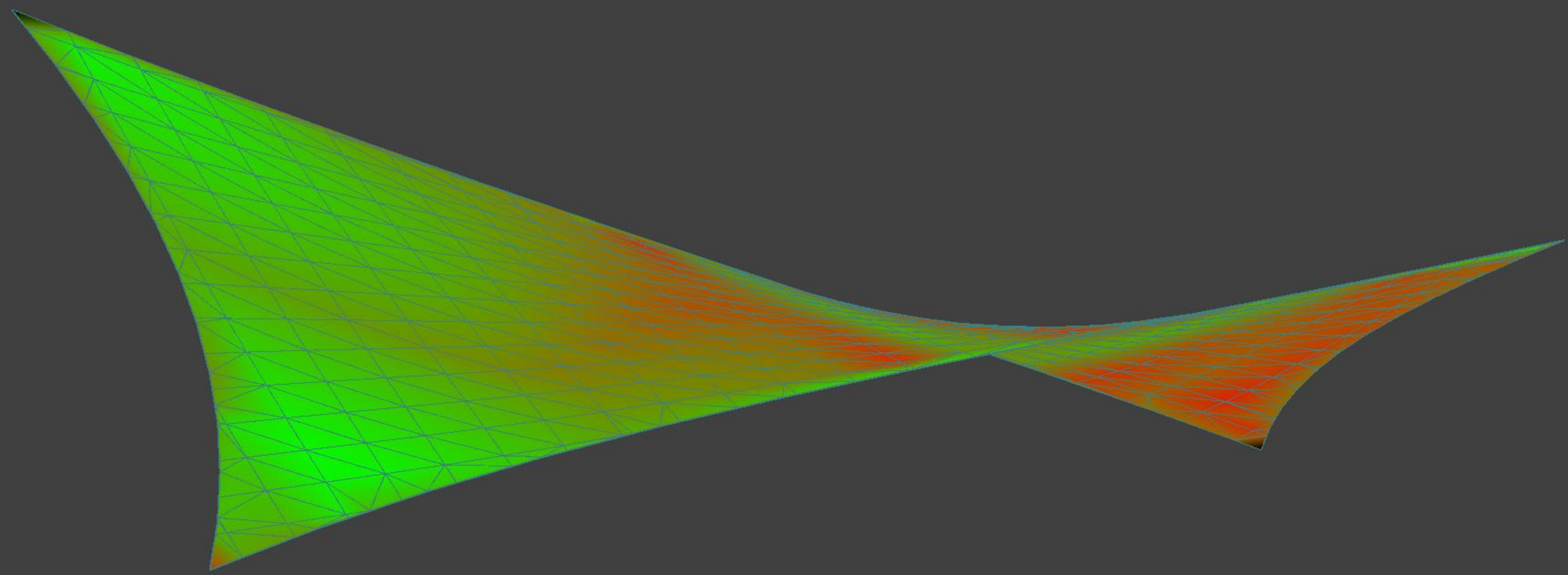

Tensile Structure with Architectural Opportunities of "ETFE" as a Membrane Material

Master's Thesis

Hossein Rezaeehagh

Tensile Structures with Architectural Opportunities of "ETFE" as a Membrane Material

by

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POLITECNICO DI MILANO
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Hossein Rezaeehagh

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Tensile Structure with Architectural Opportunities of "ETFE" as a Membrane Material

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Department of Architecture and Urban Studies

Abstract

Using fabric as protection against rain, wind and sun is nothing new, tents in various shapes can be found in all parts of the world, and has been around more or less since humans started weaving textiles. They are easy to build and light to transport. In Arabia and North Africa they have long used fabric stretched over alleys to create shade and in a smaller scale the umbrella could also count as a fabric structure, shading the sun and protecting from the rain. The big tensioned membrane structures we see in buildings today gained popularity at the world Expo in Montreal, 1967, with Germany’s contribution, designed by Frei Otto and Rolf Gutbrod. The design for the pavilion, “a tent-like roof made of a net of cables”, won partly because the lightweight construction would be very economical to transport overseas (Klaus- Michael Koch, Karl J Habermann, 2004). Although the original design was a tensile membrane structure, it was finally built as a cable net structure, using the membrane as a secondary cover.

Today by the vast expansion of technology and transformation rate of data, people need peaceful spaces far from the stress of their occupied lives more than any other time. Besides, human beings have always been following the rules and forms of the nature. They seek for perfection in the nature surrounding them. In order to express qualities of the nature in architecture, architects started to use curve lines in their designs. They also created wide spans in interior and exterior spaces by the use of new technologies. Only a few construction methods lead to the creation of stirring delightful spaces. Tensile fabric structure is one of these successful methods.

This paper shall point to the history of Tensile Architecture in the human living period and its acceptance in urban context and will try to produce a brief introduction of major membrane materials such as PTFE, PVC and Silicon Coated Polyester, but the main focus will remain on ETFE and its architectural and environmental benefits as a tensile material in the forms of both foils and cushions. The ETFE’s chemical and mechanical properties will be discussed including two analyses whose aim is to offer the main advantages of this material versus traditional and conventional solutions. The benefits like lightness, strength, cost effective, constructing time, sustainability and recyclability and at the end case studies with detail drawings will explain better the idea of tensile membrane structures.

ACKNOWLEGEMENT

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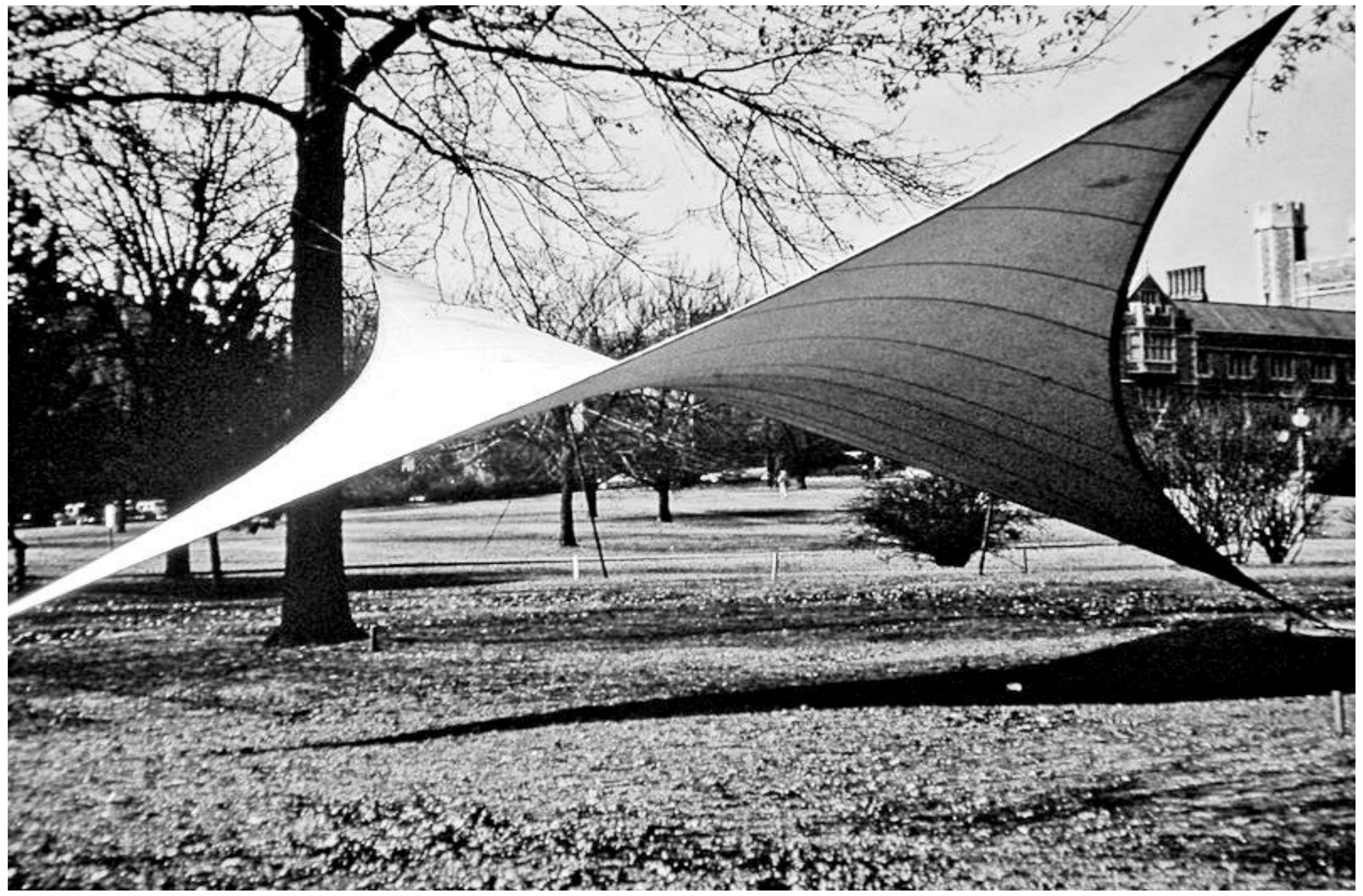


Figure 1) Garden show bandstand, Kassel, 1955

The search for structures demanding a minimum of material and time arises from the desire to be extremely economical with the energy available. This search has often led to surprising results. It is the task of every builder to provide, to utilize, and to extend living space. In this the construction materials are a means to an end, although they often have the disadvantage of taking up space themselves or, because of their rigidity, oppose the natural trend toward change. To minimize or eliminate these disadvantages a :ask of prime importance.

Frei Otto, Tensile Structures

The advent of new materials and construction technologies throughout history has often led the designers of buildings to rethink, and sometimes reshape, even the very meaning of architecture. During the last 40 years tensile structures have developed as a new structural form capable of dramatically spanning large distances with minimum means. Architects and engineers inspired by the idea of an architecture of minimum materials have frequently sought ways to do, in Buckminster Fuller's terms, **'more with less'.** Ever since the German architect/engineer Frei Otto and his collaborators first elevated the traditional tent to a modern building type, the enormous potential of cable-net and membrane structures for creating building envelopes with light-weight stressed skins has been waiting to find more widespread realization in architectural applications.

Figure 2) German Pavilion, Expo Montreal, 1967

Figure 3) Top view of the roof structure of the Olympic Estate in Munich 1972

Figure 4) Interior grandstand roof structure of the Olympic Estate in Munich 1972

Tensile Membrane structures combine creativity and aesthetics with resource-conserving materials, short construction period, low costs, long life and wide range of applications.

The state of the art materials like PTFE (Teflon) coated fiberglass, silicone coated fiberglass and the PVDF/PVC coated polyester are waterproof, fire resistant, anti-UV and anti-dirt, thus require very little maintenance. As the materials are lightweight, the structures are able to achieve longer spans and are easily constructed. These result in substantial costs savings in the foundation and the supporting structures. But the main draw to designers and developers may be the varying forms, shapes and aesthetics that the materials can provide. These structures serve as the primary architectural form determinant and provide much of the building envelope system.

The development of a typical tensile structure undergoes a simple process. The architectural and engineering design begins with shape determination or form finding analysis under load. The form and shape can be modified or adjusted to suit the stress/load boundary conditions. Once the design is completed, the next steps would be fabrication of fabric and supporting structures, and finally, erection. Fabrication of fabric begins with patterning which is a process of selecting an arrangement of two-dimensional panels to develop the three-dimensional surface. The erection or installation of the fabric structure would require careful handling of the materials as well as knowledge of the behavior of the materials. Introduction

2 Background

Traditional Tensile Architecture: The Tents of Nomad Cultures

Tents and suspension bridges are the chief manifestations of traditional tensile building which relate directly to mankind's activities. The modern world discovered suspension bridges almost two centuries before tents began to be seriously considered as a suitable prototype for modern tensile building. The 19th century benefited from advances in metallurgy and the experience gained in constructing large bridges contributed to the prodigious increase in spans in the first half of the 20th century. The tent was ignored except for military uses, circuses, natural disaster relief, cricket matches, garden parties, and the like, until the 1950s. There are two categories of traditional tents; nomad tents belonging to hunters, fishers and pastoral nomads, and urban tents used by princes and warriors. Nomad tents include the conical framed tent of Northern Eurasia and North America, the cylindrical framed tent having a conical or domical roof of the Central Asian steppe lands, and the black tent of the Middle East. A fourth type, the ridge tent, is an ancient form found in cultural resistance regions. Urban tent types are not unlike nomad tents, the pavilion resembles the ridge tent and the parasol-roof or bell tent is similar to the *kibitka*, except that it has a stressed roof cloth and lacks a supporting framework.

The Tent has been adopted in one form or another, by a large number of people living in widely differing environments. Despite some shortcomings it was popular because of its lightness, portability, and ease of erection were advantageous in regions in which building materials were scarce and where economic survival demanded mobility.

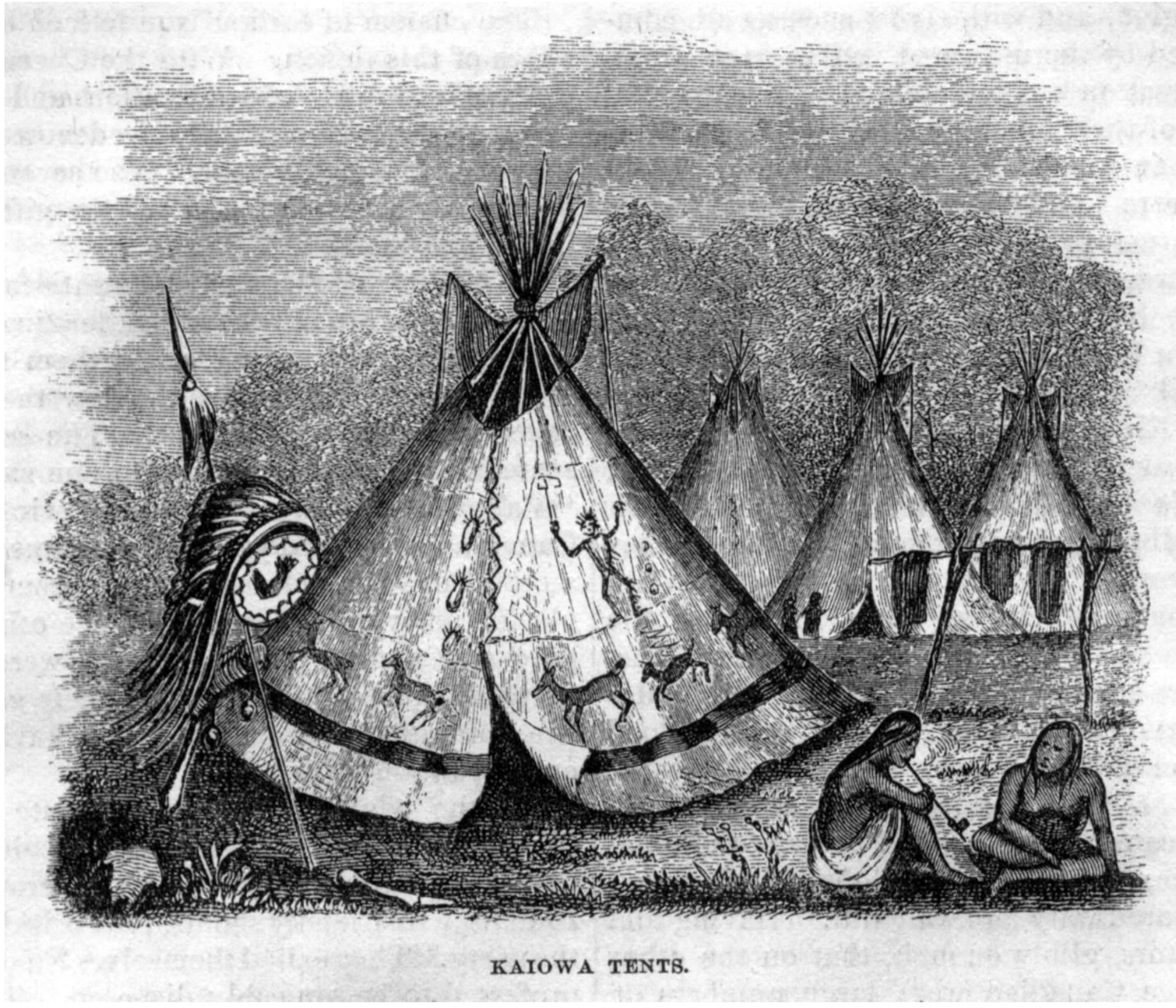


Figure 5) Kaiowa Tent Indians of North America, circa 1850's

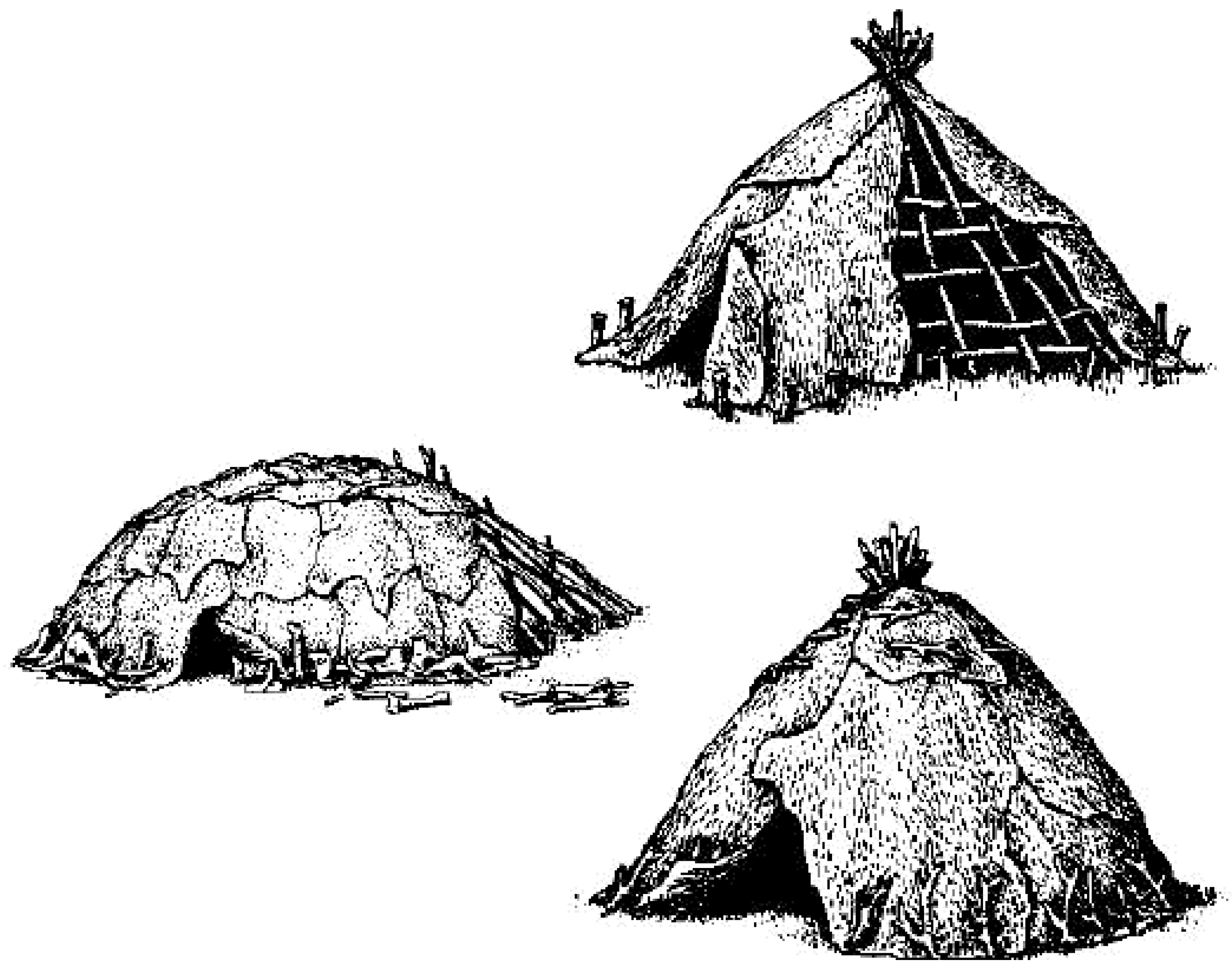


Figure 6) Three Ice-age shelters built on an ancient terrace of the Dneister river

Figure 7) The summer house of the Yakuts hunters and reindeer herders of South Siberia, Russia. It's called a Urasa. The frame of the Urasa is made from slender timber poles resting on an internal circle of ornately decorated sturdy pillars. The frame is covered in birch bark which has been boiled in milk to give in elasticity and strength.

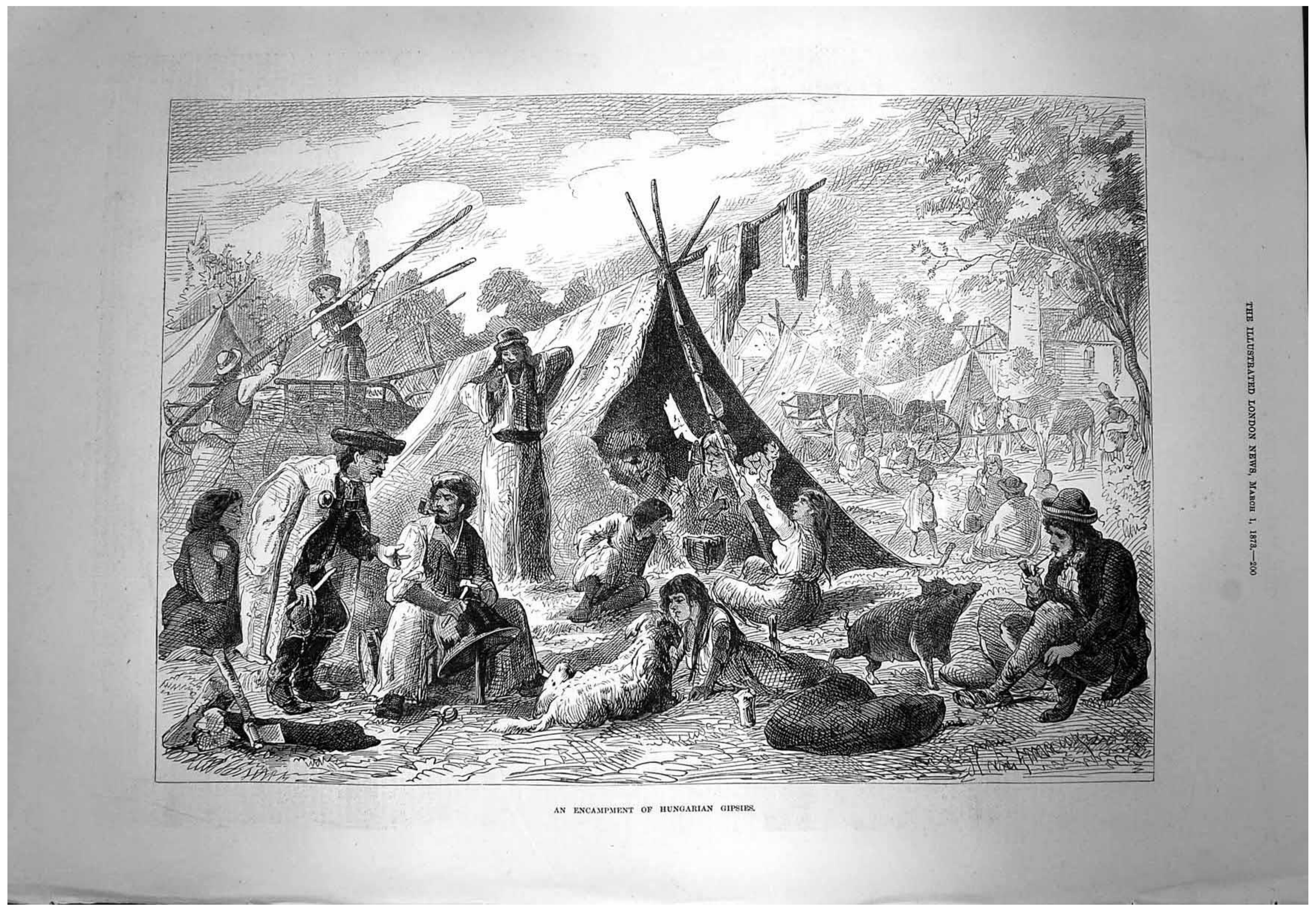


Figure 8) An Encampment of Hungarian Gypsies

The association of tents with a specific way of life is strong among nomadic pastoralists and, to a lesser extent, among hunters and fishers. The factors which led hunting peoples to adopt the tent were even more compelling in the instance of the nomadic pastoralist. The Tent has been adopted in one form or another, by a large number of people living in widely differing environments. Despite some shortcomings it was popular because of its lightness, portability, and ease of erection were advantageous in regions in which building materials were scarce and where economic survival demanded mobility. The association of tents with a specific way of life is strong among nomadic pastoralists and, to a lesser extent, among hunters and fishers. The factors which led hunting peoples to adopt the tent were even more compelling in the instance of the nomadic pastoralist.

The tent is commonly found in dry-climates. Precipitation rather than temperature is the factor: tents are found in regions subject to extreme heat or cold but rarely in areas receiving abundant rainfall. It seems that this common factor of low and unreliable precipitation, usually less than 254 mm and up to 508 mm, is decisive in the choice of the tent as a dwelling. Although the effect of meagre precipitation is complex, there are two aspects that favor the tent. Firstly, low precipitation results in a nomadic way of life because sedentary agriculture is either impossible or unreliable except at isolated oases, where some form of economy based on hunting or herding of animals adapted to the harsh conditions is probable. Secondly, low precipitation affects the type of vegetation, inhibiting the growth of trees which might otherwise constitute a valuable source of building materials. Low precipitation then not only promotes a nomadic form of economy but also restricts the range of dwelling choices.

Pastoral nomads normally live in portable dwellings of the tent type, which can be readily transported along with the family while the herds migrate. The inclination in live in portable dwellings is a fundamental attribute of pastoral nomadism, and is as much a part of its nature as the herding of animals and the following of regular patterns of movement.

Nomads derive a major portion of their subsistence from large flocks of animals which cause them to follow recurring patterns of movement from season to season in pursuit of suitable grazing and water.

Their tents are designed to shelter a single family - the fundamental economic unit - which is the social and political level at which the herds are owned. Five or six tents may be grouped to form a herding unit for the pooling of labour for tasks that can be performed cooperatively, and for additional security from attack. The social, political and economic organization of the tribe need not extend beyond the herding unit.

It has been argued that house form is determined by socio-cultural rather than by physical forces by reason of the low criticality of buildings. Simply stated, 'because physical criticality is low, socio-cultural factors can operate , because they can operate, purely physical forces cannot determine form'. This requires further examination in the case of tents. The low criticality promulgated by Amos Rapoport is modified by the pastoral nomads' attempts to utilize marginal resources in areas too dry, too elevated, or too steep for agriculture to be a viable mode of livelihood. This increased criticality is decisive in the selection of the tent as a portable dwelling in competition with other alternatives. Once the requirements of light weight, demountability, and portability have been met by the adoption of a tent dwelling, then socio- cultural factors come into play. It is the action of socio-cultural factors which causes the diversity of tent details in practically identical migratory regimes.

It might well be found that the association of the major tent groups (the conical skin covered tent, the felt covered *kibitka*, and the black goat’s hair tent) with extensive regional cultures in the northern hemisphere indicates the presence of common physical factors.

Figure 9) Asian Kibitka Tent

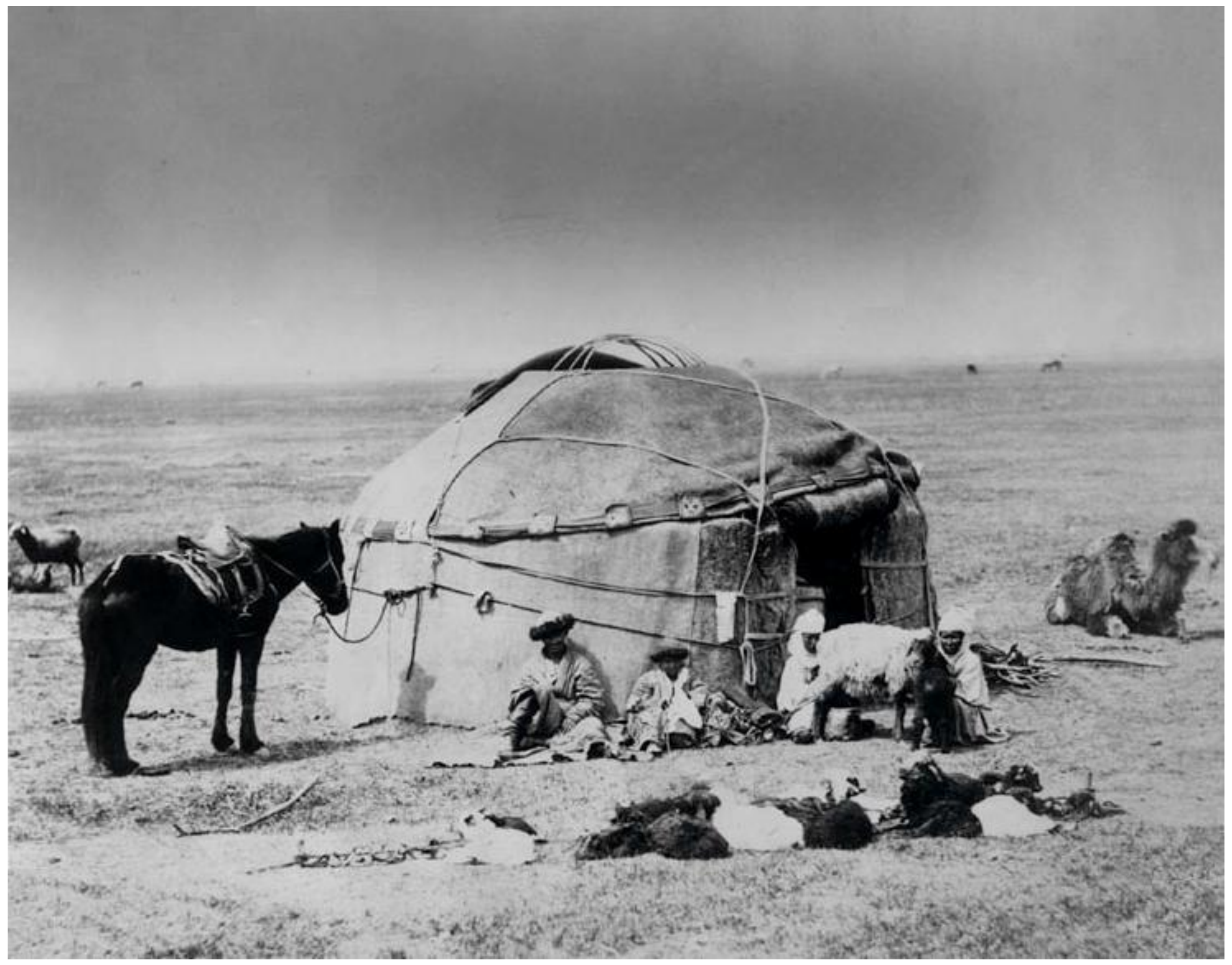


Figure 10) Central Asian nomads with Kibitka Tent - early 1900s

Tents Types

Different types of tents had been used during the history according to the location, climate, needs and cultures, introducing them may not be the subject of this research, hence we name some them with short description: 1.Bell Tent 2.Lavvo 3.Tipi (Teepee) 4.Kibitka 5.Yurt 6.Black Tent

The conical tent is essentially a primitive dwelling used by peoples at the hunting stage of culture. It is retained as a summer dwelling by many nomadic or semi-nomadic herders and even by some sedentary agricultural tribes. The tent consists of a conical framework of inclined poles, arranged in a circle with their upper ends secured at the peak. The construction of the pole frame and the used to cover it, but not the form, is exceptionally uniform throughout Siberia.

Figure 11) A Sami (Saami) family in Norway with Lavvo Tents, around 1900

Figure 12) Nordic Sami (Saami) people in Sapmi (Lapland) in front of two Lavvo Tents. The Sami people in the photo are Nomads. Sweden.

The most significant different are the types of primary support structure, the method of securing the upper ends of the poles at the peak, the type of frame used to suspend the cooking vessels over the heart and its degree of integration with primary support structure.

The Black Tent is hardly a primitive form, but rather the most recent product in an evolutionary series. Its prestressed velum is tensed in an aerodynamic shape over minimal wood supports, and is able to withstand the strongest winds. The black tent, unlike the conical tent and the kibitka, is a non skeletal tent with a prestressed velum. Of the major tent types, the black tent is closest in its form and construction to 20th century prestressed tensile architecture. The transformation of the early black tent from a skeletal non-prestressec dwelling to a non-skeletal structure was made possible by the replacement of mats and leather awnings by a woven velum strong enough in tension to be prestressec. The transitory status of the black tent is confirmed by the fact that differences between the tent and huts tern to disappear in primitive dwellings.

Figure 13) Tipi Tent, North American Family

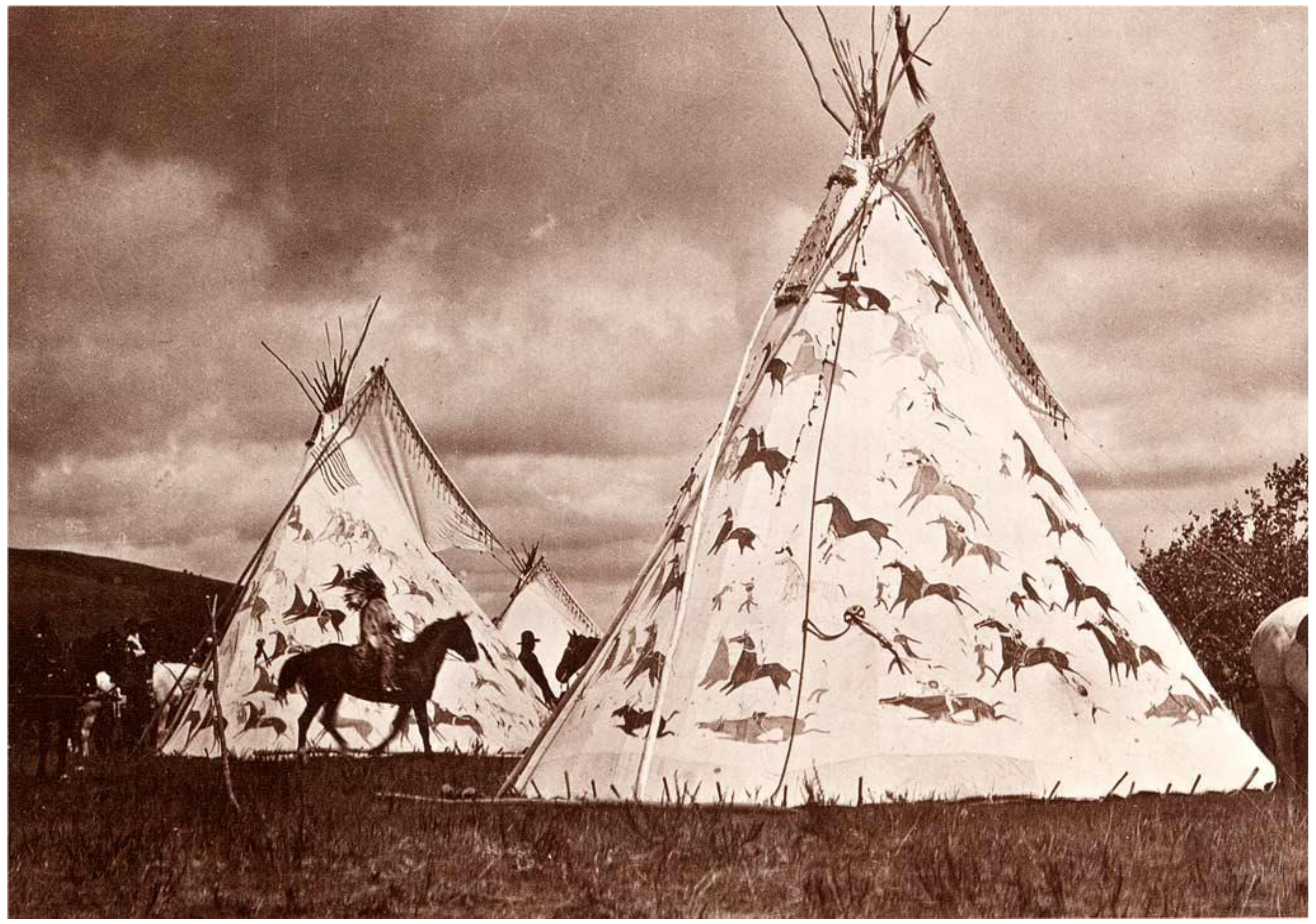


Figure 14) Sioux native American with Tipi (Teepee) Tents

Figure 15) Black Tent

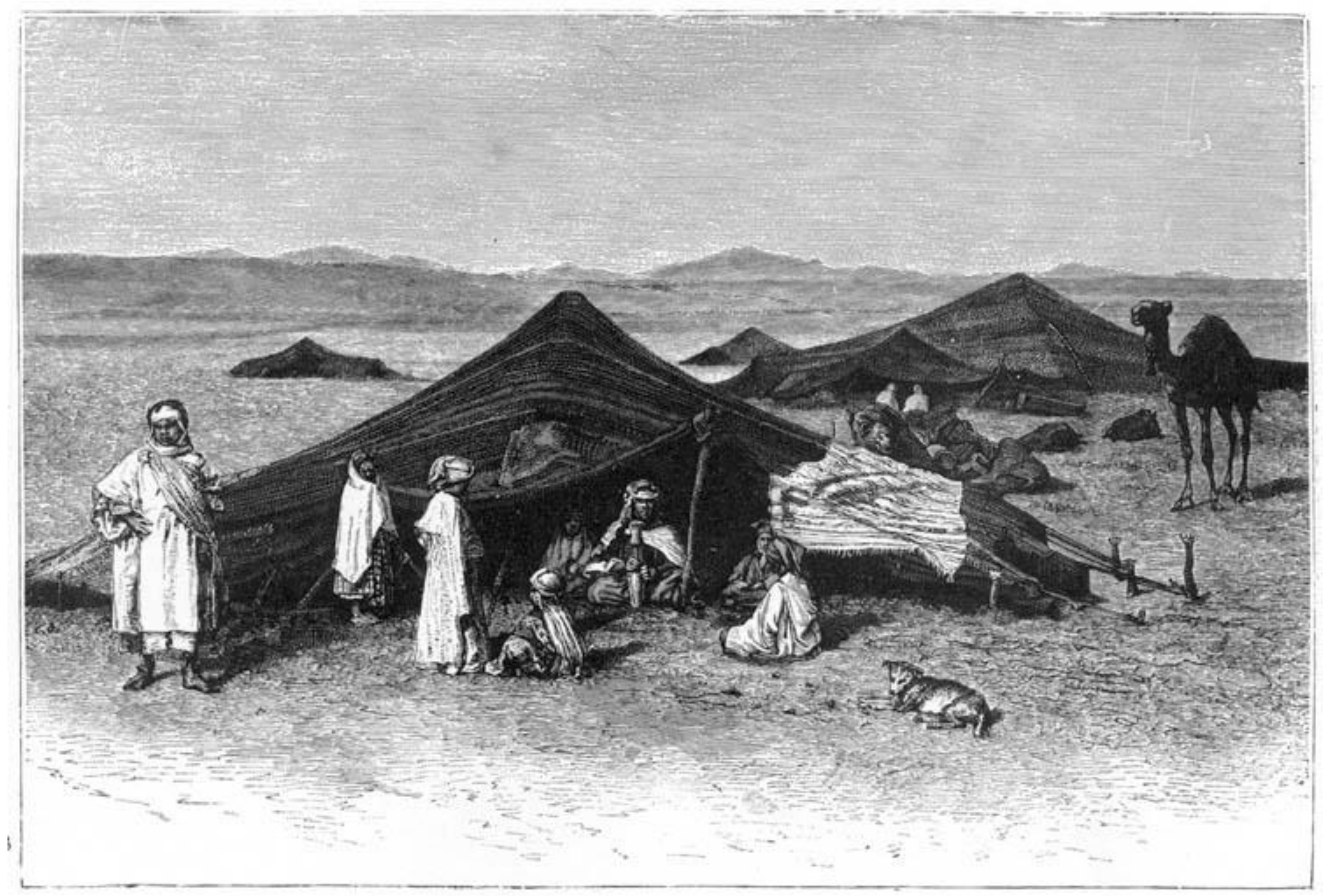


Figure 16) Black Tent

Modern Tensile Architecture

The triumph of suspension bridge builders in the late 1920s and 1930s made tensile architecture inevitable and the Second World War merely postponed the event until 1952. The sporadic essays at tensile architecture after 1840 failed to generate wide support for the principle. Shookhov's series of pavilions in the 1890s very nearly overcame the general mistrust of tensile structures. Modern architects in the twenties identified tension as specifically modern because it was seen as the opposite of compressive historical architecture. The interest in spatial tension and efficient structure as an expression of Rationalism attracted the avant-garde whose enthusiasm was not matched by their knowledge of tensile form. Two kinds of tensile architecture emerged in the 1950s: engineer's tension which was technically motivated, and architect's tension which sought to exploit the novelty of the new tension forms. Some architects were, it is true, attracted to tension because of its technical advantages, but they were in a minority. The choice of the tent as a prototype of tensile building by Frei Otto enabled him to reconcile structure and form. The unity of form, structure and expression in his best work is proof of Frei Otto's mastery of the tensile medium.

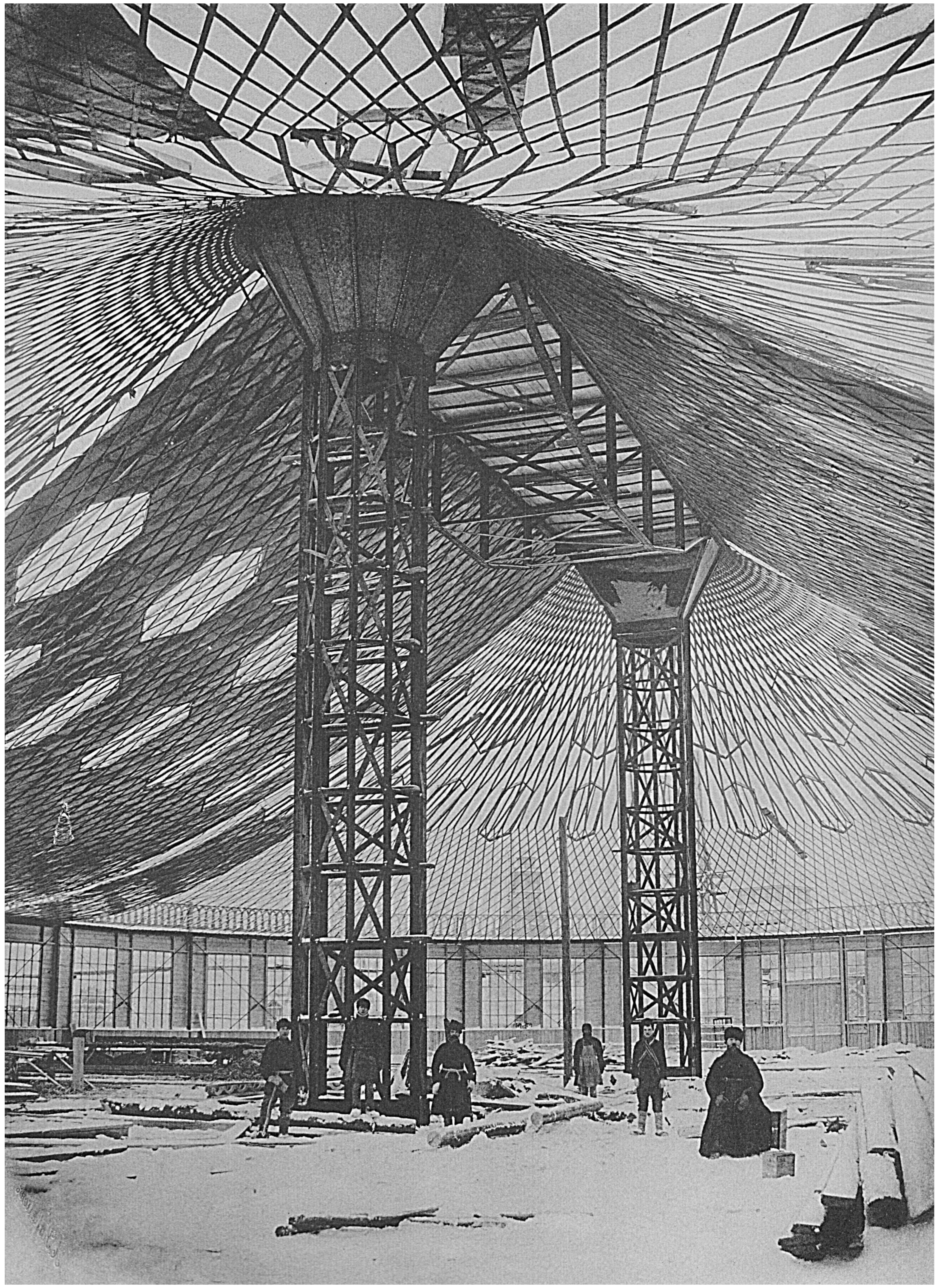


Figure 17) Tensile steel lattice shell of Oval Pavilion by Vladimir Shookhov, 1895

Early Tensile Architecture 1820-1950

The early tensile architecture of the 1950s was afflicted by an inability to match structural form with the appropriate technology in a way which was adequate as architecture. The disparity between technology and structural form, since the two are closely linked, arose because the forms derived from suspension bridges had only limited application to architecture, whereas tent forms were much more suitable. Efforts aimed at deriving a modern tent technology from that of the suspension bridge met only limited success. The confusion between form and technology which underlies much early modern tensile architecture was not fully resolved until the emergence of a modern tent technology at Montreal in 1967. Modern architecture was based on late 19th century technology but it was not until the 1950s that engineers and architects began to take an interest in tensile architecture. The architectural implications of the 1 9th century development of the suspension bridge were largely overlooked until the 1950s. The increased awareness of the aerodynamic behavior of tension-loaded structures which flowed from post-Tacoma research prepared the way for modern tensile architecture. The suspension bridge and the tent are tension-loaded structures which differ in their spatial character and usage. The former is a tensile linear system whose chief function is that of a long span structure. By contrast, the tent is a tensile surface system which has been widely used by nomadic peoples as a lightweight portable dwelling. Of the two, the tent is most closely identified with shelter. Primitive forms of suspension bridges and tents abounded in traditional cultures prior to the industrial revolution but whereas the suspension bridge acquired a modern technology, the tent remained relatively undeveloped until recently.

Tensile architecture developed late and was preceded by a number of isolated experiments, the work of engineers for the most part, extending as far back as the nineteenth century. The earliest examples of tensile building in the nineteenth century are the roofs by Bederich Schnirch in Czech Republic, (1824-26), and the central span of the roof of the Naval Arsenal at Lorient, France, in 1840, both Of which illustrate the close connection that existed between the suspension bridge and tensile building, at least in the early phases.

In 1927 Buckminster Fuller envisaged multi-storey buildings with their floors suspended from a central mast.` The concept was projected for a ten storey building at the- North pole and his Dymaxion House, 1927-9. The roof and first floor were suspended from a central mast which also served as a service core. At the same time, Heinz and Bodo Rasch, in Wuppertal, Germany, published a sketch of multi-storey housing suspended from a linear series of masts.

During the early 1930s, simply suspended steel sheets were used to cover large grain silos at Albany, St. Louis, and at Memphis, both in the United States. The suspension principle was employed, somewhat clumsily, for the roof of the locomotive roundhouse pavilion at the Chicago World Fair in 1933.

The classical drum of Bernard Lafadle's French Pavilion at Zagreb in Yugoslavia in 1935 concealed a steel suspended roof. The shallow 2 mm sheet metal saucer-shaped roof rested on a single layer of racial cables anchored to a steel compression ring mounted on columns. The comparatively modest diameter of 36m apparently protected the roof from the destructive effects of flutter. Lafaille's interest in _tension-loaded sheet metal roofs developed from the construction of sheet metal shell structures. A year earlier, Eugene Beaudouin and Marcel Lods had envisaged a suspended steel cable roof with a diameter of 430m.

3 The Development Towards Urban Use

In the 1960s, architects inspired by futuristic ideas, proposed radical changes to the urban environment. Visions of mega-structures covering whole towns of futuristic layout and of massive proportions appeared on drawing boards across the world. A number of designs for cities of the future proposed the use of large tension structures because of their potential for covering large areas with minimum means (Fig. 18). The majority of these visions were however to remain on paper, probably due to the fact that these radical ideas completely ignored the traditional development processes of our towns and cities, and the cultural context within which we live.

Propositions for the urban use of fabrics and flexible membranes, at a more manageable scale, did appear however in the avant-garde architectural magazine '*Archigram*'. One proposal in 1970 for the 'metamorphosis of an English town' prophetically envisaged the use of 'minimal skins, cheek by jowl with ... the Edwardian store . . . or the odd, old terraced house'. But it tended to be the more glamorous large-scale mega-structures, such as the 'walking cities', that commanded most attention at the time (Figs. 19 & 20). In 1977 architects Foster Associates proposed to cover 4 acres of public space in Hammersmith, London with a transparent fabric roof, but it was not until the beginning of the 1980s that tensile structures were to first appear in permanent applications on the urban scene. This was made possible largely due to the developments in membrane fabrics that led to the introduction of polytetrafluoroethylene (PTFE) coated fiber glass, a new structural membrane capable of taking large forces without the necessity for a supporting cable-net.

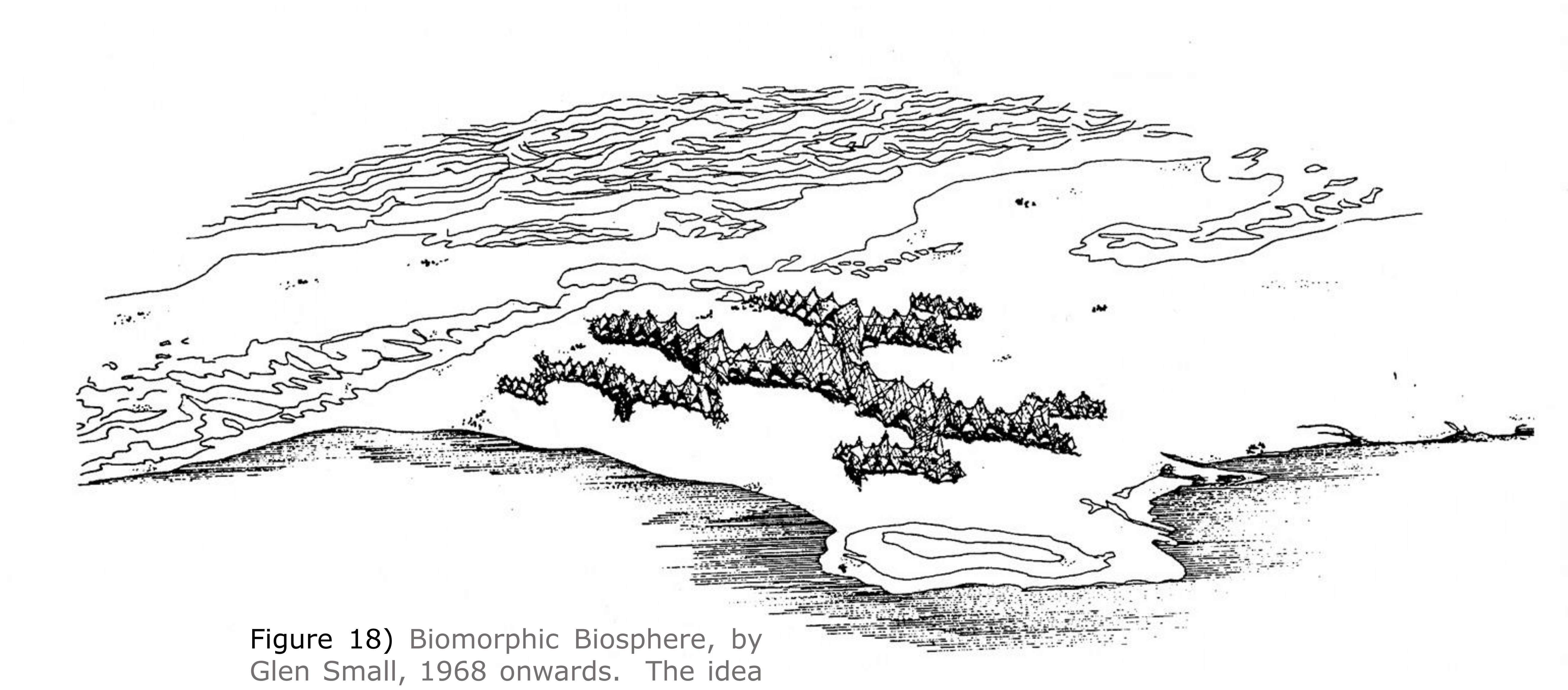


Figure 18) Biomorphic Biosphere, by Glen Small, 1968 onwards. The idea of urban use of tensile structures existed mainly in the context of urban organism, rather than for incorporation of tensile structures within existing cities

One of the earliest examples appeared within a suburb of Paris in 1984, as part of the Italian architect Renzo Piano's renovation of the Schlumberger research facilities in Montrouge (Fig. 21). From a distance the tensile roof appeared no different to some of the early pavilion structures of Frei Otto. However, from within the Schlumberger structure provided an early hint of the possibilities of combining membranes and conventional construction within an urban setting. (Fig. 22)

In 1987 Michael Hopkins and Partners completed the design of the enclosure of Basildon town center, which proposed to use a 10 000 m² transparent tensioned fabric roof. However, like the Foster proposal, this large-scare project was never executed (Fig. 23).

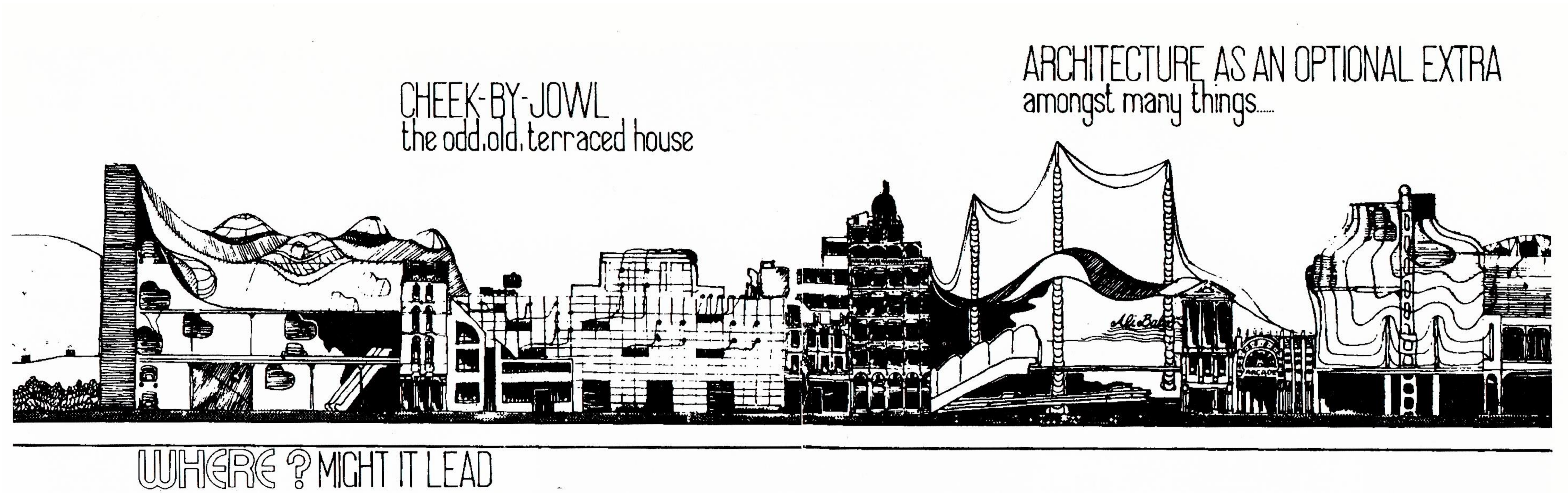


Figure 19) The Archigram proposals tended to be seen as provocation for a new mode of living, rather than as serious attempts to bring new techniques into architectural applications within the urban situation

Figure 21) At Schlumberger the fabric roof was set within a inhabited landscape, perhaps showing that the architects were still hesitant about combining membranes with conventional architecture

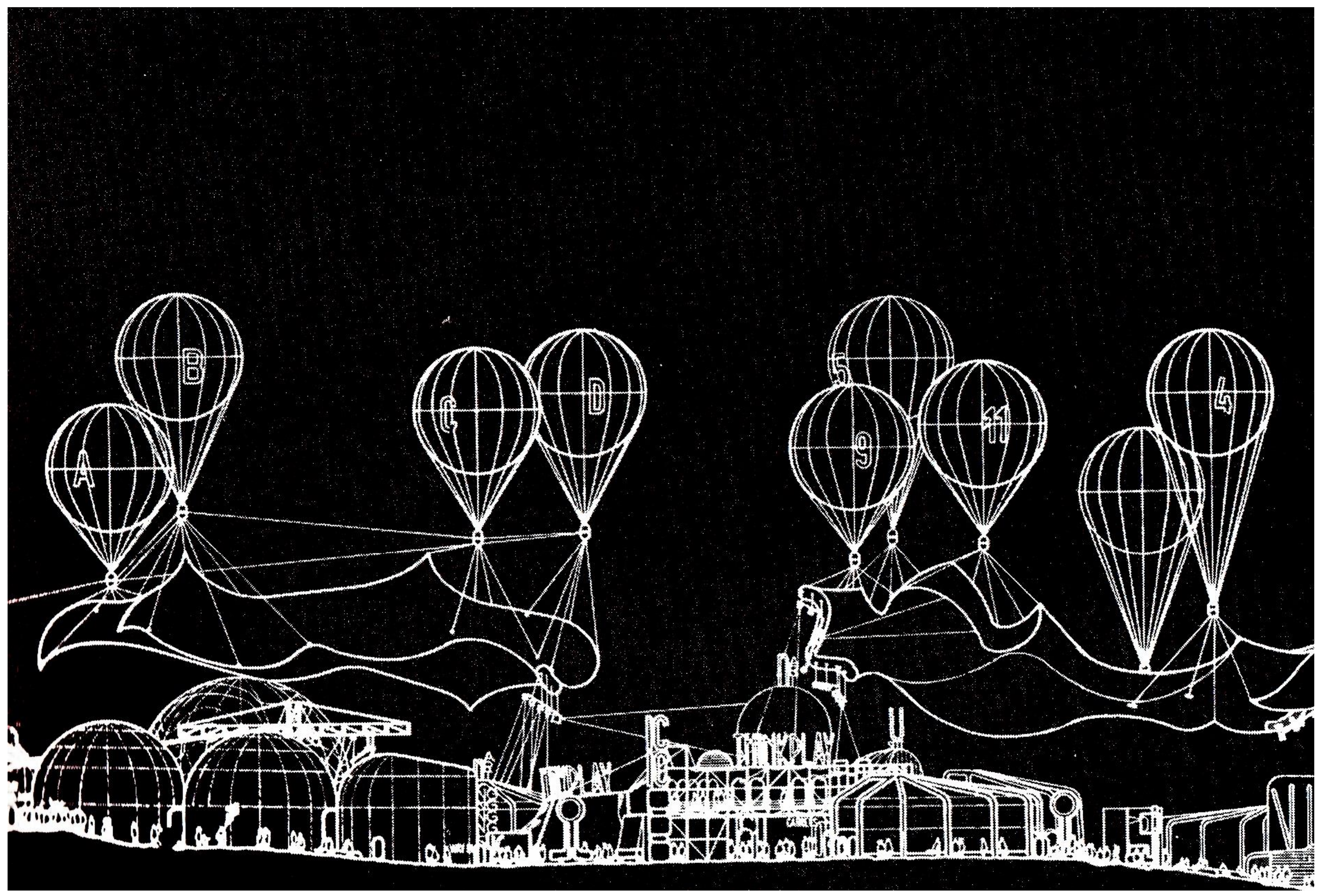


Figure 20) Instant City, by Peter Cook, 1969

Figure 22) Schlumberger Renovation, Paris, France, 1985

Figure 23) Original design for Basildon Town Square, 1987

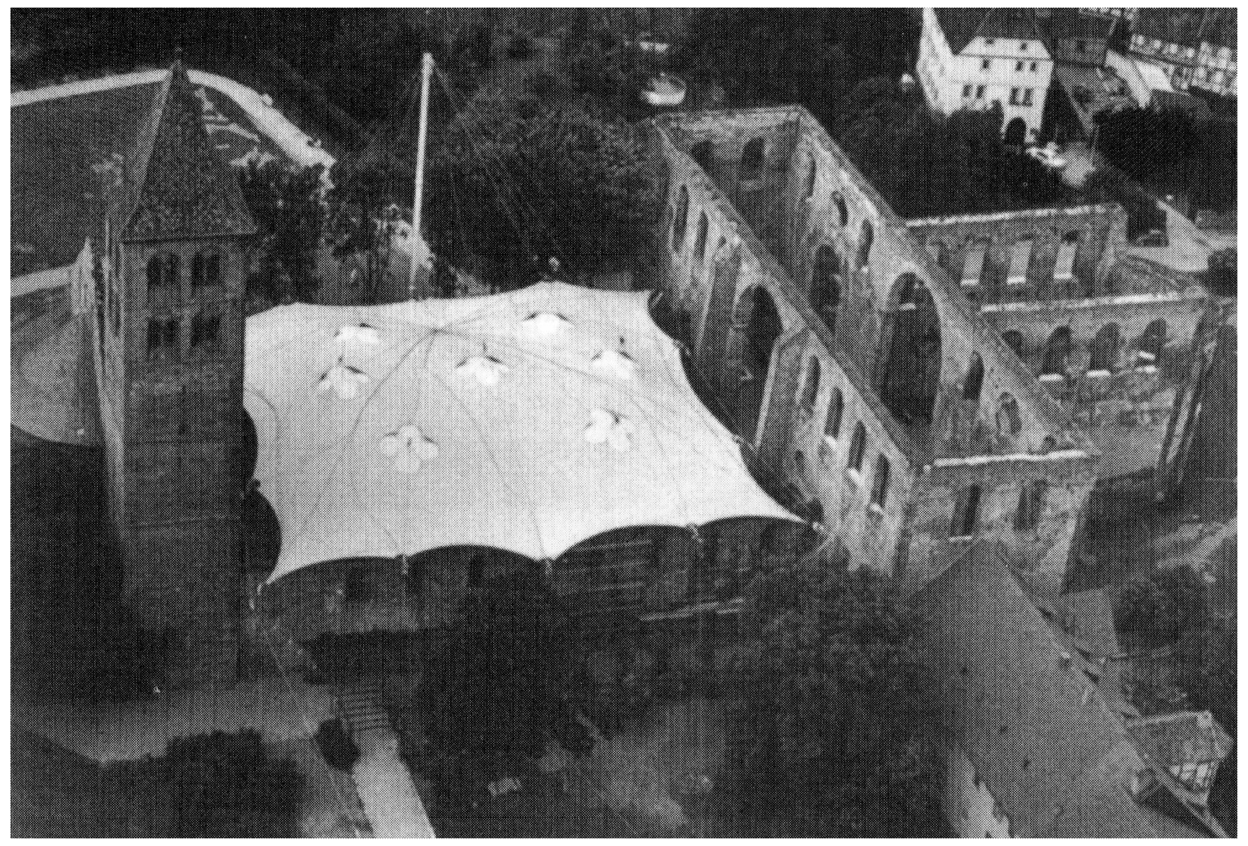


Figure 24) Retractable roof structure of the Open Theatre, Bad Hersfeld, 1968, Frei Otto

Membranes and Conventional Construction

Some 16 years before the completion of the Schlumberger roof in Paris, the idea of using a membrane in conjunction with traditional construction had been applied in a very different situation. To cover the audience area during the theatrical events taking place within the Abbey ruin at Bad Hersfeld in Germany, a retractable fabric canopy was erected with permanent arrangements of steel masts and cables. This structure demonstrated some of the delight that the combination of a lightweight skin and solid masonry could evoke, but it provided no clues as to how membranes and masonry could be combined to form more fully enclosed spaces. (Fig. 24)

The first purpose-built, permanent structure designed to utilize masonry construction in combination with structural membranes and cable-net was built to house the Diplomatic Club in Riyadh. This building, completed in 1986, advanced the use of membrane construction with masonry, by attaching the lightweight structure directly to a curved inhabited wall. The massive wall provided a curved surface to which the geometry of the conical and saddle-shaped roofs could satisfactorily be connected in both structural and aesthetic terms (Fig. 25).

Whilst successful in showing how membranes and cable-nets could be combined with traditional construction, the project in Riyadh left unanswered the question of whether the doubly curved surfaces of tension structures could successfully be adapted to the rectilinear geometries of conventional structures. Many early projects that attempted to combine tensile roofs with rectilinear construction tended to look awkward, as it proved difficult to successfully marry the scalloped edges of the roof membrane with conventional planar construction. Often the resulting combination looked rather like a badly fitting circus tent attached to a simple shed - unless, as at Munich, the walls were carefully curved to suit the scalloped edges of the membrane.

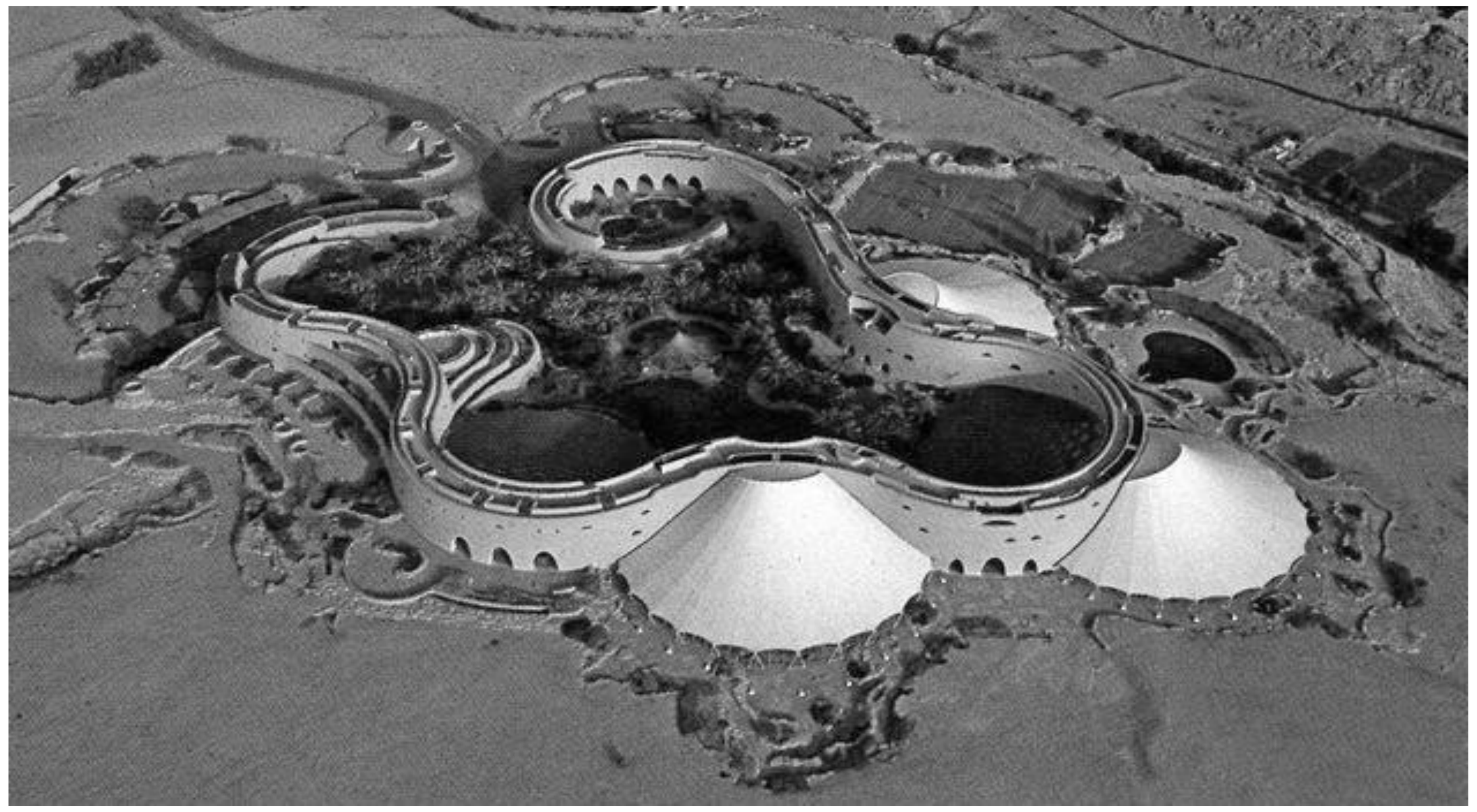


Figure 25) The Diplomatic club - Masonry Construction in combination with membrane structure and cable-nets, Riyadh 1986, Frei Otto

Figure 26) Schlumberger, Cambridge: a large membrane roof, adapted to a rectilinear framework, 1985

A rather sophisticated version of the 'tent-on-a-shed' approach appeared in England in 1985 set in a field outside Cambridge. The building, another research facility for the Schlumberger Group, consisted of a three-bay fabric structure, attached to rather elegant rectilinear steel framed boxes. The building for Schlumberger, designed by Michael Hopkins, skillfully demonstrated that a large membrane roof could be adapted to a rectilinear framework and still achieve a satisfying, if somewhat challenging, architectural form (Fig. 26). When this building appeared it attracted a great deal of attention due to the application of its membrane roof, but the complex steel framework required to hold the membrane in its required shape demonstrated to what lengths the designers had had to go to adapt the geometry of the membrane to the rectangular buildings beneath.

In the same year, on the other side of the Atlantic, preparations were being made for the 1986 Expo in Vancouver, Canada. A ship-like building appeared in Vancouver harbor replacing the British Columbia Pier. This new building, built to house the Canada Pavilion, used a large fabric roof to cover the main exhibition hall and to evoke a maritime imagery. On this project a double-layer membrane was employed to improve the environmental and acoustic performance of the fabric skin (Fig. 27). Retained for permanent use as a convention center after the Expo had finished, this building created a striking image, and at the time came closest to finding a permanent urban application for an enclosing tensile fabric roof.

However, perhaps because the Vancouver building was yet another Expo offshoot and the building in Cambridge was a facility with experimental associations, the general acceptance of the use of fabric roofs for conventional permanent buildings was still not widespread, at least in Europe. In America the use of fabric roofs for large out-of-town shopping malls and sports stadia had begun to be more commonplace (Fig. 28).

Figure 27) Canada Pavilion, Vancouver, Expo 1986

Membranes in the City

Although it had been demonstrated that tensile structures were capable of being used to create fully enclosed buildings, it was probably the use of an open membrane roof over a grandstand in London that finally brought the architectural application of membranes in the city into wider acceptance.

Lord's Cricket Ground, set in a traditionally built part of London, is owned and run by the Marylebone Cricket Club, a long-established and generally conservative organization. When a new grandstand was required the architect Michael Hopkins proposed the use of a tensioned fabric roof in order to evoke the image of a traditional village cricket marquee. It was this aspect of the design more than any that made it acceptable to use an innovative approach in such a setting. The success of this building provided convincing evidence that membrane roofs when appropriately used could make an architecturally satisfying contribution within the urban context.

Thus by 1986 tensioned fabric roof structures had appeared within the city as permanent additions to conventional structures, and had been used on less urban projects to create fully enclosed spaces. Yet to appear was a significant building within a traditional urban setting that combined a membrane or cable-net supported roof with conventional construction to enclose an environmentally conditioned space.

Although urban tensile architecture is still in its infancy, more durable and higher-performance materials are now available compared with the 1950s and 1960s, when the development of membrane materials was still new. The structural performance of membrane fabrics is now more widely understood and some of the original structures are performing satisfactorily after more than 20 years of use. There is still tremendous scope for innovation and further developments in the field of lightweight surface stressed structures and, as designers become more confident, the architectural potential of tensile structures will surely be more widely exploited. Whether these new forms will play a significant role within the urban context remains to be seen. However, what is certain is that as the architectural and technical difficulties of combining tensile structures with conventional architecture are overcome, and more of the benefits of the combination of the two are discovered, the opportunities for the use of tensile architecture within the city will increase. One can only wonder which other radical visions may yet be transformed into urban realities.

Figure 28) Florida Mall, an example of an American Large-scale tensile roof structure out of town

The Ceiling in the Public Domain

Throughout the historical development of architecture the ceiling, out of reach of everyday functions, has always been subject to innovations and symbolism. Since in tensile buildings the roof and the ceiling are very often identical, the impact of the ceiling is worthy of closer consideration.

While walls have been amongst the simplest structural and architectural elements, ceilings and roofs have always been a structural challenge — allowing for, and often requiring, architectural innovation and interpretation. The desire for larger spans, and column-free space has throughout history led to new roofing techniques being developed. Traditionally, once a new technique had been established, it was used not only for spanning large volumes but also for the purposes of architectural expression. Tensile structures have also been developed due to their potential for covering large spans. But more recently they have also been used to cover smaller volumes, where the aim has been to exploit their architectural potential.

The Ceiling in Modern Architecture

During the modern movement, a new attitude towards the ceiling developed. The rationalist approach required simplicity and dismissed decoration. Under purely functional criteria, there was no reason why the ceiling should be anything other than a simple plane. This reductionism, coupled with the invention of the suspended ceiling, led to the ceiling being neglected as an expressive architectural element. Instead the ceiling became merely a convenient container for air-conditioning ducts and other kinds of servicing equipment.

More recently, architects have started again to take an interest in the ceiling landscape. In buildings such as Stansted Airport near London, the potential for the ceiling to make a significant contribution to the character of a space is eloquently demonstrated. Here the ceiling is used to introduce and modulate daylight, and becomes the building's main architectural gesture (Fig. 29). This approach, over a highly serviced modern airport terminal, would not have been possible without careful consideration of the location of the building services.

For buildings that utilize a translucent or transparent tensile roof, the opportunities to hide the services are similarly reduced. Therefore, whenever servicing is required within a tensile covered space, particular attention needs to be paid to the careful location of services, with the incorporation of special service nodes, raised floors or some other suitable means. Once freed from a purely functional role the ceiling can again become used for the purposes of architectural expression.

The Ceiling: Hierarchy of Space

All buildings consist of an arrangement of a group of spaces which are necessary to fulfil a function. The range of spaces, required to make a building work depends on its function; but with any arrangement of spaces there are always some which are considered more important than others. In the public realm, architects have frequently aimed to express such a hierarchy in order to enable people to achieve a better understanding of a building.

Just as in a city, the major spaces and the minor spaces of a building are required to be treated differently if the hierarchical order is to be clearly understood. The upper boundary of a space, i.e. the ceiling, can take on an important role in expressing these differences in function.

Different structural systems are often required over the major spaces of a building because of the necessity for larger spans. Due to their capacity for dealing with large spans, tensile roofs are appropriate for use over the larger spaces within a building. While satisfying the different structural requirements that a large space entails, tensile structures can also be used to create a different architectural expression that is evident both within the building and from the outside.

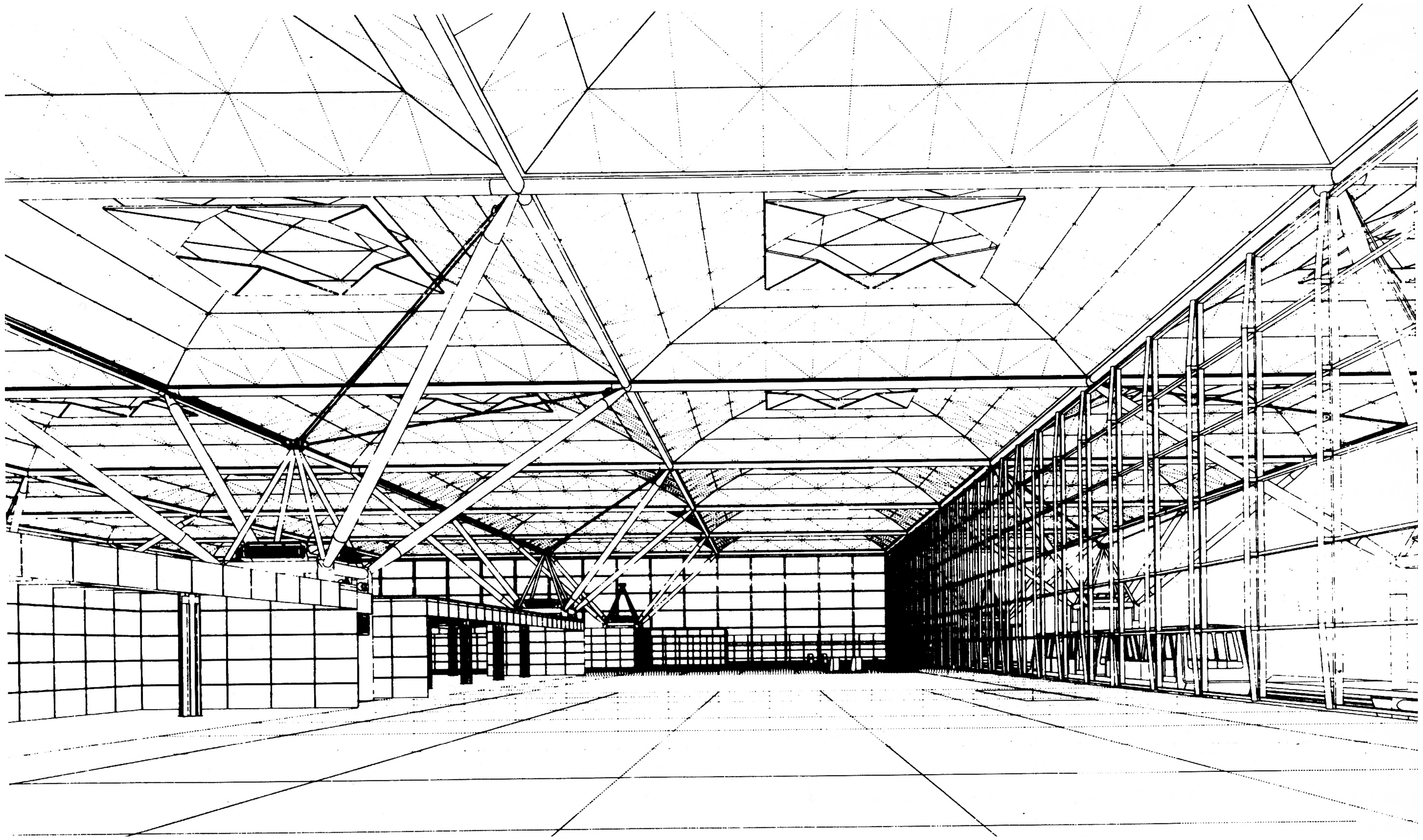


Figure 29) In buildings such as Stansted Airport in London, the potential for the ceiling to make a significant contribution to the character of a space is clearly demonstrated.

4 How Do The Tensile Structures Work?

General Concept

Conventional building structures of concrete, steel, wood or masonry have two main properties: gravity and rigidity. It is these properties that make them stable and capable of transmitting load. Masonry walls stand up because of their bulky weight. Steel frames carry load by means of their rigid strength and resistance to bending.

In tensile structure gravity and rigidity arc not available as the critical structural properties. Fabric structures, in particular, arc so light that their weight is almost negligible. And the materials of which they are made, such as fabric and cables, are highly flexible. Other means have to be harnessed, therefore, to give stability and strength to a structural system consisting of flexible members. Their components require arrangement in a specific geometric form (surface shape), while being subjected to a specific pattern of internal stresses (prestress pattern).

The geometry of tensile structures is, therefore, not arbitrary, but follows strict engineering rules. Once the boundaries and support points of the structure have been set and the prestress pattern selected, there will be only one three-dimensional surface shape under which the structure is in equilibrium at all points. The exact configuration of this surface shape is not known beforehand, but is calculated in a mathematical process called form finding or shape generation.

Fortunately, the basic principles which control the relationship between prestress pattern and surface shape arc relatively simple. The actual computation of the geometry is, of course, per-formed by computer. The purpose of this chapter, however, is to develop an understanding of the major forms which satisfy these conditions.

We have already discussed why, as structural elements, tensile members are more efficient than compression members: slender compression members tend to avoid carrying load by buckling. Unless they have a certain minimum thickness, they will bend out of shape and fail, regardless of their direct material strength. They bow out, one could say. Structures made of tensile members, on the other hand, become more stable with increasing stress levels. The stress will pull each member into line, making the structure taut. Thinner tensile members are better at adapting their shape to the load pattern. Making full use of their high material strength, tensile members will carry the load by the most direct route, in uniform, concentric tension. The load acts along the center line of a rope or cable. Each fiber of the rope or each strand of the cable carries its equal share of stress.

There is, however, one particular problem which comes with this flexibility: one single tensile member alone will not make a reliable structure, because it will change its shape drastically when the load changes in magnitude, direction or distribution. A clothesline with laundry will assume a smooth downward bow in response to both its own weight and the weight of the items of laundry which hang from it. We call this funicular shape of a cable a catenary. As long as there are no other forces acting on the system, it will stay this shape. If, however, we add a wet shirt in the middle, this shape will change, deflecting down-ward where we added the shirt, and flattening out at each side to retain its overall length and static taut. If there is wind, the situation will change dramatically: under gusty conditions, the clothes-line will lose its initial shape, flapping up and down. Indeed, a steady upward wind may even reverse its curvature for a time.

During this process, our line will go through a "slack" stage, during which the stabilizing tensile force is lost. This chain of events may be acceptable for a clothesline at worst, some laundry may fall off and get dirty — but for a building structure such uncontrolled behavior is not acceptable. Steps have to be taken to control the behavior of tensile structures and their components.

The problem of the clothesline could be solved in a number of ways: weights could be Hung on the line. Certainly, this would be awkward and require a stronger rope, but for a building it might be a useful idea. The roof of the New York's Madison Square Garden Arena, for example, carries the mechanical equipment room, which acts as the "weights" to hold the structure down.

Alternatively, we could stabilize the clothes-line by adding a reversed cable on top, pushing down on the line with struts. This alone would prove ineffective, since the structure would simply flip sideways or invert. Stay cables anchored back to the tree will avoid this. (In the circular arrangement at the Utica Arena, which we saw earlier, such "bow string" cable trusses work perfectly without stabilizers.)

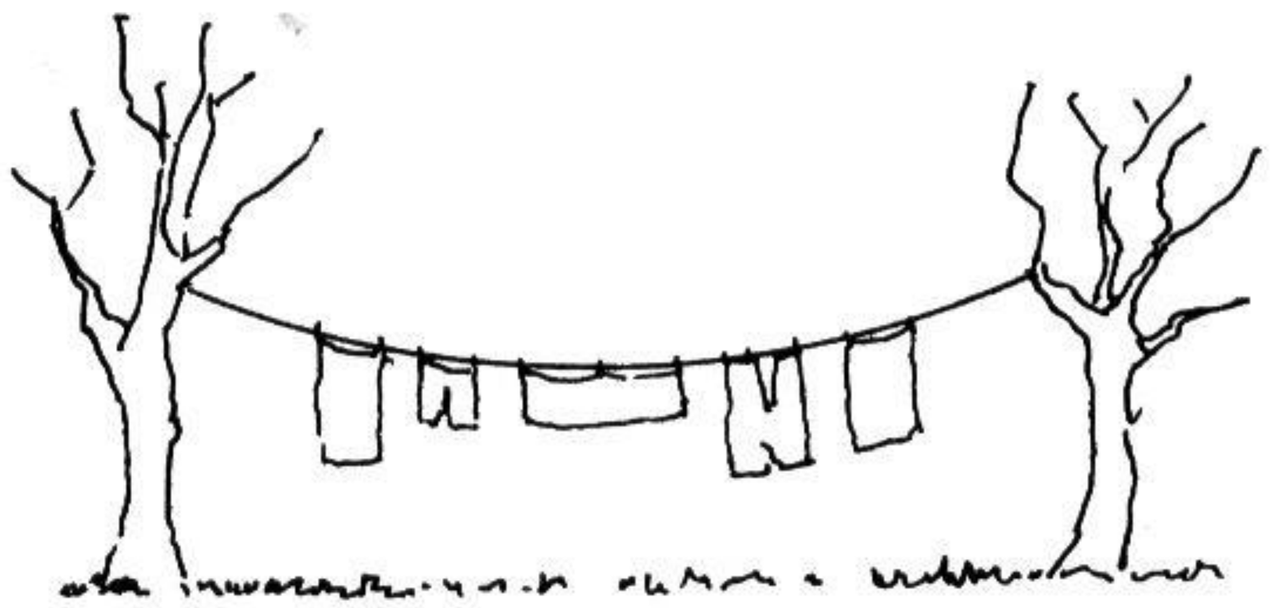


Figure 30) Clothesline with no wind

Figure 31) The clothesline will lose its shape with gust

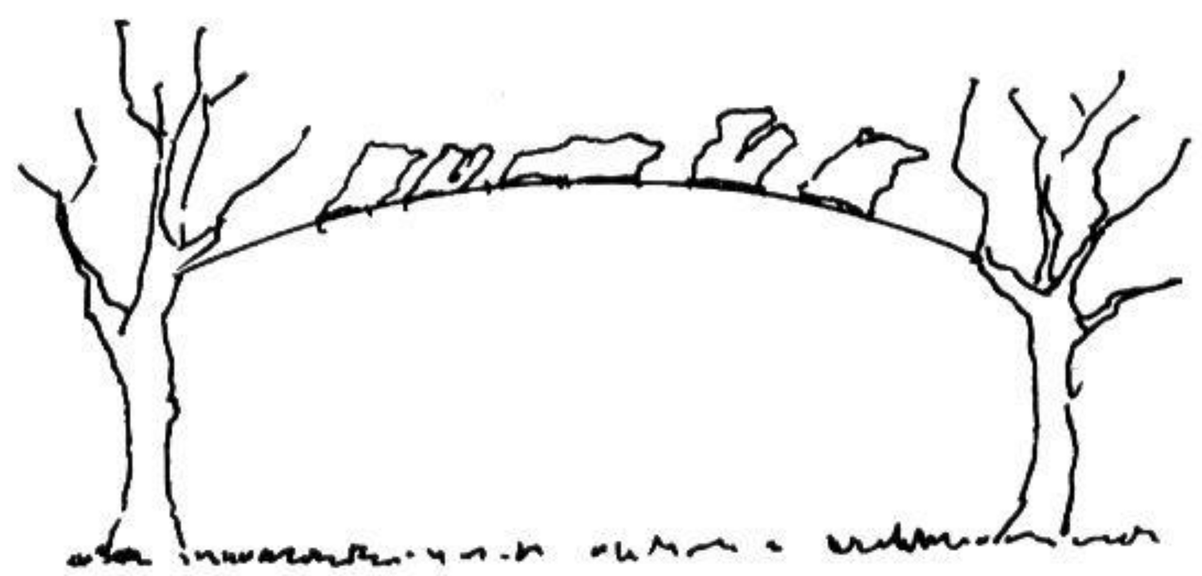


Figure 32) A steady wind flow may even reverse it

Figure 33) Weights could be added to hold the line down

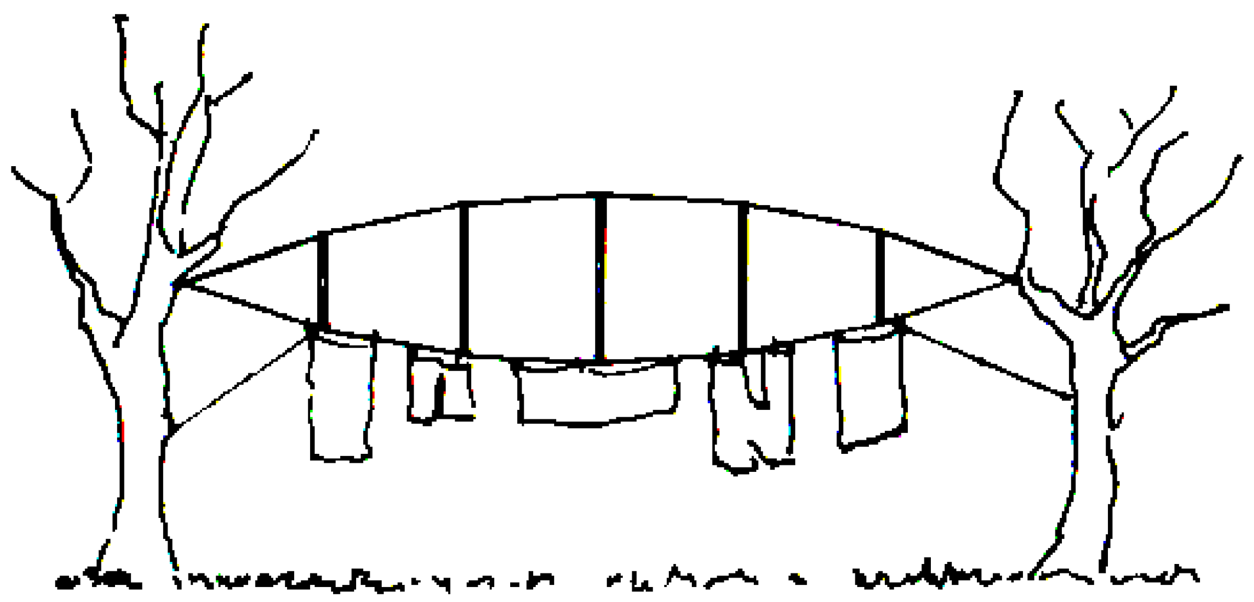


Figure 34) A second cable of reversed shape could be added above to retain the shape and resist upward loads. Stays are needed to keep it from rotating

Figure 35) Adding a cable below is the most effective solution for stabilizing the clothesline

A reversed rope line below the main rope, with vertical strings connecting the two, is simpler and more effective. This is the most stable and the most sensible solution.

If we now consider these two lines to be cables in a roof structure, and turn the lower cable by 90° to run across the upper one, we will achieve a stable point at their intersection.(Fig. 36)

Adding two more tip-down cables parallel to the first will generate two more stable intersection points (Fig. 37). The addition of edge cables placed between the upper and lower support points be-gins to turn this arrangement into a two-way cable net (Fig. 38) which is completed by adding denser sets of cables, parallel to the original ones, in each direction (Fig. 39).

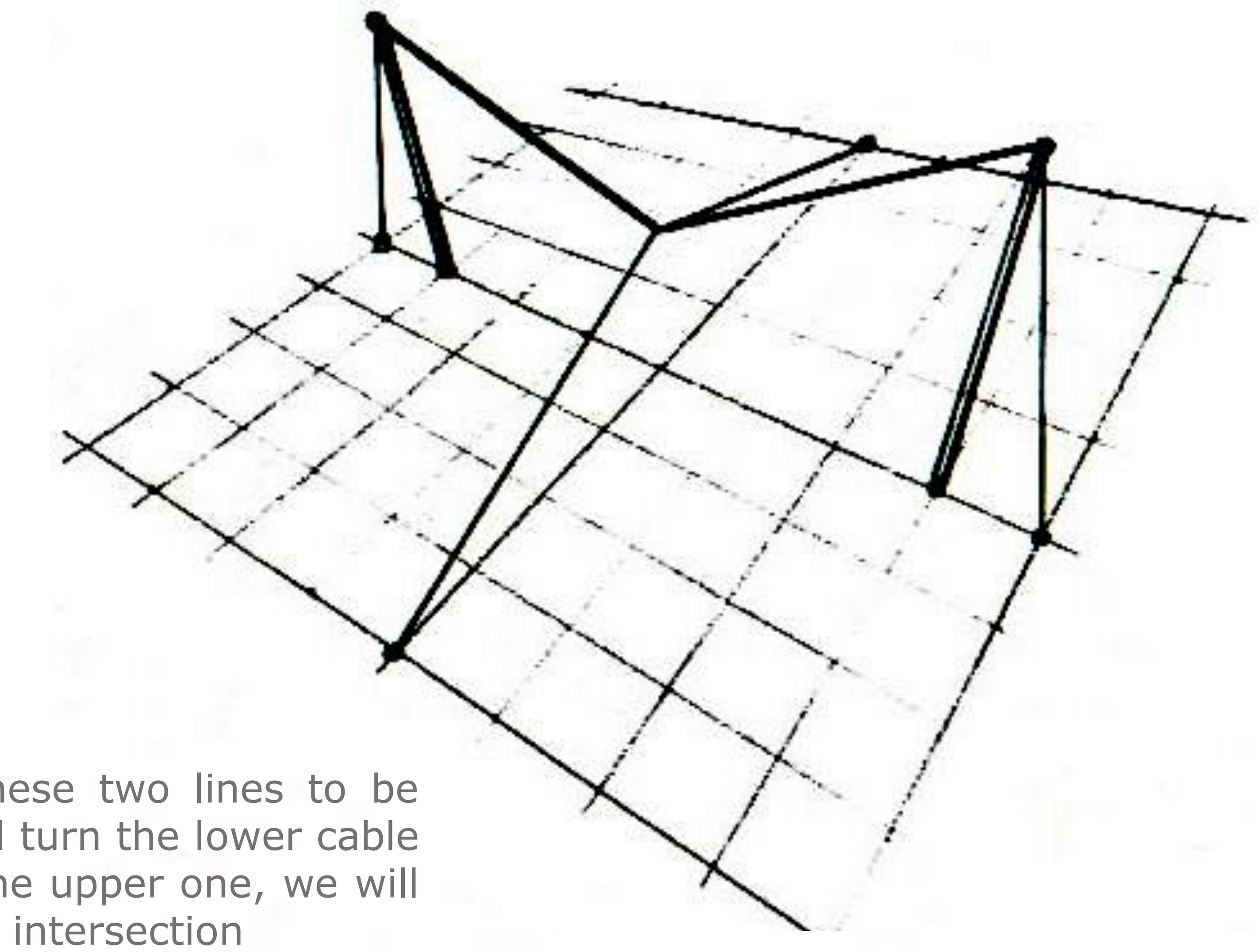


Figure 36) If we consider these two lines to be cables in a roof structure, and turn the lower cable by 90 degree to run across the upper one, we will achieve a stable point at their intersection

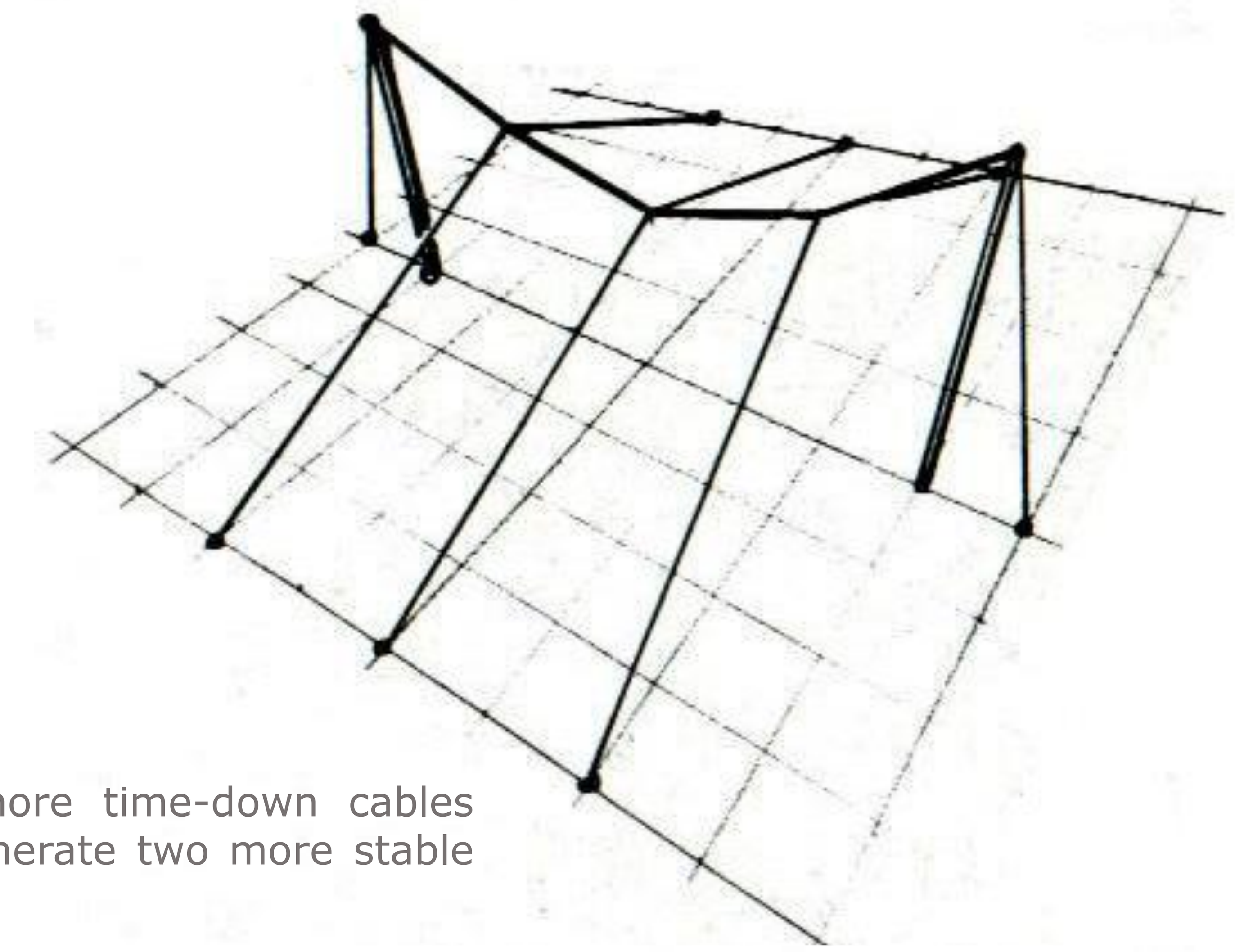


Figure 37) Adding two more time-down cables parallel to the first will generate two more stable intersection points.

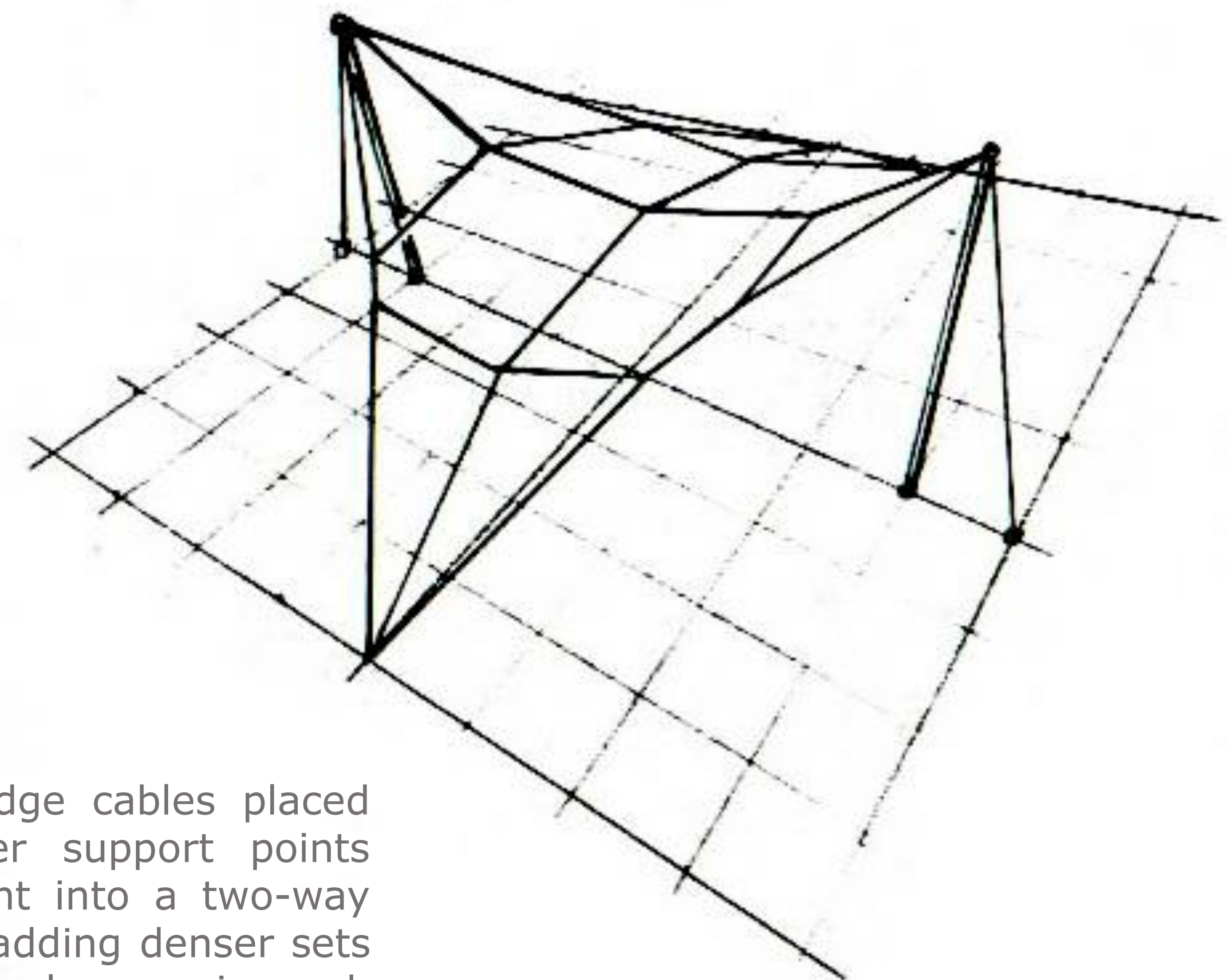


Figure 38) The additions of edge cables placed between the upper and lower support points begins to turn this arrangement into a two-way cable net that is completed by adding denser sets of cables, parallel to the original ones, in each direction.

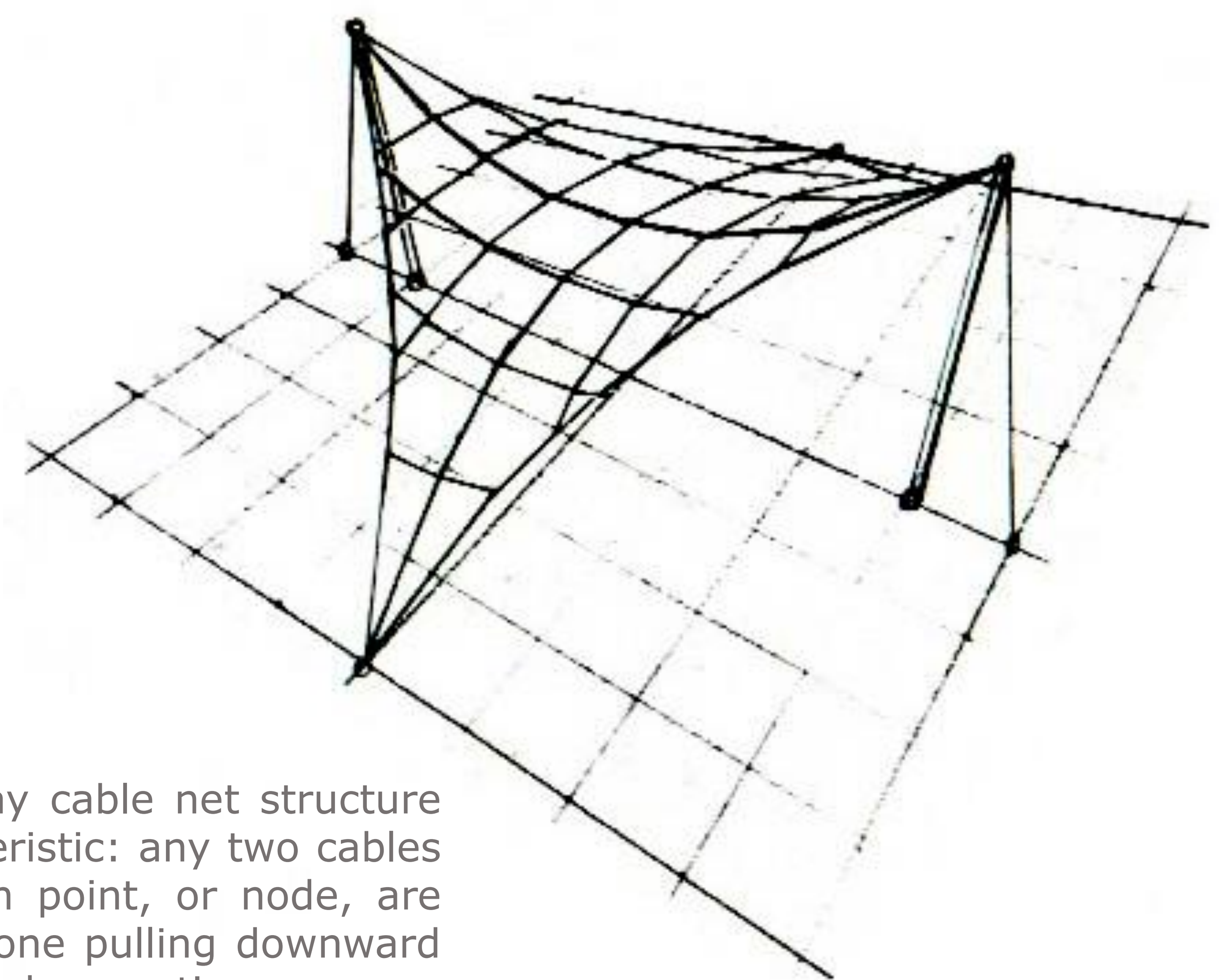


Figure 39) We get a two-way cable net structure that has one unique characteristic: any two cables that meet at an intersection point, or node, are bent in opposite directions, one pulling downward and one pulling upward, thereby exerting pressure against each other. When we put this cable into tension, we increase the internal tension. The higher the initial tensions, or pre-stress level, the more stable and stiff the cable net system will become.

We have now arrived at a two-way cable net structure which has one unique characteristic: any two cables which meet at an intersection point, or node, are bent in opposite directions, one pulling downward and one pulling upward, thereby exerting pressure against each other. When we put this cable net into tension, we increase the internal pressure at each node. The higher the initial tension, or prestress level, the more stable and stiff the cable net system will become.

The surface structure we have generated by this process is called a four point structure. It is the simplest form of a saddle shape, the basic structural. It's easily possible to produce a model of this basic surface shape: just take a cloth napkin (or even better, a piece of stretch fabric) and lay it on a table. Hold down three corners with a finger at each corner. (This is a social game: you need at least two people as it only works if a little tension is put into it!) Then pull up the fourth corner, and you have the basic shape of a four point structure.

The edges could be four rigid beams. A better solution is to use four edge catenaries. To make it a real structure, the three low points need to be firmly anchored against uplift and lateral movement, and the high point requires a vertical and horizontal support, such as a mast and a cable. We now have all the components required to make a strong and stable structural system. If we proportion the elements correctly, we can carry snow and wind at any level of load for which the structure is designed. Snow will mainly be carried by cables which curve downward; wind uplift by those which curve upward. In either case, the edge catenaries will transmit the cable forces to the anchor points which, in turn, will bring them safely down into the firm ground.

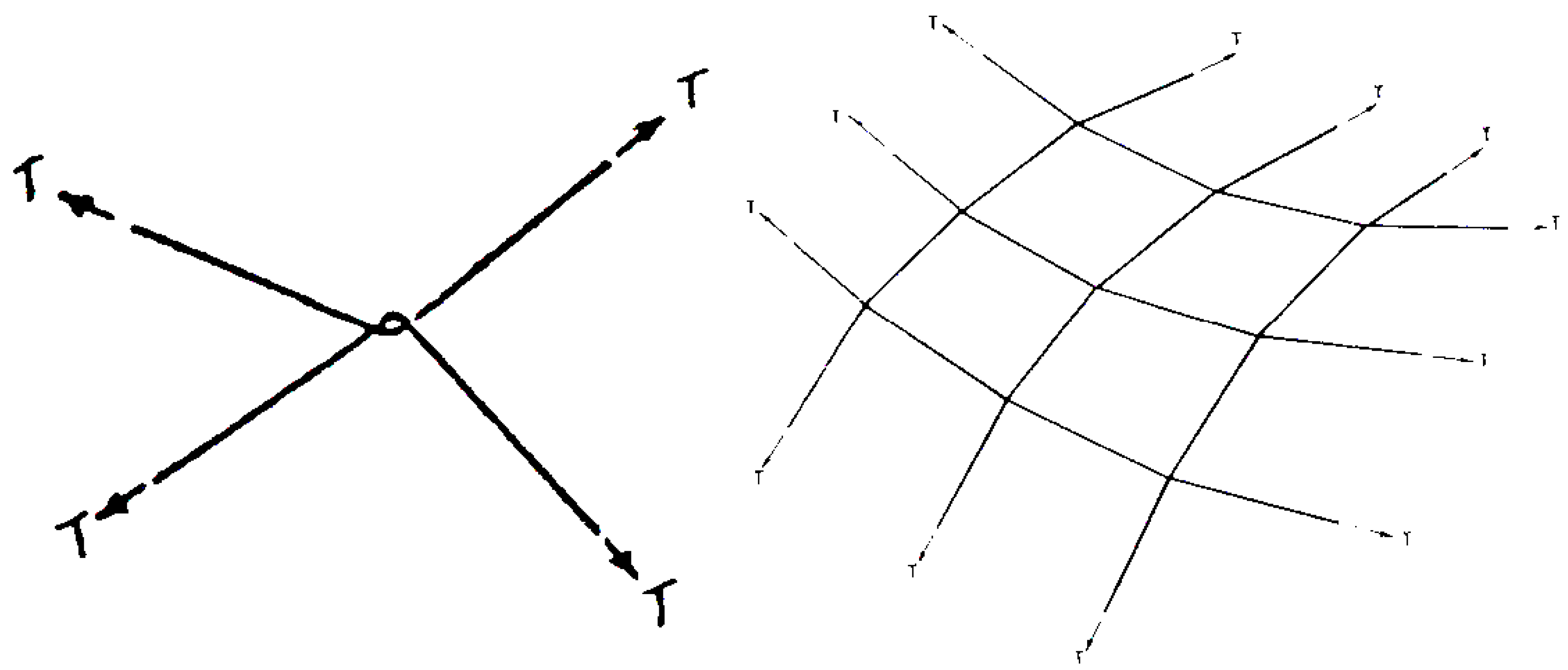


Figure 40) Force diagram of a typical node in a tensile saddle surface, and part of a typical anticlastic surface net

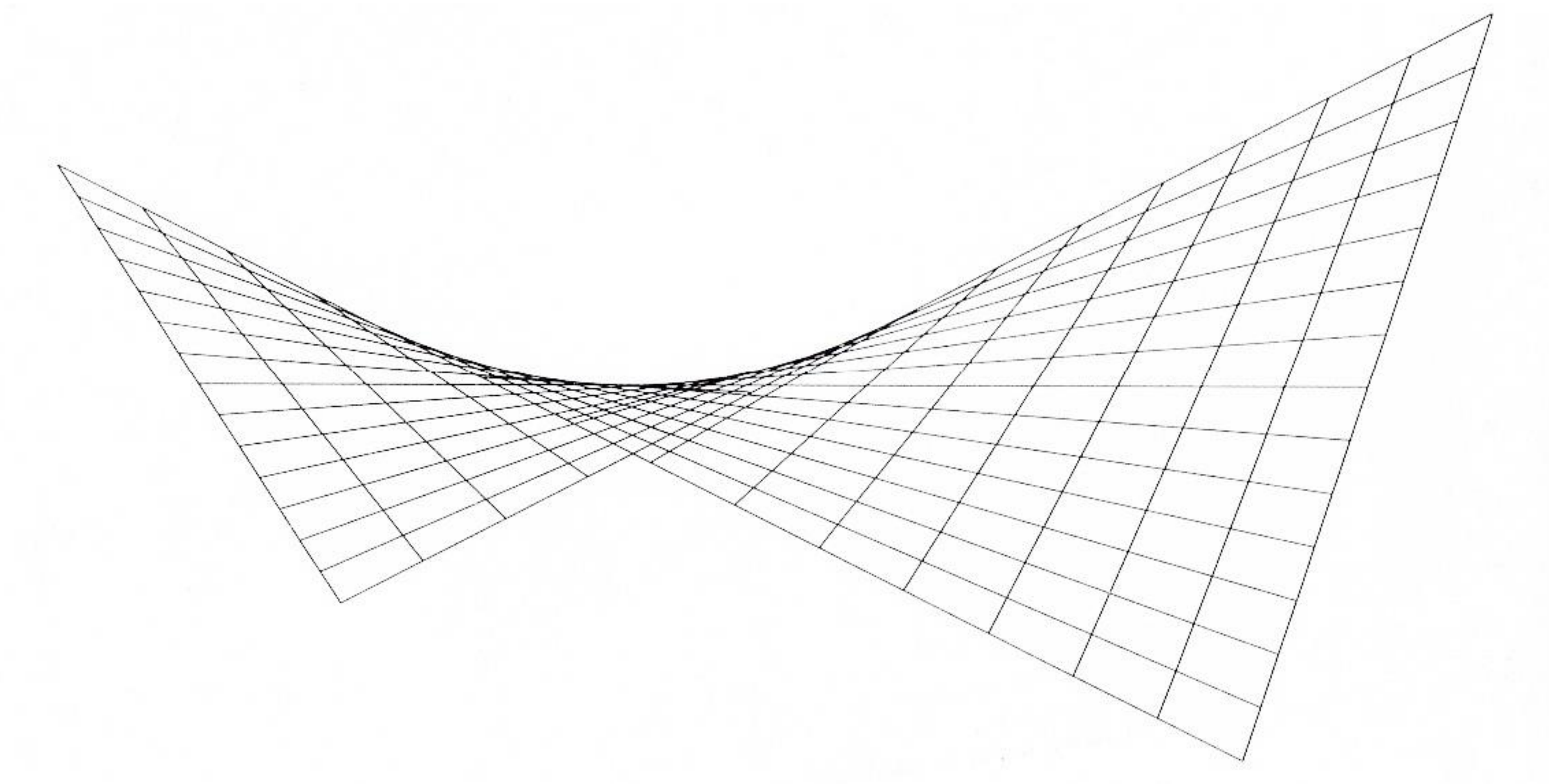


Figure 41) The purest shape compromise intersecting sets of parabolas, it is called a hyperboloid. It is also characterized by the fact that in the two diagonal directions, the nodes are connected by straight lines

Prestress is introduced by the simple means of pulling one corner outward. Shortening one of the tie-down cables will achieve this. This will have the effect of tilting the mast outward, while the edge cables connected to it will want to flatten, thus putting stress on the net cables, which all interact with each other. Provided that all members of the cable net have been fabricated to the right length and are connected to each other in the right places, all members will end up with the exact tension they were designed for. One com-mon choice is for the tension to be uniform in the entire net.

If the surface is not a cable net but a continuous fabric membrane, in the structural analysis the net lines shown will represent strips of fabric. For patterning purposes, the net lines — in one direction only — represent the edges of the fabric strips from which the membrane is to be made. Cable lines still represent cables, and edge catenaries run in fabric sleeves or attach to the membrane with metal clamps.

As all this demonstrates, four is the absolute minimum number of anchor points for a tensile structure. A surface generated by connecting only three points will be a flat triangle. Four support points are needed — with one of them in a different plane than the other three — because curvature is a critical aspect of a tensile structure.

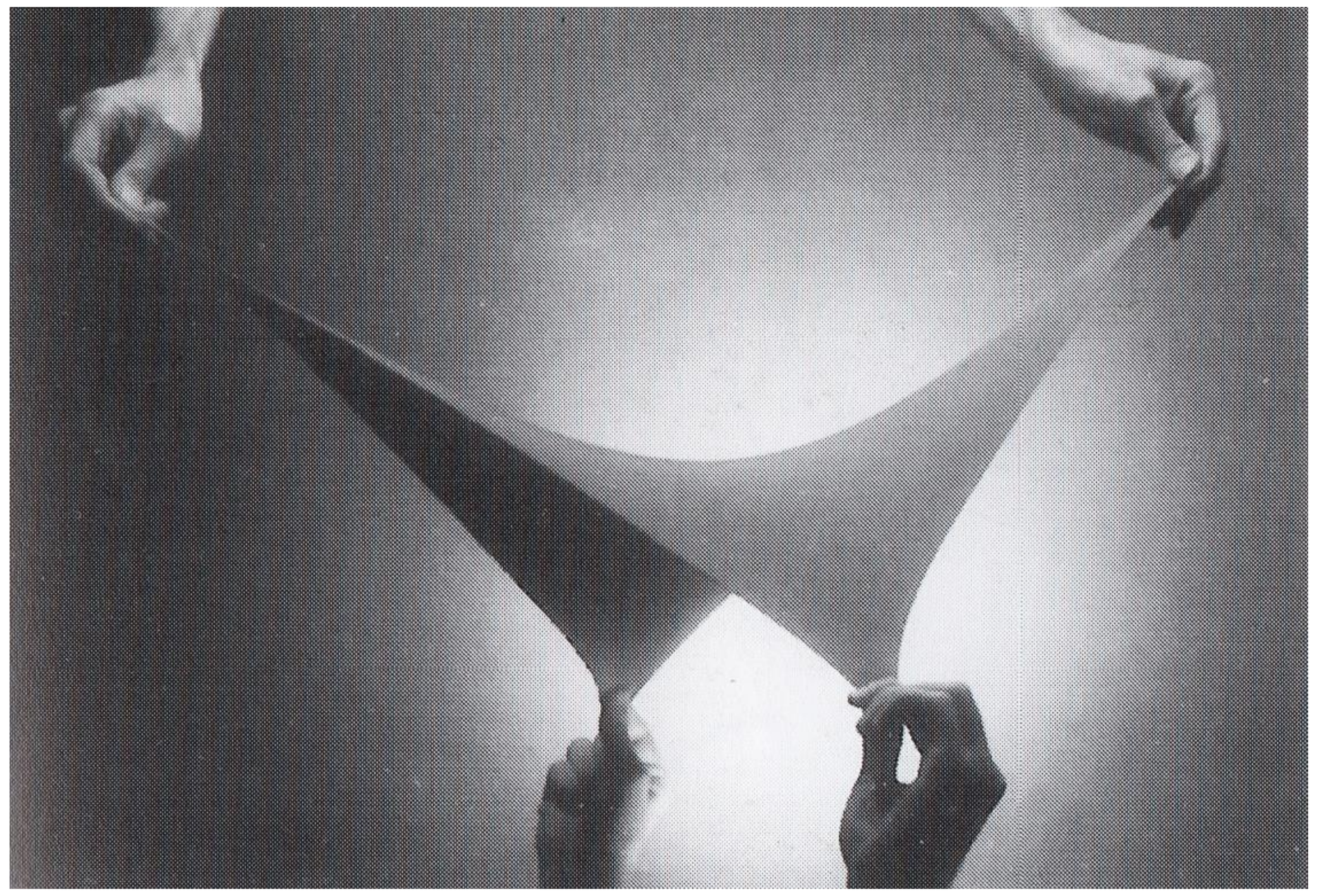


Figure 42) The shape of a simple four point structure can be produced by stretching a square piece of flexible material out of its flat plane.

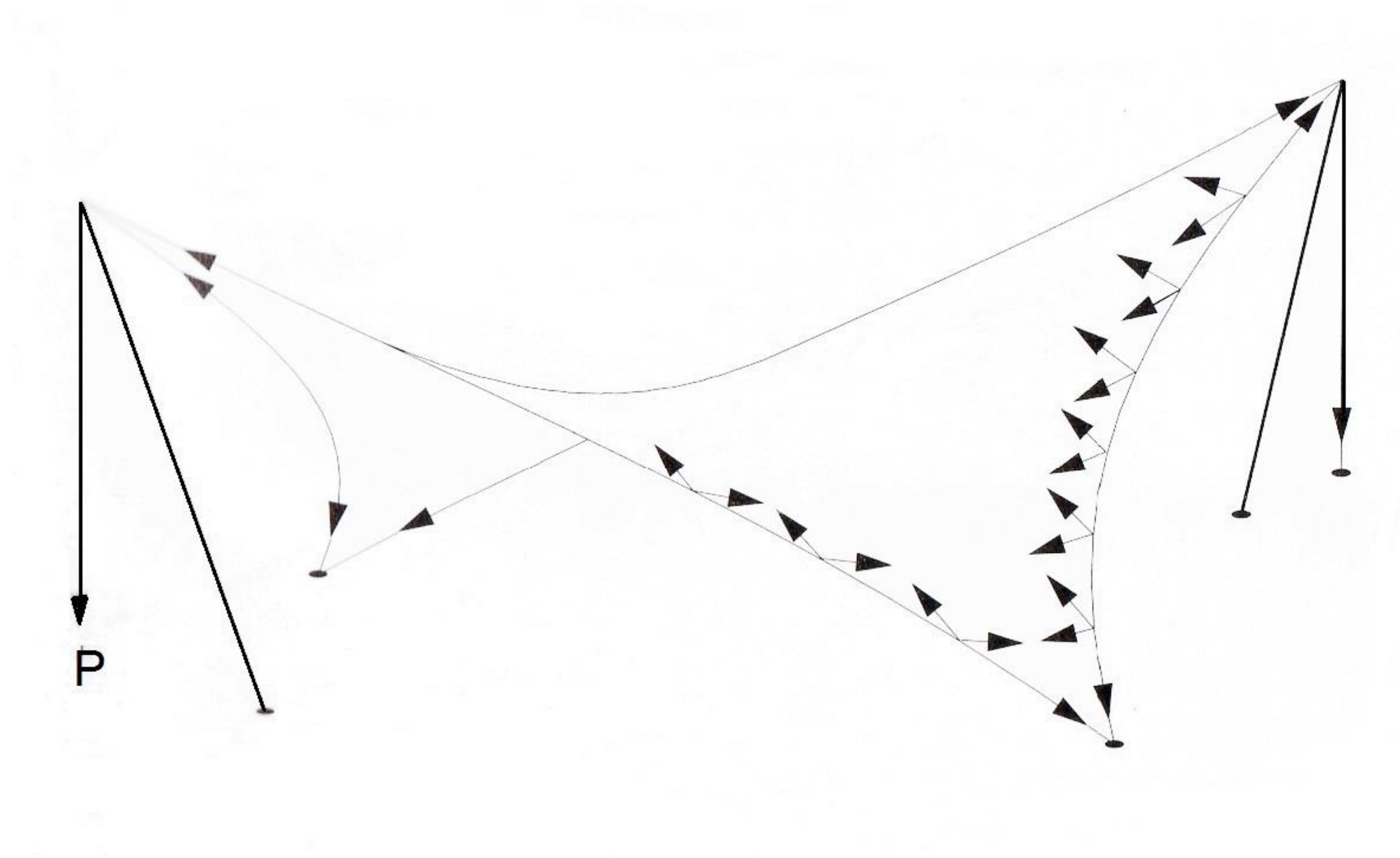


Figure 43) Force flow as a result of pulling down with prestress force P at one of the struts.

This phenomenon distinguishes tensile structures from rigid structural systems, which require three support points for stability. A stool with three legs is perfectly stable; a table with four legs may wobble, since only three legs are needed for a particular load distribution and the fourth leg might not touch the floor, at any rate not without inserting a matchbook under it. We can see, there-fore, that for static rigid structures, the dominant geometric element is the triangle, and the critical number is three.

For objects and creatures which move, the number three is not sufficient. I remember a dog in our neighborhood. He had lost a leg in some kind of mishap, but somehow managed to hobble around, looking almost as awkward as us humans when we walk. Having only two legs, we move by leaning forward until we are about to fall on our faces. In order to prevent this potentially embarrassing event, we quickly extend a leg for-ward, and having now gained a step in the process, repeat it. Human perambulation is quite an unstable and risky undertaking, and depends on the flatness of the feet, the stiffness of the body and clever timing. This is not a very satisfactory arrangement, and is at least partially responsible for the combination of instability, flatness, and rigidity of our minds!

A normally constructed dog has four legs: three to stand on reliably, and one to move for-ward with. Equally, a well conceived automobile has four wheels: three to roll on, and one to pop in and out of potholes. Without that fourth wheel the undampened shock caused by one of the three-wheels crashing into a hole is unacceptable.

For dynamic structures, therefore, the critical number is four, and the ability for the fourth support to flex — the spring in the wheel of the automobile, or the muscles and tendons in tic dog's leg is essential.

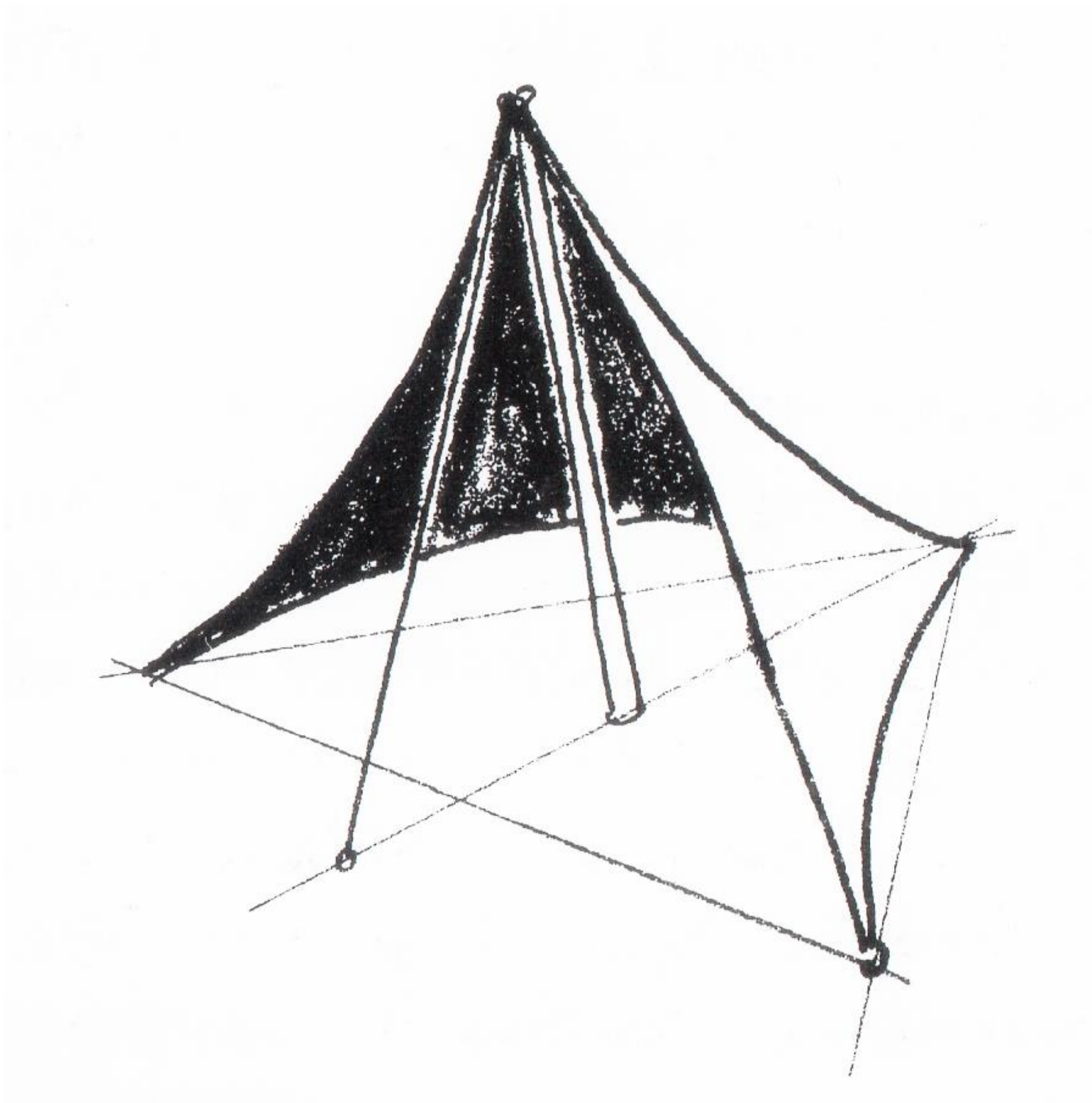


Figure 44) Single four-point structure. Three points share the ground as a common plane. The fourth is created by the pole.

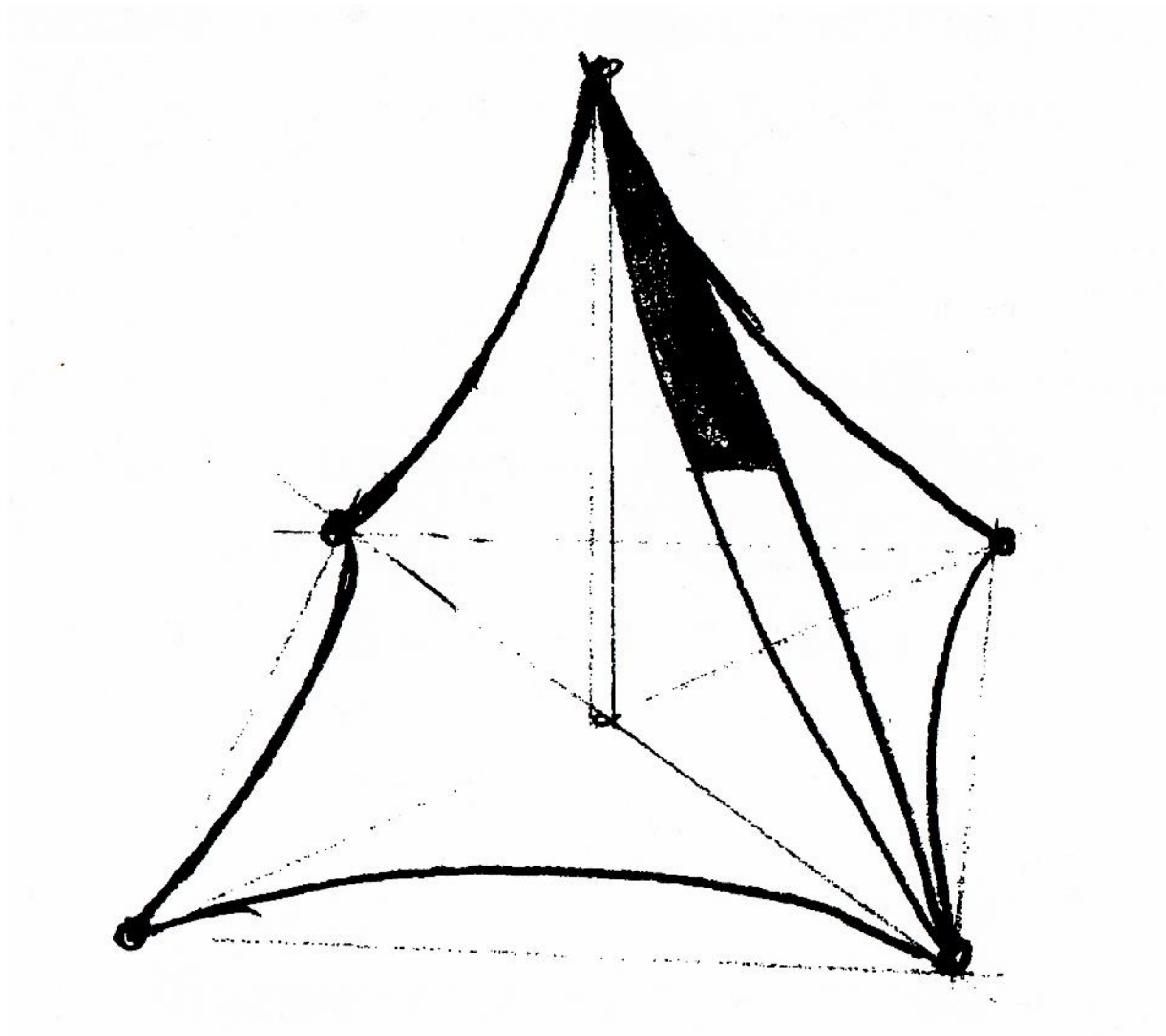


Figure 45) Two four-point structures, held by a single pole, cover a square

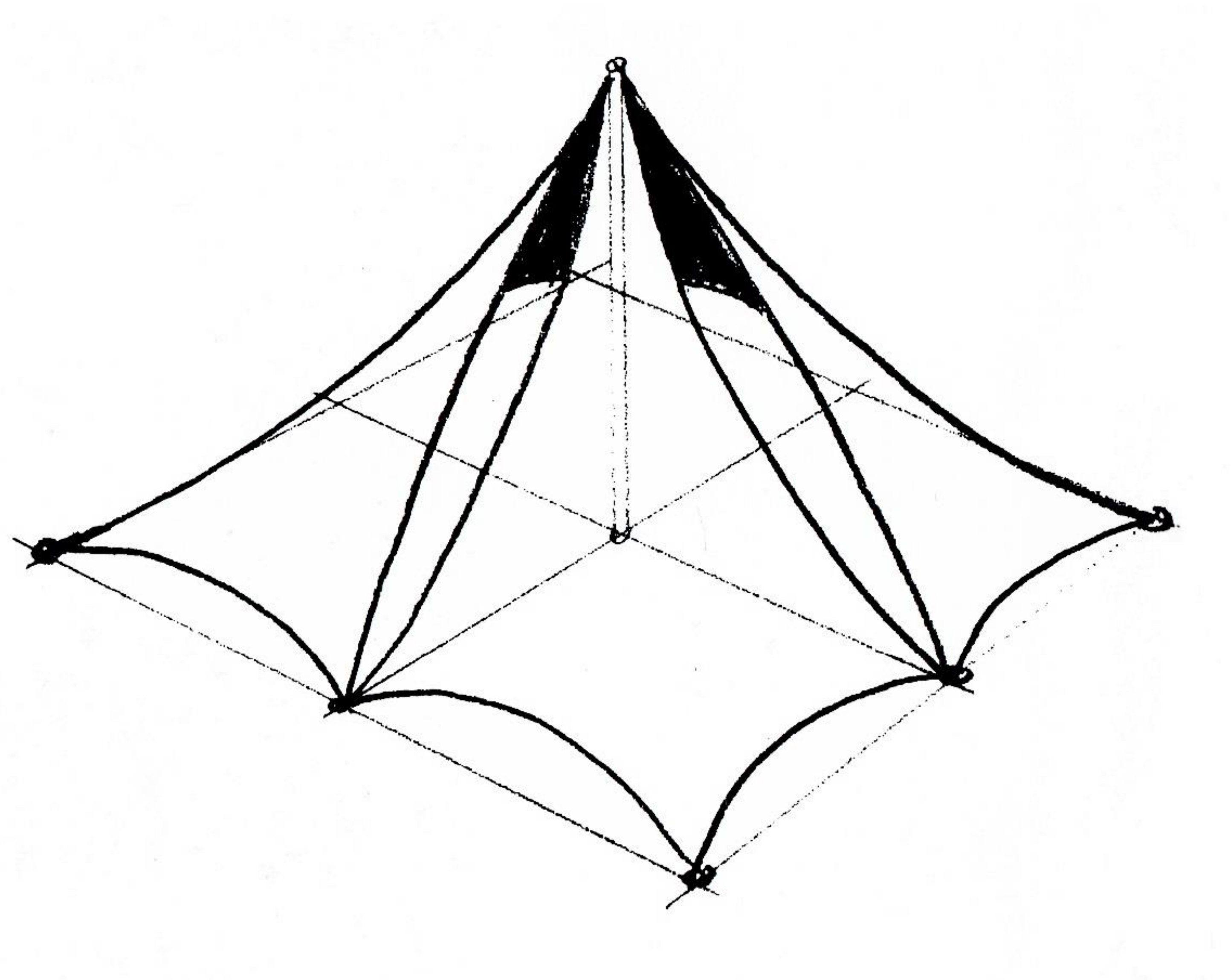


Figure 46) Four four-point structures cover a larger square. One radial cable could replace each pair of adjacent edge catenaries in the slope of the structure

In this sense, tensile structures are dynamic structures. Their critical number is also four, and the flexibility of their elastic components helps them adjust to changing load conditions. The dominating geometric element is a four-sided trapeze, and the four point structure is its simplest manifestation.

The geometry of four-point structures can have numerous variations, depending on the positioning of their support points. The combination of two or more four-point structures leads to a large variety of interesting tent forms. Several four-point structures can be combined by sharing their high points. Larger spaces can be covered by combining a number of four-point structures and varying the height of their supports. As the Georgia Dome in Atlanta demonstrates, they can also become modular elements in surfaces covering very large spaces.

More general V, large saddle surfaces can have many different edge elements and edge configurations. In fact, every fabric element which spans between four support lines formed by arches, beams, or cables becomes a saddle surface which can be made of orthogonal material such as woven fabric. Alternating lines of upward (ridge) and downward (valley) curved cables form excellent boundaries for generating efficient membrane surfaces. The ridge cables carry gravity loads, such as the weight of the structure or snow, while the valley cables resist wind suction loads. Indeed, these wind loads can be quite substantial: at hurricane speed, the airflow across an upwardly curved surface will cause upward suction loads equal to the weight of two feet of snow.

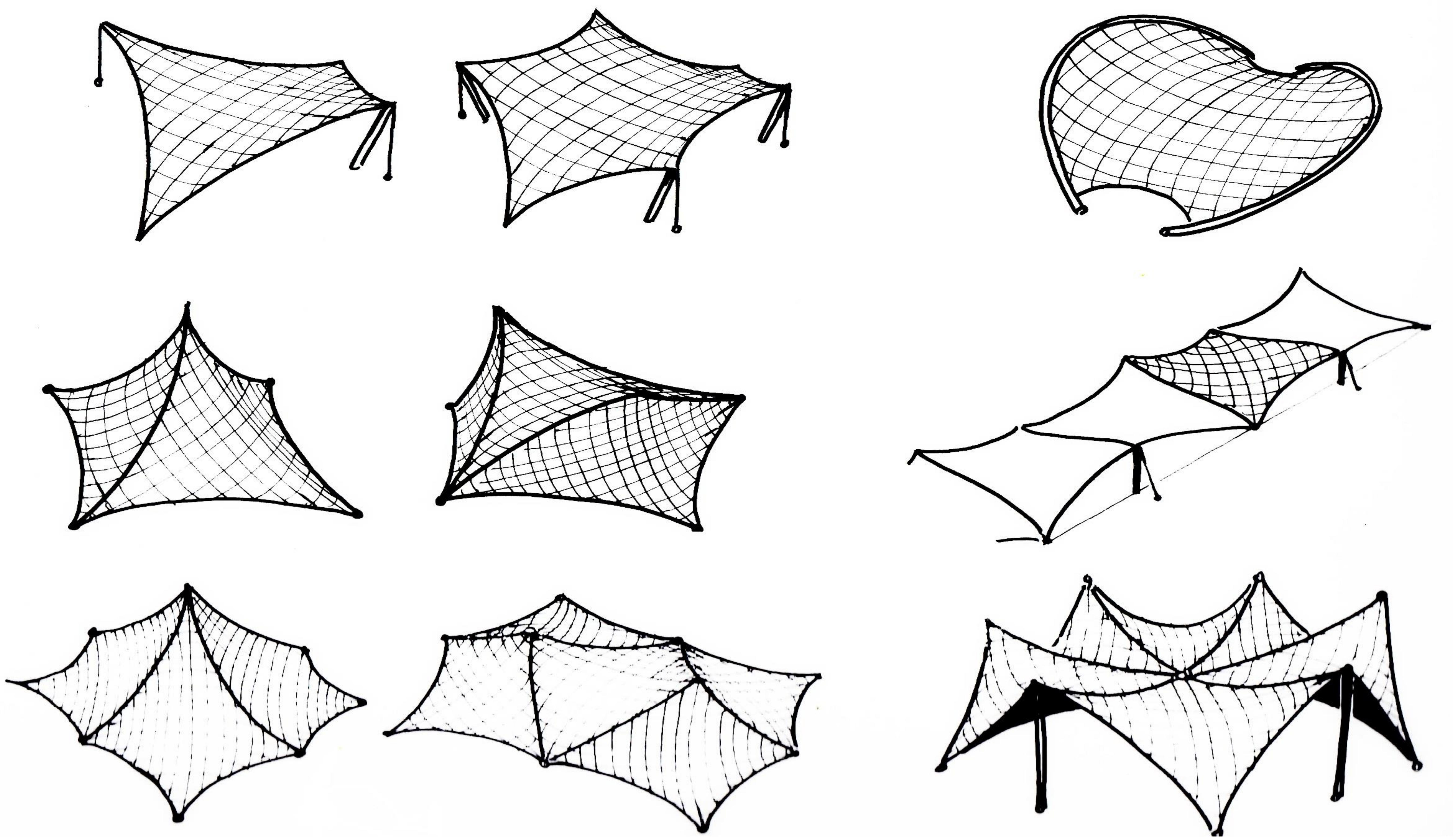


Figure 47) Variations and combinations of saddle surfaces

The space between these alternating cables is filled with a surface representing a double-curved net which consists of lines that run both parallel and orthogonal to the cables. If the apex of the valley cables is located at a sufficient distance below the bottom of the ridge cables, the fabric membrane represented by this net can carry both the downward and upward loads on the cables at safe stress levels.

The simplest structural configuration which this alternating cable pattern can generate is one which is suspended between two rows of masts. In this case, the ridge cables hang between the tops of the masts, and the valley cables are attached to ground anchors located on the same line as the masts, and half way between them. To prevent the mast tops from moving inward, tie- down cables are required, which are anchored outside the structure.

This arrangement has sonic disadvantages. The forces from the tie cables will greatly increase the load on the masts. Also, the high points of the structure arc at the outside lace, creating large openings which, in the case of an enclosed building, creates large end walls. Moving the masts inward greatly improves this condition. The shape of the ridge cable then looks exactly like a suspension bridge and the shape of the valley cable like an inverted arch. The terminal roof at the new Denver International Airport is designed this way.

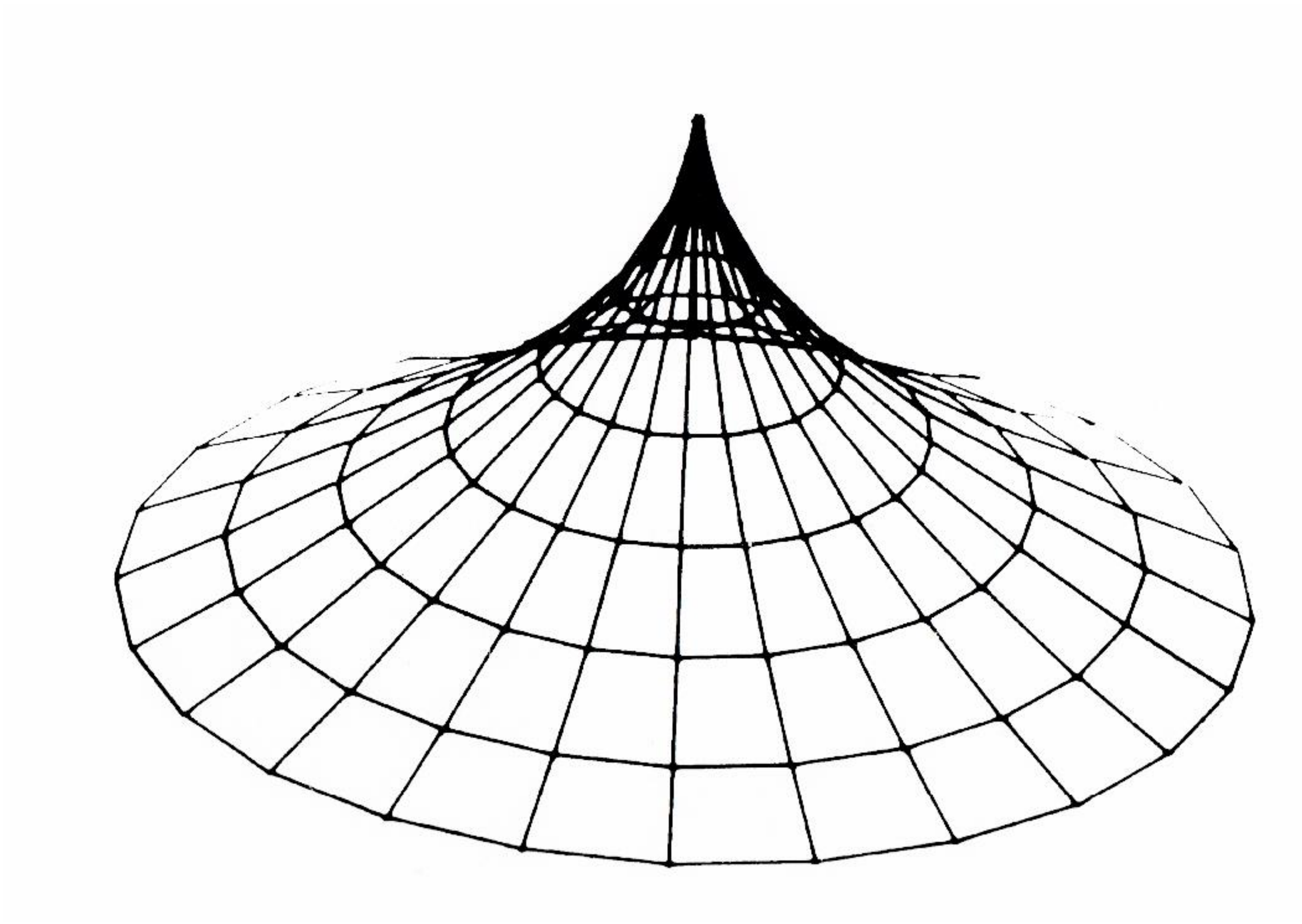


Figure 48) Net of primary radial tent shape with radial and ring

This circular configuration represents, in a sense, the transition to radial tent structures. Radial tent shapes are the alternative to saddle shapes. They are the only other way of satisfying the principal requirement that at any node in the net, two intersecting lines pull in opposite directions. Surfaces defined in this way are called Anticlastic surfaces, meaning that the curvatures in the two major axes are of opposite direction. All tensile structures must possess anti-clastic shapes. (Synclastic surfaces, on the other hand, are characterized by intersecting net lines which curve in the same direction. Domes and pressurized membranes are typical examples of structures with synclastic surface characteristics.) The two principal anti-clastic surface geometries derive directly from the coordinate systems which are used to generate them. The different types of surfaces is fully described in the next topic.

Tensile Structures Forms

Tensile structures are unusual in that the stresses in the structure determine the shape, and vice versa. This is a direct consequence of using a fabric, which has no appreciable stiffness out of the plane it lies in and no appreciable bending stiffness. So the shape of the structure has to follow the stress.

Before any external loads are applied, the stress in the structure is the designed in prestress, caused by deliberately making the fabric panels and cables undersize, so that they prestress when stretched out to the correct size. When an external load is applied to the structure the main response of the structure is to change the internal stresses to accommodate the load. A secondary response is the deformation of the structural shape. This means there are only certain shapes that are possible to make as tensile structures, and all of those shapes will in small sections resemble a saddle shape, with local curvature in two opposing directions. This is called an anticlastic surface. The fabric tensions in these two opposing curvatures will pull against each other, leading to a local force balance, and providing out of plane stiffness.

Within these restraints, it's possible create cone tents, hypar sails, and barrel vaults, all of which exhibit local anticlastic surfaces. Illustrations of these basic shapes are shown here. The limitations on size and proportion of these structures are material strength limitations. As the size of a structure goes up, the stresses on the structure due to external loads increase, and at some point exceed the strength of the material.

Although it is perfectly possible to design any size model with a computer simulation, it is useful to have a rough idea of the likely stresses in the structure during the design stage, to avoid designing beyond the fabric, cable or fixed points capabilities. Simple methods of estimating the stress values, using approximation and some simple maths, can be used for this.

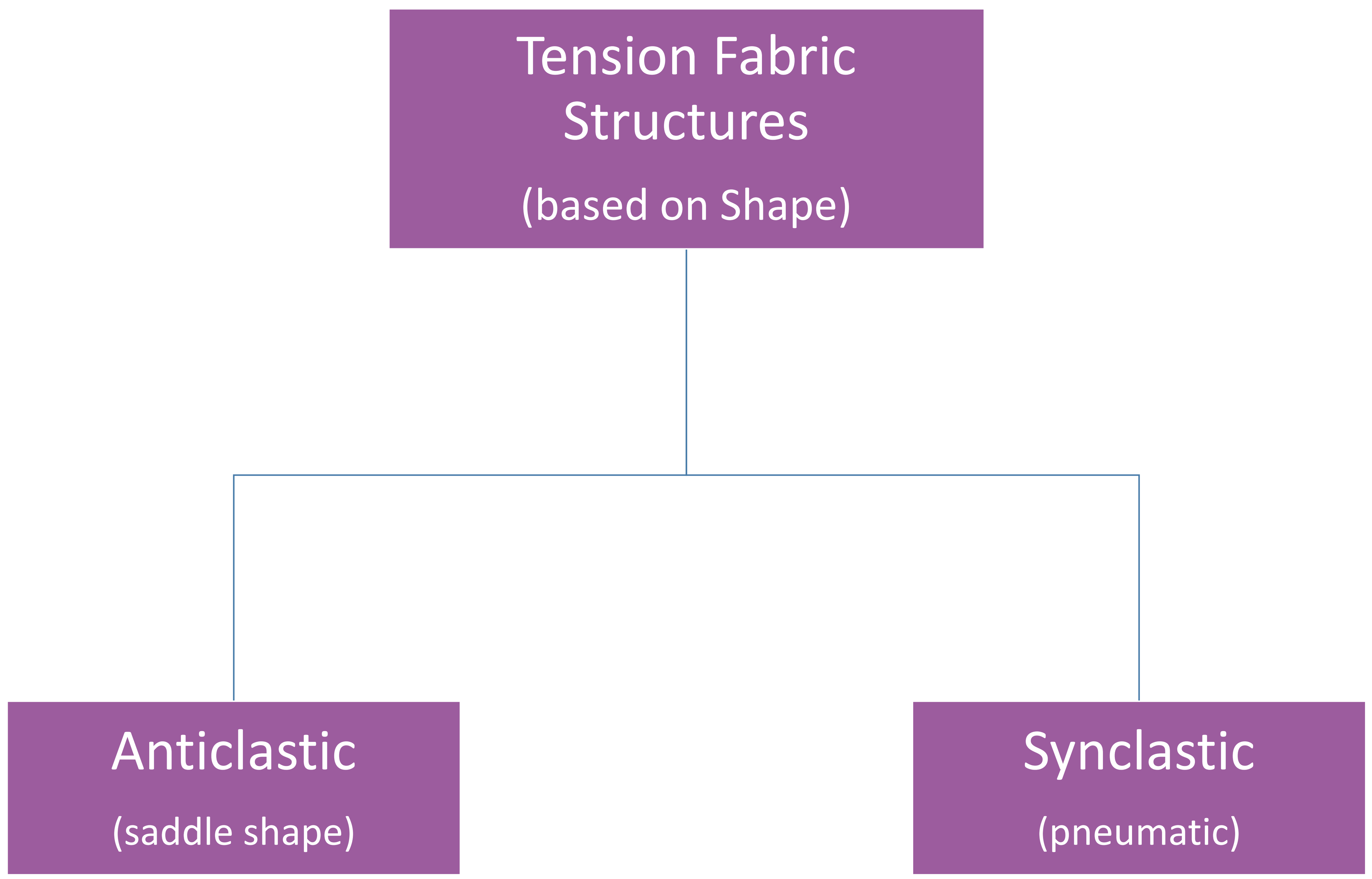


Figure 49) Tensile Structure Types, based on shapes and figures

Anticlastic Forms

Anticlastic structures are pure tensile fabric surfaces having a curvature at a given point and in a particular direction, which is of the opposite sign to the curvature at that point in a perpendicular direction.

Tensile structures are stabilized by anticlastic curvature and prestress. Anticlastic curvature means that the fabric is curved simultaneously in two opposite directions. Two basic geometries may be used to create anticlastic curvature: One is the Saddle shape, the other the Radial tent (Barrel Vault shapes could be added). It is from combinations and variations of these geometries, that all tensile structures are shaped.

Prestress is the introduction of permanent tension into the fabric in two opposing directions. Without anticlastic curvature and prestress, the fabric would flutter in the wind and destroy itself within a short time. The amount of curvature and the amount of prestressing force must both be sufficient to maintain stability under expected wind and snow conditions. If the curvature is too flat or if the prestressing tension is too low, excessive deflection or flutter will occur.

The design of a tensile structure usually begins by experimenting with simple physical models. These often are made of pantyhose material or stretch fabric, either of which is easily stretched and manipulated. After a general shape has been established with the model, a computer is used to find the exact equilibrium shape. determine the stresses in the fabric and supporting members under wind and snow loadings. and generate cutting patterns for the fabric. The design process is referred to as font: finding, because a tensile structure cannot be made to take any arbitrary shape. just as a hanging chain will always take a form that places its links in equilibrium with one another, a tensile structure must take a form that maintains proportionate amounts of tension in all parts of the fabric under all expected loading conditions. The designer's task is to find such a form.

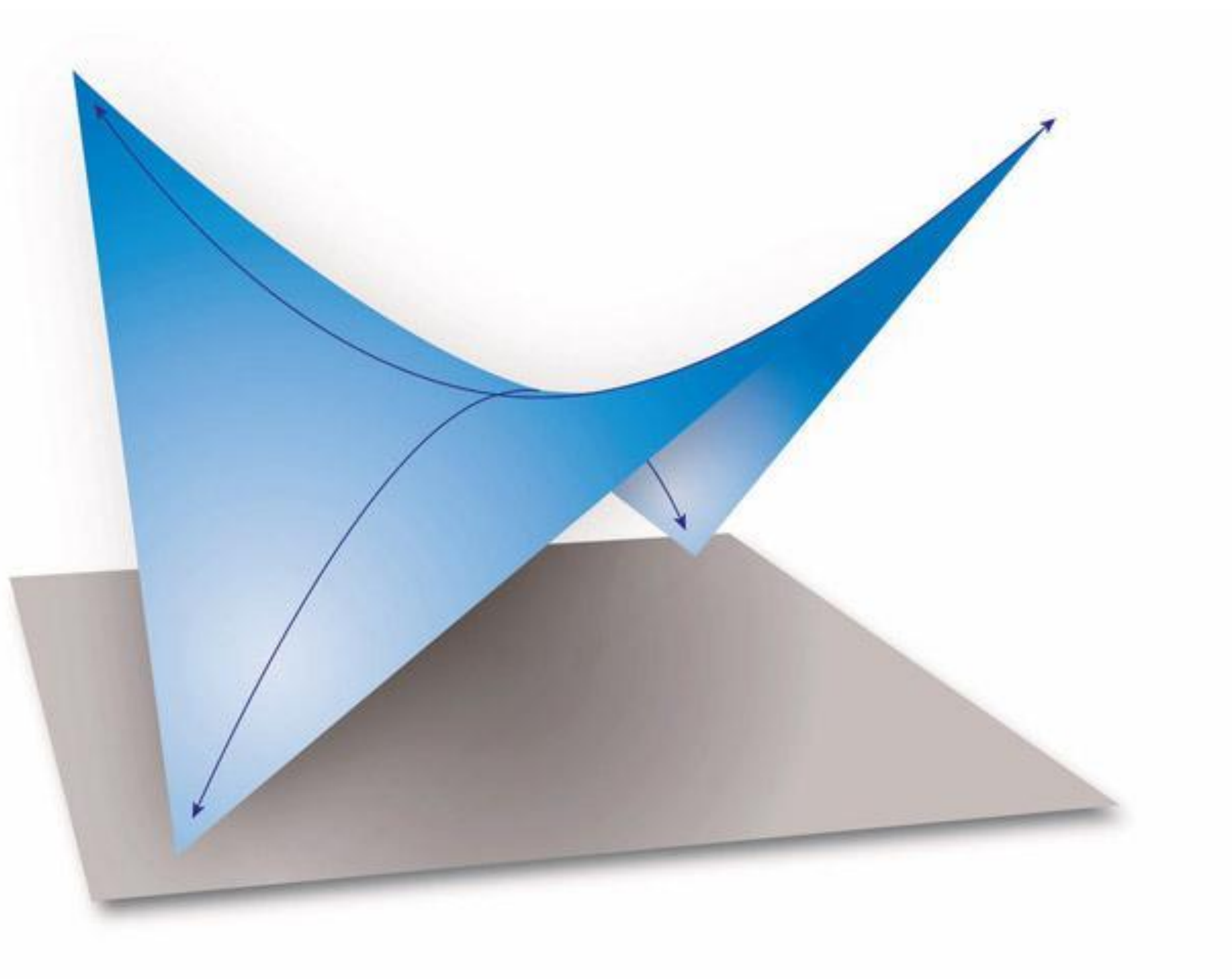


Figure 50) An example of Anticlastic shape

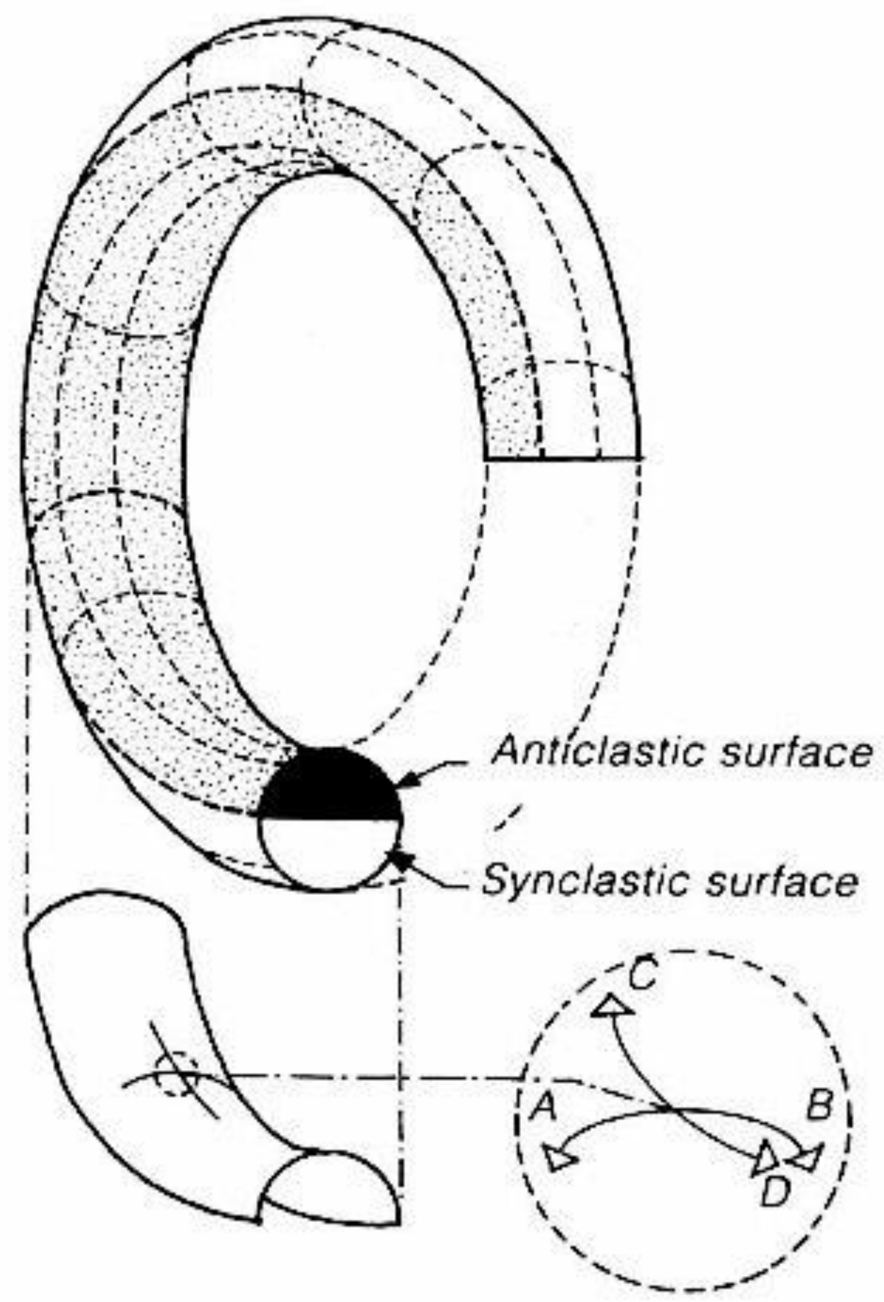
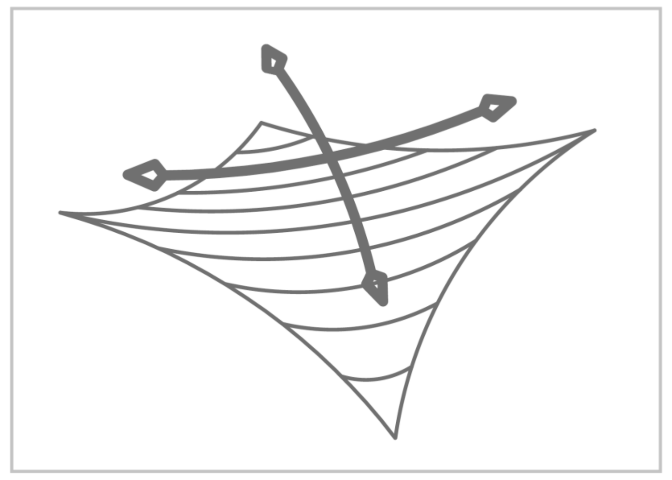


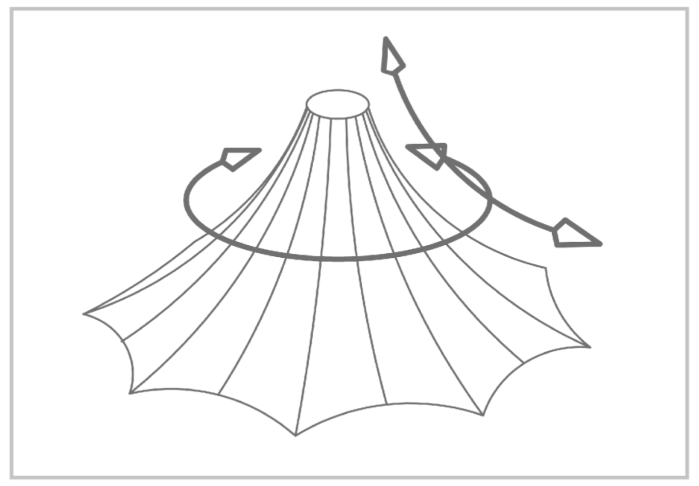
Figure 51) Opposite direction of forces

1 

Hypar

Two opposing high points and two opposing low points. The Hypar is a contemporary free-standing canopy which can be used to create shade or shelter in open spaces such as quadrants, courtyards or school playgrounds. The structure features curved support columns with a hyperbolic paraboloid-shaped roof creating a striking structure. A twisted freeform shape

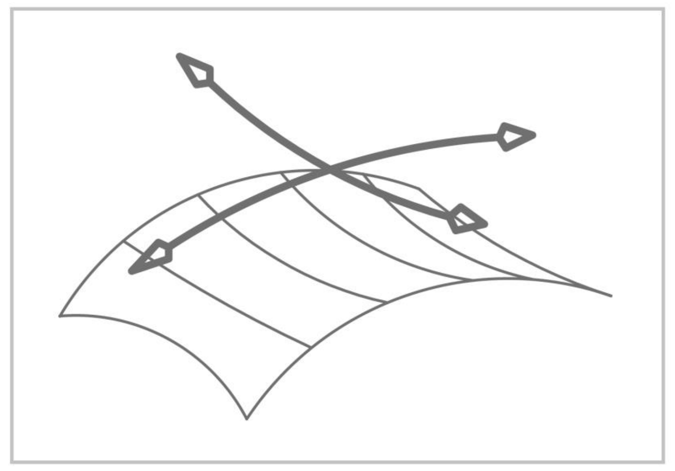
Example: Tanzbrunnen, Koln, Germany

2 

Cone

Single cone, multiples cones, fixed edges, catenary edges, cables edges, height variations, inverted cones etc. A cone shape, characterized by a central peak

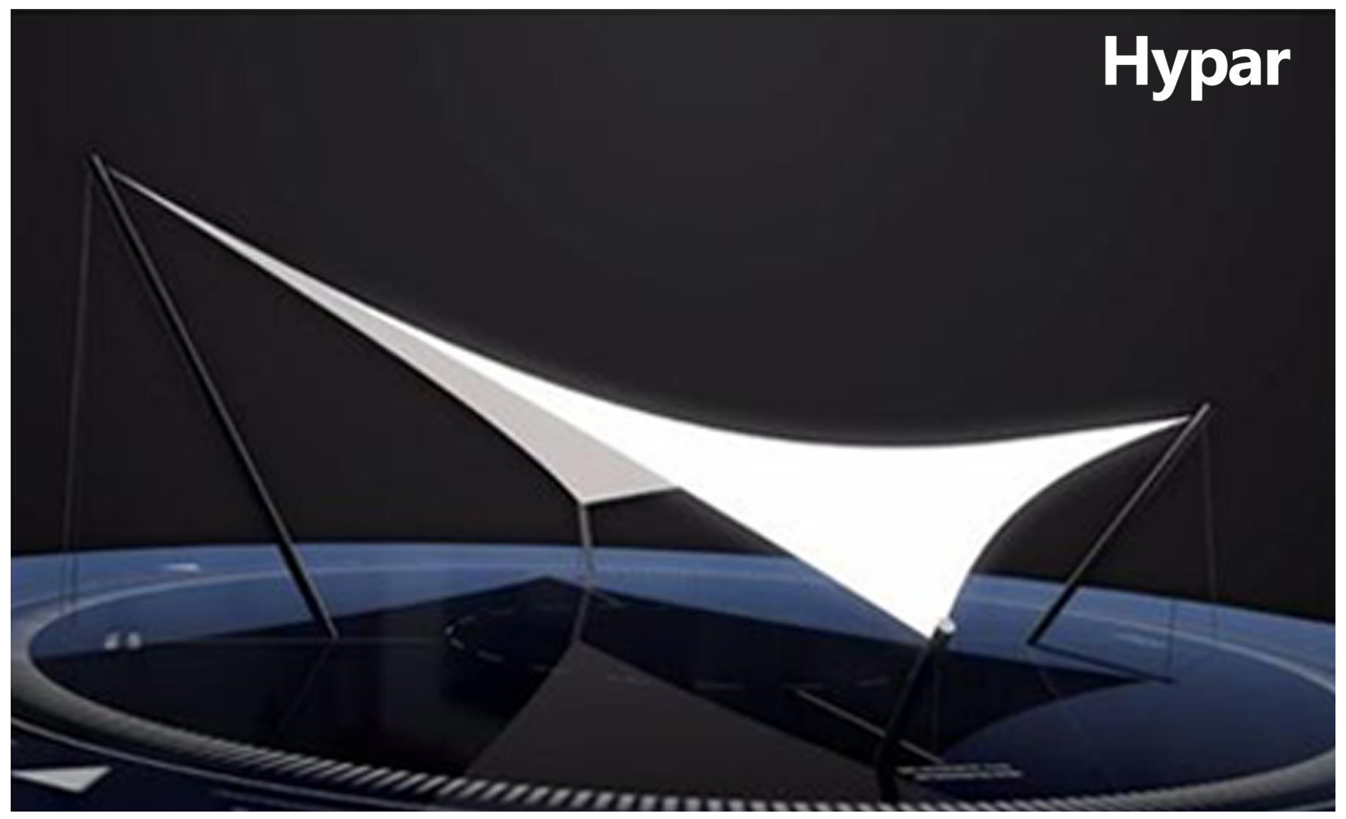
Example: Recreational Clinic, Masserberg, Germany, Case Study 3, in non-ETFE case studies chapter

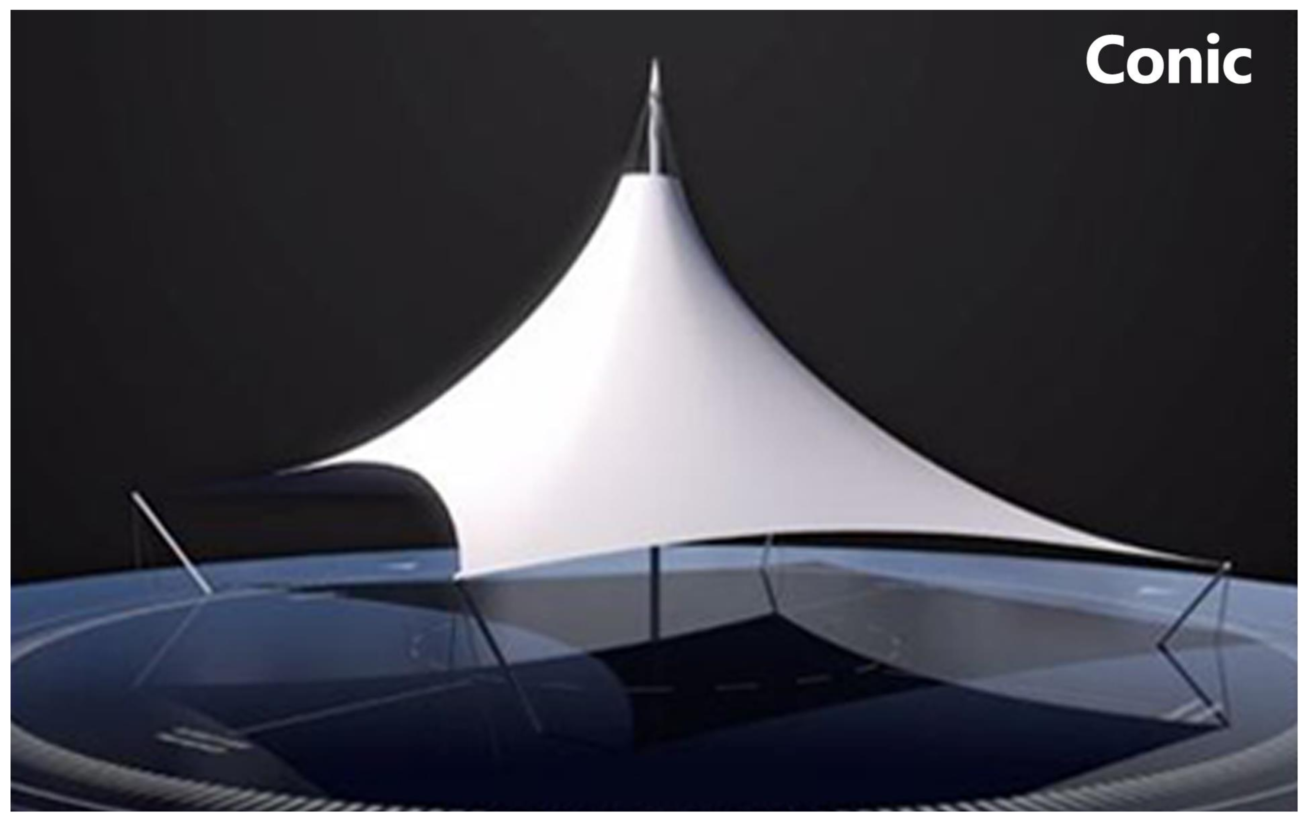
3 

Barrel Vault

Parallel arches and crossed arches. An arched shape, usually characterized by a curved arch design

Example: Festival Theatre, Llangollen, UK





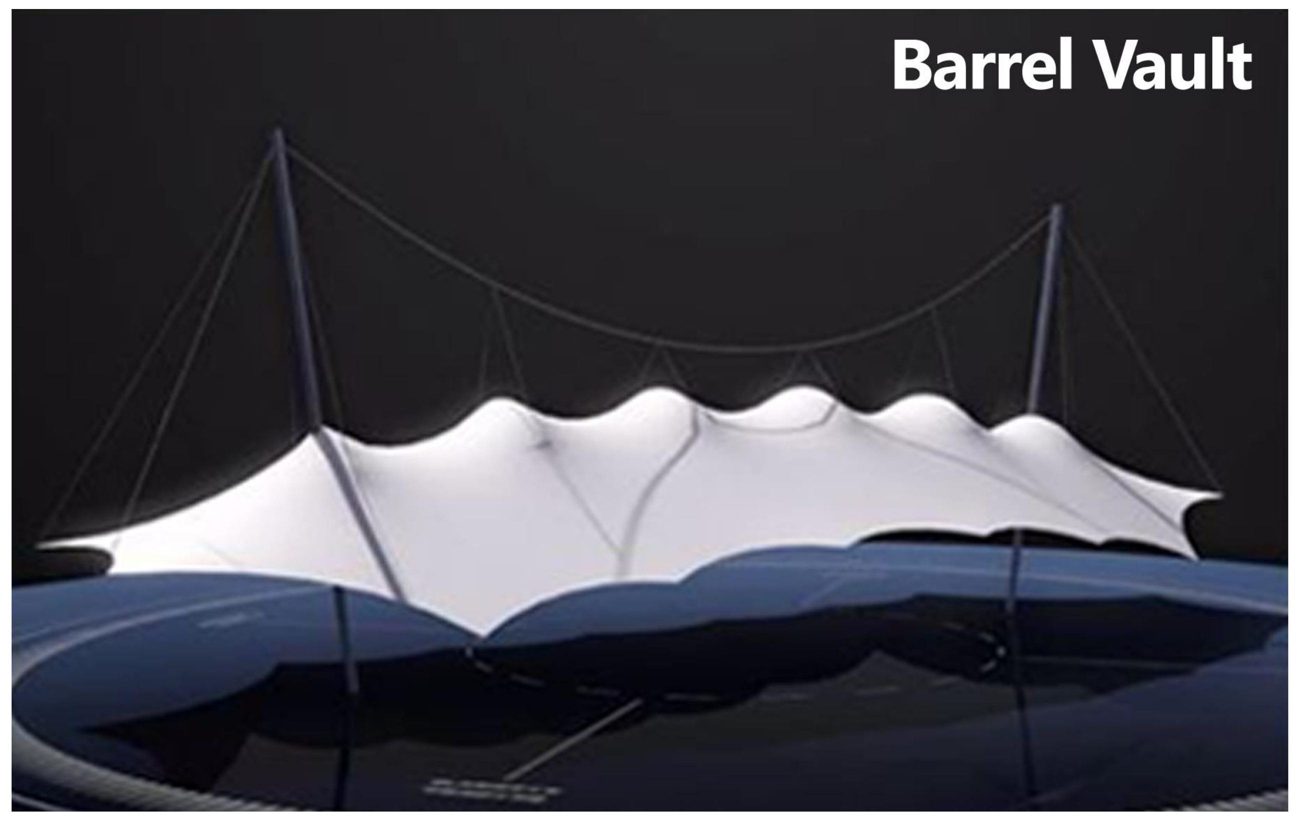


Figure 52) Different Anticlastic Forms

Hypar Anticlastic Shape

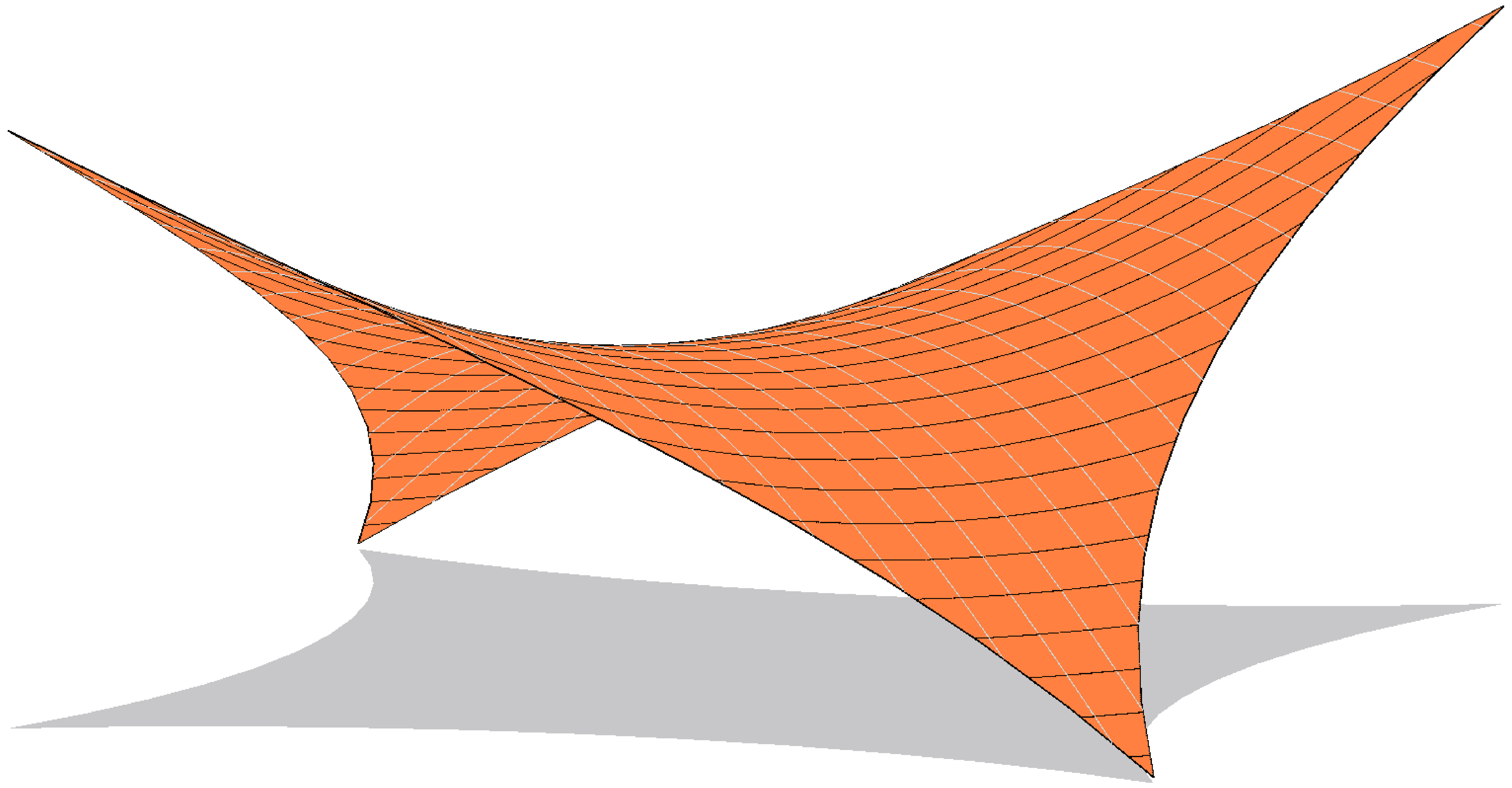


Figure 53) Perspective View

Figure 54) Hypar shading in park

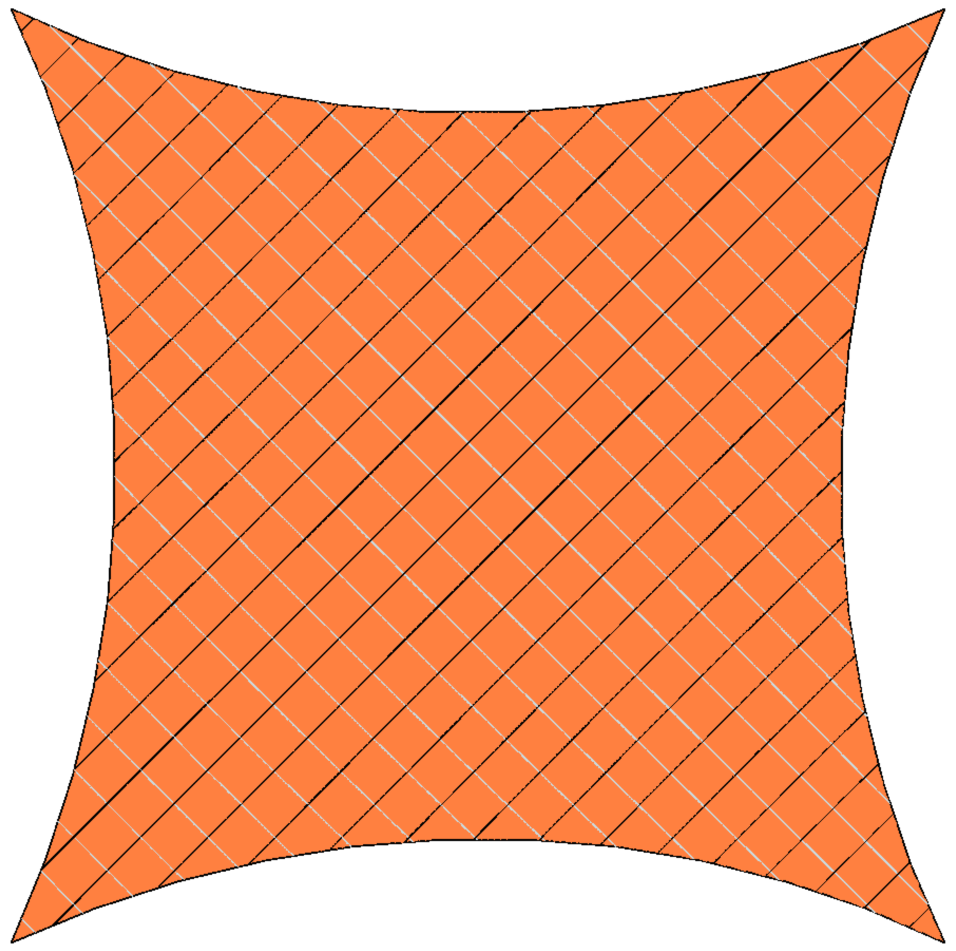


Figure 55) Top View

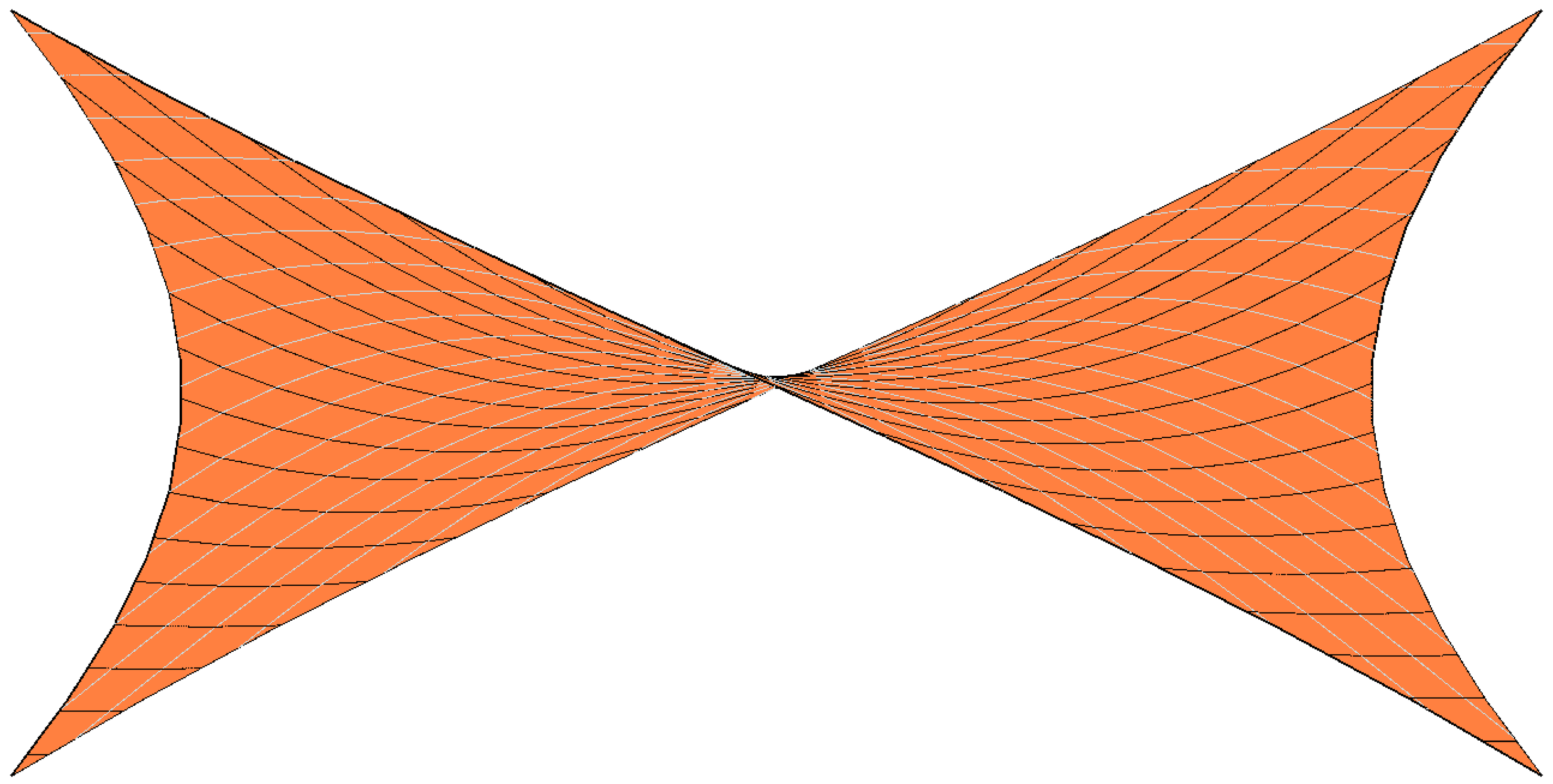


Figure 56) Side View

Conic Anticlastic Shape (Surface High Point)

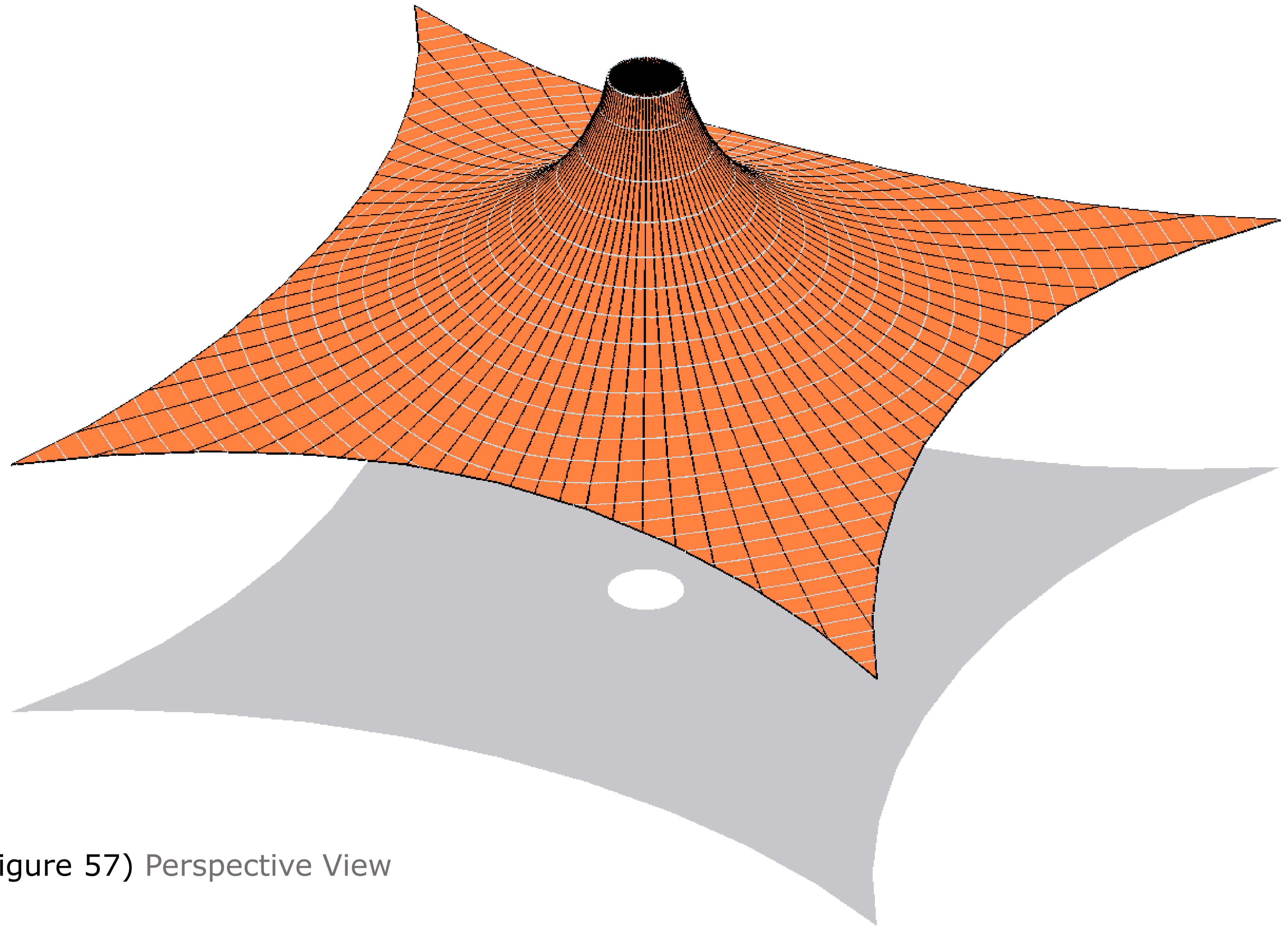


Figure 57) Perspective View

Figure 58) World's Fair Park Amphitheatre
Knoxville, Tennessee, USA

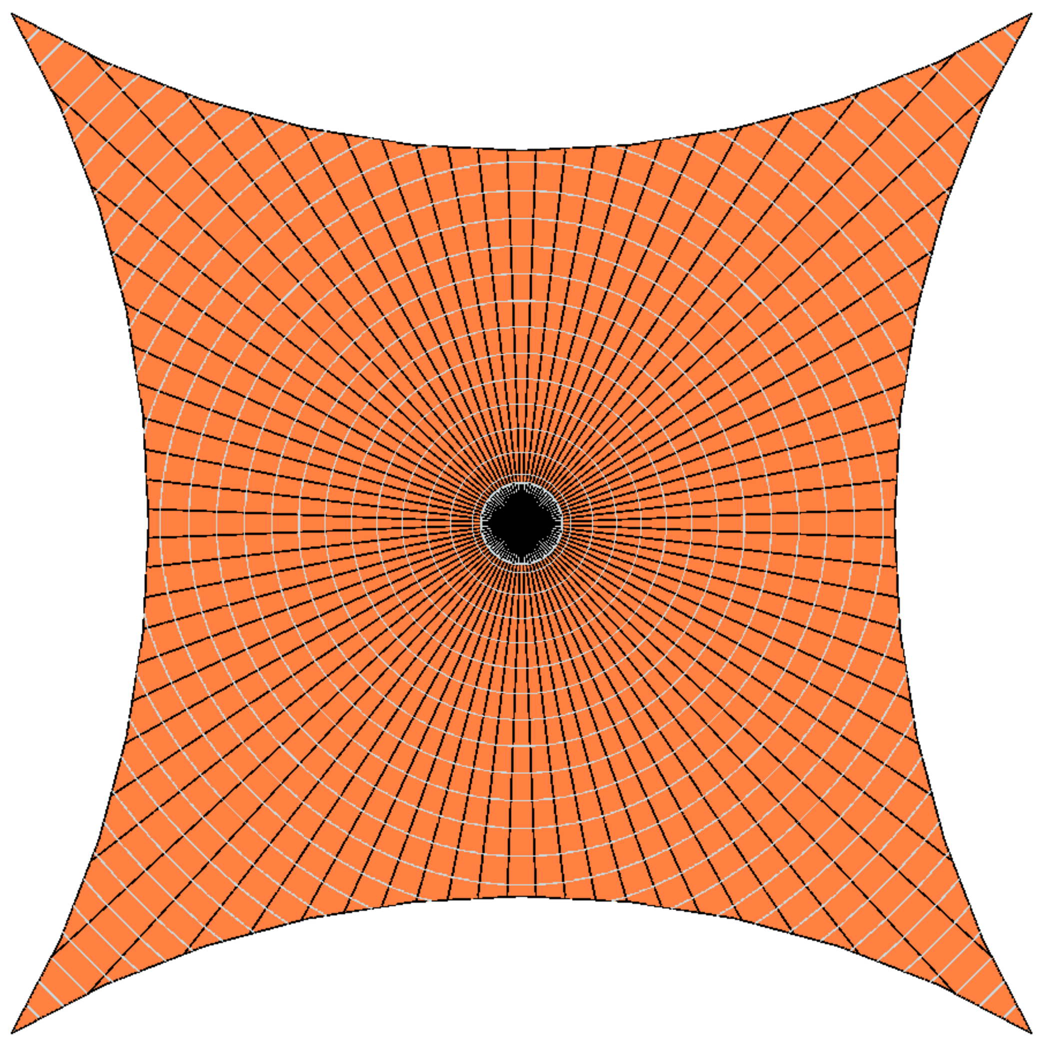


Figure 59) Top View

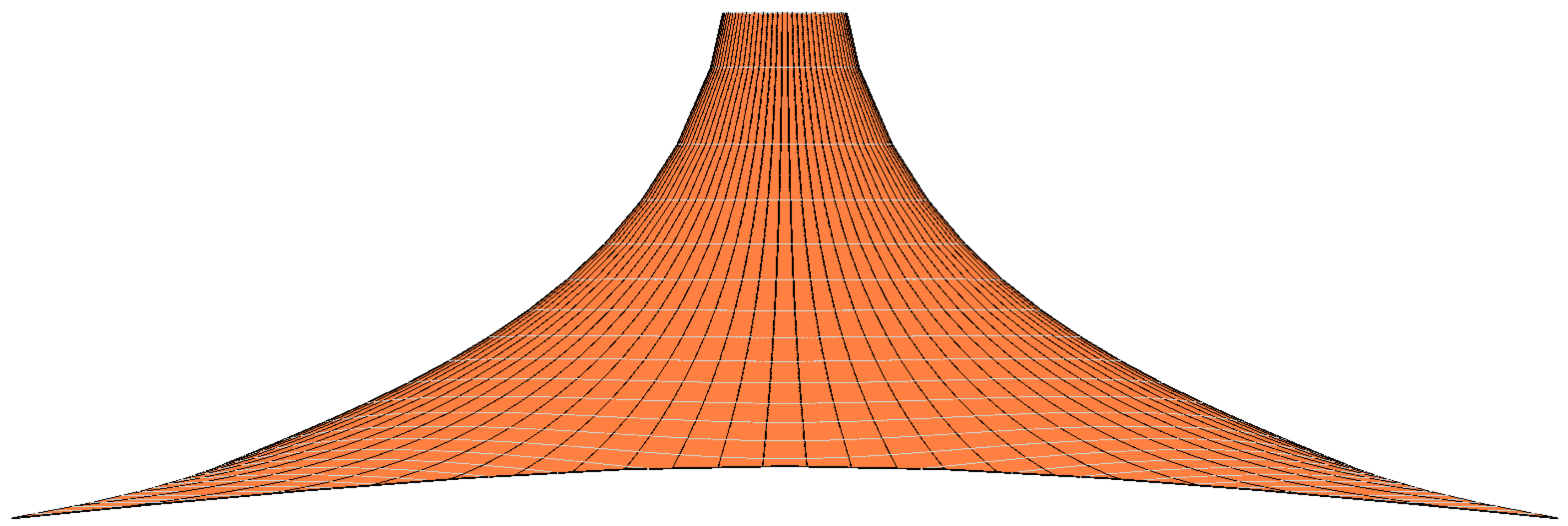


Figure 60) Side View

Conic Anticlastic Shape (Surface Low Point)

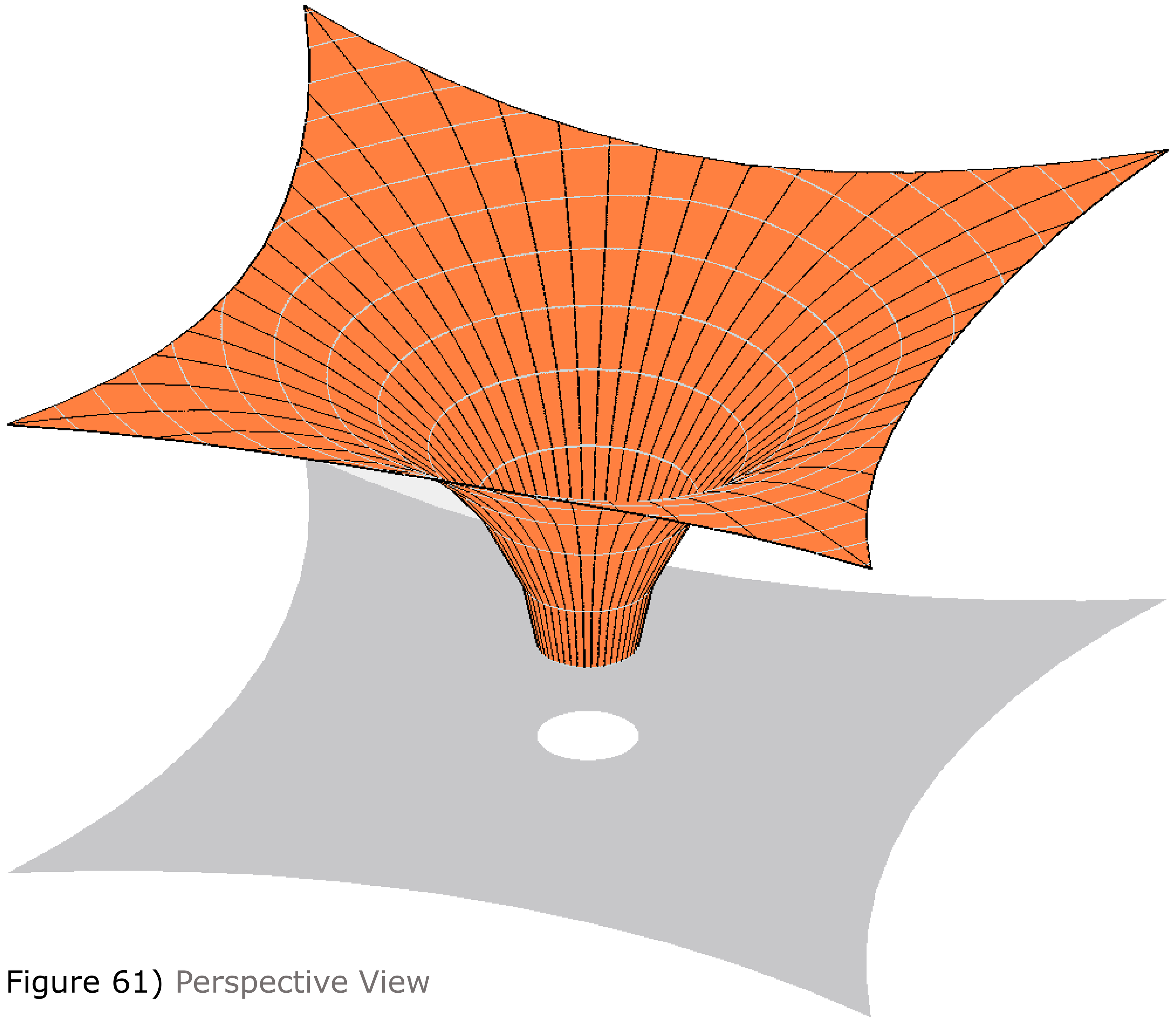


Figure 61) Perspective View

Figure 62) Prophet Mosque, Medina, Saudi Arabia

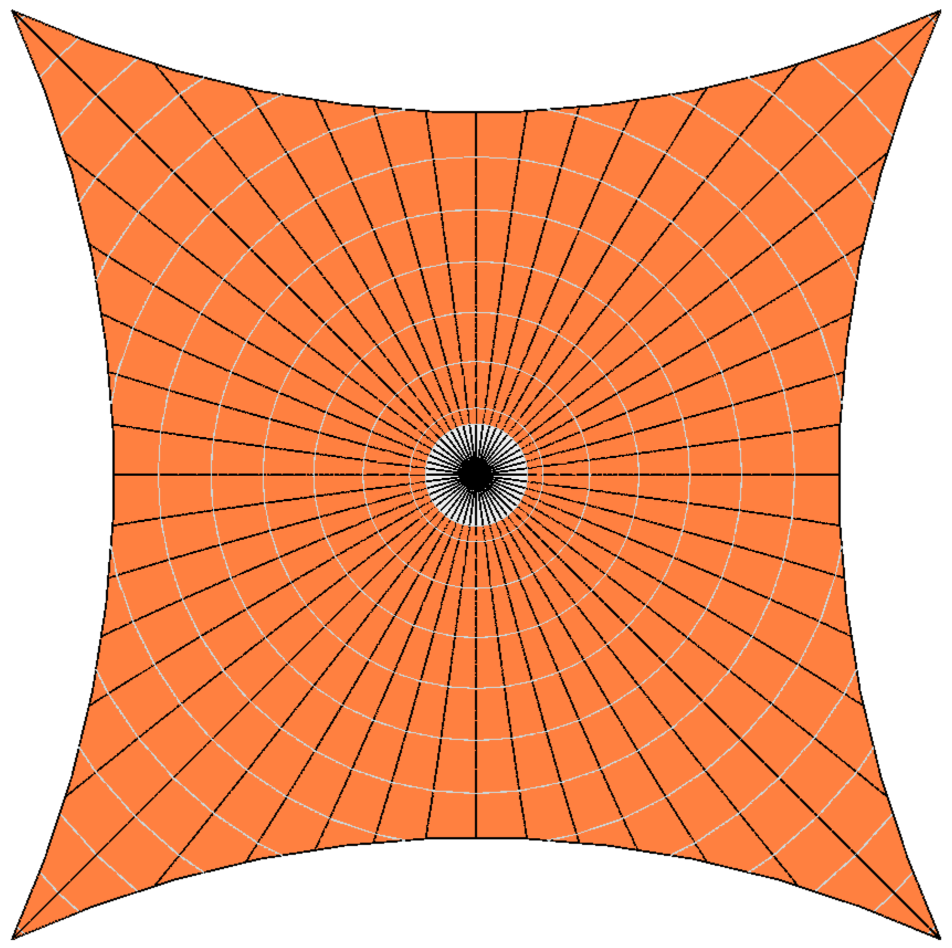


Figure 63) Top View

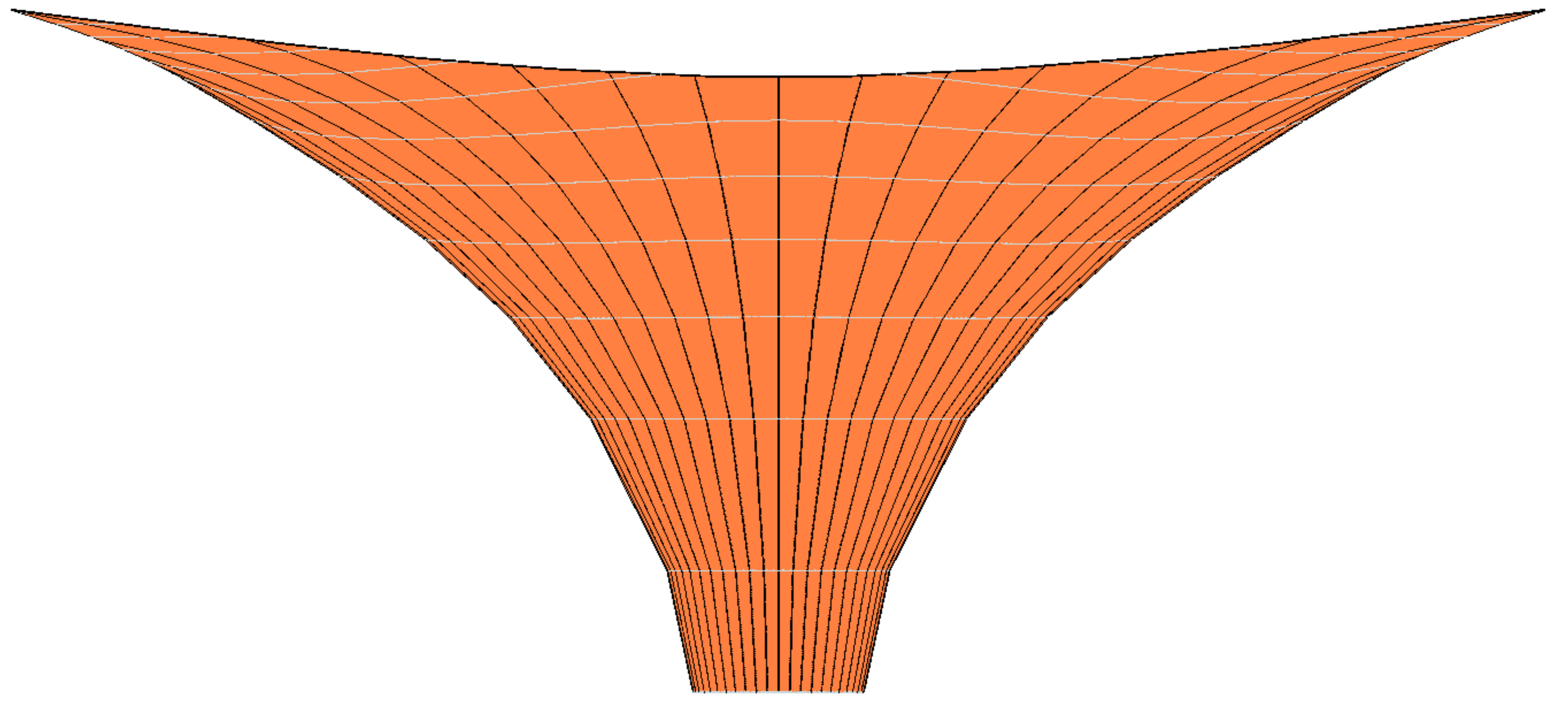


Figure 64) Side View

Barrel Vault Anticlastic Shape

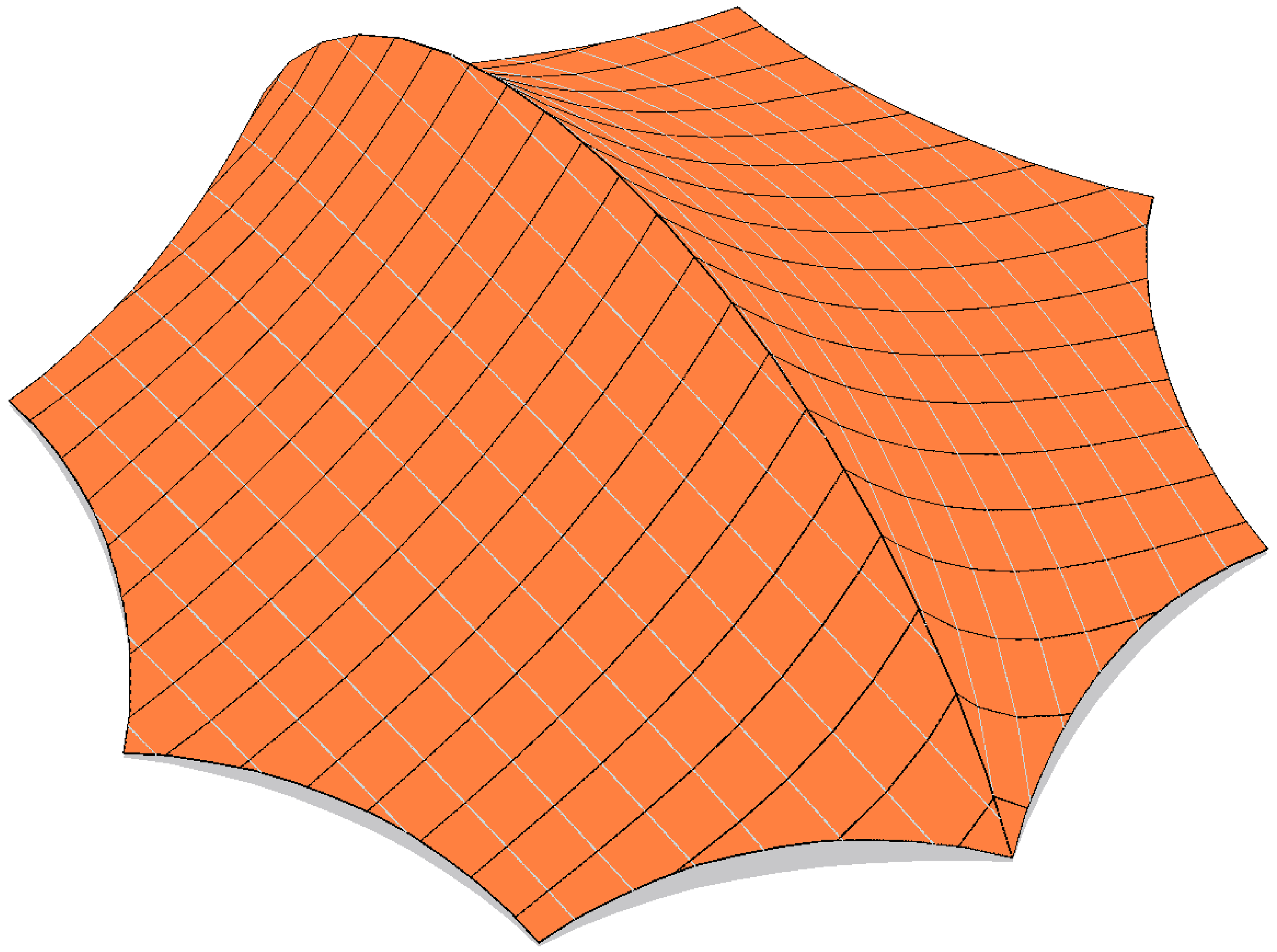


Figure 65) Perspective View

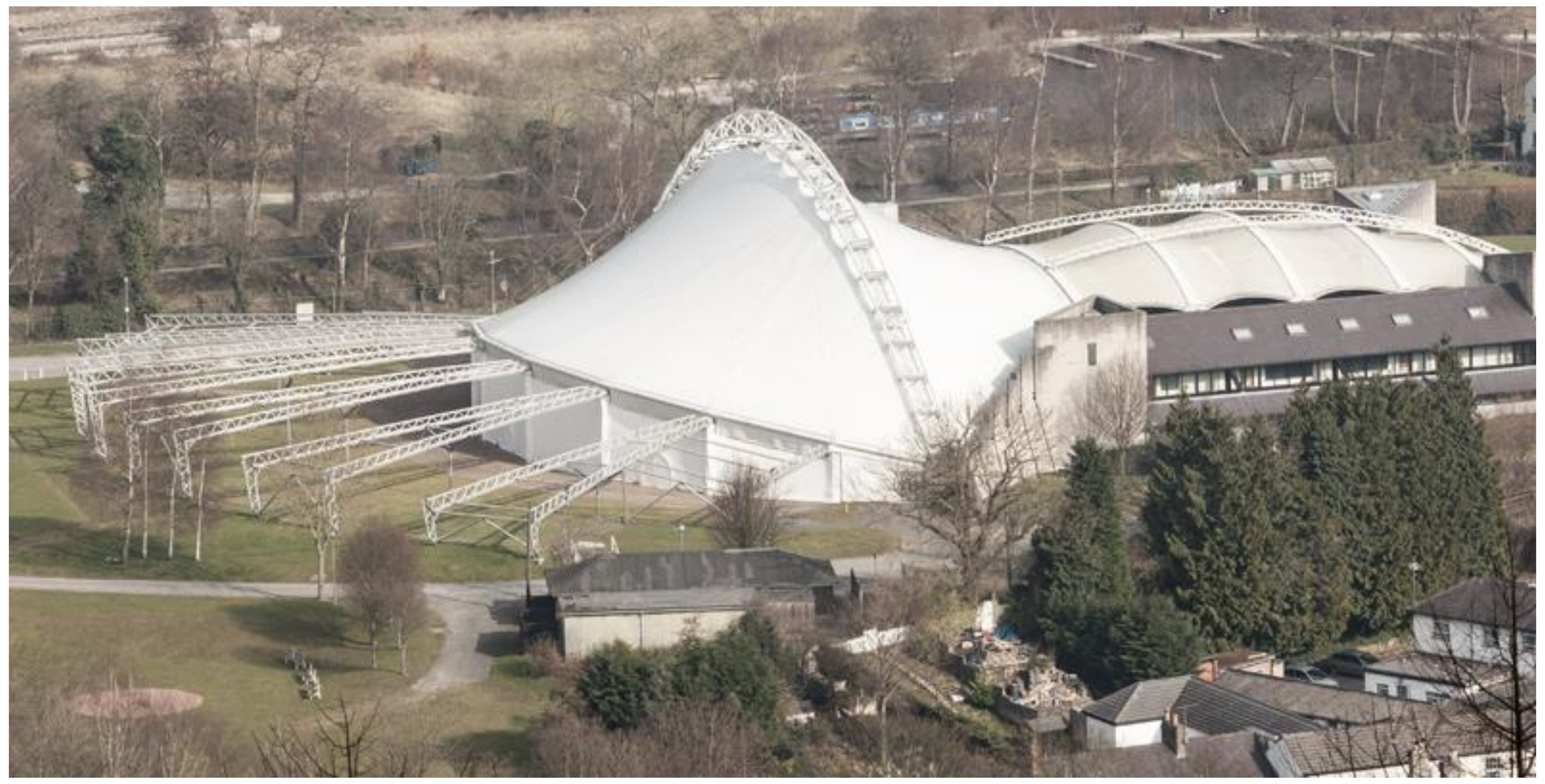


Figure 66) Royal International Pavilion, Llangollen, UK

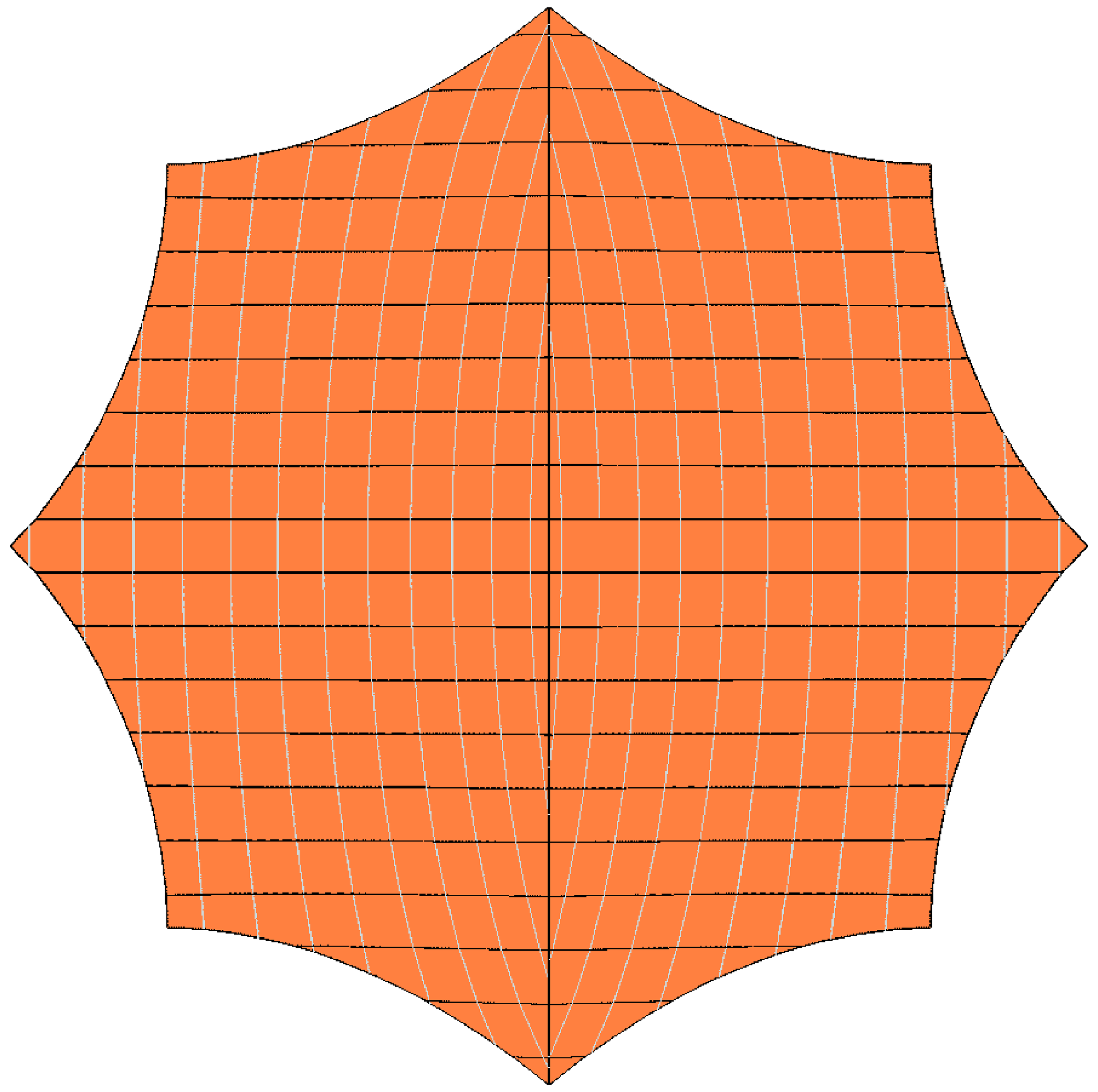


Figure 67) Top View

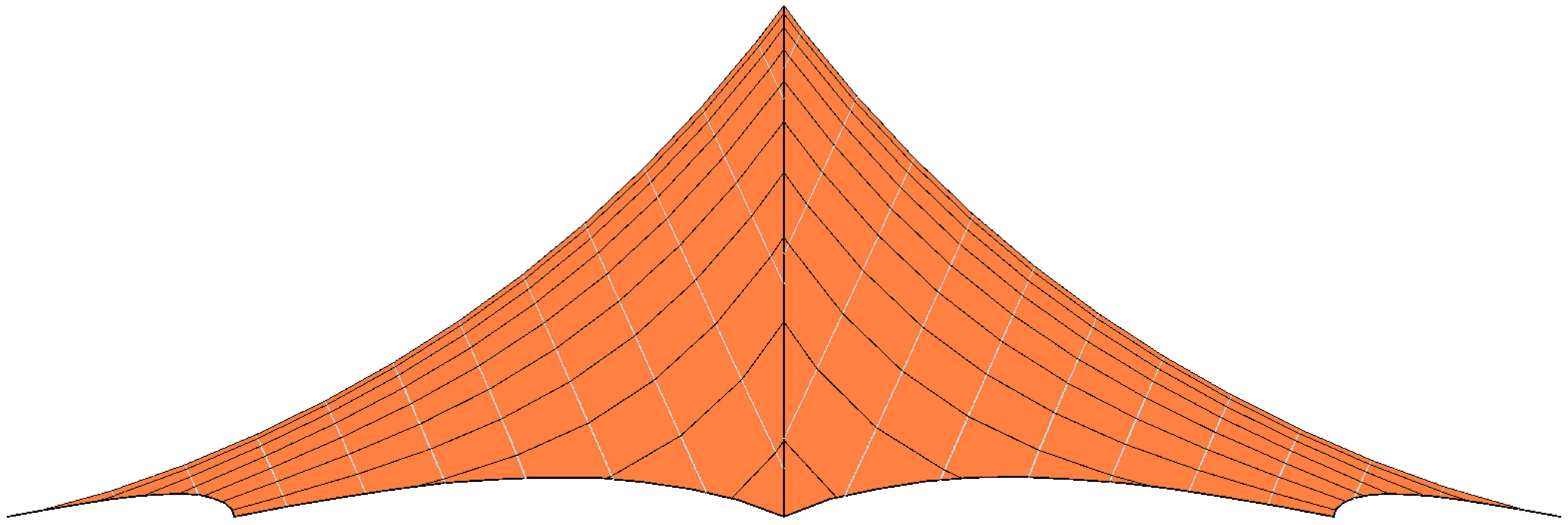


Figure 68) Perspective View

Synclastic Forms

-A Synclastic form is a mono-shell whose axial and radial curves are oriented in the same direction, either concave or convex.

-A good way to know whether a form is synclastic is to remember that a synclastic can be positioned so that it can hold water.

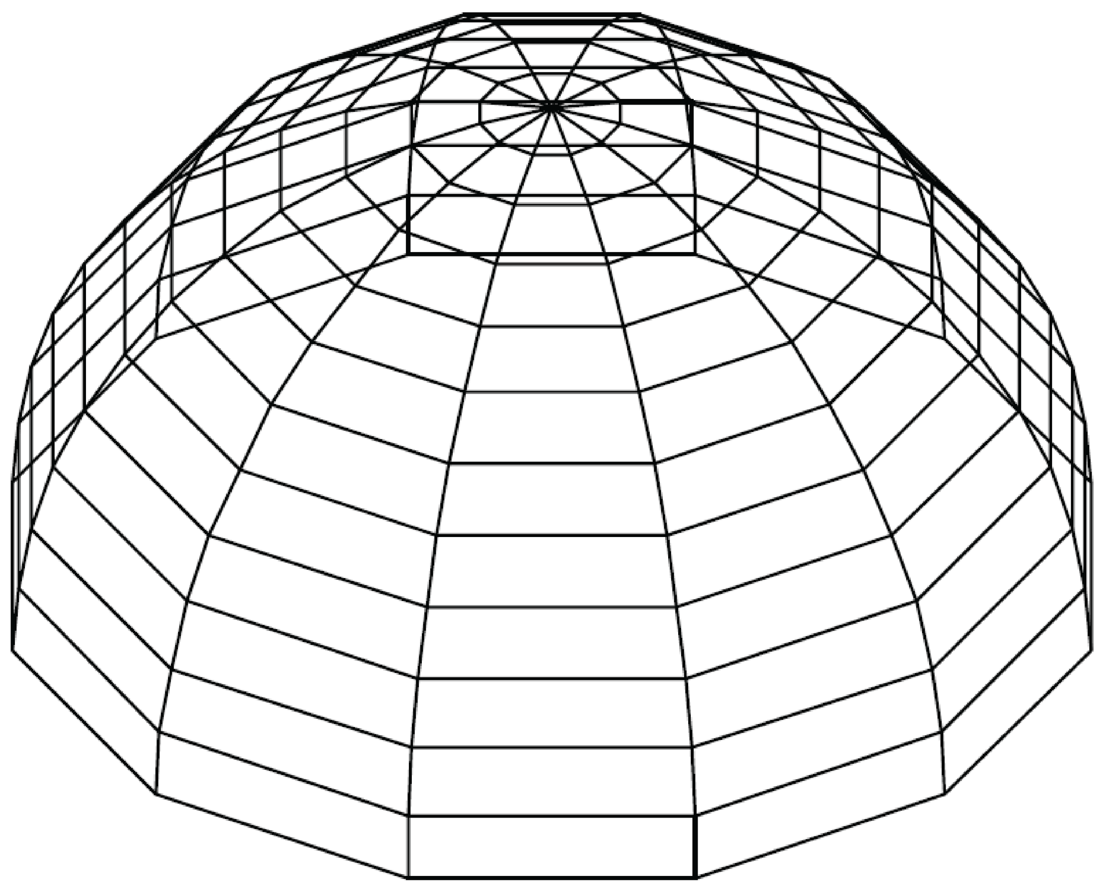
In general Synclastic tensile structures are referred to Pneumatic or Inflated Structures due to the

Shape characteristics.

Inflated structures are held in shape by a balance between an internal inflation pressure and the membrane tension. A small section of tensile structure looks like a saddle, but a small section of an inflated structure is synclastic and looks like a part of a sphere.

A tensile structure for finding program cannot find these shapes. But often the shapes are simple surfaces of revolution that are easy to draw in CAD programs.

The same paneling program that would be used for tensile structures can then panel these surfaces.



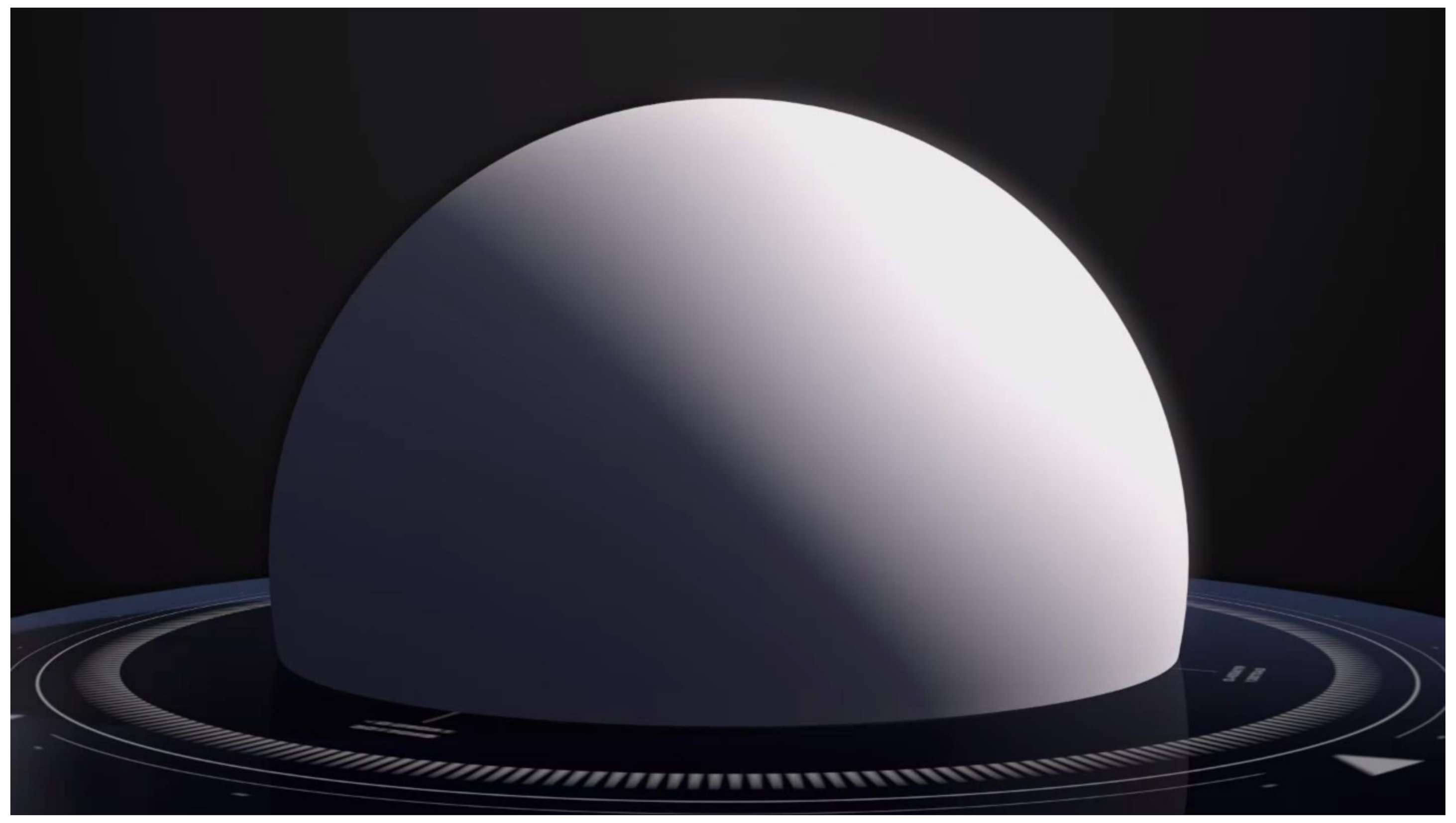


Figure 69) Examples of Synclastic form

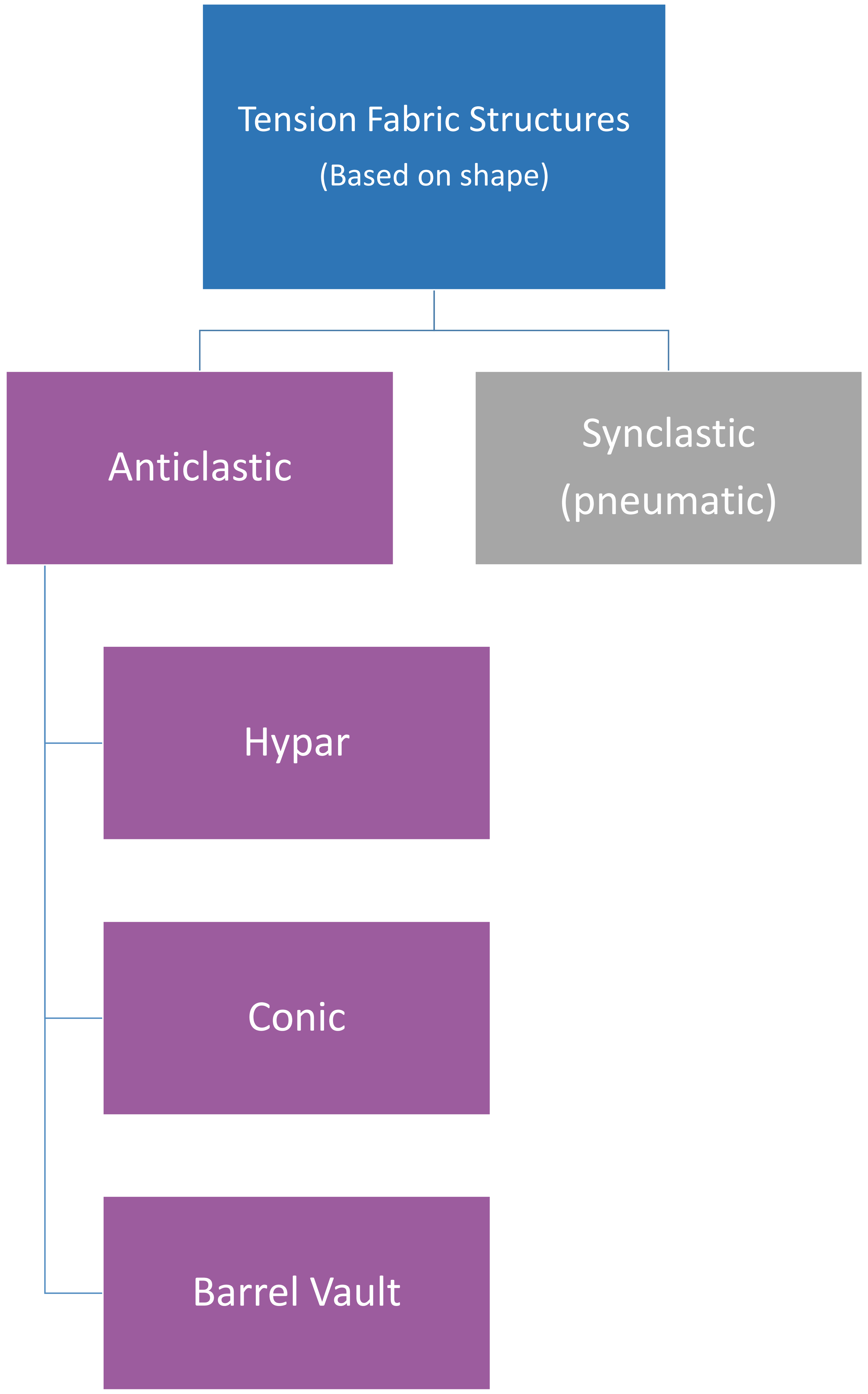


Figure 70) Tension structural possible forms

Pneumatic Structures

Pneumatic structures are essentially Membrane structures, which are stabilized by the pressure of compressed air and are tensile skinned, closely related to suspended structures. Inflatable structures are typically classified as Pneumatic structures and are structural forms stabilized wholly or mainly by pressure differences of gases, liquids etc materials in bulk. On solid ground, pneumatic structures had a first breakthrough as shelters for radar devices after World War II. The shelter needed to be lightweight, mobile and deployable in short time and without any metallic parts, ideal requirements for pneumatic structures.

During the Word War II, and after the invention of nylon, pneumatics started to be used in military operations, as emergency shelters and decoys. At the end of the War, the increase in the number of military air operations demanded implementation of a large and sophisticated network of radars over the American territory. In order to protect these radars from extreme weather conditions, such as in Alaska, the American Army sponsored a group of researchers at the Cornel Aeronautical Lab, led by Walter Bird, to develop thin non-metallic shelters, avoiding interference with the radar signals (Topham, 2002). In 1948, Bird and his team achieved the construction of a 15m diameter pneumatic dome, the prototype for a series of large "radomes" (as they have been called) built by Birdair Structures. This company, established by Walter Bird, also pioneered, during the 1960's, the commercial application of pneumatics, as covers for warehouses, swimming pools, sport facilities and factories. Other similar companies soon appeared in Europe and Japan.

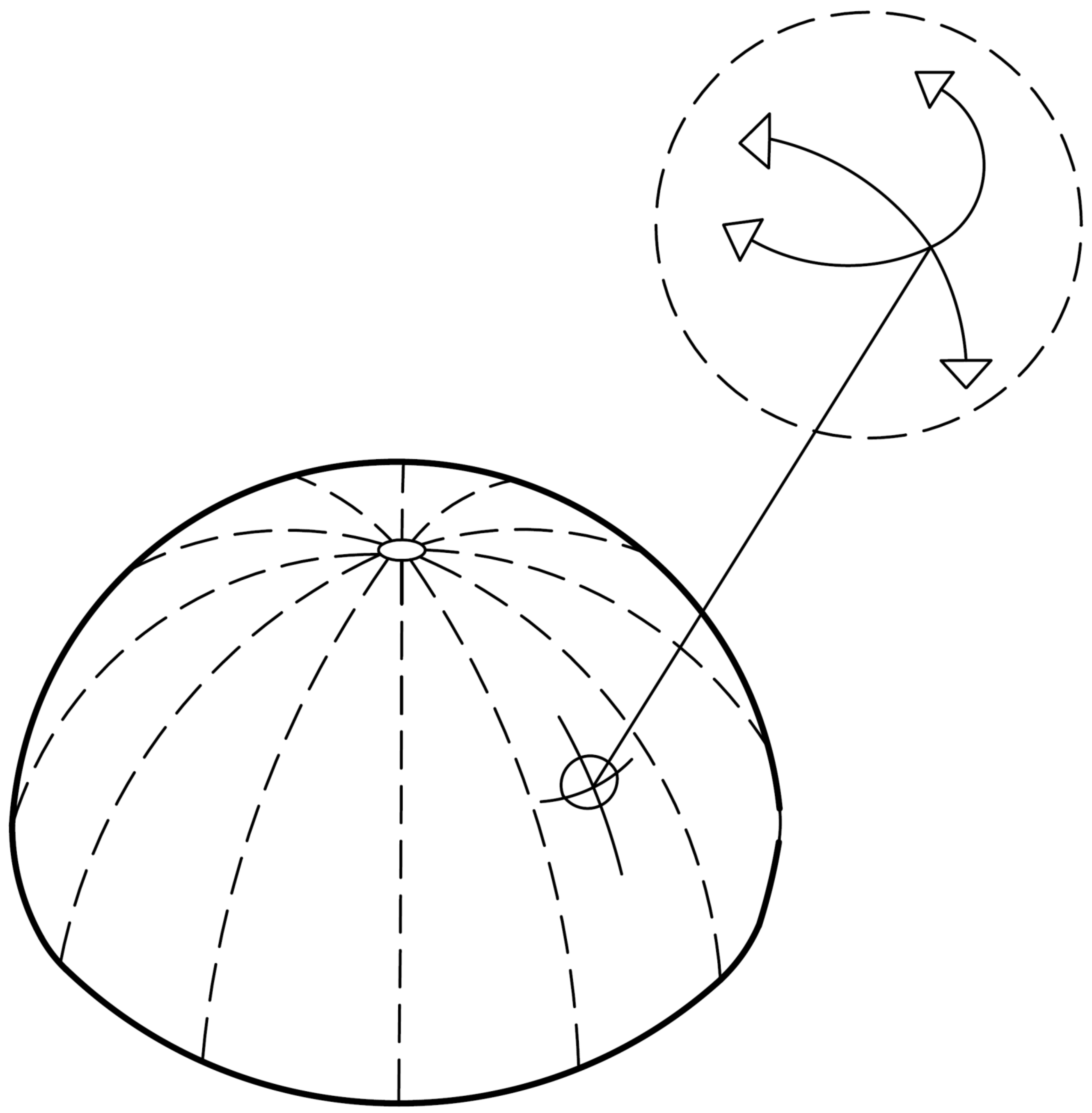


Figure 71) forces directions

Figure 72) Inflatable Teahouse: Traditionally the Japanese tea house would be made with natural materials such as wood, bamboo, and rice paper, but Kuma has used a High-Tec fabric ,Gore Tenara, as a replacement. The fabric is sufficiently flexible to allow the structure to be deflated and inflated many times, enabling it to be moved as required. Garden Museum , Frankfurt 2007

5 Lighting the Membrane Covered Space

Light has always been an important factor for the perception of space within architecture. Due to the translucency of most membrane materials, tensile structures can allow large quantities of light to penetrate the building skin, However it is not just the quantities of light that effects our perception of space, but also its quality. Therefore the use of light in tensile architecture requires careful consideration.

Daylight

Daylight is very capricious. Light in the morning is completely different to light during the day and in the evening. It constantly varies in its intensity and color: however, the intensity of light is not of primary importance. As Rasmussen points out, the adaptability of the human eye is surprisingly great:

> *Bright sunlight may be 250,000 times more intensive than moonlight and yet we can see the same forms in the light of the moon as we can in broad daylight. The amount of light reflected from a white surface in winter is less than that reflected from a black surface of the same size in summer but still we see the white as white and the black as black. And we can clearly distinguish a black letter on a white ground (1959, p. 187)*

This is due to an effect called lightness constancy, which means that the human eye perceives surfaces in terms of their reflection. There is also an aspect known as shape constancy, which means that even with the above mentioned different light levels our perception of a certain shape will be the same.

Although this sounds as if the human eye is able to adapt to every kind of light condition, we do experience situations where excessive lighting causes problems. Too bright light sources can cause a blinding effect due to reflecting glare. This however can be avoided by diffusing the light before it is received by the human eye. There are two possible ways by which this can be achieved. Firstly, sunlight or light emitting from a source can be directly diffused before it is reflected off a surface. And secondly, the degree of glare can be affected by the reflectivity of a surface: that is whether it is shiny or matt has an influence on the degree to which the light reflected off a surface is diffused. And once diffused, light does not cause a blinding effect due to glare.

A further problem of strong directional light sources is that they cast very dark shadows, resulting in harsh images with strong contrast. But these contrasts are enhanced by the fact that our eyes automatically reinforce boundaries so that they read sharper than they are. As a result, objects appear to have a hard character, and our eyes, unable to adjust to the contrast, cannot pick up the details.

To avoid both undesired glare and too dark shadows, we have a natural desire to diffuse light. For artificial light sources this is usually achieved with lampshades or indirect lighting, reflecting the light off a diffusing surface. And in daylight, particularly when there is direct sunshine, light diffusion can be achieved with blinds and curtains. The images created by this light will then be softer, which means that the boundaries perceived are not too sharp and there is less contrast. Thus shadows are less dark and the details of the surface are easier to see.

Lampshades, blinds and curtains are made of all kinds of translucent materials. And just like these materials, structural foils and fabrics also act like a lampshade for daylight. The light transmitted into membrane covered spaces is highly diffused due to the properties of the membrane and also due to the splayed reflections off the double-curved membrane surface (Fig. 73).

Quantity of Light

When considering the quantity of light it is important to realize that membrane structures often allow daylight to penetrate into the space in much larger quantities than with conventional solutions.

The range of translucency of structural membranes depends very much on the material and its strength. The translucency varies from a range of 5-15% translucency for PTFE coated glass cloth to 8-30% translucency for PVC coated polyester cloth top-coated with PTFE. Materials such as transparent foils with higher translucencies are available but they have considerable restrictions in terms of durability and breaking strength. Common translucency factors of 15% and 30% for structural membranes might not seem excessive. However, considering the fact that during 85% of the year there is a minimum of 5000 lux available on the exterior (in daytime in Central Europe), there will be 1500-3000 lux available on the interior. For an average working space, however, approximately 300 lux are required, which leaves us with up to ten times more light on the inside of the membrane covered space, and this can cause problems.

For people within such a space the ceiling surface often appears bright relative to the rest of the space. So there could be a permanent temptation to look up towards the brighter surface, because a higher illuminance catches our attention. In these circumstances the human eye adapts to the high light level of the ceiling, resulting in the lower parts of the space appearing dark or gloomy. Therefore it is very important to make sure that the surfaces which

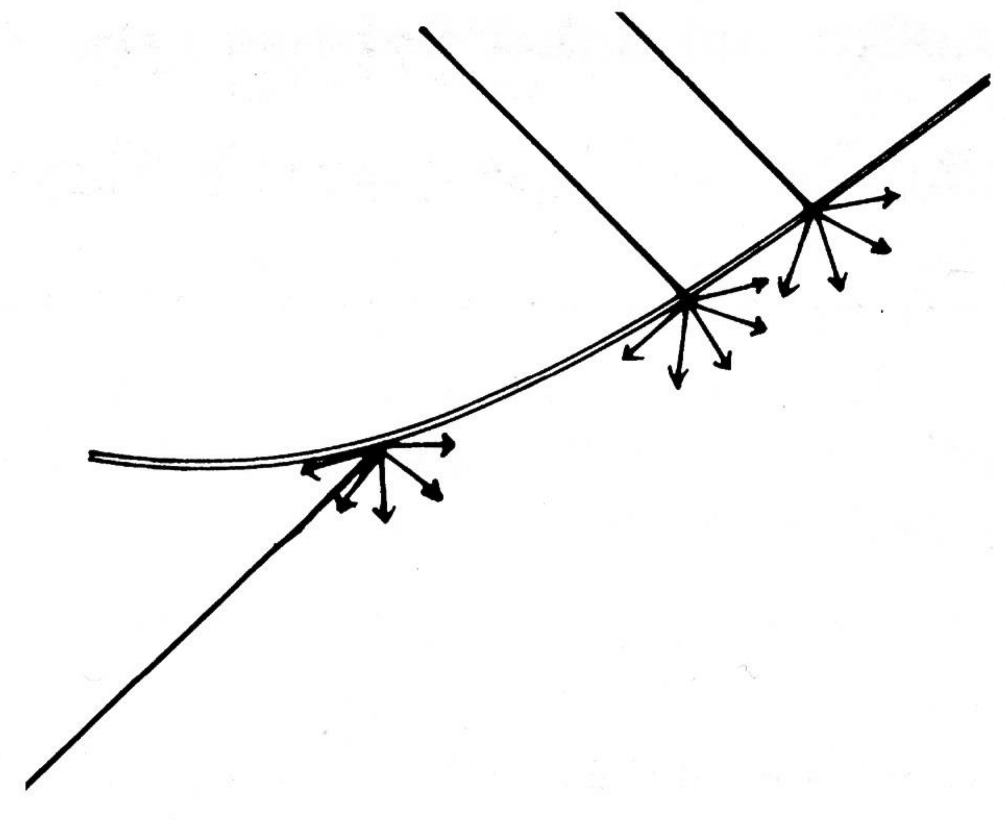


Figure 73) Light through the membrane being diffused

reflect the light in the lower parts of the space, such as the walls and the floors, are of light materials or lit by additional sources.

In the atrium spaces in the Imagination Building the walls are painted white to allow for plenty of reflected light. Additional downlights have been employed to supplement the light levels lower down. The aim is to create surfaces which reflect light rather than absorb huge amounts. By these means a more evenly distributed light level has been achieved.

Additional Direct Light Source

With an increasing level of diffused light, direct light sources become much more important. Too much directionless, diffused light not only softens shadows but can brighten them to a level where hardly any shadows are apparent. Shadows are necessary for our understanding of surface texture and relief: therefore it is important to provide direct light also (Fig. 74).

This effect relies to a large extent on the vector:scalar ratio of light. Although the vector:scalar ratio does not completely define the modelling effects of light, it is still a useful measure. It has been demonstrated that people prefer lighting which has a vector:scalar ratio between

1:2 and 1:8, which is based on the modelling of the human face (Wilkinson, 1984, p. 286). It is difficult to say how much transparent area there should be compared with translucent area, but it is important to recognize that there is a need for both, and to aim for a vector:scalar ratio within the range given above.

There are two possibilities of how direct light can be allowed into these spaces. The simplest are conventional window surfaces which can be used to supplement the diffused light level of a membrane covered space. Where conventional windows are not possible or not desired, transparent surfaces can be incorporated in the design of a membrane roof to bring directional daylight into a space. An example is Bull Computing Research Center, Paris, where transparent elements are used between

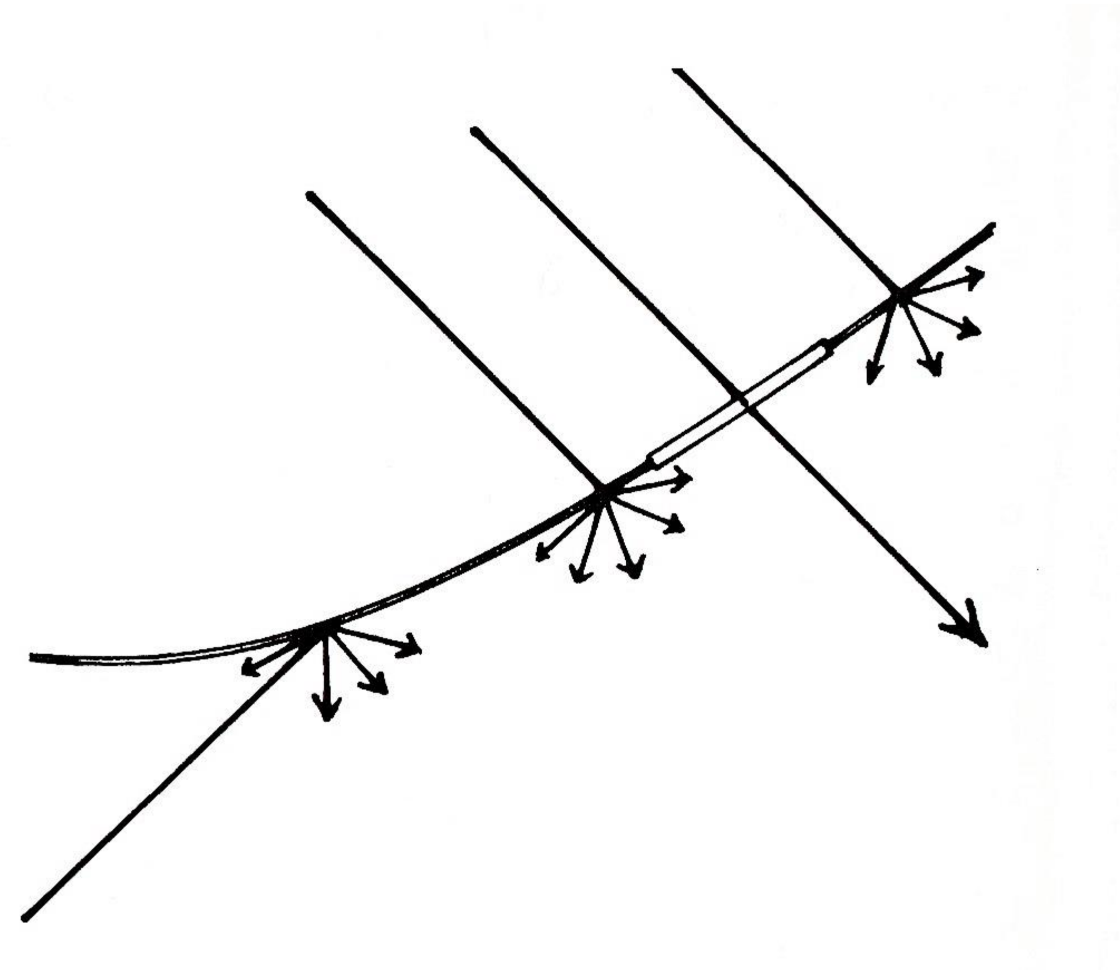


Figure 74) Penetrating direct light through the transparent areas incorporated in the membrane surface

the individual fabric panels. This allows direct sunlight into the space which casts a constantly changing pattern onto the internal wall surfaces. Due to the diffused light coming through the membranes, these shadows are softened and thus the contrast between the bright and shaded areas is not too strong, this creates a lively balance which enables us to read texture and relief while also, producing shadows which are subtle enough to bring out detail. The result gives a much richer impression of essentially simple materials purely by putting them into the right light.

There are numerous possibilities for incorporating additional direct light sources within the design of a membrane roof. As in the example of the atrium at Bull, a transparently covered arched substructure is also used at the M&G Research facilities in Italy (Case Study 1 in non-ETFE Case Studies Chapter). Both examples demonstrate the possibility of incorporating transparent materials between separate membrane panels. Another example is the Grande Arche in Paris where glazed high-point rings are used. In the case of Stamford Wharf transparent glazing is incorporated as a mediating element between the scalloped edges of the single-membrane panels. With the nearly unlimited range of different shapes of tensile structures it will always be possible for a designer to find new opportunities for incorporating transparent areas.

Windows or transparent roof elements are also of importance beyond the concern with incoming directional light. There is also the aspect of views out of a membrane covered space. The visual connection can be important for psychological reasons as it provides relief from the sense of enclosure, and can show how the internal space relates to the outside world. The direct view as a reference contributes to a comprehensive understanding of one's own position within space and time. The work of Ne'eme establishes that in conventional buildings occupants are likely to be dissatisfied with a window area of less than 20% of external wall surface (Stone, 1984, p. 278). It is difficult to provide a comparable value for a membrane covered space. It is equally hard to assess to what extent incoming light and the view out are important for such a figure. All it can show is that there is a certain demand for both. While there is usually plenty of incoming light in spaces covered with translucent membranes, the view out needs consideration.

Hidden Light Source

Where membrane and conventional structure are joined together, further opportunities for the introduction of light exist. If we take the example of the Imagination Building, we find the membrane being 'wrapped' over the end walls. Instead of fixing the membrane directly against the end walls, an outwards tilted strip of transparent glazing is keeping the membrane and the wall visually separate.

The idea of incorporating hidden light sources was frequently used in baroque architecture. There we also find windows in the surrounding vial structures for directional daylight and diffused light coming from the domed ceiling landscapes. But the light source for the diffused light cannot usually be seen. Only its effect is experienced as a ring of light above the far protruding entablature, which reflects the incoming light upwards into the domes.

Similarly, hidden light sources can be used to create an oversailing, hovering impression of the membrane roof. While the hidden light sources in the baroque examples were essential to light up the dome, the membranes of tensile structures allow plenty of light to penetrate into the spaces they cover. Therefore hidden light sources are not important for the quantity of light in the space, However, they are important for the quality, particularly when there are no further transparent elements incorporated in the membrane surface. Furthermore, they can be an essential tool to enhance the readability of the membrane shape (Fig. 75).

Readability of the Shape

Light itself cannot be realized unless it hits a surface on which it can show. And in return, it is the light which enables us to read a certain shape. The result is an antagonistic play between the surface of a structure and the light it reflects. In baroque examples, the light through the hidden light sources is responsible for lighting up the domes in such a way that the visitor can receive

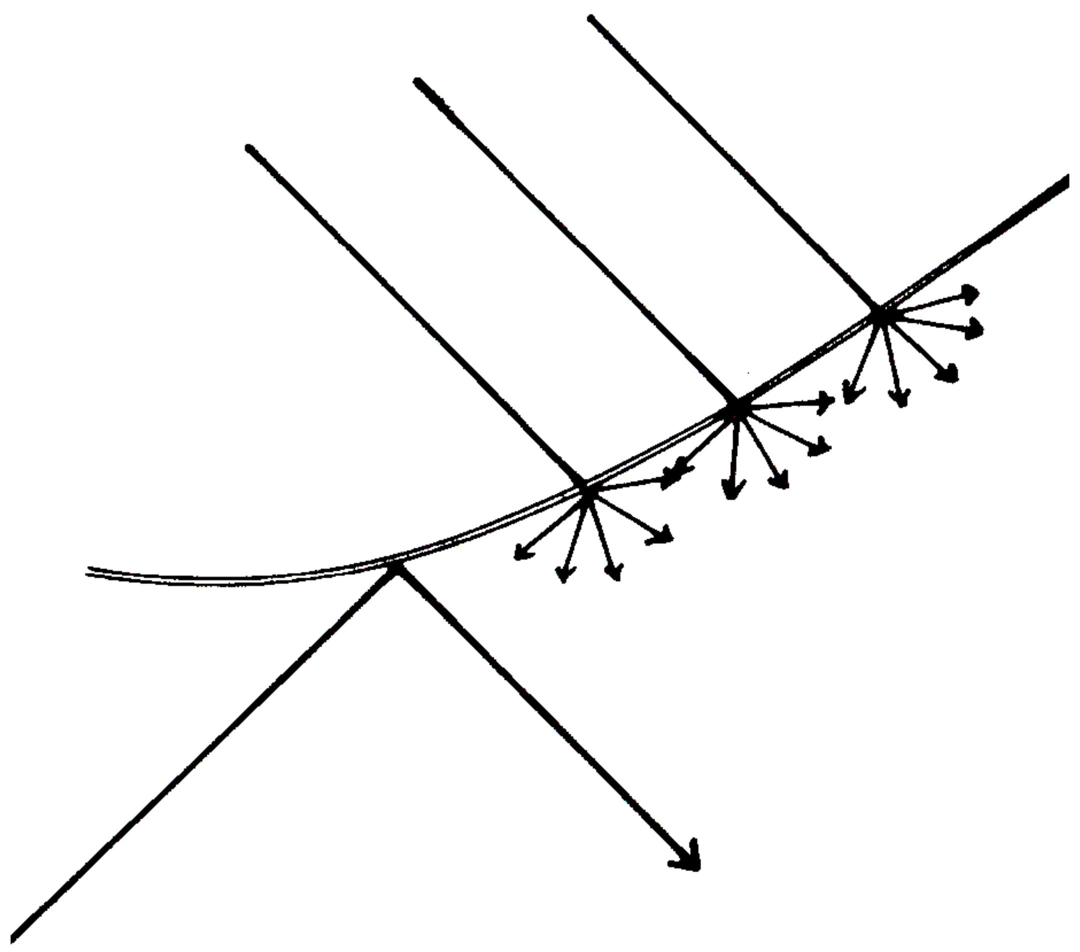


Figure 75) Light from hidden light source

full recognition of the shapes with all their subtleties and details. The curved and spherical geometries are excellent to be light-washed, grading the light from bright to shaded, displaying a soft light that fades away with the shape of the curvature.

The effects are different in a building with a translucent membrane. Depending on its translucency the light levels can be very high. Unless a designer knows how to enhance the readability of the membrane shape, it can be completely lost due to the highly diffused light through the membrane. Rasmussen describes an experiment for equally lit surfaces, pointing out the difficulties one has to face:

> *Let us imagine that we are looking at a projecting corner formed by the meeting of two white planes. If the two planes are evenly illuminated from sources that can be controlled, the light can be so regulated that the two sides will look equally light. When this happens the edge of the corner can no longer be observed by the eye. (1959, pp. 189-90)*

But this does not mean that the complex shape is lost to the observers within a space covered by translucent membranes. Rasmussen explains that due to the stereoscopic character of the human eyes one might still recognize it, particularly if it intersects with other planes. But without any difference in the amount of light being reflected off the two planes, an essential means for the readability of the form is lost. Increasing the light level does not change the situation if it is done evenly. But if the light level is changed on one of the planes so that there is a marked difference, the corner will be clearly readable, even if the total light level is much less.

Membrane structures can be very bright due to their translucency. The highly diffused light off the internal membrane surface results in an evenly distributed fog of light. Therefore, it is not easy to read the shape. But as mentioned in the example above, this can be avoided if there is a supplementary directional light source, for example a hidden light source, which brightens the parts of the membrane that are facing the incoming light (Fig. 76). The parts that are not receiving this supplementary light appear slightly darker. This effect can be further enhanced depending on the texture of the inner surface. There are two different possibilities which both depend on light being reflected at a shallow angle beneath the membrane surface.

If the surface texture of the interwoven fabric is rough enough, it can cause a subtle grading of light on the inner membrane surface as, due to the curvature, the light is received and reflected by the threads at different angles. If the surface is very smooth, the light can leave subtle light patches of glare on the curved surfaces. In both cases the shape of the membrane becomes more apparent due to enhanced surface contours.

However, the level of recognition of such an effect on the inside of the membrane can be very low, unless there is a comparatively strong source to balance the brightness of the diffused light penetrating the membrane.

Therefore one ought to pay attention to the angle of the reflecting surface and the material. A light glossy surface would reflect more light than a dark matt surface, with all the possible variations between.

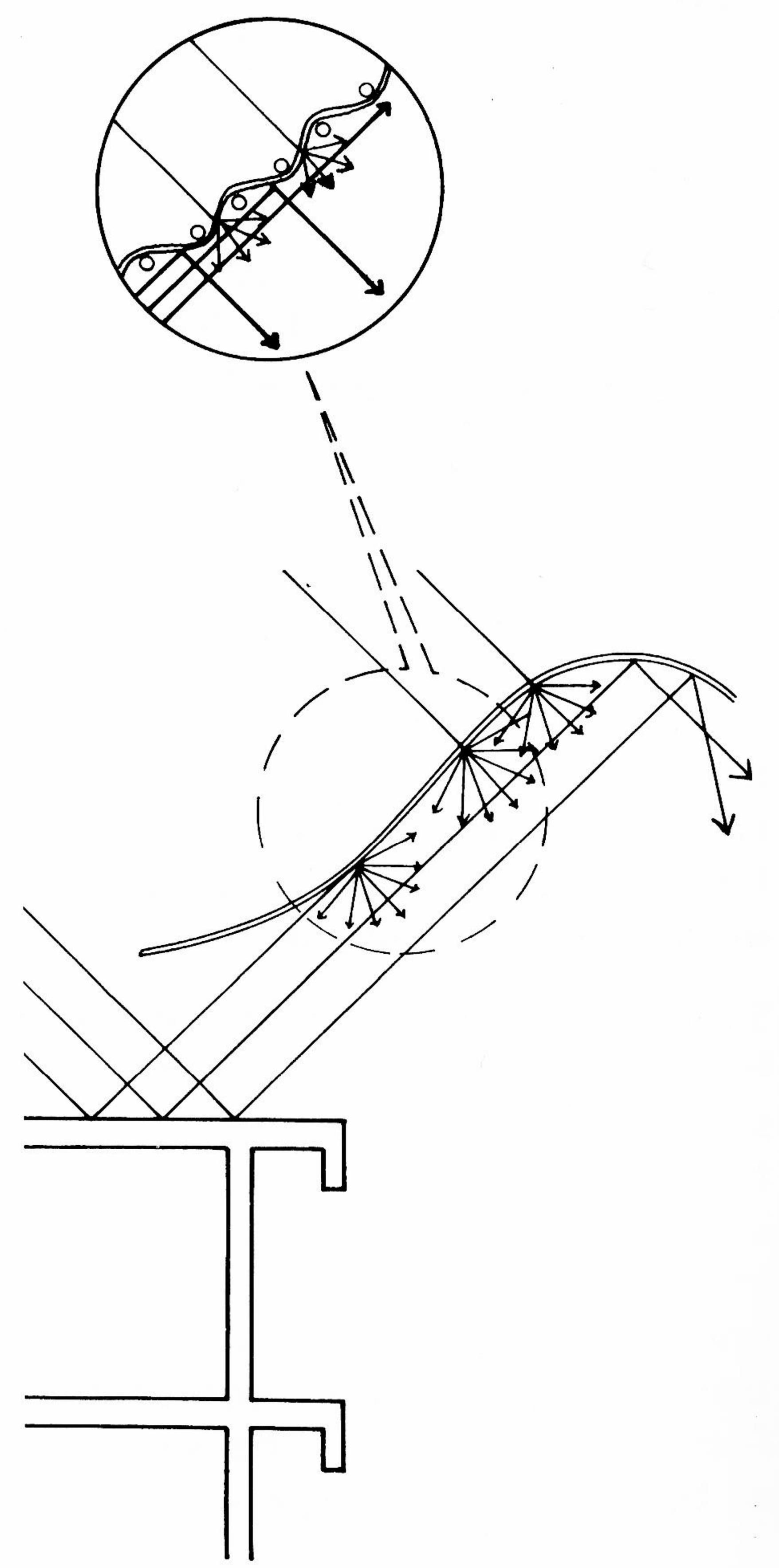


Figure 76) Indirect light supporting the readability of the membrane shape

Water can be used as a strong reflector of light and in addition can contribute lively ,patterns on the inside of the membrane. The Bigo Tent of the harbor redevelopment in Genoa, Italy, by Renzo Piano, is an example where both direct light through transparent areas in the membrane surface and light reflected off the water surface have been used. The sunlight introduced through the transparent, eyelid-shaped, glazed openings casts light patches onto the transparent membrane, pointing out its subtle curvature (Fig. 77).

Further down, along the scalloped edges, light is reflected off the water surface beneath the membrane, creating a constantly changing pattern depending on the intensity of the sunshine. As a result, the forms of the roof structure can be experienced despite the shallow curvature.

This example demonstrates the importance of introducing subtle but directed light and reflecting it towards the curvature of the membrane. Using the suggested possibilities for incorporating glazed areas or hidden light sources the shape will be clearly readable in daylight as an important feature of the building.

Figure 77) Light Patches due to direct light through the transparent areas, cast onto the inside of the membrane of the Bigo Tent.

The Rich Light Spectrum

Both membrane fabrics and foils act not only as a diffuser but also as a filter, absorbing or reflecting certain wavelengths of the full spectrum. Therefore the light filtering through is not as rich as daylight. Glass has a similar effect: it also reflects and absorbs certain wavelengths. However, the light penetrating through clear glass does not change color and quality to the same extent as the light penetrating through most structural membranes.

In order to experience the full quality of daylight with its special colors according to the various times of the day and year (such as green and blue in the morning, blue and white during the day and red and violet in the evenings), in occupied spaces it is vital to have sources of daylight coming through clear transparent surfaces. Light through clear glazed areas, or light which is reflected beneath the membrane, washes along the curvature of the cloth, enhancing the readability of the shape of the roof. In addition this less diffuse daylight contributes to the creation of a more stimulating and enriching light quality as it merges with the diffused light penetrating the membrane. (However, the level of recognition of this effect by the occupants of a space may be partly subliminal.)

By these means a comparatively large spectrum can be achieved in the interior of a building. This can be an important health aspect, particularly for large buildings where people have to work inside for most of the day. Beyond the positive stimulating effect, daylight is also much healthier than artificial lighting. Compared with conventional structures, which are mostly side lit or have at the most some incorporated roof lights, the amount of daylight in spaces covered with translucent membranes is much higher. This also results in an increased amount of UV light, which improves the hygienic conditions within a space.

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Light and Color

The color of light can have a strong influence on the spatial impression and also on the visual comfort of an observer. A space is usually recognized as comfortable if it is lit by warm light, whereas it appears uncomfortable if it is lit by cold light. The light color, however, can be influenced by colored surfaces which reflect light. Christopher Alexander et al. claims: 'we know that people have a clear subjective impression of the relative warmth, or coldness, of different spaces' (1977, p. 1155). Based on a number of empirical results, their study revealed a maximum of warmest judgments at a dominant wavelength of 610 nanometers, which is in the middle of the orange range. And they emphasize that individual observer stability in such judgments is high.

But there are spaces painted in blues and greens, which are considered to be cold colors, where the impression is of warmth. Therefore, as Alexander et al. point out (Fig. 78):

> *... it is vital to remember that this pattern requires only that the light -the total light in the middle of a room, coming from sunlight, artificial lights, reflections from walls, reflections from outside, from carpets - the total light, lies in that part of the color triangle we call 'warm'. It does not require that any individual color surfaces in the room should be red or orange or yellow - only that the combined effect of all the surfaces and lights together, creates light in the middle of the room which lies in the warm part of the color triangle. (pp. 1155-6)*

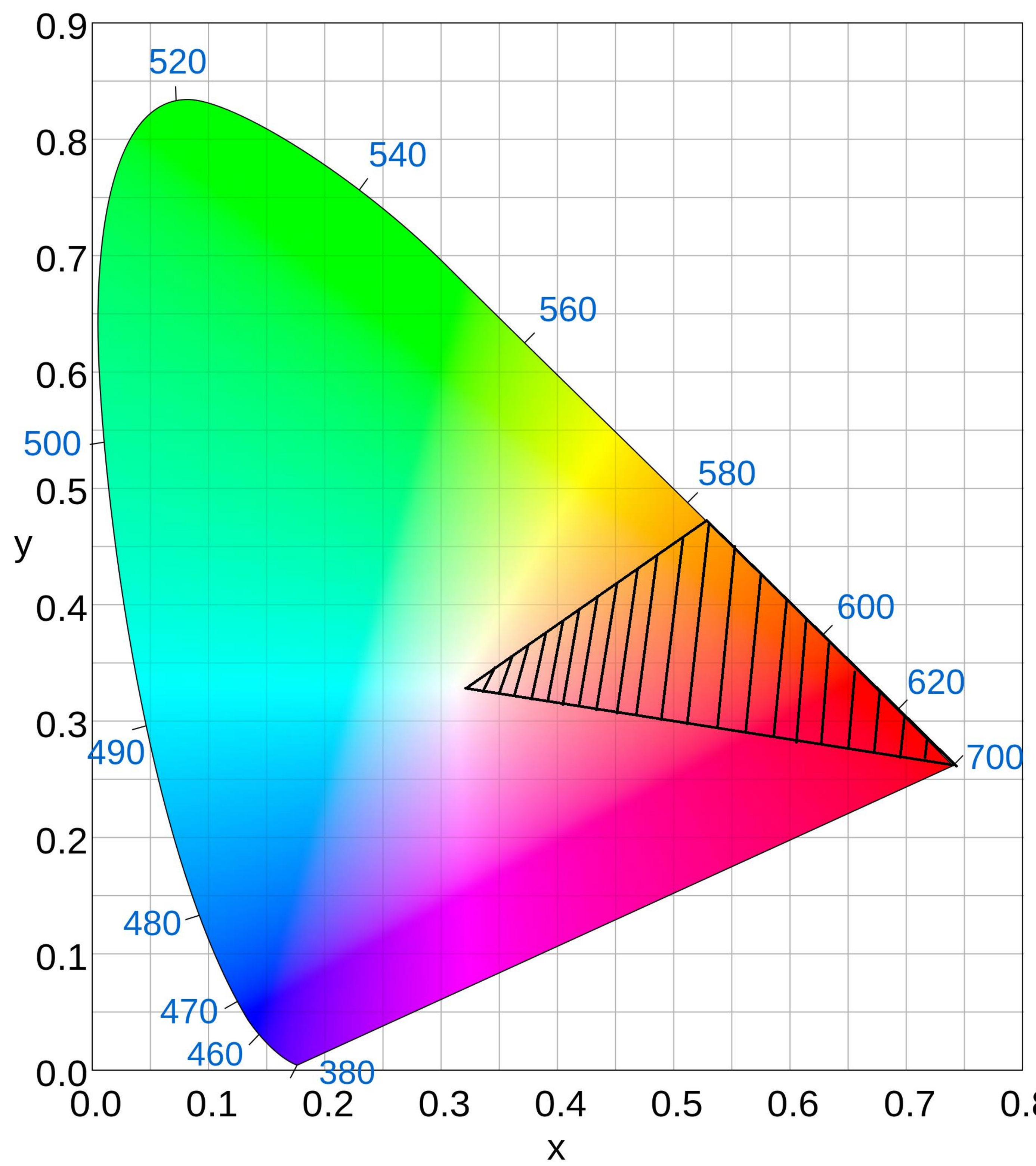


Figure 78) Chromaticity diagram showing the range of warm light

One can easily imagine that colored membranes can be used to influence the spatial impression. The mixing of tinted diffused light through the membrane with natural light, either reflected off a surface underneath the membrane or as a direct light source, can be explored in order to create the desired atmosphere.

Artificial Light at Night

The perception of membrane covered spaces at night, when lit by artificial light sources, is very different. If they are internally lit, these buildings become outstanding glowing lanterns in the night sky. Due to the translucency of the membrane, the use of uplighters shining onto the membrane surface is not very efficient as a means of illuminating interior spaces. Therefore they should only be used to illuminate the membrane surface.

Depending on the type of membrane used, large amounts of the light will now penetrate the membrane from the interior to the exterior. Therefore, additional downlights are usually necessary as major light sources to illuminate the space below. Consequently, the shadows cast in this light will be different than during the day and the light not as soft. The uplights, however, are of importance for the readability of the shape of the membrane structure at night. They have to fulfil the function at night that indirect sources of daylight fulfil during the day. Therefore, the light from the uplights should also be introduced at a shallow angle to the membrane surface to highlight its texture and shape.

Due to the layering of the .fabric the translucency of the seam lines is lower than through the single membrane just beside the joints. Hence they appear as dark strips in the surface of the cloth. It has been explained earlier that the human eye enhances contrasts. What might be a disadvantage in other regards becomes an advantage in this case. The seam lines are clearly readable and as they are part of the membrane surface they follow the double-curved geometry and support the readability of the non-planar structure with its subtly modelled surface, due to indirect light sources and the stereoscopic effect of the human eyes.

The seam lines that are outstanding during the day, supporting the readability of the shape, are not as apparent at night. However, if the effect of the readability of the seam lines is essential even during the night, the membrane roof can be brightly lit from the outside.

Both daylight and artificial light considerably affect the perception of any membrane covered space. Because of the unique translucency of structural membranes the use of light takes on an even greater significance in tensile architecture. If insufficient attention is paid to either the quantity or the quality of light during the design process, the finished building can be rather unsatisfactory, resulting in interiors which can appear dark, gloomy or even claustrophobic despite a very bright membrane surface. However, if a designer understands how to use the particular properties of membranes to good effect the result can be excellently lit interior spaces of an almost magical quality.

6 Environmental Behavior of the Covered Space

Having dealt with the lighting of membrane covered spaces in the previous chapter, in this chapter we discuss the effect of the choice of membrane on the thermal and acoustic performance of tensile covered spaces.

In any building, whether tensile or conventional, both the visual and the thermal influences of light have to he in balance. Membrane buildings can benefit from the large amounts of daylight that penetrate their translucent skin, but due to their light weight and low insulation values they are also environmentally very sensitive. A well designed building should strike a balance, so that the visual requirements are met without large amounts of energy being required to control the internal climate. Therefore it is of importance to consider the influence of daylight in connection with the other environmental criteria of a tensile covered building.

One of the dangers of using membrane structures is that they are employed for their various beneficial characteristics such as translucency, low cost, flexibility and speed of construction, while important environmental considerations are neglected. The outer skin needs to be carefully chosen, in terms of the desired internal environmental criteria and in consideration of the local environmental conditions. Whether the building consists of a covered cable-net or a pure fabric structure is not important to these environmental considerations; it is the thermal balance of the fabric skin, i.e. heat loss versus heat gain, which is critical. This should be considered in relation to the heat gain and heat loss from the whole building envelope.

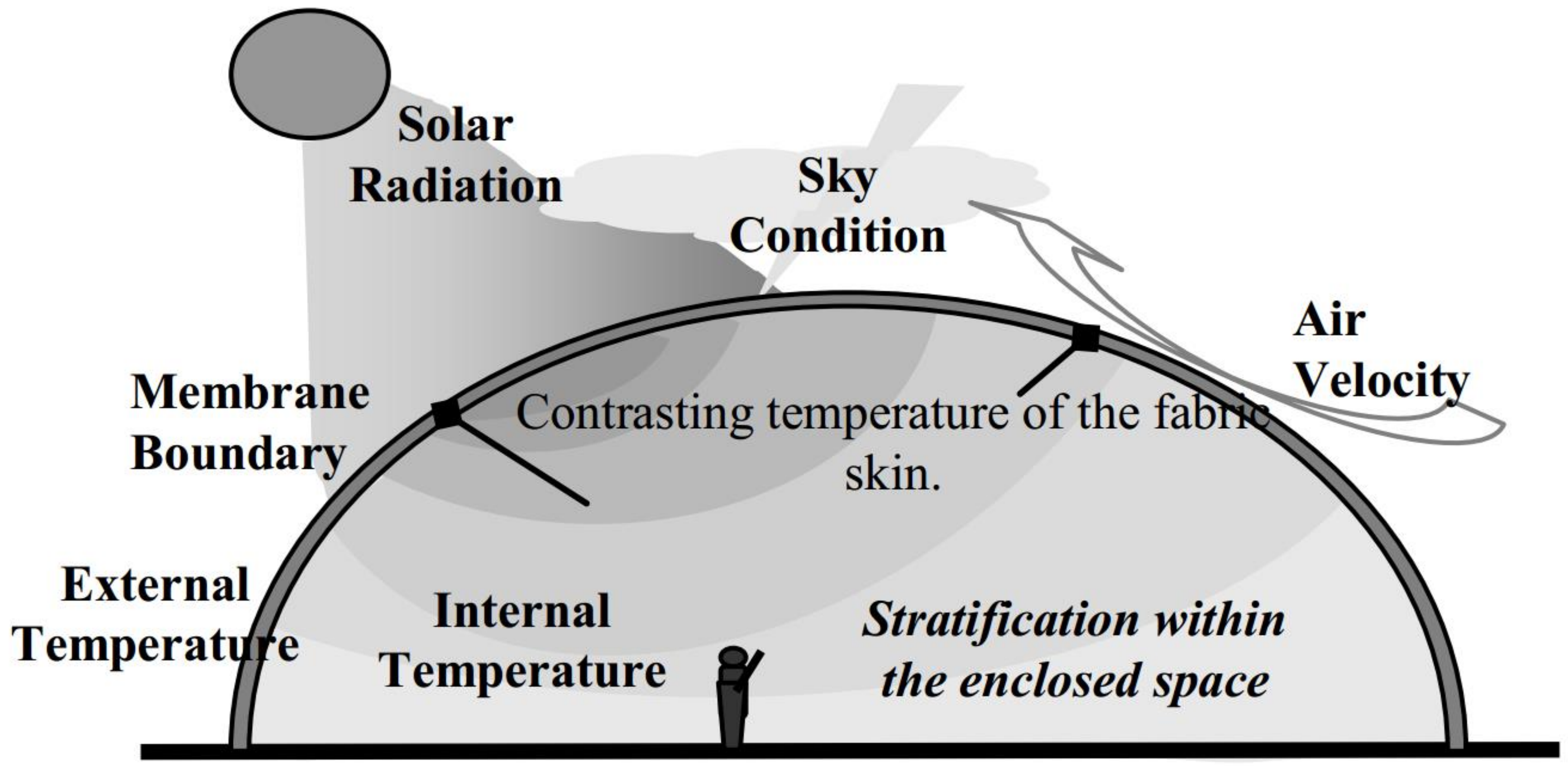


Figure 79) Factors affecting the heat transfer through tensile membrane enclosure

Membrane as Filters

When designing with lightweight membranes it is sensible to consider them as environmental 'filters' rather than as 'barriers' to the weather. They act to moderate and regulate the external climate rather than to shut it out completely.

When designing the external skin the aim should generally be in hot climates to arrange for a greater heat loss than heat gain, and the reverse in cold climates. As already mentioned, lightweight structures are environmentally very sensitive: thus they warm up almost instantaneously to incident solar radiation and equally cool down very quickly when the outside air temperature begins to fall. This does not necessarily need to be seen as a problem. For example if lightweight structures are used to cover spaces which have intermittent use this characteristic could enable these spaces to be heated up quickly whenever needed, rather than continuously heated. Thus in certain circumstances these characteristics could be used to save energy. As the application of membranes for the skin of fully enclosed buildings is still undergoing development, insufficiencies in environmental performance may to a certain degree be tolerable for the benefit of exploration and possible discovery. However, excessive energy consumption for heating or cooling buildings is hardly tenable in our environmentally threatened era. Therefore, greater care must be taken by the designer to fully understand the environmental implications when deciding on the use of a membrane as part of the building envelope. However, when comparing membrane buildings with more conventional structures a more comprehensive energy balance than just heat gains and heat losses ought to be considered. A higher energy consumption due to greater heat gains or losses is often counterbalanced by the vast amounts of daylight penetrating the membrane. Depending on the chosen degree of light transmittance of the fabric, daylight can, if skillfully used, provide a building with plenty of overall light, thus saving energy due to a significant reduction in the requirement for artificial lighting. Furthermore, the overall light received from natural daylight is usually of better quality due to the nature of its richer spectrum, and in addition the continuous changing qualities of intensity and color provide the occupants of the building with information about the time of day and the external weather conditions.

The Use of Membranes in Cold and Hot Climates

In order to develop a better understanding of the thermal characteristics of membrane buildings it is useful to consider their performance in cold and in hot climates separately.

In cold climates the major concern is usually excessive heat loss through the membrane skin. Given that a certain amount of heat loss is to be expected, in all but the most highly insulated buildings, it makes sense to first consider whether membrane buildings have any inherent characteristics that can counter this effect.

By taking advantage of heat gain due to solar radiation which penetrates the fabric skin during the day, the requirement for heating can be reduced. Therefore, the fabric structure should be designed to allow the transmission of environmental heat from the outside to the interior of the building. But it is just as important that the fabric skin should also be able to trap the heat so it will remain within the building as long as possible. This means that the skin should be designed to enhance the greenhouse effect as described in the following.

The thermal and visual performance of a building skin is governed by the manner in which it reflects, transmits or absorbs any part of the electromagnetic spectrum. Transparent materials such as glass will transmit short-wave solar radiation, but reflect a portion of long-wave radiation that is given off when surfaces within the space are heated up. This results in the internal temperature increasing, and this phenomenon is known as the greenhouse effect. This situation can be achieved in membrane buildings by the use of a transparent or a translucent skin, and may be further enhanced, in the case of transparent films, with a low-emissivity coating which reflects long-wave radiation. Such a skin could then be used in combination with transparent insulation in order to reduce the rate of heat loss back to the atmosphere (Fig. 80). In summer, however, this approach can lead to unwanted, excessive heat gains even in cold climates. To prevent this,/ movable sunshades or insulation should be incorporated into the design. Another option to prevent overheating is to make use of the thermal stack effect (Fig. 81) in combination with a sensible arrangement of high- and low-level vents.

As previously mentioned, a sensible approach when designing membrane buildings is to consider the fabric structure as merely a filter, which is then used for creating an intermediate climate or meso-climate which acts as a mediator between the exterior climate and the environmentally controlled interior of the building.

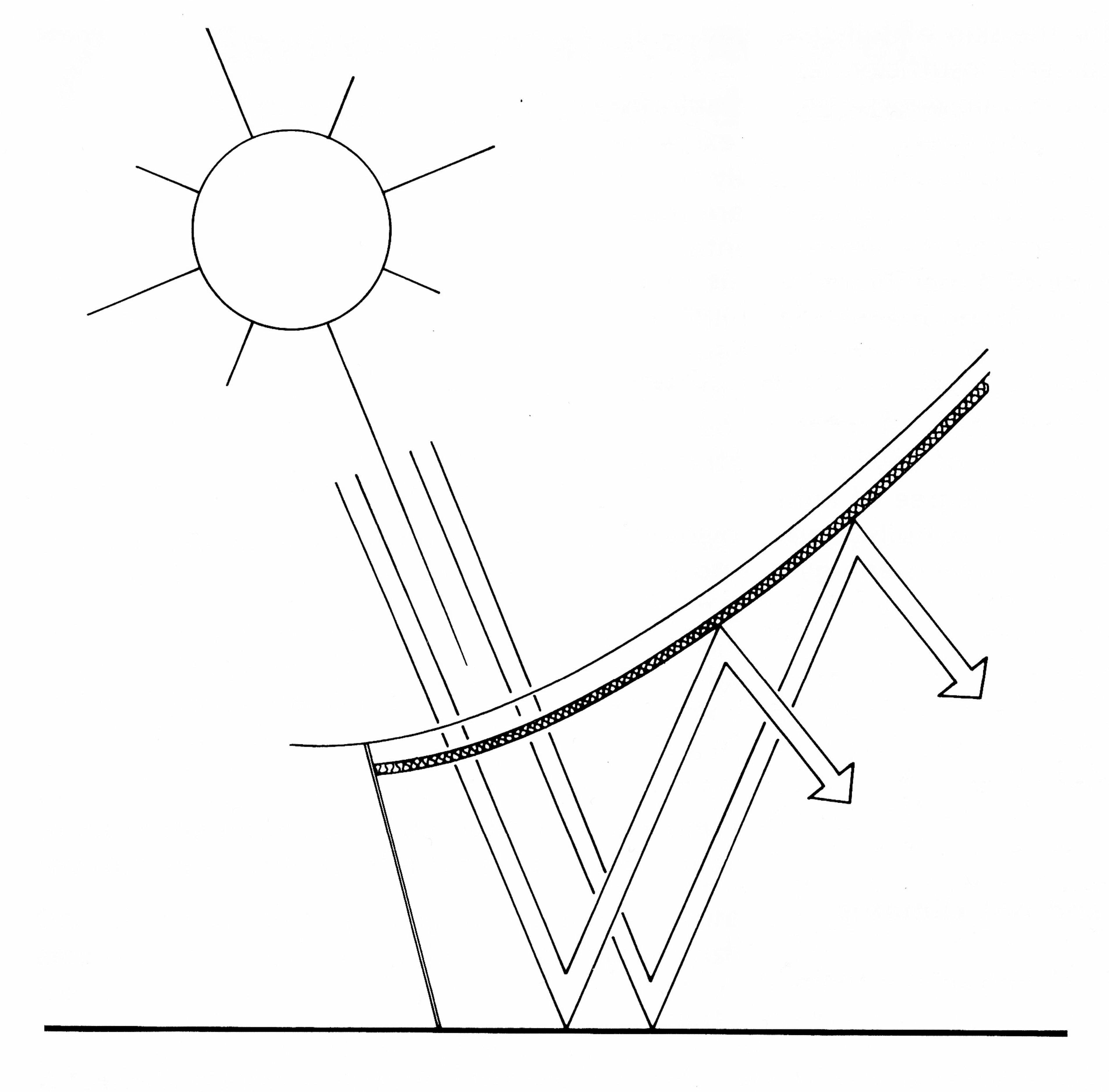


Figure 80) Membrane buildings can use the greenhouse effect to their advantages

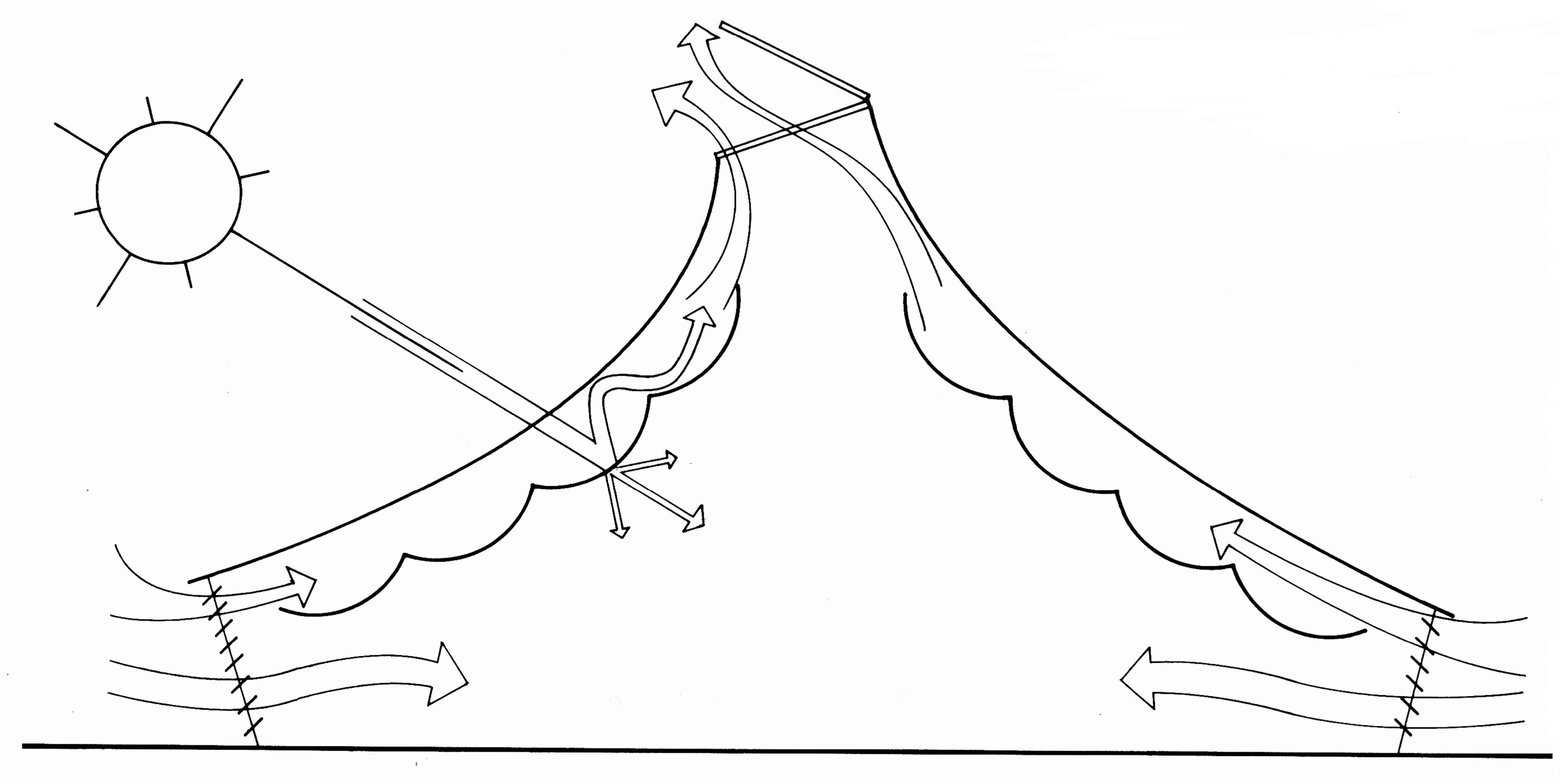


Figure 81) Movable sunshades and the use of the thermal stack effect can be used to prevent overheating

An Imagination Building Atrium

An example of this kind is the six-storey atrium of the Imagination Building. The atrium is used as a transition space which does not require environmental conditioning to the same level of comfort as the surrounding offices. The fabric structure allows the penetration of solar radiation into the atrium, keeping it warm in winter. Additional heating is provided by the heat loss from the adjacent offices. Recirculators are used to transfer the warm air gathering beneath the membrane roof to low level where it is required, thus evening out the thermal gradient of the space.

During the summer months, the use of vents at roof level to encourage natural ventilation, plus the large air volume, prevent the atrium from overheating.

In the single-storey, top-level gallery, however, where the air volume is much smaller and a greater level of environmental comfort is required, a double skin has been applied to improve the thermal insulation (Fig. 82).

In hot and sunny climates it is excessive heat gains that one has to take steps to avoid. Where solar gain is a problem, a reflective outer skin can be used to reduce incoming radiation while still allowing for some daylight penetration. A low-emitting inner surface can be used in addition to prevent thermal radiation being re-emitted into the structure from the hot skin. A second skin can further improve the internal climate and is of an even greater benefit if the gap between the two skins can be ventilated. The moving layer of air caused by the stack effect helps to remove excess heat and therefore contributes to further moderating the internal temperature.

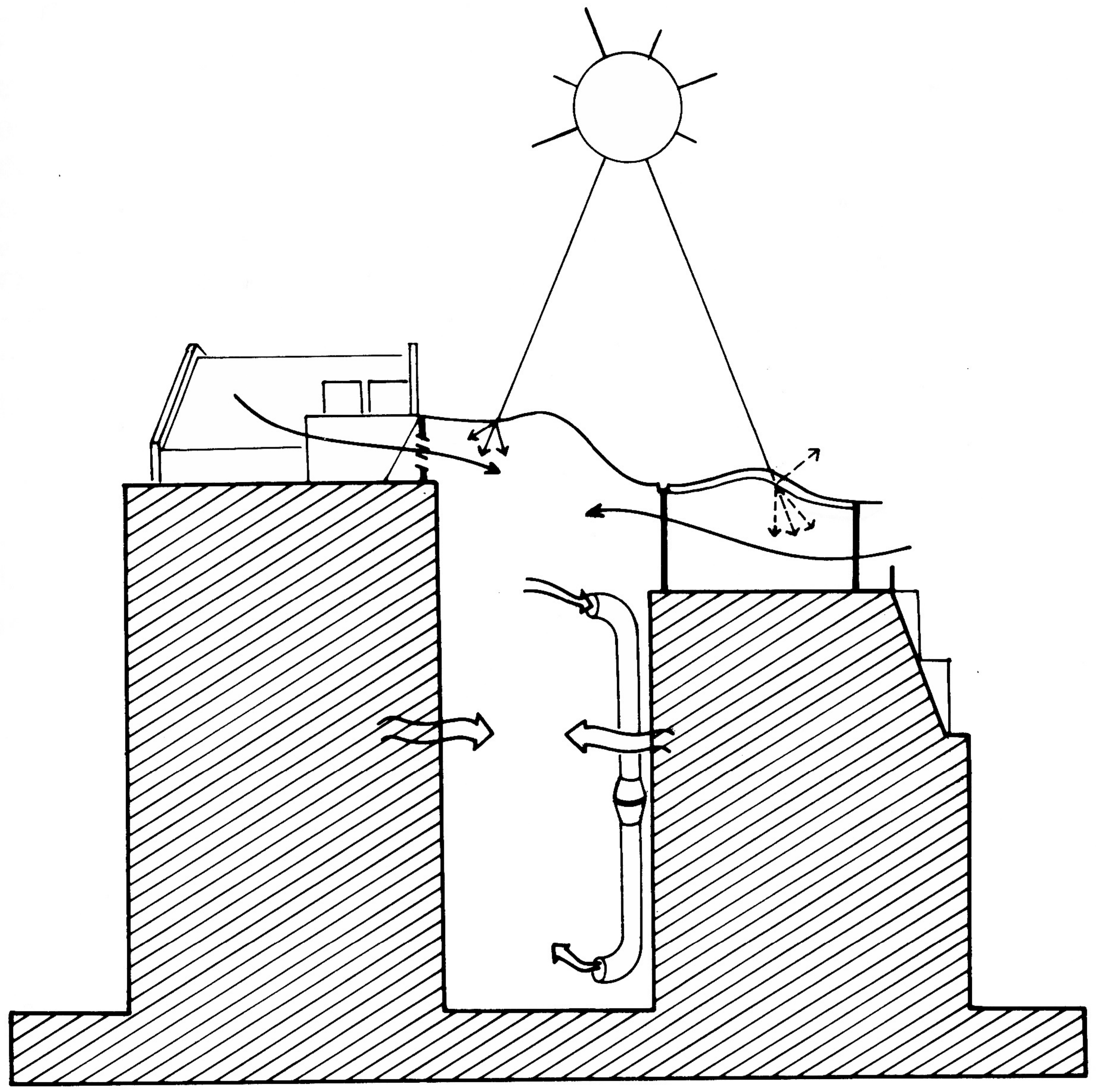


Figure 82) The translucency of the fabric skin permits excellent daylight transmission throughout the year and therefore reduces significantly the requirement for electricity to provide the building with artificial lighting

One recent example where these principles have been put into practice is the GCC Conference Centre in Kuwait, (Fig. 83) designed by the architect John Rowe-Parr together with structural engineers Atelier One and service engineers Atelier Ten. This conference center represents one of the most extreme uses of tensile structures in hot climates as it is fully exposed to the desert sun. But it is also extreme in other respects. The design team had to face the challenge of providing an adequate environment for royalty and heads of state, to be built and fitted out within 116 days in the aftermath of the Gulf War. Due to the tradition of the bedouin tents, these structures enjoy a greater acceptance in Arabic countries: nevertheless the client (the Kuwait Ministry of Works) was initially skeptical as to whether the fabric structure would be able to provide the high-performance conference facilities they required. Great care was therefore taken to achieve a comfortable internal climate.

Figure 83) GCC Conference Center, Kuwait, 1993

On the GCC tent an exterior layer of white membrane has been employed as a shading layer with a reflectance of 70% to ensure a minimum of solar absorption. The interior membrane itself consists of three layers: a white PVC outer layer, on top of a 75 mm mineral wool insulation in foil faced bags, with white PVC as an inner layer. A large air gap between the interior and exterior membranes allows for the heat reradiated and convected off the inner surface of the shade to be removed by natural ventilation. The conduction heat gains increase the temperature beneath the exterior membrane shade and cause a buoyancy: this induces an upwards air movement, which vents through the top cowl of the structure. This ventilated double-layer system ensures that the total transmission of incident heat is not greater than 10%. However, in this case the client still insisted on an additional air-conditioning system being installed, just in case the levels passive system failed to provide the environmental comfort levels normally expected by heads of state (Fig. 84).

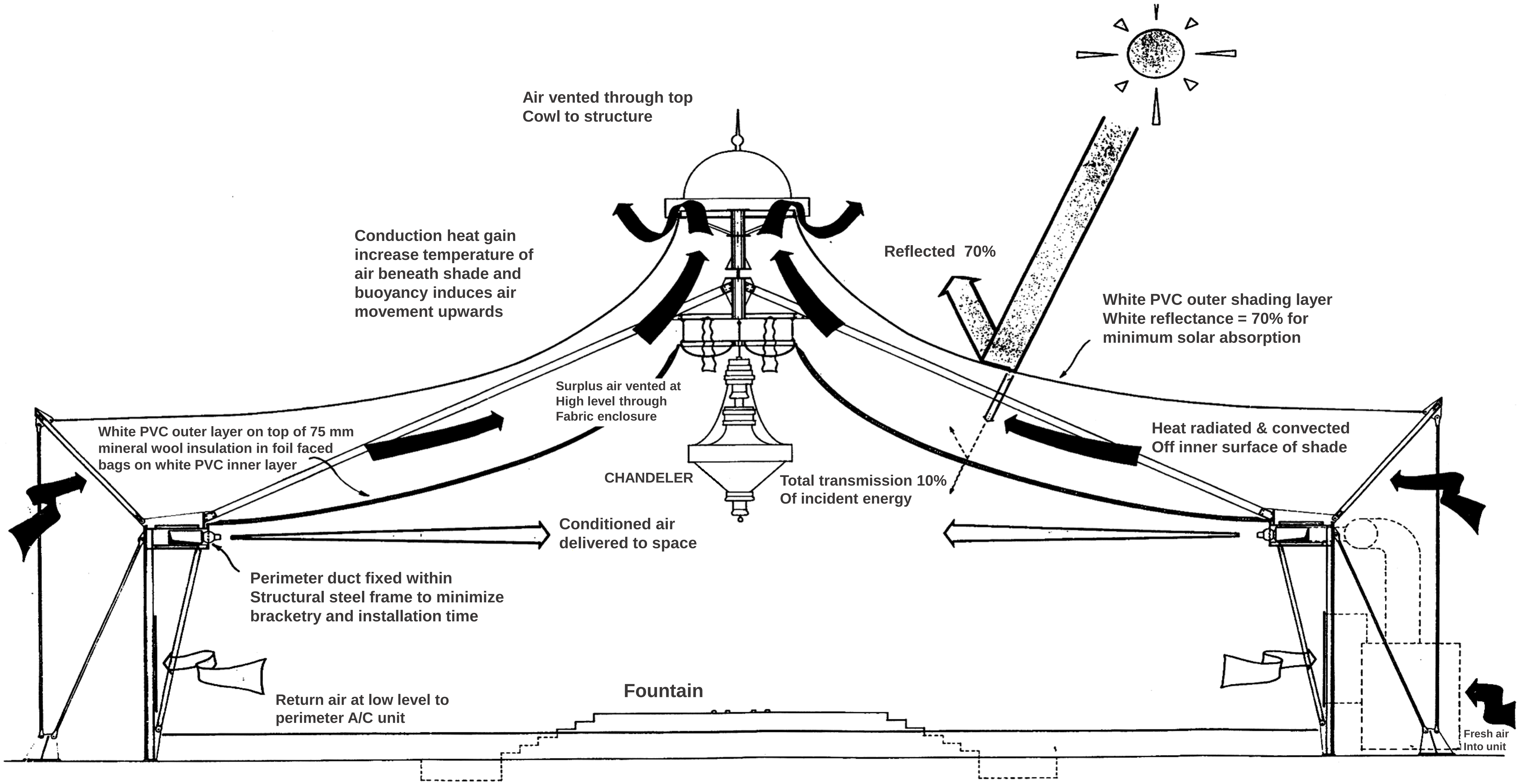


Figure 84) Section of GCC Conference Center

Thermal Mass and Lightweight Structure

Buildings combining lightweight skin structures with more solid, conventional structures exist already. Therefore, the idea is not new. But the clarity with which the design team of the Universal Shelter made the environmental aim for thermal inertia a central design issue is new and inventive. With the insight this project affords, new ways to tackle the design process, which take into account the environmental characteristics of all the constituent elements of a building, can be employed when designing membrane buildings.

A particularity apt demonstration of this principle was used in the research building for the Sinco group by the Belgian architect Philippe Samyn, where even the lake that surrounds the building was brought in to play a part in the environmental control of the interior spaces. The design deliberately uses an internal concrete structure and ground slab to achieve a high thermal inertia (Fig. 85). The surrounding take cools down the outside air temperature, and air intake vents are set at water level to ensure that air is further cooled before it enters the building envelope. The membrane roof covers the clustered fully serviced spaces, and creates an internal meso-climate which reduces the energy requirements of the occupied zones of the building.

Further uses of the combination of massive and lightweight structures are possible. At the Diplomatic Club in Riyadh, translucent membranes were used to cover large-span spaces backed by a long and massive inhabited wall structure. The masonry and concrete structure of the wall give the building thermal mass, while providing accommodation for more environmentally sensitive activities.

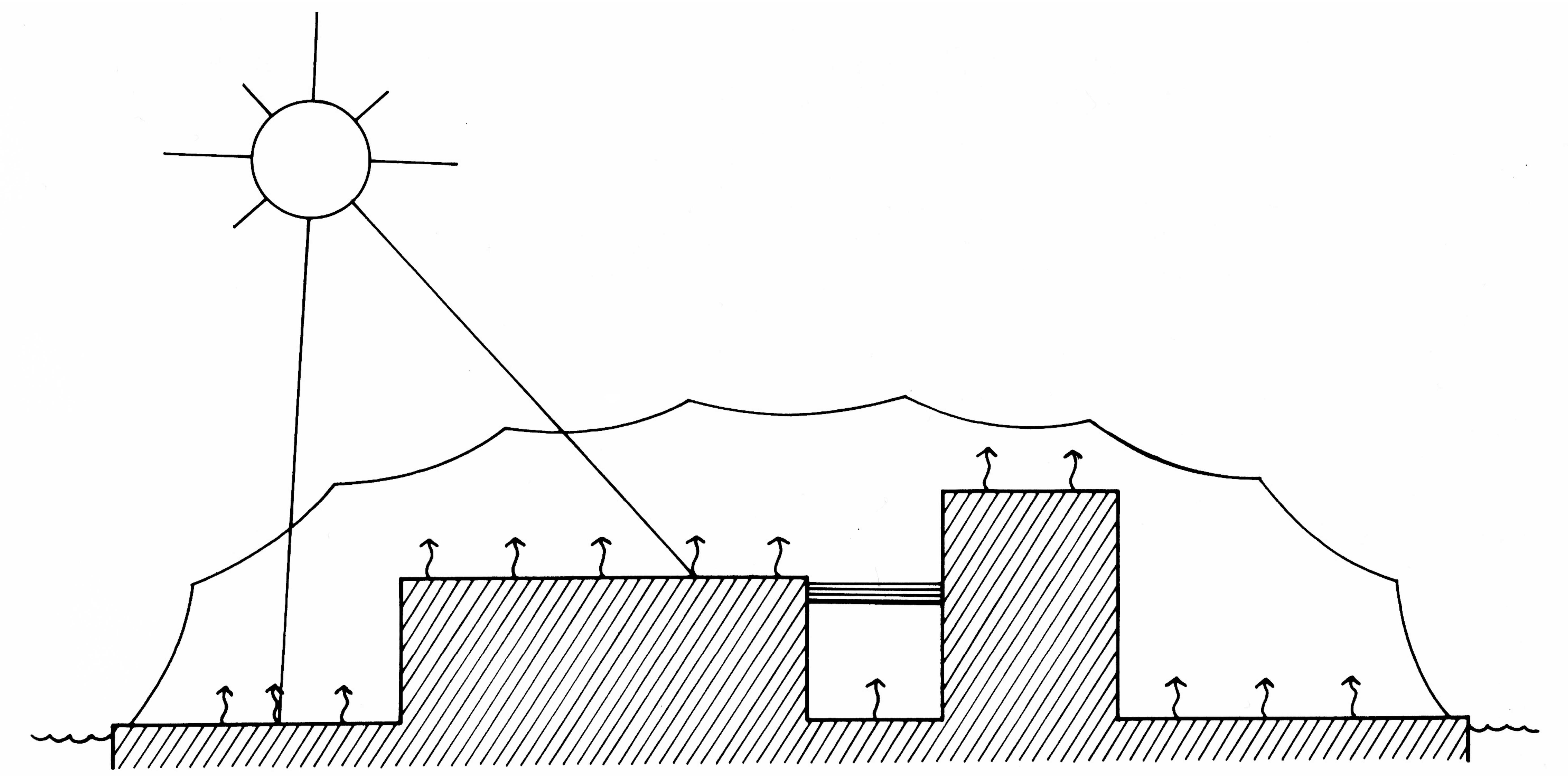


Figure 85) The thermal mass of the concrete structure can be used to achieve thermal inertia

The Requirement for Ventilation

All the imaginable combinations of tensile structures over, between or in front of the thermal mass of conventional structures have one important requirement in common: whether they are used in hot, cold or moderate climates a sensible arrangement of vents must be provided. What is considered sensible depends a lot on the design of each specific building. However, to give clarity to the principle in the use of high- and low-level vents in combination with a transparent skin and high mass structure, it is worth studying the design of the so-called 'air collector', invented by Edward S. Morse in 1882 (Fig. 86).

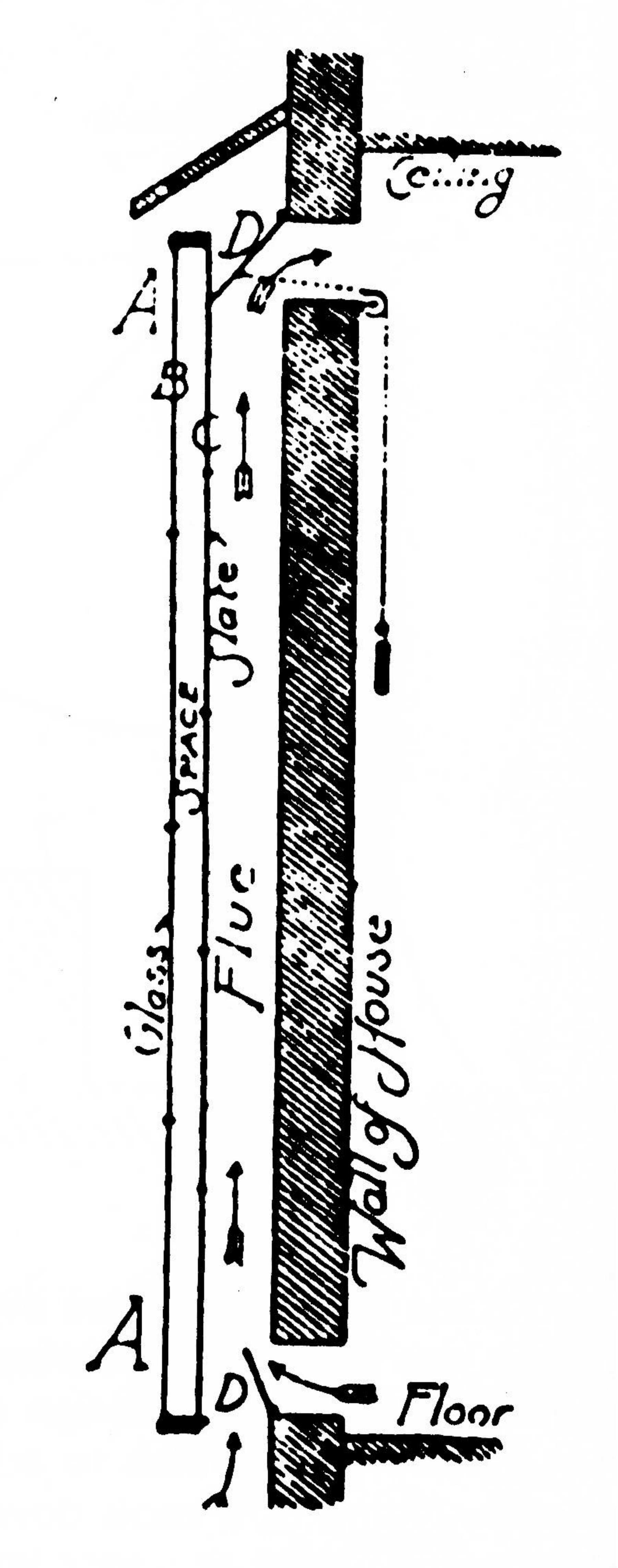


Figure 86) The original design of the air collector by Edward Morse in 1882

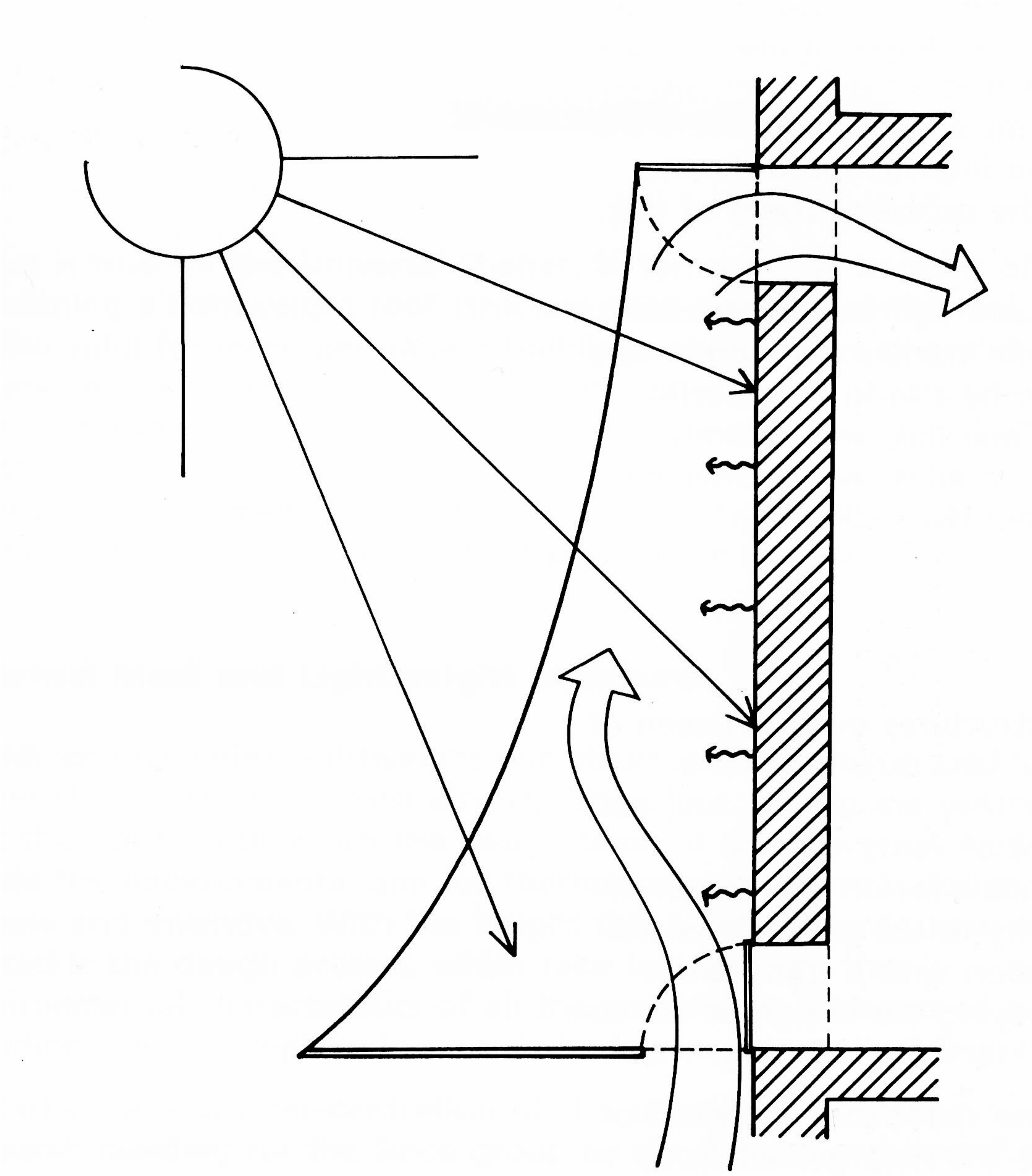


Figure 87) Preheating of fresh air

The aim is to create a ventilated intermediate space that is backed or surrounded by thermal mass which can store the heat gained from solar radiation. When this heat is reradiated from the thermal mass the different combinations of vents provide various options. Fresh air can be preheated before it is drawn into the rooms (Fig. 87). Recirculated air can be reheated, for example at night (Fig. 88). Used air can be vented from the rooms within (Fig. 89). Finally, to prevent overheating, air can be circulated straight through the void to remove excess heat (Fig. 90). In this case the shape of the lightweight skin and the reradiation off the thermal mass can be used to enhance the thermal stack effect.

As soon as there is diagrammatic clarity about the various venting conditions to be achieved, it is then possible to decide where the various openings should be located.

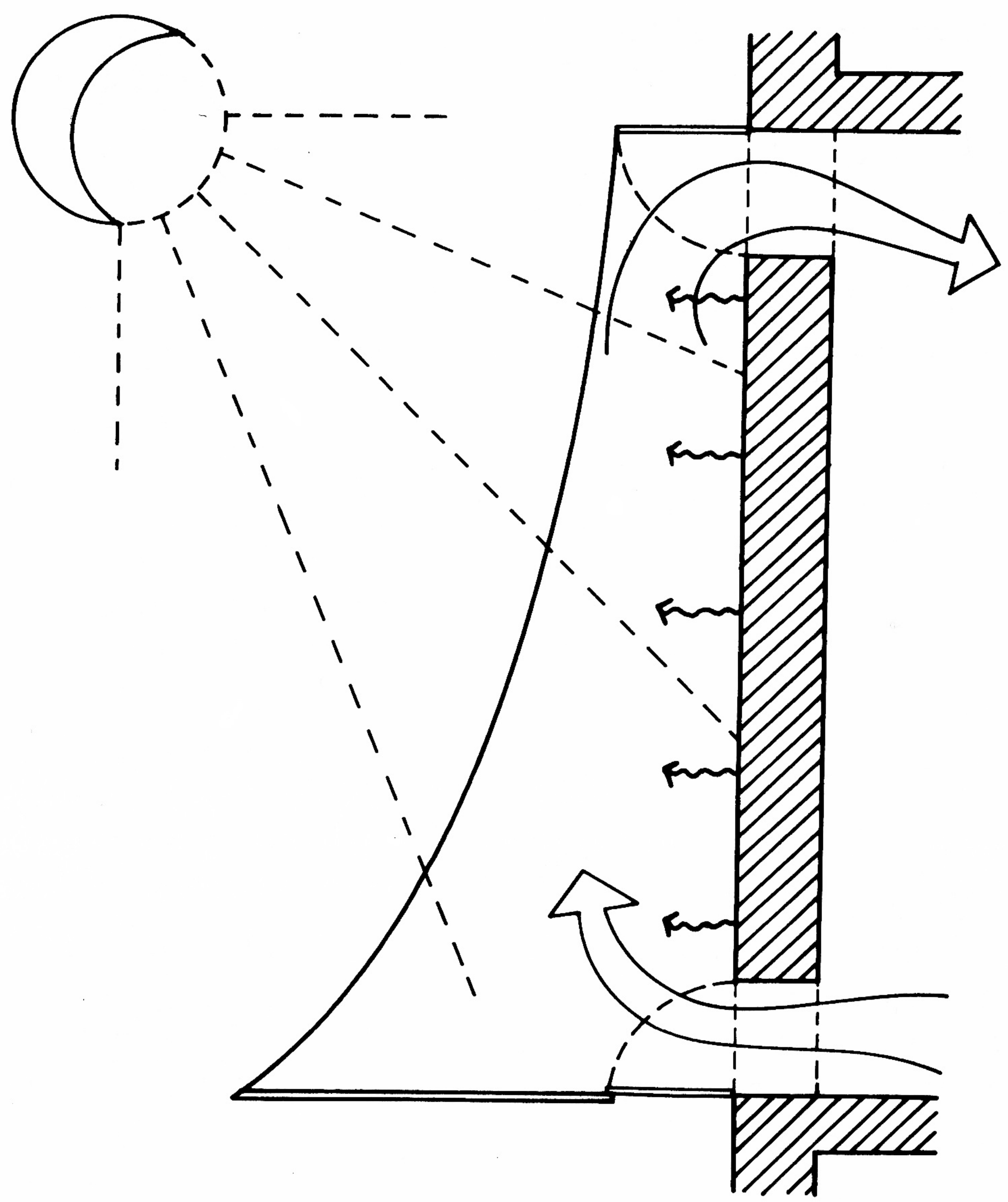


Figure 88) Reheating of circulated air

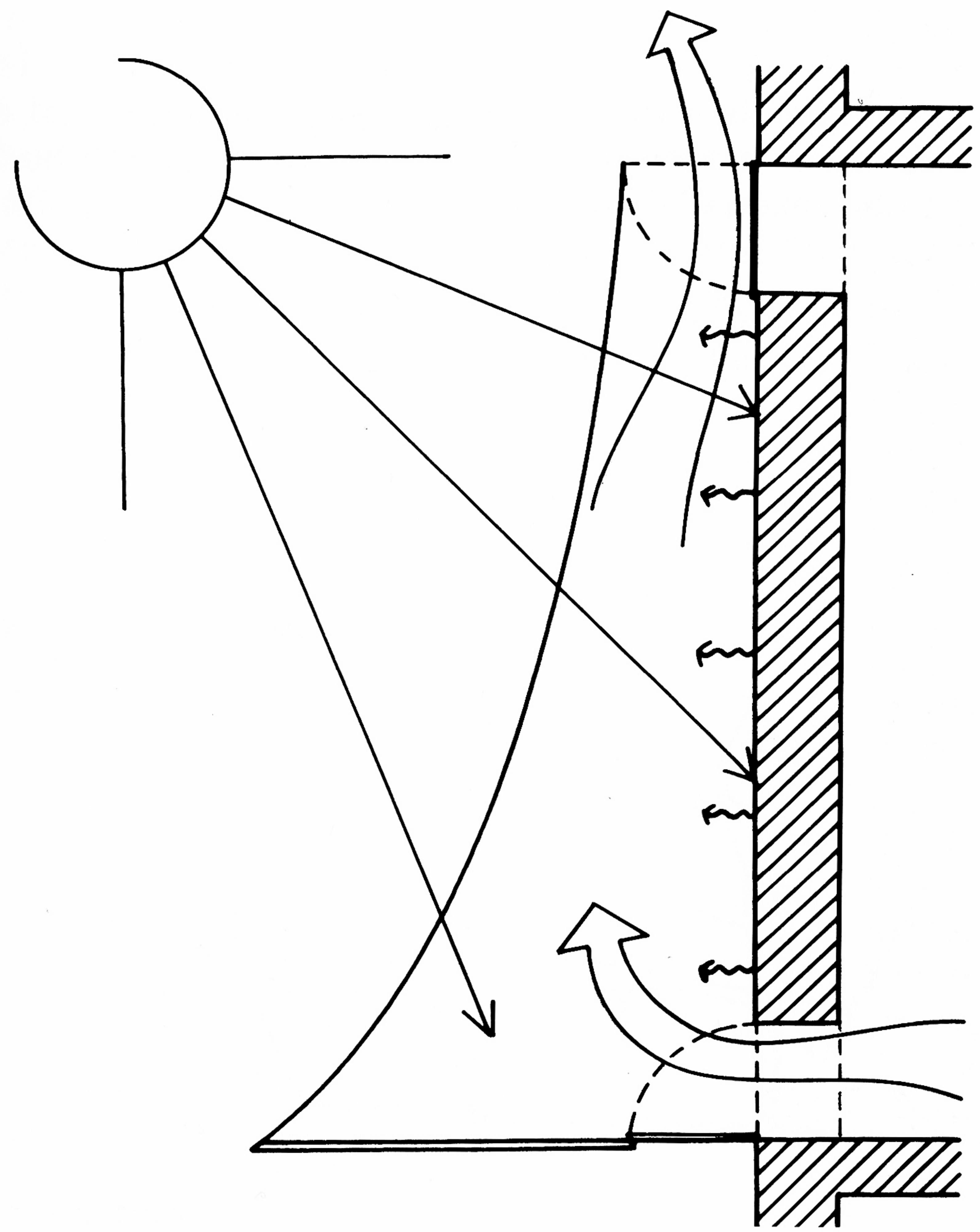


Figure 89) Venting off used air

Acoustic Aspects

The acoustic performance of a membrane covered space is determined by three main criteria: (1) the sound absorptive/reflective characteristics of the type of membrane used; (2) the geometry of the internal space; and (3) the volume of the enclosed space. Since membrane structures are often used for temporary performance pavilions a certain amount of research has been carried out into the acoustical performance of membrane covered spaces. Jaffe Acoustics in the USA helped architects FTL of New York in analyzing the acoustic criteria of the first Pier Six Music Pavilion in Baltimore (Fig. 91).

Due to the low mass of fabric structures very little low-frequency sound is reflected. The fact that the membrane is not completely rigid also means that a certain amount of low frequency sound is absorbed by damping effects. Special care therefore needs to be taken if the space is to be used for non-amplified performances.

The sound transmission characteristics of membranes are also, as one mig-it expect, very different from conventional structures. Lightweight membranes provide very little resistance to the transmission of airborne sound. This can to some extent be increased by the use of multiple layers combined with insulation materials, but mass is the best way of containing sound, especially in the low frequencies. it is therefore advisable to try and avoid any problems in the first place careful planning of the building in terms of its location and internal arrangement. Where a tensile structure is used in combination with more massive construction, noise generating activities, or those that may be acoustically sensitive, should be housed in the parts of the building with the most massive construction.

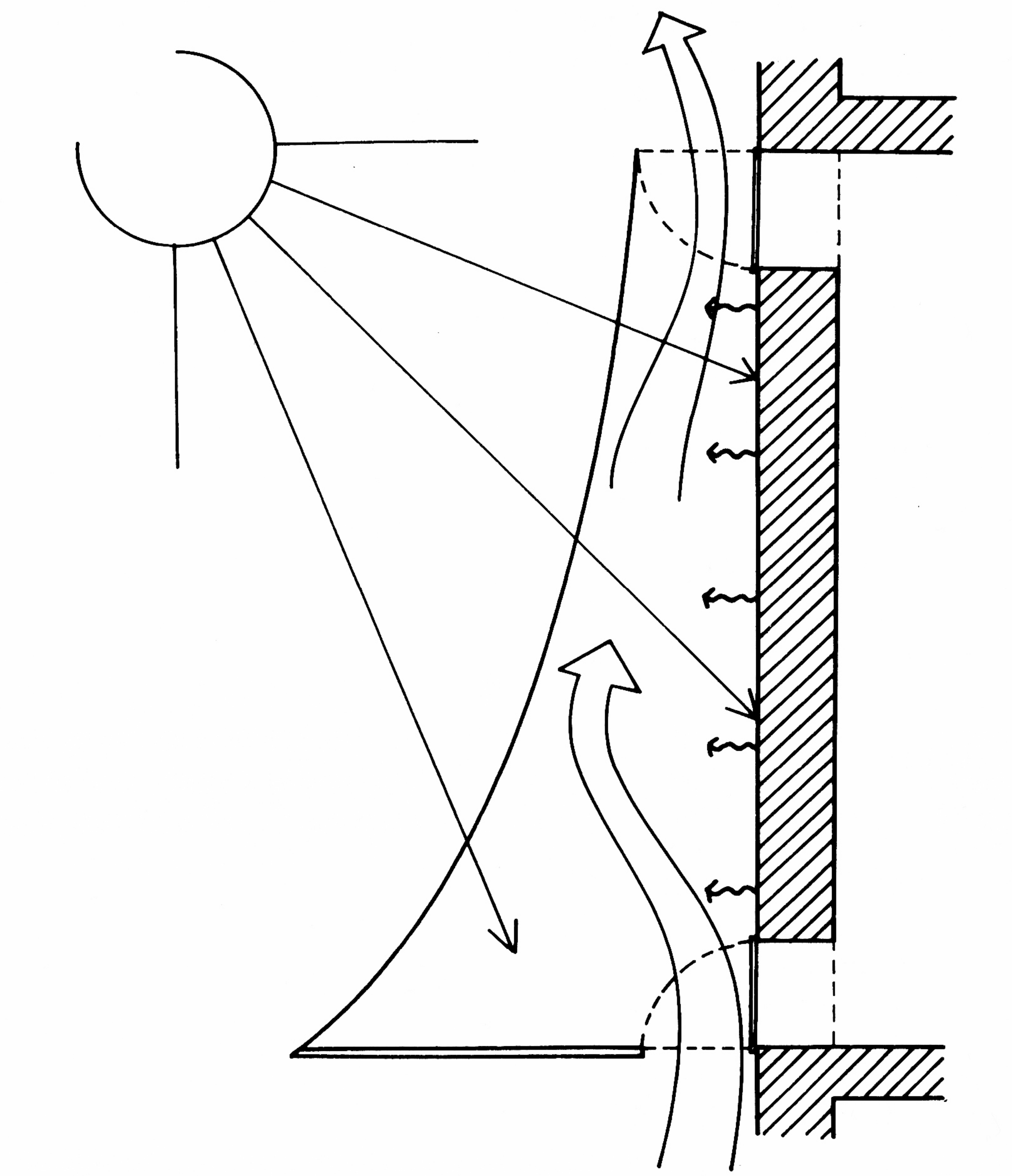


Figure 90) Getting rid of excess heat

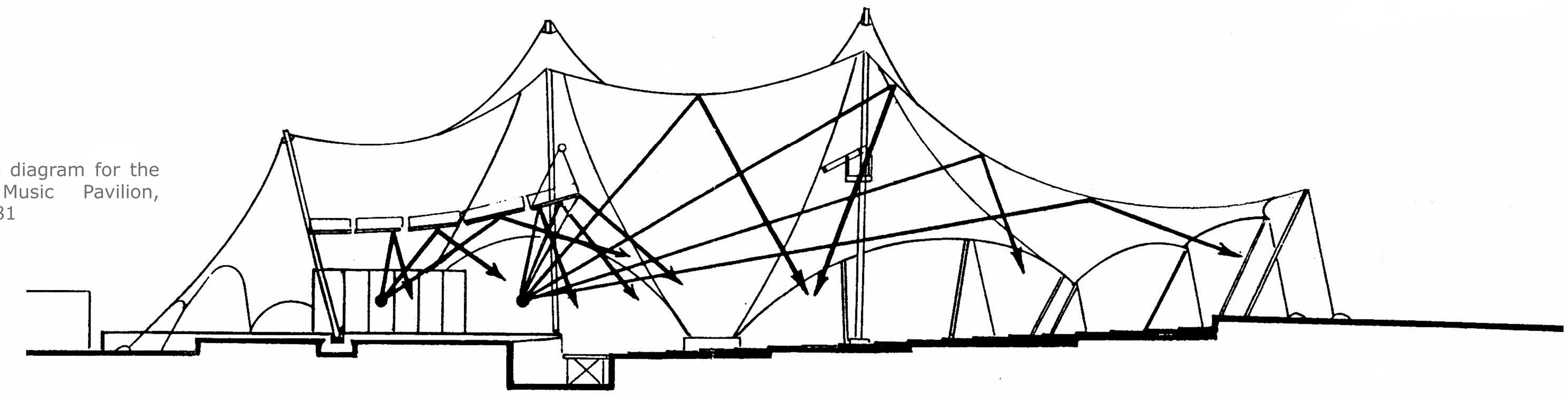


Figure 91) Acoustic diagram for the first Pier Six Music Pavilion, Baltimore, USA, 1981

Use of Topology to manipulate the internal environment

As mentioned earlier the unclear understanding of the environmental behavior of spaces enclosed by tensile membrane structure might be an obstacle for different applications of the structure. Designers must think of other ways of using the fabric membranes in order to offer significant benefits to the occupiers and the clients. Sometimes the misapplication of the technology after selling it to the client leads to dissatisfaction with the internal conditions. This usually happens when using the structure in a function different than what it has been designed for at the first instance.

Tensile structures can be used as microclimate modifiers in a number of different ways. For example the use of retractable fabrics or canopies, the arrangement of the internal thermal mass, as shading device, for inducing airflow inside the enclosure, some of these ideas are discussed below.

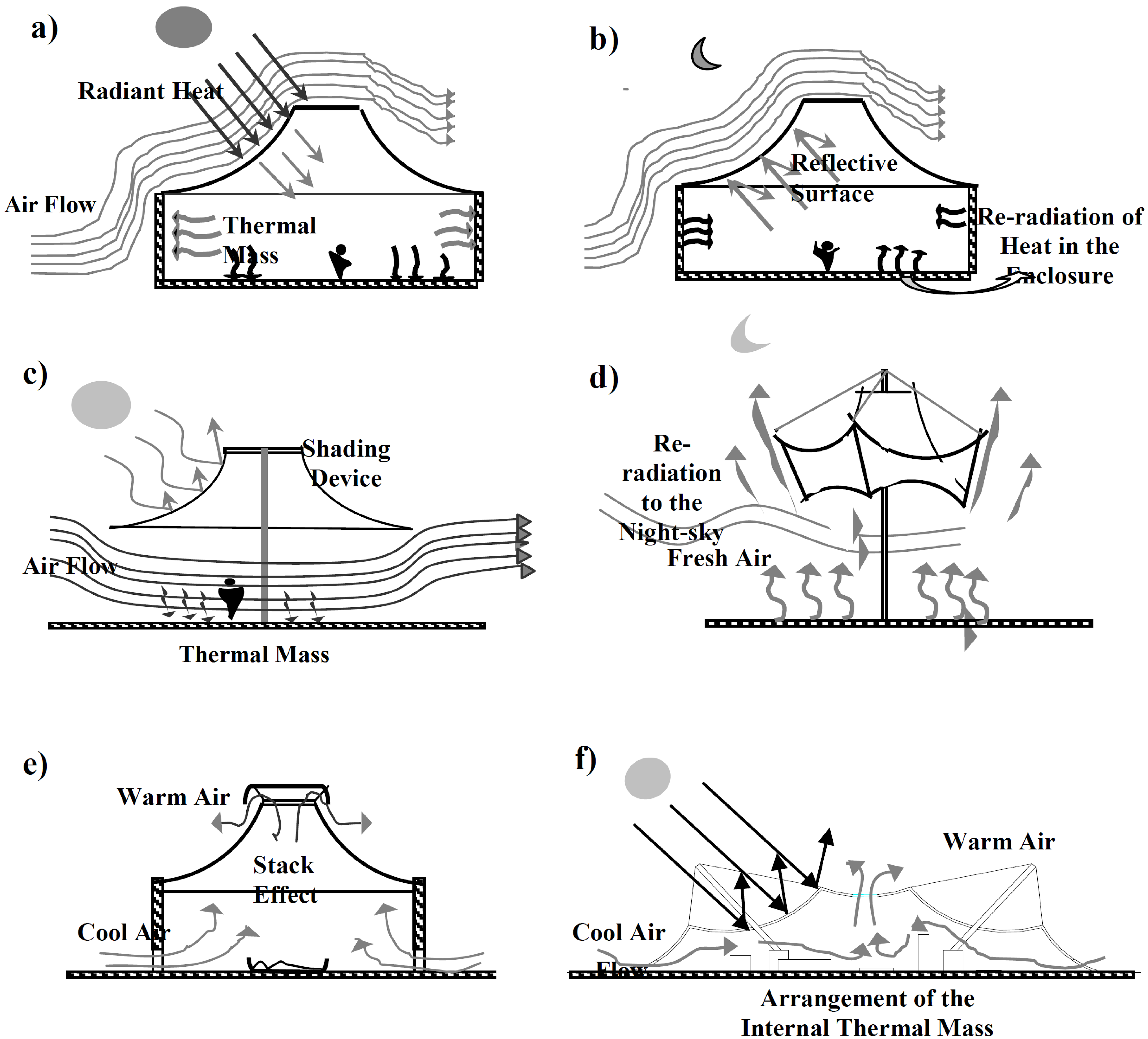


Figure 92) Using topology in manipulating internal comfort within or underneath the structure

In winter fabric structures should be tight to prevent prevailing wind as shown in figure 92 (a & b). Making good use of the thermal mass, as in walls and floors to store heat during the day and re-emit it into the enclosed space at night. At the same time it should prevent re-radiation of heat absorbed in the daytime to the night sky. Having internal highly reflective membrane surface and the form of the structure itself can help in this. It can be used as shading device in hot climates where the sun heat is extremely high.

Early wind tunnel experiments that I had run at Nottingham University, and through the accurate visualization of airflow had shown that air tends to deflect downward just as it enters the structure, this can be effectively used in inducing airflow in fabric membrane structures in hot climates, figure 92 (c) and can be used for natural ventilation also.

The use of retractable canopies or fabrics in hot climates can be very useful as opening the structure at night will permit cross ventilation and also re-radiate the heat absorbed during the day to the night sky. Fountains and pools can be used along with this structure for cooling, as passive cooling techniques figure 92 (d). Figure 92 (e) shows how the stack effect can be effectively used in these types of structures. Painting the annex with a darker color can simulate the absorption of more solar radiation so as to heat up faster than the rest of the fabric, this will rapid the escape of the warmer air out, and cooler air will replace it faster. Tensile fabric membrane structures can be effectively used as a buffer zone between the external environment and the internal one as shown in figure 92 (f). The accurate studied arrangement of the thermal mass inside the structure can work as micro-environment controller in both hot and temperate climates.

Recycling

So far all the environmental aspects considered, have been to do with buildings in use. As concern is growing globally about all the aspects of a building's environmental performance, the recyclability of building materials is becoming an increasingly important issue. Since cable-net structures mainly consist of steel components which can already be fully recycled, attention is being directed to the membrane materials themselves.

With the increasing use of membrane structures and a life expectancy of between 10 and 20 years for certain membrane materials, manufacturers have already been under pressure to research the recyclability of industrial textiles. In Germany a joint venture company, Polywert Faserrecycling GmbH, has been formed for this purpose. This organization aims to find ways to minimize and avoid residual materials created during the manufacturing process and to create material cycling loops.

For pure, uncoated fabrics and also some foils, a full recycling process is already possible. But when used for membrane structures, fabrics are usually coated. As yet, they cannot be fully recycled, but have to be shredded and then added to the coating compound when new membranes are produced. This down cycling process makes it at least possible to re-enter some of the old membrane material into the production cycles. It thus reduces the amounts of materials needed for new coatings significantly. This process is still rather new and can therefore be seen as a preliminary method rather than as the final achievement. Under the pressure of growing environmental concerns, the eventual objective for the manufacturers is the full recyclability of all membrane materials.

7 Tensile Membrane Materials

Introduction

Structural fabric is the material which defines lightweight tensile structures. As a primary structural element, structural fabric must have the strength to span between supporting elements, carry snow and wind loads, and be safe to walk on. As the enclosure element, it needs to be airtight, waterproof, fire resistant and durable. In most cases, it also needs to transmit daylight, reflect heat, control sound, and be easy to keep clean.

Structural fabrics in common use today consist of a structural base material, such as fiberglass or polyester cloth, covered with surface coatings such as PVC (polyvinyl chloride, popularly called vinyl), Teflon or silicone. The much less expensive PVC-coated polyester fabrics are generally used for temporary structures. Teflon-coated fiberglass fabrics have found use in most of the permanent building applications completed in the last two decades. A recent development for permanent buildings is the use of silicone-coated fiberglass fabric. Silicone-coated polyester is also a possibility, and just one of a range of other combinations of materials. New versions of PVC-coated poly-ester with dirt-resistant top coats and tear-resistant weaves show increased strength and durability at little additional cost, and at the same time offer potential for great reductions in construction costs, thereby widening the market of fabric structures for permanent buildings.

The structural fabric membrane is often rein-forced with or supported by linear flexible elements, usually high strength steel cables.

Finally, a tensile structure needs rigid structural elements to support the flexible fabric and cable membrane, generate its peaks, form its Ledges, and create the anchors which hold it down.

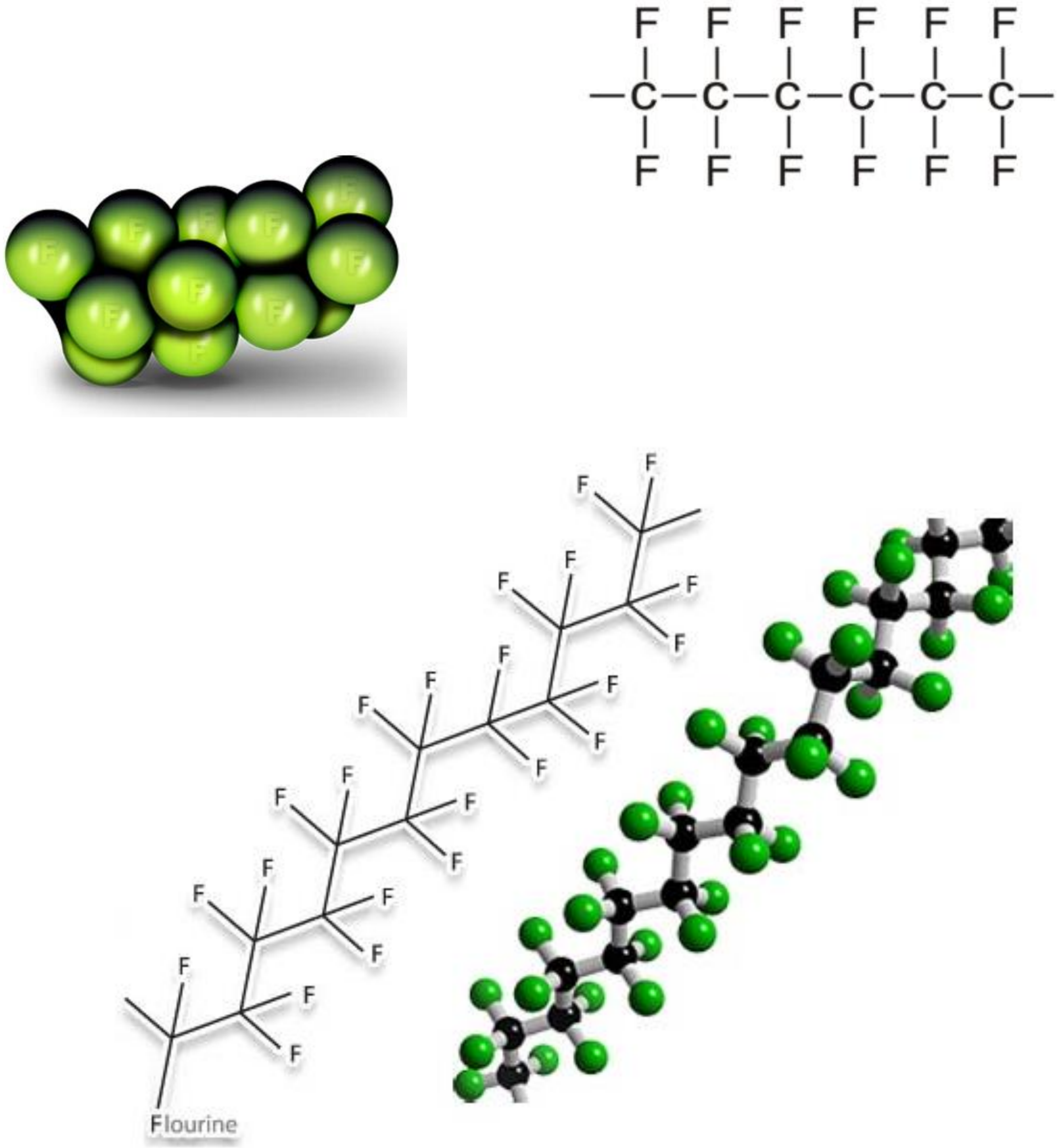
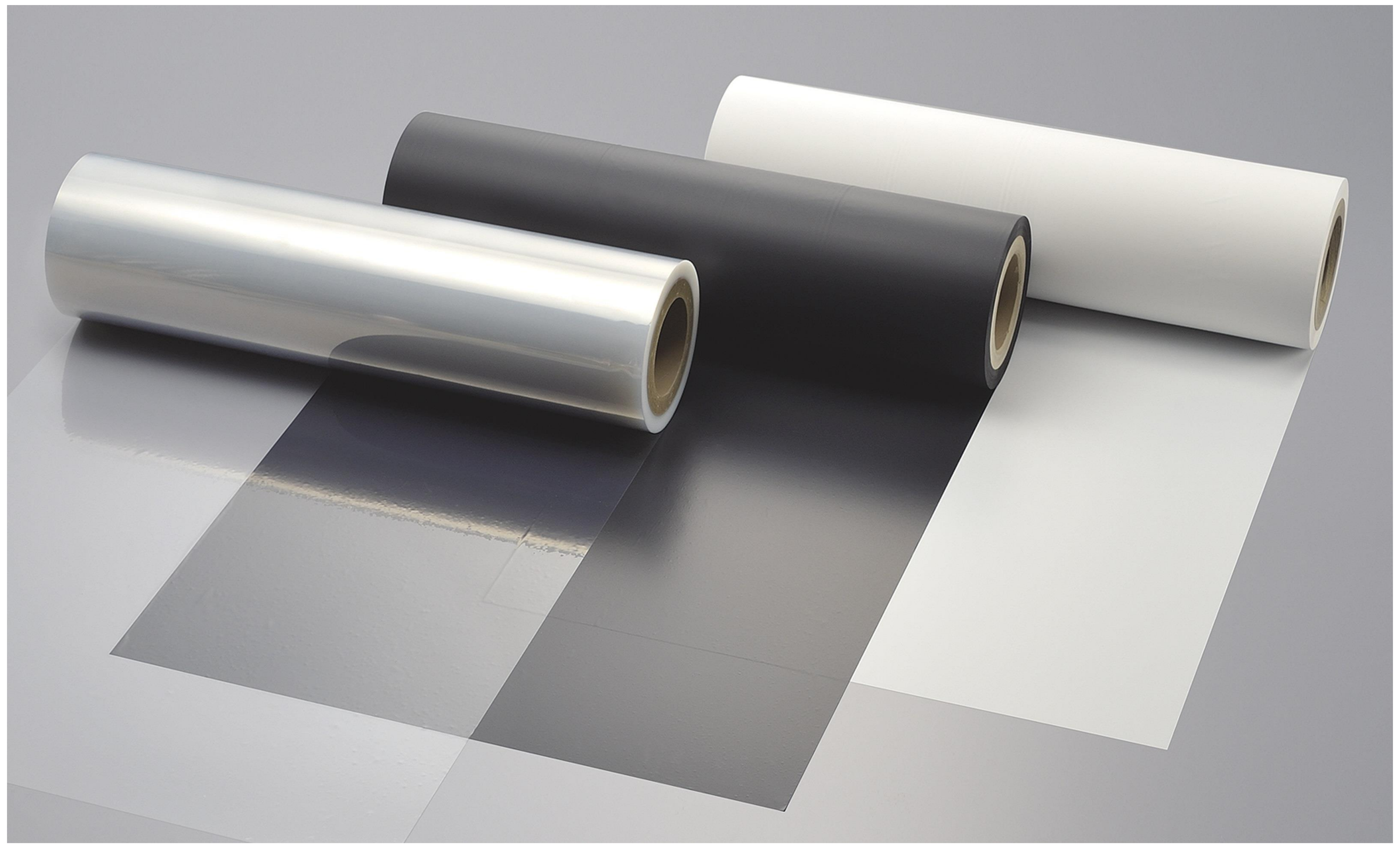


Figure 93) Polytetrafluoroethylene, PTFE



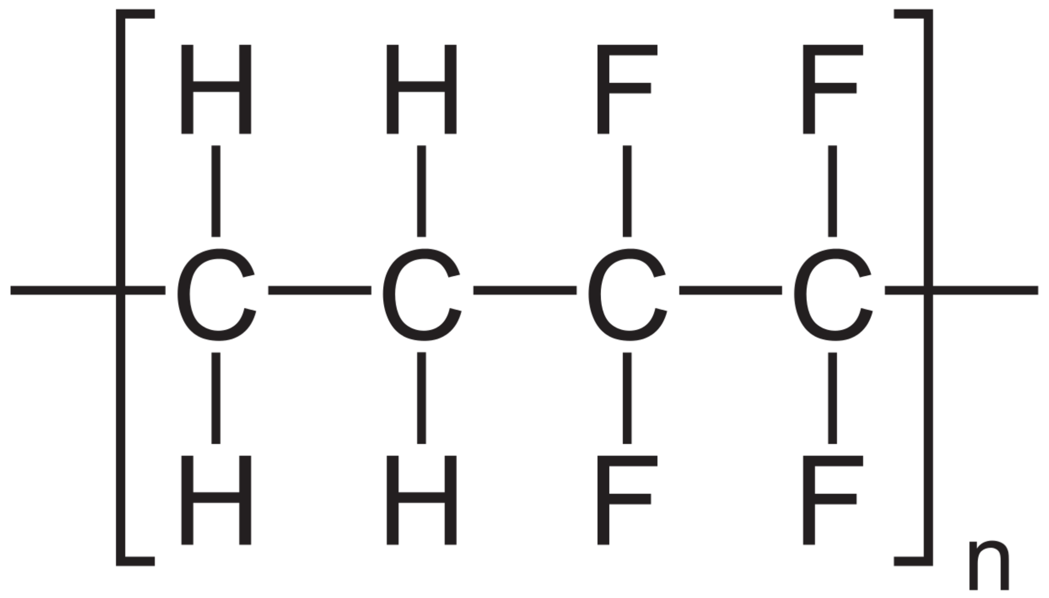


Figure 94) Ethylene tetrafluoroethylene, ETFE

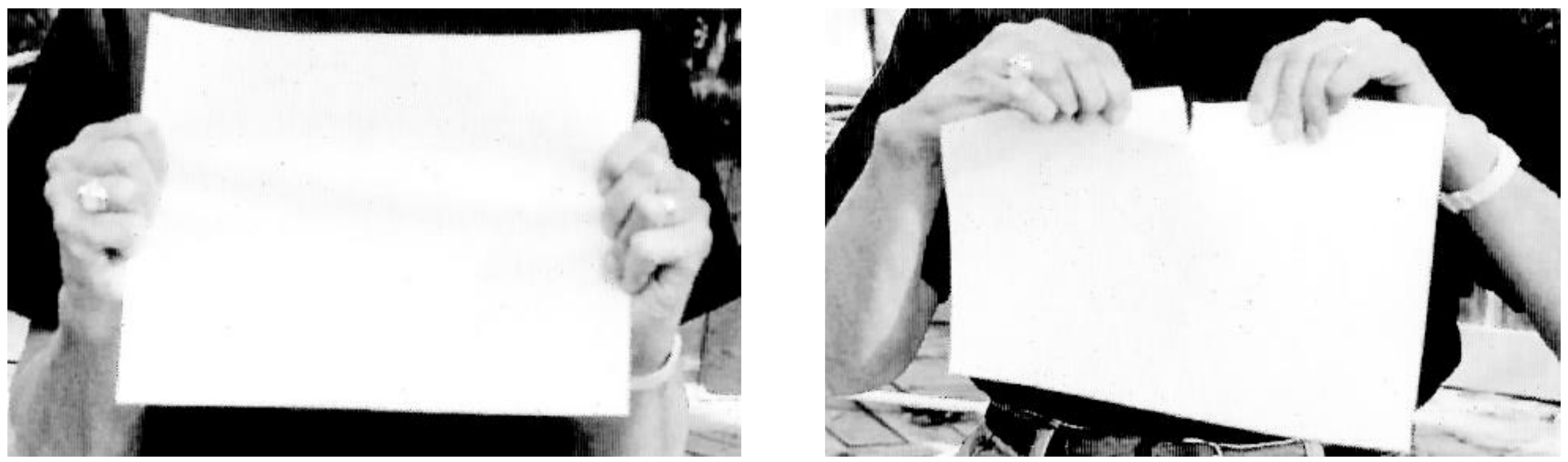


Figure 95) It is hard to break a sheet of paper, but it's easy to tear it. The same is for fabric

For the tensile structure to function properly there must be a hierarchy of elasticity of the materials. The membrane must be more flexible than the cables. They, in turn, must stretch more than the rigid members which support them. When such a hierarchy exists, the structure will be easy to build, and behave in a predictable and efficient way under load.

The rigid support elements are masts, struts, frames, arches and edge beams. They are generally made of materials which we now consider "conventional" despite the fact that none of them existed even a hundred years ago. These materials include steel, reinforced and pre-stressed concrete, laminated wood, aluminum, and, most recently, a number of composite synthetic materials.

The most important component of a tensile structure, and the key to its successful functioning is the fabric membrane. Although excellent materials have been developed and used successfully for several decades, the future of tensile architecture still depends on the evolution of fabrics which cost less, are easier to handle, and exhibit properties that, with regard to permanent buildings, are better than current materials. In evaluating structural fabrics, three facts are important: structural strength; behavior during construction and use; and surface properties. The ability of the fabric to carry load depend mainly on two properties: tensile strength and tear strength. Grab a sheet of writing paper in the middle of the two short sides and try to pull it apart. If you do it carefully, you will probably not be able to break the paper. Now hold the paper at two points close together along the same edges using the thumbs and forefingers of both hands.

Translucency the most important: bringing daylight into the building may result in significant energy savings and a healthier, more efficient and more attractive interior environment. Low heat absorption allows further energy savings, some times even the elimination of air-conditioning. Surface properties which avoid the accumulation of dirt, or facilitate its removal, not only help to maintain the sparkling appearance which is now associated with fabric structures, but also help retain the translucency and reflectivity levels required for the efficient functioning of the building.

Fabric Membrane Types

There are many types of tensile membrane materials and specifications available in architectural market. Each has it's own benefits as well as their shortfalls that defines which tensioned membrane material and Specification needs to be used for a particular project.

Requirements of Architectural Membranes

Tensile Strength: The first and most important property of any architectural membrane is to have enough tensile strength to be able to carry the loads that are applied to the structure. These loads include wind load, snow load, dead loads, and any live loads that may occur on the building. The tensile strength of an architectural membrane is directly related to the reinforcing base fabric that is used to make the membrane and further to the tenacity of the fibers or tapes that are used to make the base fabrics. Exterior coatings that are applied to the base fabric contribute little or nothing to the overall tensile strength of the architectural membrane.

Seam Strength: In addition to the tensile strength of the architectural membrane itself, it is very important that the architectural membrane be able to carry loads across seams, and to attachments at the frames and cables of a tensile membrane structure. Most tensile membrane structures are designed with large clear span spaces that are wider than the architectural membranes. This requires that the membrane be fabricated into very large panels, and that each fabricated panel may have as many as 50 to 100 individual architectural membranes pieces. As a load is applied to a large fabricated panel on a tensile membrane structure, the load is carried by the base fabric and individual fibers that make up the base fabric. However, since the base fabric is not continuous over the entire fabricated panel, the loads must be transferred across the fabricated seams; which in turn creates a shear force across the seam.

Biaxial Stretch: Another important property of any architectural membrane is to understand the biaxial stretch properties under given load requirements. Different base fabrics/fibers will respond significantly different under similar loads; some fibers will stretch significantly before breaking (greater than 30%) while other fibers stretch very little at break (less than 5%). Not only is the amount of stretch important, but it is also necessary to understand the percent of recovery that the fabric will have after seeing a given load. The biaxial stretch properties of architectural membranes at given working loads will assist Structural Engineers in determining the shape of a tensile membrane structure, as the membrane deforms under loads. This understanding may limit the use of certain types of architectural membranes on certain structures.

Tear Strength: While the tensile strength and elongation properties of an architectural membrane are important in designing and engineering a tensile membrane structure, it is the tear strength of the membrane that may be critical to the structures longevity. A tear in a fabricated membrane panel on a tensile membrane structure can occur due to stress concentration, when a hole is penetrated in the membrane or when high stresses are applied to a specific area of the membrane, such as an attachment point.

Significant tear propagation can result in a breach of the weather-proof membrane and the ability of the membrane to carry working loads. Membranes that tear and ultimately lose tension are susceptible to significant damage due to wind-whipping of the material.

The tear strength of an architectural membrane is related to a combination of factors. These factors include; the elasticity of the yarns, the weave construction, density and size of yarns, tensile strength of the fabric, hardness of the coating compound, and adhesion of the fibers to the coating compound. Generally speaking, the greater the elasticity of the yarn; the more the yarns can slide within the coating compounds; the softer the coating compounds; the lower the adhesion of the fibers to the coating compound; the higher the tear strength. Architectural membrane manufacturers must balance adhesion properties such that a given membrane has good seam strength and good tear strength.

Weather Resistance: Another fundamental requirement of any architectural membrane is to provide weather and water resistance to the interior of the building. Unless the tensile membrane structure is designed as only a shade structure, the primary purpose of the structure is to provide a dry and comfortable space within the building. This means that the architectural membrane should be waterproof, as produced, and as it ages. It also means that all seams and attachments of the membrane to the frame or cables must also be waterproof. One of the significant advantages of heat sealed seams is that you create a monolithic layer of the coating compound which provides a very good waterproof seal.

In addition to the functionality of a tensile membrane structure, many of these buildings are constructed because they provide a desirable aesthetic value to the building. The aesthetics are created by the design of the structure, often having high peaks and sweeping curved lines as well as clear open space within the building. It is important that the architectural membrane that is used on a structure can provide the acceptable aesthetics to that structure, and that it maintains its aesthetics throughout the life of the building.

In general, the aesthetic properties of an architectural membrane are either related to the color of the membrane, or the amount of light transmission that a white membrane may display. It is often desirable to use a semi-translucent white membrane on a tensile membrane structure. This provides diffused natural lighting to the interior of the building, reducing the amount of artificial lighting that is required during the day time and creating a much more desirable space. At night time, these same structures will glow with interior lighting, creating a highly visible structure from anywhere in the neighborhood.

Because so many tensile membrane structures utilize a translucent white architectural membrane, it is important to design membranes that have consistent whiteness and translucency. It is also important that an architectural membrane be able to maintain its aesthetic properties over the expected life of the building. This means that membranes should not yellow or retain excessive dirt on the exposed surfaces. In addition, architectural membranes need to address concerns related to fungus and mildew growth in many locations.

Fire Resistance: Another critical requirement of an architectural membrane is that it must be able to meet the appropriate Building and Fire Code requirements for a given structure. All architectural membranes that are used on any non-agricultural buildings should be designed such that the membrane will not support a flame. As a minimum, all such membranes must meet the requirements of NFPA-701 Fire Tests for Flame-resistant Textiles and Films.

In addition to meeting the requirements of a flame-resistant membrane as specified in NFPA-701, architectural membranes can further be divided into non-combustible and limited combustible materials. Non-combustible membranes will utilize a non-combustible base fabric such as woven fiberglass, and will generate very little smoke when placed into a fire. Because of these properties, non-combustible membranes are often required by Building and Fire Codes for any large scale permanent buildings that will hold large numbers of individuals, such as arenas and other public spaces.

Longevity: A final requirement for any architectural membrane is that they must maintain all of their properties over the expected life of the structure. The expected life of any given architectural membrane should be clearly understood, and if the desired life of the building is greater than the life of the membrane, than provisions should be made to replace the architectural membrane at the appropriate time. This is commonly done on many tensile membrane structures and should be viewed as the same as replacing a roof on a conventional building.

Light-Related Properties: Light absorption, reflection and transmission are fundamental when choosing the right material for architecture purposes. These factors can be used to help lighting and shading of space enclosed. They may affect the thermal properties of the interior. Indirect light, illumination and energy related questions may be considered in relation to these properties. These properties are described by using percentages. For example ETFE foil may reach a 95% transmission rate, PTFE coated fiberglass can reflect 70% of light. The color chosen can affect the absorption rates up to 25%.

The performance of today's architectural fabrics depends upon the weaving pattern, choice of substrate, and coating. Each type of composite has unique properties and characteristics that suit it to different applications. The proper selection of membrane material is based on the proposed structure's size, form, function, project economics, and desired longevity. Structural fabrics in common architectural use today include:

Figure 96) A woven polyester base fabric with vinyl coating

Figure 97) PTFE in different colors and coatings

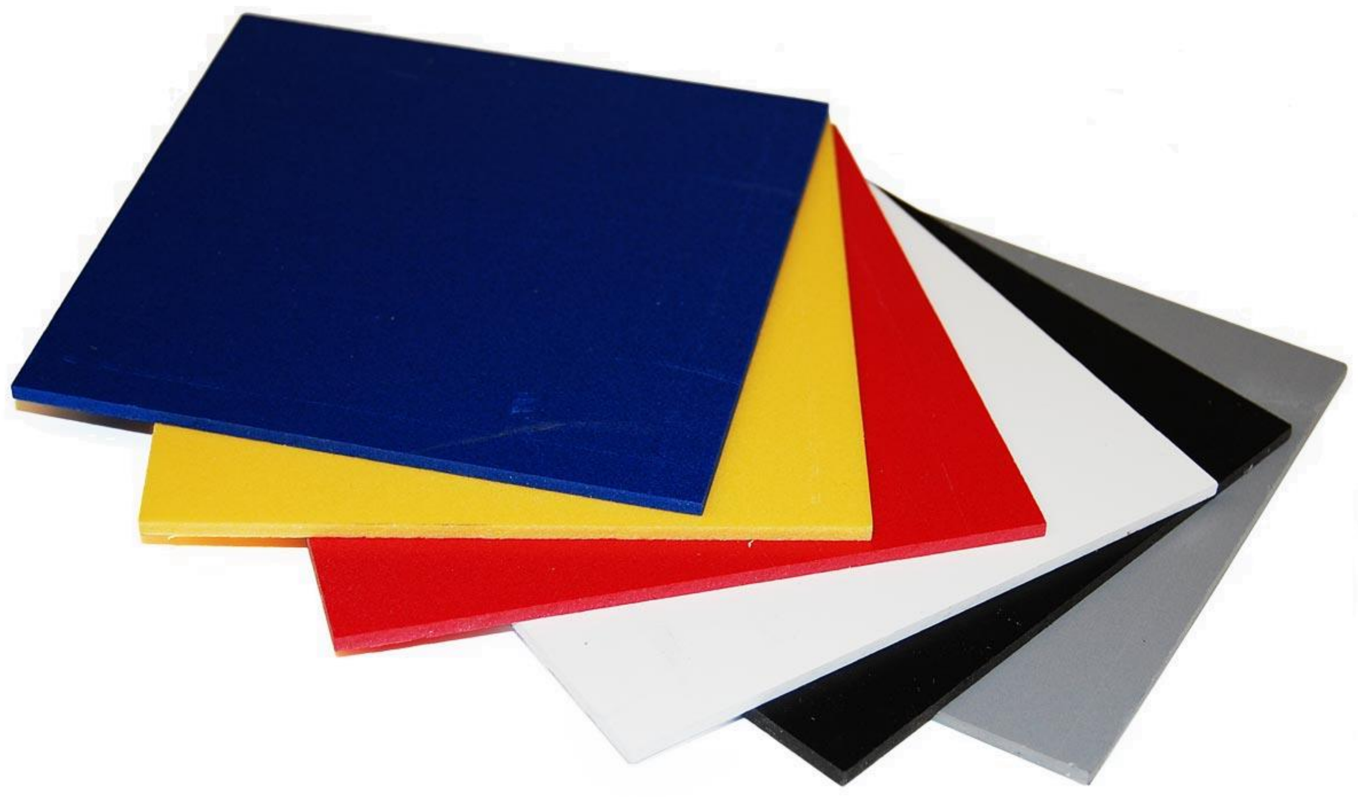


Figure 98) PVC sheets in different colors

Choosing Fabric Type

There are a number of fabrics that can be used for tensile structures and to select the appropriate one you need to ask yourself the following questions:

What lifespan do I want from the structure/fabric?

There are fabrics that range from a 1 year lifespan up to 50 years and more.

What color do I want to the fabric to be?

There are numerous choices available but the further from White you go the more the other points here are usually compromised (i.e. lifespan, translucency, fire retardancy)

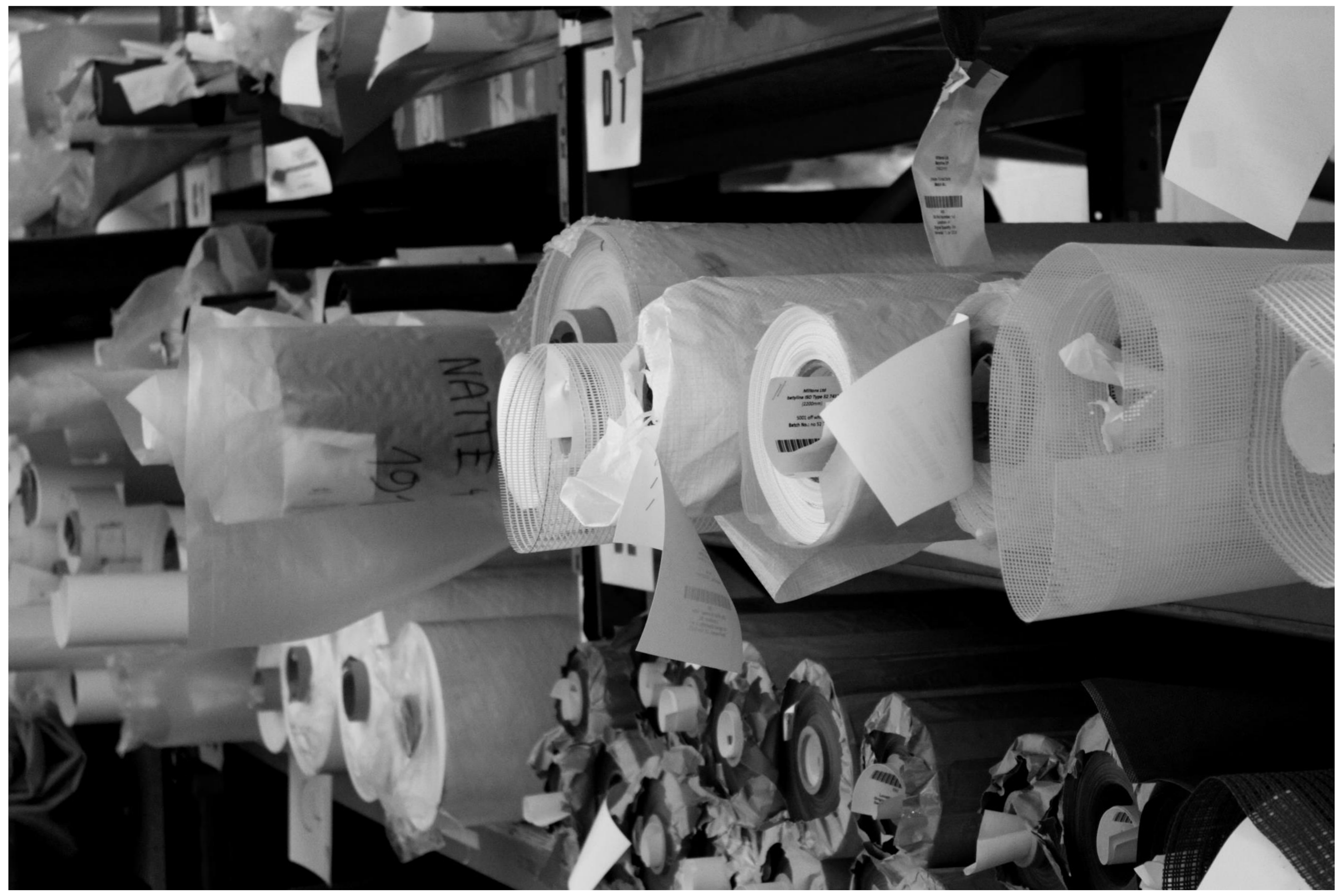


Figure 99) A proper fabric material selection, will ensure a sound tensile structure.

What appearance do I want the fabric to have, the choices being:

Translucent fabric - Fabrics can let in as much as 35% light)

Opaque fabric - Desirable for an event arena of a venue where precise control over the light levels is required

Mesh Fabric – These can allow you to look right through the fabric from a distance while still providing wind and solar protection (thus often used for facades, sunscreens, ceilings, etc)

What fire retardancy do I require – Fabrics are available in a wide range of fire retardancy and this question is becoming more important as architects and clients start to more fully consider the entire lifecycle and usability of a structure

How often do I want to clean the fabric – Major technological advances have been made in the coating of architectural fabrics, giving them amazing self-cleaning characteristics. This is usually a cost vs. ease of access exercise to determine the most appropriate fabric.

Answering these questions may lead us to decide the proper and best material which suits our tensile structure.

Teflon-Coated Fiber Glass (PTFE)

PTFE (*polytetrafluroethlyene*) is used world wide as the preferred material for large-scale permanent structures or structures requiring long life and with specific construction code compliance requirements. PTFE has excellent weather, temperature and chemical resistance in addition to its durability and strength. This material has a life span of over 25 years and is manufactured in accordance to standards such as ASTM E-108 and E-84. PTFE varies in translucency from 7% to 15% and reflects between 68%-75% of incident sunlight. The quality of light transmitted is color balanced, diffused and free of shadows and glare.

Before installation, PTFE has an irregular off white or slightly brown color, which is caused during the manufacturing and fabrication process. Once exposed to direct sunlight, the external surface of the membrane bleaches to a milky white within a matter of days.

PTFE is the obvious option if long life and low maintenance are the most important factors in selecting a fabric. This material requires heat-sealing at the seams to join fabric pattern sections and has a life span of over 30 years.

PTFE coated high translucency fabric is a dynamic tensile material unmatched for its aesthetics and durability making it ideal for large scale roof and tensile membrane structures. PTFE coating is chemically inert and capable of withstanding a wide range of temperatures in any climate. The low-surface adhesion properties of the material result in a fabric membrane which is easily cleaned by rainwater and is immune to UV radiation.

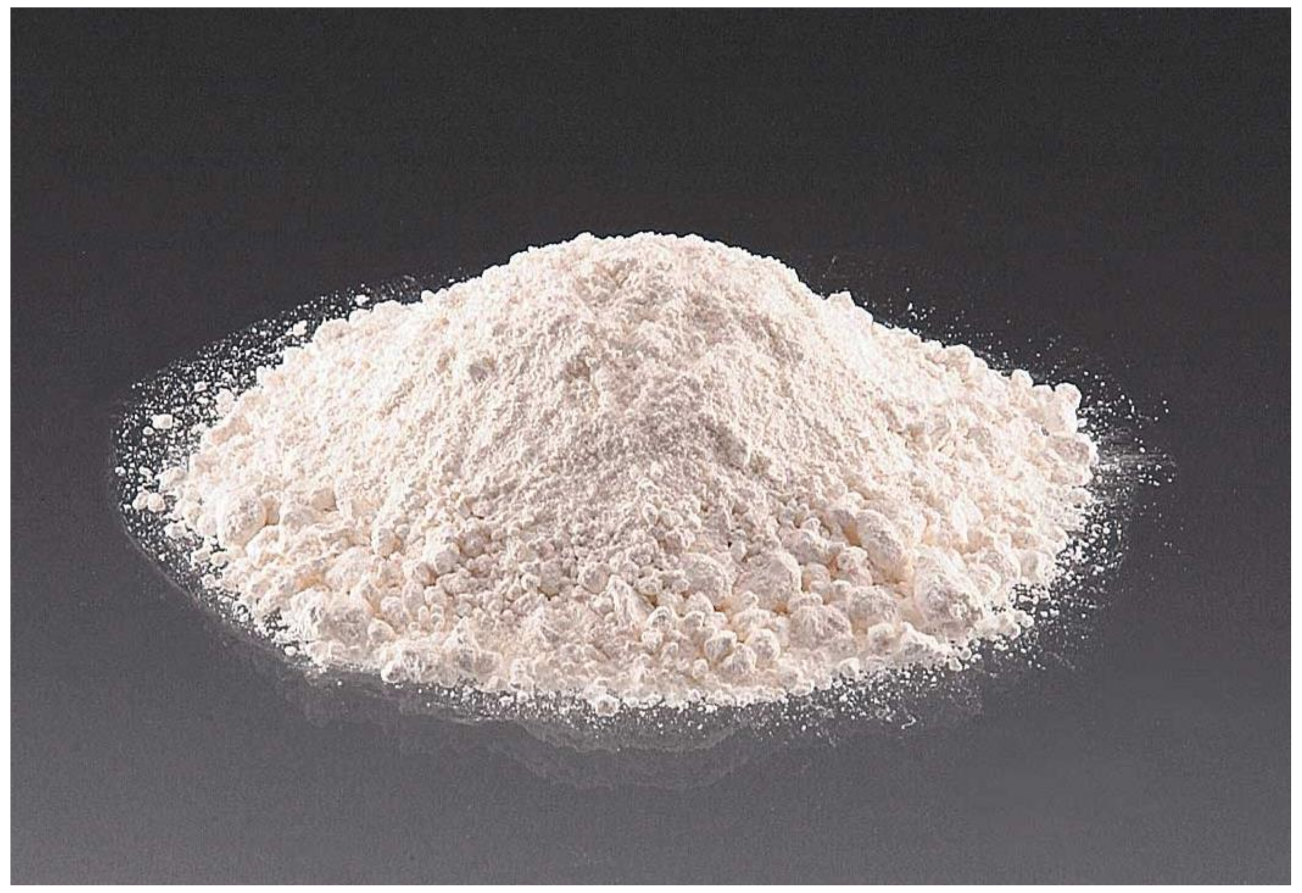


Figure 100) PTEF powder

Property	Value
Density	2200 kg/m^3
Melting Point	600 K
Thermal Expansion	$135 \cdot 10^{-6}$ K^{-1}
Thermal Diffusivity	0.124 mm²/s
Young’s modulus	0.5 GPa
Yield strength	23 MPa
Bulk resistivity	10^{16} Ω·m`
Coefficient of friction	0.05–0.10
Dielectric constant	ε=2.1,tan(δ)<5(-4)
Dielectric constant (60 Hz)	ε=2.1,tan(δ)<2(-4)
Dielectric strength (1 MHz)	60 MV/m

Table 1) PTFE Technical Data

PTFE is considered a high performance plastic, with a step up of engineering plastics such as polyamide and polyacpetal in the hierarchy of polymers, as well as its price. PTFE has very high viscosity, which prevents it from being processed in the same manner as other thermoplastics (injection molding, extrusion etc), so its use is required in powder form, for compression molding and subsequent sintering at high temperature.

Despite having high impact resistance, PTFE relative to engineering plastics has low tensile strength, creep and to the use, in some applications requiring the incorporation of fillers such as fiberglass, bronze, carbon fiber, stainless steel and synthetic coal. Also common is the incorporation of graphite and molybdenum disulphide to further improve their sliding and anti-adhesive properties, since the coefficient of friction of PTFE is lower than almost all other plastics. (like the Teflon used as non-stick coating in pans)

Property	**PTFE**	**TFM**	**PFA**	**FEP**	**Polypropylene**
Appearance	Ivory-white, opaque	Ivory-white, opaque	Translucent	Transparent	Translucent
Density (g.cm)	2.20	2.15	2.15	2.14	0.9
Melting Point (°C)	327	327	305	270	160
Max. Service Temperature (°C)	290	290	260	205	140 Short 110 Long
Chemical Resistance	Excellent	Excellent	Excellent	Excellent	Good except for HC and oxidising agents
Water absorption	Nil	Nil	Nil	Nil	Nil
Hardness (Shore)	60	60	63-65	63-65	60-75
Tensile Strength at 23°C (MPa)	20-40	40	15-25	20-30	25-40
Elongation at break (%)	250-500	250-500	100-250	250-300	600
Flammability	Non-flammable	Non-flammable	Non-flammable	Non-flammable	Ignites on flame contact & will burn
Electrical Resistance (Ohms.m)	10	10	10	10	10
Cost Index	1.0	1.5	3.0	2.5	0.25

Table 2) PTFE and its modified subdivisions (technical data)

Main Properties

PHYSICAL AND MECHANICAL PROPERTIES	ELECTRICAL PROPERTIES
•Outstanding non-stick properties. •High tensile & tear strength. •Very low elongation at break, the most important property required for any conveyor belt. •Light - weight - requires very low power to drive	•Unsurpassed dielectric properties, make the belts the only suitable choice for use in micro-wave Ovens. •Unique electrical insulation properties.

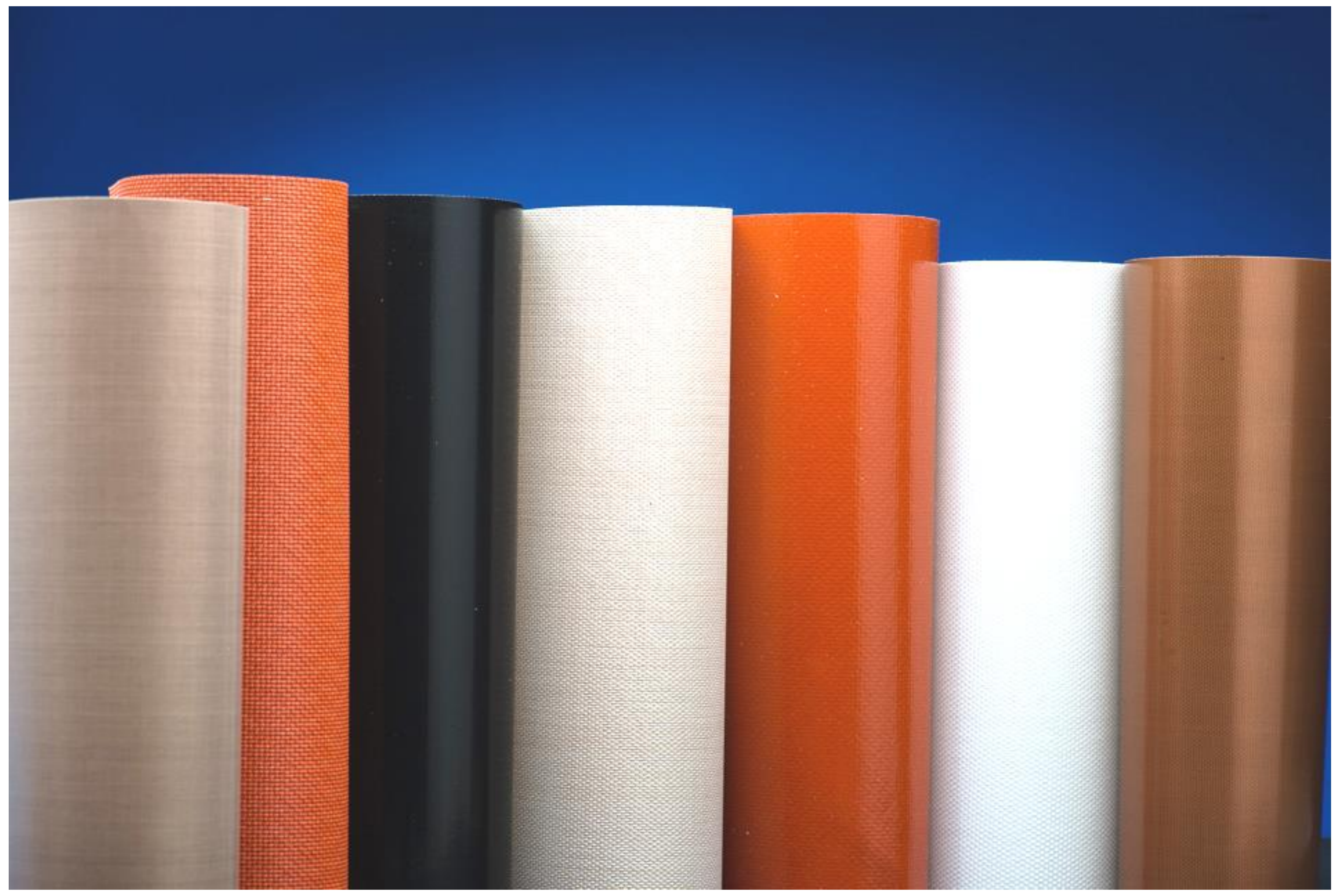


Figure 101) PTFE (Teflon)® is a material of remarkable properties : Nonstick, friction free, self lubricating, non-wettable, nonflammable, non brittle, non-toxic, resistant to atmospheric conditions, resistant to fungus growth are some of its major properties. Its electrical properties are equally outstanding. All properties are maintained over a wide temperature range -200^{0}c to +360^{0}c.
FIBRE GLASS too is a material of remarkable properties. Fabrics made from continuous filament yarn exhibit superior properties in terms of high tensile strength, low elongation, high temperature resistance etc.

CHEMICAL PROPERTIES	THERMAL PROPERTIES
•Non-toxic - Safe for hygiene •Inert to almost all chemicals, paints & solvents •Non-wettable, lower moisture absorption than 0.01% at 100°c •Immune to fumes & fungus	•Conserves heat energy during passage through oven or dryer. Does not loose energy through radiation. •Retains all properties throughout wide operating temperature range. •Operating temperature tem. -200^{0}c to +360^{0}c.

PTFE fiberglass is additionally Energy Star and Cool Roof Rating Council certified. During scientific tests of its solar properties, it was discovered that PTFE fiberglass membranes reflect as much as 73 percent of the sun's energy while holding just seven percent on its exterior surface. Certain grades of PTFE fiberglass can absorb 14 percent of the sun's energy while allowing 13 percent of natural daylight and seven percent of re-radiated energy (solar heat) to transmit through. PTFE's fiberglass yarns maintain ultimate tensile strength of 500,000 PSI and a modulus of elasticity of 10.5 PSI x 10^6 compared to steel, which offers 40,000 PSI and 29 PSI x 10^6respectively. Under normal conditions, the fabric behaves elastically and does not undergo significant stress relaxation or creep. The woven fiberglass gives the PTFE fiberglass membrane its mechanical strength. These filaments, known as beta glass, are the smallest diameter available and provide the membrane with maximum flexibility. The fibers are drawn from hot melt glass through platinum dies into continuous filaments, and are then twisted and plied into yarn bundles. The yarns are woven into a wide structural fabric, which is then coated with PTFE fiberglass to complete the process.

Thermal Performance

The insulative properties of **PTFE** coated glass is similar to the performance of conventional glazing. The equates to a U-value of approx. 4.0 5.0 for a single layer membrane, and 2 2.5 for a twin layered membrane. Twin layered membranes have a light transmission level of approximately 50% of a single skin structure.

Solar Performance

The typical characteristics of single skin tensile fabric roofs to sunlight are approximately 75% reflection, 10% absorption and 15% transmission.

Fire Performance

All Teflon coated glass cloths are inherently non-flammable and achieve Class 1 in surface spread of flame testing and class 0 performance in BS476 pt6 Fire Propagation tests.

Life

PTFE is actively bleached by UV light, which had the effect of maintaining a bright white appearance in the long term. The Teflon coating provides a chemically inert layer which resists the build up of environmental pollution. The material had been extensively tested both in the laboratory and out in the field and no degradation or loss of strength is observed. The material does not become brittle or discolor over time. It is anticipated that the material has a life in excess of 30 years.

Weight

Single skin **PTFE** roofs typically weigh 1.5kg per m2, and thermal sandwich roofs typically weigh 3.5kg per m2

Acoustic

As lightweight material with limited mass, **PTFE** fabric roofs are acoustically relatively transparent, but provide a degree of absorption and noise attenuation. The inclusion of an insulted layer greatly enhances the acoustic attention of a tensile roof, particularly for mid to high frequency noise sources. This is particularly helpful for lessening the ringing reverberant in din that can affect courtyard and atrium environments.

Cleaning

PTFE coated glass roofs are extremely low in maintenance due to the cleaning action of rain on the Teflon outer layer. Typically, cleaning is recommended every 2-5 years, depending on the location of the structure and its exposure to environmental pollution. The fabric is sufficiently strong to support a mans weight on its surface, so cleaning simply requires the incorporation of man-safe systems to access the roof surface. **PTFE** roofs do not need to be cleaned internally.

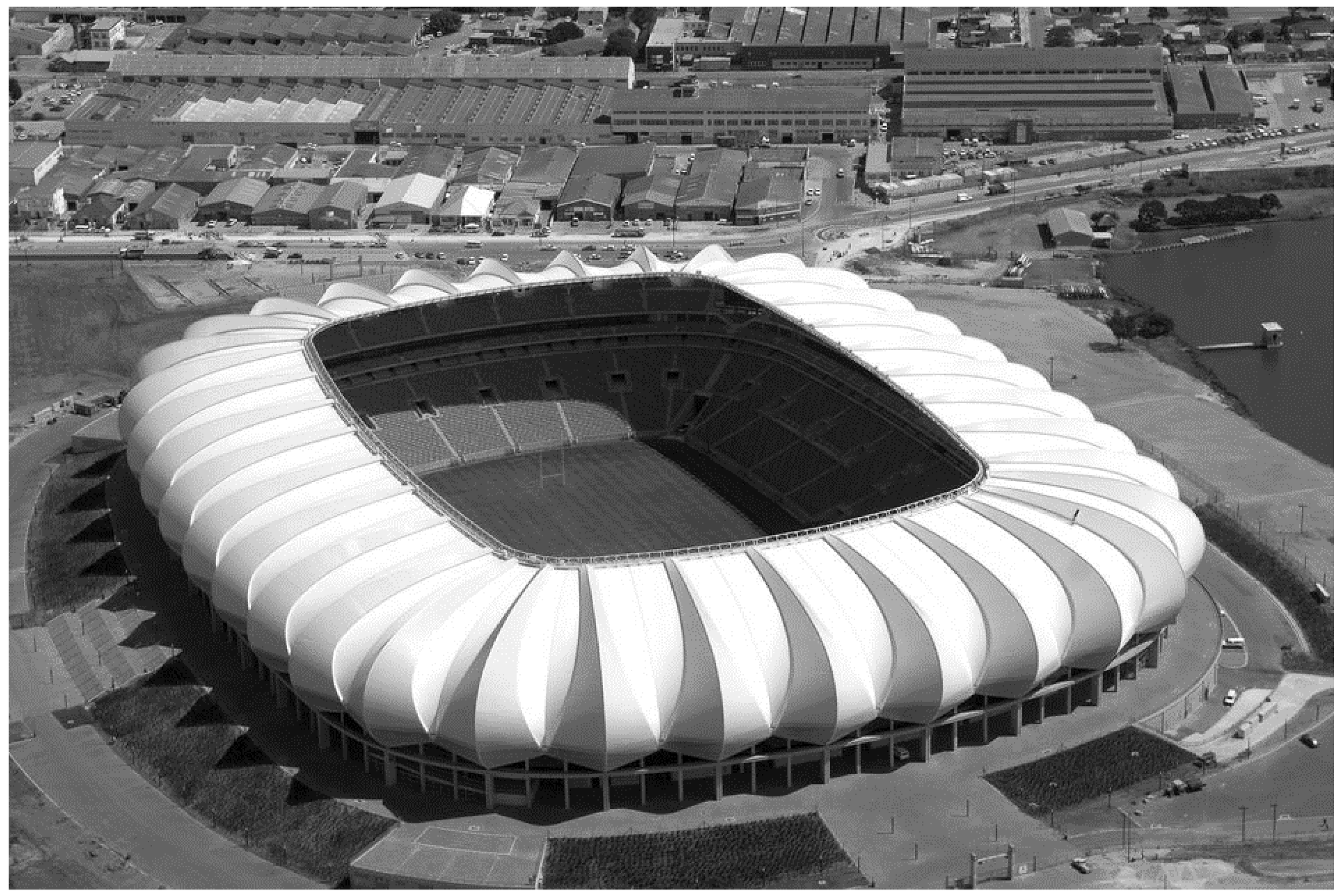


Figure 102) Nelson Mandela Bay Stadium in Port Elizabeth, South Africa 2009

Vinyl-Coated Polyester (PVC)

PVC is the most cost effective membrane material and, therefore, an ideal choice for both temporary and permanent tension structures. The fabric came into prominent use in the 1960's replacing nylon, which had been used almost exclusively until that point. The material is soft, pliable and less expensive than PTFE. It is available in a variety of types to meet a wide range of structural requirements. It has a minimum of stretch in a wide range of temperature and humidity conditions and the coating process prevents mildew, stain and streaking.

Most **PVC** fabrics will have some form of top coating applied to keep them looking new and clean. These topcoats can be acrylic solutions, polyurethane-acrylic solutions, PVDF solution coats or a PVF film lamination. Vinyl laminated polyester is primarily used for temporary structures while vinyl coated polyester is used for both temporary and permanent structures.

PVC material has a life span of 20-25 years. It comes in a variety of colors and textures, but is subject to creep (stretching under load), thus requires periodic re-tensioning. This material is sealed using radio frequency (RF) equipment.

PVC polyester is mainly used for beautifully shaped tensile fabric structures, however its wide range of colors and suitability for printing also makes it ideal for banners. Because PVC polyester can be folded, it's suitable for both temporary and retractable structures.

The **PVC** polyester coating includes UV stabilizers, fire retardant additives, coloring and anti-fungicides and it can be fully recycled – making this a well-rounded fabric.

PVC polyester is used on structures all over the world and in every environment. Applications include: covered walkways, entrance features, outdoor classrooms, play areas, stadiums, event spaces, brise soleil.

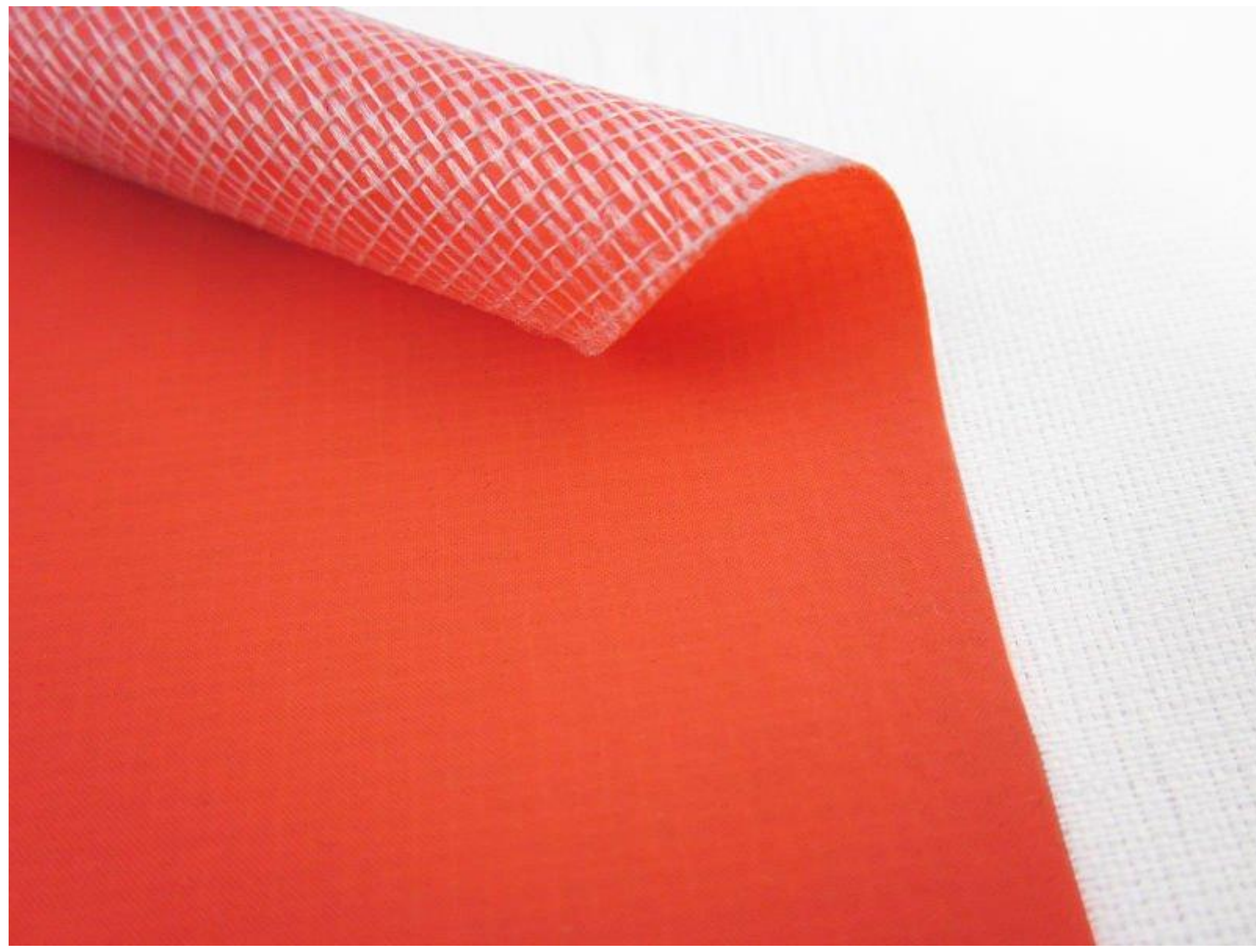


Figure 103) Vinyl Coated Polyester

The molten vinyl coating (PVC) makes it waterproof with a high resistance to dirt, mildew, oil, salt, chemicals and UV. The vinyl coating on the fibers give the material added strength and durability. Vinyl coated Polyester is a very dimensionally stable fabric that does not tear with any ease, nor will it stretch, crack, rot or mildew.

The PVC coating liquid contains chemicals to achieve the desired properties of color, water and mildew resistance, and flame retardancy. Fabric can also be manufactured that contains high levels of light transmission or can be made completely opaque. After the coating has been applied to the scrim, the fabric is put through a heating chamber that dries the liquid coating. PVC coatings are available in a range of colors, although non-standard colors can be pricey. Colors may be subject to minimum order runs that allow the coating machine to clear out traces of any previous color.

Vinyl-coated polyester is composed of a polyester scrim, a bonding or adhesive agent, and exterior PVC coatings. The polyester scrim supports the coating (applied initially in liquid form) and provides the tensile strength, elongation, tear strength and dimensional stability of the finished fabric. The scrim is made of high-tenacity, continuous-filament yarns, which have high dimensional stability, and can be bent thousands of times without losing any tensile properties. The base fabric's tensile strength is determined by the size (denier) and strength (tenacity) of the yarns and the number of yarns per linear inch or meter. The bigger the yarn and the more yarns per inch, the greater the finished product's tensile strength. For architectural applications, base fabrics typically weigh between 0.084 and 0.33 kg/m², with a tensile strength between 52 N/cm and 114 N/cm, although fabrics intended only for tent use may have lower measurements.

The adhesive agent provides a chemical bond between the polyester fibers and the exterior coatings and prevents wicking of moisture into the fibers. Wicking is the capillary like action of fiber to absorb water, which could result in freeze-thaw damage.

this fabric comprises of polyester strands (giving the strength) coated in PVC (to give the protection from the elements). It usually offers the best compromise between performance and cost as lifespans of up to 30 years are available for about a third of the cost of using PTFE. It also offers good translucency and fire retardancy and is available in a range of colors.
It must be noted that PVC fabrics are available in a massive range and at the lower end they only last a couple of years and exhibit very few of the positive characteristics noted above.

PVC (Polyvinyl Chloride) fabric membrane is the most widely used tensile and tension membrane fabric. PVC is commonly produced in white, but can be produced in a multitude of colors depending on individual project requirements.

Figure 104) Research Laboratory Venafro, Pozzilli, Italy 1992

The membrane material of the roof is a PVC-coated Polyester fabric with tensile strength of 150 kN/m in warp and weft direction.

When produced in white, this flexible fabric membrane reduces radiant heat gain thus keeping interior temperatures cooler in warmer environments and saving energy. PVC is commonly coated with protective acrylic lacquer, PVDF alloy or 100% PVDF top coatings.

Main Properties

Non-Wicking

The ability of a material to resist moisture from wicking into the polyester yarns is important for both structural and aesthetic reasons. Continuous filament polyester yarn can pull water into the space between the filaments by capillary action. If allowed to do so, this moisture can affect the adhesion properties of the material, causing seam problems or delamination of the coating compound. Even small amounts of moisture present in the base fabric can be a source of fungal growth, causing the material to discolor. This creates an aesthetic problem when viewed from the inside of the building.

Non-wicking properties are achieved by the selection of polyester yarns, the adhesive coat, and the coating procedure. In recent years, the use of anti-wick polyester yarns has greatly reduced the problems associated with wicking. The yarns are treated with a finish by the yarn producer to reduce wicking. In addition, the application of an adhesive coating compound that fully saturates the base fabric is another effective way to eliminate wicking.

Ultraviolet Light & Weathering Resistance

The principle in extending the life of a structure is to maintain the tensile strength of the base fabric. To do this, it is necessary to protect the base fabric from UV light and other factors. With PVC-coated polyester fabric, it is the top exterior coating compound that provides protection from UV light. The PVC compound must be formulated to either reflect UV light or absorb the light, so that the UV light cannot affect the base fabric or the PVC compound itself. This is normally accomplished with the proper selection of pigments, the use of UV absorbers, or a combination of both. The formulating process gets further complicated when considering the desire for different color structures or light transmission into the structures.

Fungus and Mildew Resistance

Architectural fabric structures are frequently used in hot and humid environments, which are susceptible to fungus and mildew growth. Fungus growth on a PVC-coated polyester fabric can be not only an aesthetic problem but can lead to structural problems with the material. Frequently, fungus growth on a structure begins with a collection of dirt on the surface of the material.

To minimize the potential problems of a fungal attack on the material, manufacturers will incorporate a fungicide into the adhesive coat and the exterior coating compound. In addition, the use of a top-coating system to reduce dirt collection on the material will help reduce fungal attacks. While not a routine test, laboratory testing is done when a material is developed to assure that the material does not support the growth of fungus or mildew.

Flame Resistance

Architectural fabric structures are frequently used in hot and humid environments, which are susceptible to fungus and mildew growth. Fungus growth on a PVC-coated polyester fabric can be not only an aesthetic problem but can lead to structural problems with the material. Frequently, fungus growth on a structure begins with a collection of dirt on the surface of the material.

The best way to describe the flame resistant characteristics of a PVC-coated polyester fabric is to refer to it as a "limited combustible" material. The material will burn when in the presence of a flame source, but will be self-extinguishing once the flame is removed. This property can actually be an advantage when considering what happens during a fire inside an architectural fabric building.

Silicon-Coated Fiberglass

Silicone coated fiberglass is an inexpensive alternative to PTFE with many of its attributes. It has very high tensile and tear strength and is more flexible than most other materials. The seaming process requires an adhesive that takes less time to cure than PTFE, which reduces labor cost. It is long lasting, flame resistant, stable, and is available in a range of colors and translucence.

Silicon coated fabric has a greater tensile strength than polyester coated with polyvinyl chloride (PVC), however being slightly brittle in its nature it can be subject to damage from prolonged flexing. Silicone coated fabrics 'as with PTFE fabrics' are not subject to ultra violet attack, which is why they have an expected 30-years plus lifespan.

Silicone Coated Fiberglass Fabrics are made from woven fiberglass substrates that have been coated on one or both sides with silicone rubber. The products surface friction is much higher than that provided by a fabric coated with PTFE, yet allows the user to retain comparable release characteristics. In fact, some products that may adhere to PTFE coated fabrics may not adhere to silicone coated surfaces.

Silicon Coated Fiberglass Cloth is a unique cloth constructed from a fiberglass base cloth and coated, on single or both sides, with a specially compounded silicon rubber. It possesses the properties of high temperature-resistance, anti-corrosion, high strength, durability and longer life-expectancy. It is widely used in aerospace, chemical industry, machinery, metallurgical industry etc.

These fabrics exhibit the strength and tear resistance of fiberglass, as well as, provide excellent release properties. The silicone coating has a high chemical resistance, which is impervious to mild alkalies, non-oxidizing acids, most salts, mineral and lubricating oils, air, moisture and sunlight. The non-toxic, odorless and tasteless qualities of the coating enable the fabric to be used in many food handling operations.

Figure 105) Silicon Coated Fiberglass

Features:

-High strength and tear resistance
-High dielectric strength
-High resistance to wear and flexing
-High chemical resistance, impervious to mild alkalis, non-oxidizing acids, most salts, mineral and lubricating oils, air, moisture and sunlight
-Operating temperature range from -100°F to +500°F
-Non-toxic odorless and tasteless

Main Properties

Translucency

Silicone Glass is an elegant option offering up to 42% light transmission in white. This strong, yet lightweight glass fiber fabric is available in an array of colors allowing architects, designers and end users to add bold color to their landscape.

UV Allowance

One of the many benefits of Silicone Glass fabric is its ability to block out short wave UV-B light. UVB is harmful to people and animals. Silicone Glass does allow the transmission of UV-A light which essential for photosynthesis, allowing plants to grow under a structure made of this dynamic fabric.

Figure 106) Italian Pavilion, Shanghai, Expo 2010

Figure 107) Zenith Music Hall, Strasbourg, 2008

Silicon coated fiberglass realized some improvements in tear strength, handling, translucency, and cost, but a number of structures developed problems with seam strength and dirt accumulation that raised concerns about the material. At present, the material has not found a secure position in the marketplace.

Being a type of rubber, silicone is very flexible, and when coated on fiberglass, can reduce damage from folding. Silicone when burned (at high temperature, given its high heat resistance) leaves merely an ash of silica dioxide.

Mechanical Characteristics

The Silicone provides a somewhat "softer" costing for the brittle fiberglass fibers, which proponents of the material believe prevents the fiber glass filaments from abrading each other when the material is creased or mishandled. Several portable or seasonally erected structures have in fact been built using silicon coated fabrics. Other believe that the softness of softness of the coating allows the fabric to bend to such a small radius when creased that fiberglass filaments are more easily broken. Flex fold testing appears to indicate that PTFE and silicon coated materials retain a similar percentage of their initial strength when creased.

While the softness of the silicon coatings allows undamaged fiberglass fibers to rope slightly at the end of cut or tear in the fabric, testing to date has not demonstrated a significant improvement in tear strength.

Silicon coatings unlike PTFE coatings are not applied at temperature that crimp the fiberglass fibers upon cooling, because of this, the full stiffness of the fiberglass yarns is realized in the finished fabric, which has extremely high stiffness in both warp and fill directions that makes it unforgiving of errors in patterning or fabrication. (Geiger 1989)

The builders of silicon coated fiberglass structures had difficulty in creating seams between the strips of fabric within a structure, resulting in major seam failure on several structures. Unlike PTFE coated fiberglass structures that use heat welding of seams, silicone coated fiberglass seams must be made using adhesives, and some engineers prefer to limit the use of silicone coated materials to designs where fill fiber (and seam) stress can be maintained at a low level (Huntington 1990).

Durability

The "softer" properties of the coating that improved its handleability and tear resistance also made it more susceptible to the accumulation of stains from dirt, pollution, or other sources. Some stains proved difficult to remove and the initial pristine whiteness of the fabric was difficult to maintain. Structural engineer Horst Berger mirrored the frustration of others with this property of the material in saying "the cleaning problem (with silicon) can be solved. All you need to do is find a way to close those little pores with something other than dirt" (Berger 1992, personal communication).

Light Transmission

Early materials had translucence of 35 % or more with high strength fabric, while PTFE produces of the time were limited to less than 20 %. The materials provided daylighting approaching that of glass skylights and permitted healthy growth of nearly all plant species.

Fire Resistance

Early silicon coated materials were limited in fire resistance, but more recently developed products have performed well enough on world wide standards to attain the noncombustible rating previously limited to PTFE coated fiberglass.

Cost

Both material cost and installed cost for structures using silicon coated fiberglass fall into a range generally below that of PTFE coated fiberglass but well above that for PVC coated polyester.

8 ETFE Film (Ethylene Tetrafluoroethylene)

ETFE (Ethylene Tetrafluoroethylene) is a lightweight material increasingly used in building applications. It has gained popularity mainly due to its daylight transmittance and the potential for energy savings. When used as cladding ETFE sheets are usually assembled into cushions, which are inflated for structural reasons. ETFE cushions can provide thermal insulation with reduced initial costs and less structural supports as compared with a conventional glazed roof. Limited research regarding the modelling of ETFE in building applications and limited availability of information on material properties led to the present study. Designers are currently facing difficulties when carrying out energy optimization studies as part of the design process. For example, since ETFE is not entirely opaque to longwave radiation, merely treating the material as a standard glass layer can lead to errors when evaluating its thermal performance. In order to enable building designers to assess the performance of these systems, maximizing performance and managing risk, it is essential to gain knowledge and develop methods to model this novel material. This study takes into account the longwave transmission properties of the ETFE material and discusses the need for a methodology for estimating surface temperatures, heat losses, and solar gains. Guidelines for integration are needed to define its properties and to evaluate performance during the building design process.

ETFE is a relatively new, lightweight material increasingly used in buildings, mainly due to its lightweight properties, its high daylight transmittance and the potentials for energy savings. When used for cladding, sheets of ETFE are usually assembled into cushions which are inflated (for structural reasons) by means of compressors. The system consists of two or more sheets of foil laid on top of each other and joined at the edges to form the cladding equivalent of an inflatable cushion. As stated, ETFE cushions can provide thermal insulation, with reduced initial cost investments and fewer supports compared with a glazed roof (Robinson, 2005). However, due to the lack of information on the material properties it

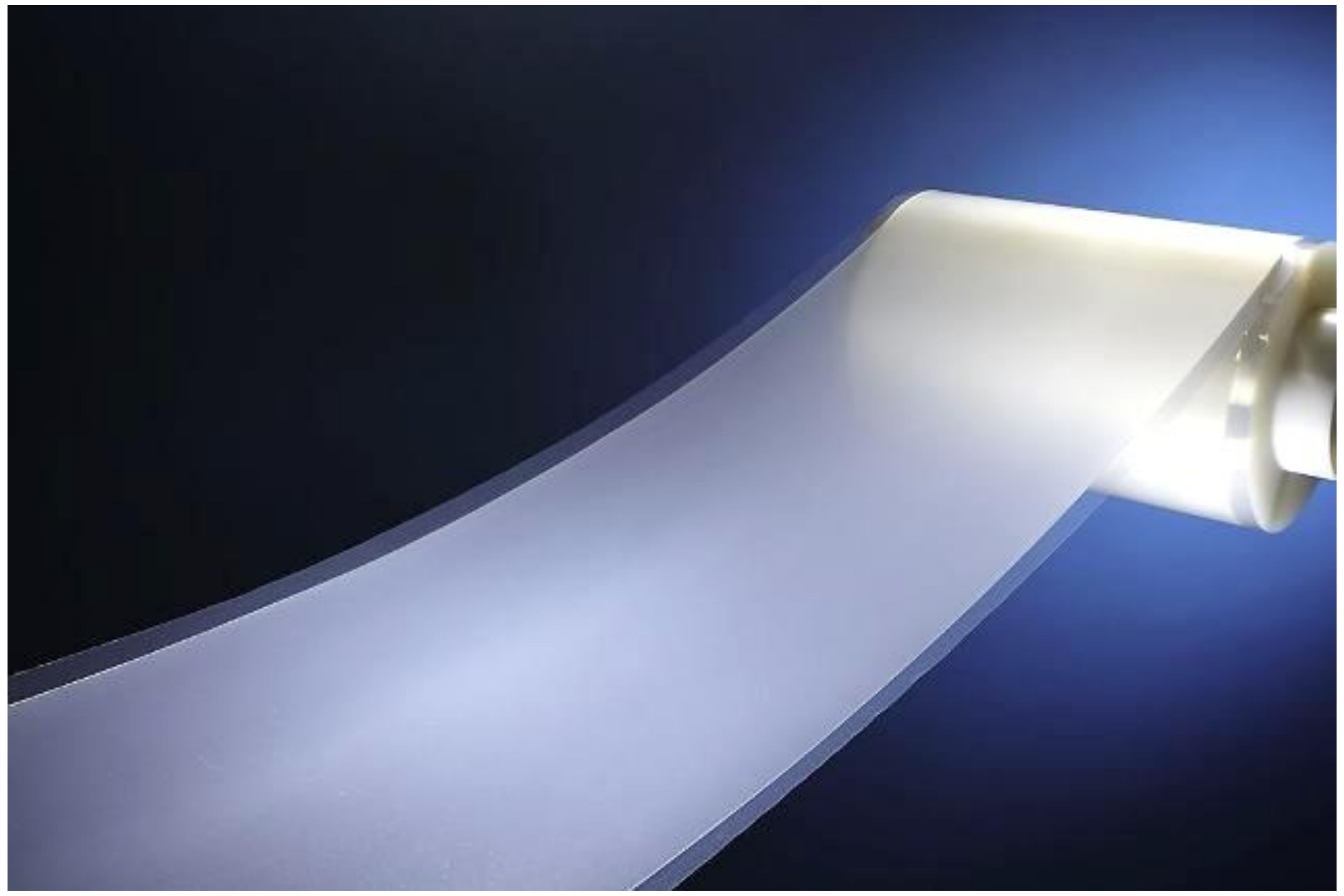


Figure 108) ETFE Film (Foil)

becomes difficult for designers to deliver energy performance optimized designs. Additionally, since ETFE is not opaque to longwave radiation, treating it as a glass layer can lead to errors, when evaluating its performance. Therefore, it becomes essential to gain knowledge and develop methods to model this material in order to maximize performance (and minimize risk).

This clear or translucent film has become very popular in the northern hemisphere when used to create entire structure out of ‘large ‘bubbles’, as it allows the use of transparent or translucent fabric while still attaining good thermal insulation characteristics. Like PTFE it is also very inert, and as such has a very long lifespan and exceptional self-cleaning and fire retardant properties, unfortunately it is also quite expensive.

ETFE is not a fabric but a film used as an alternative to structural glass. It can be supplied as a single layer membrane supported by a cable net system or commonly as a series of pneumatic cushions made up of between two and five layers. Multi-layer “foils” or “cushion” are attached to an aluminum perimeter extrusion which is supported by the main structural frame.

In the case of ETFE cushions, they are kept continually pressurized by a small inflation system the size of a washing machine which maintains the pressure and gives the foil a structural stability and the roof some insulation properties.

ETFE is a transparent material and has an approximate 85% light transmission. It can have frits or graphics applied to it to reduce its translucency.

ETFE foil has often been referred to as the miracle construction material. Used in the construction of both the Eden Projects mammoth greenhouse domes, and, for cladding the Beijing National Aquatic Centre ‘also known as The Water Cube’; ETFE is highly versatile.

A transparent / translucent polymer material, it can carry 400 times its own weight, can be stretched 3 times its own length ‘without effecting is tensile properties’, has a non-stick surface that repels dirt and is unaffected by Ultraviolet rays. Due to these amazing properties of ETFE, it has an excepted lifespan of over 50-years. However, it has a few drawbacks; these include the fact that it transmits more sound than glass, requires a more complex inflation based (cushion design) installation process, making it impractical for residential or smaller project applications. However, with the latest heat weld techniques, ETFE can be installed in a single layer form that is supported by thin steel cables; improving on installation practicality and overall maintenance requirements.

In part II of this thesis we will fully discuss the possibilities, properties and opportunities of using the ETFE foils.

Figure 109) National Space Center, Leicester, England, 2001

History

ETFE (Ethylene Tetrafluoroethylene) has been originally developed by DuPont over 40 years ago as an inert coating material for the aerospace industry. ETFE film, then conventionally used in agricultural applications such as greenhouses or for the coating of solar cells has since demonstrated its worth in the architectural sector as well. The first application in the building industry took place in the early 1980s in Europe. With the Eden Project in Cornwall, UK, the tremendous potential of ETFE had been shown. With two major projects, the Allianz Arena for the 2006 Soccer World Cup and the "Water Cube" at the 2008 Beijing Olympics, ETFE film has gained recognition and is now being considered the premium material for transparent cladding applications whether in roofing or facade construction.

ETFE General Characteristics

The possibilities of ETFE may seem utterly 21st century, but it's not a newfangled product. The formula was originally developed in the 1970s by Dupont for use as an aeronautic insulation material. Made from a waste product of lead and tin mining, the resin in its raw state looks a bit like sugar.

After ETFE is heated up and extruded into a paperthin film, it can be welded into large sheets that can themselves be used as building skin or can be woven together into cushions pumped with air. The ETFE sheets are transparent, like glass, but are one percent of the weight of glass, transmit more light than glass, and cost 24% to 70% less than glass to install. ETFE sheets are also chemically inert, so they don't degrade under UV rays. Since the chemical compound of ETFE is related to that of polytetrafloroethylene (i.e., Teflon®), ETFE film is also nonstick, so it keeps itself clean.

Sweetening the deal in today's eco-conscious building market, ETFE is recyclable: At the end of its useful life—thought to be at least 50, but possibly up to 200, years—it can be melted down and reused. When ETFE sheets are fused into pillows and pumped with air, the material takes on both stability and high insulation properties, and the design possibilities are seemingly endless.

Using the unsurpassed optical properties of ETFE, in thin gauges, to replace glass, has often been attempted. The many advantages of its use in Architectural Constructions has long been recognized and has been a familiar sight in such structures

The most common usage of ETFE Foil is multi-layered cushions. Cushions are kept continually pressurized by a small inflation unit which maintains the pressure around 200-300Pa giving it structural stability, and insulation. Power consumption for the inflation unit is between 60-100w.

ETFE Films

The raw granulate is extruded into sheets called foil or film with a density of 1.012 oz. per cubic inch. ETFE is one of the most lightweight and transparent cladding materials. Due to low coefficient of friction of its surface, dust or dirt will not stick onto the film. As the film is UV transparent, it will not discolor or structurally weaken over time. ETFE can also be fully recycled.

The foil's surface is nonporous and has a low coefficient of friction, which allows the material to resist atmospheric pollution and the buildup of pollutants, dust or dirt particles. In addition, the material is unaffected by UV light and doesn't break down, discolor or weaken structurally over time. At the end of the material's fabricated use, it can be recaptured and fully recycled.

ETFE in Building Design

ETFE has approximately 95% light transmittance, but does not offer the clear visibility/transparency of glass (Robinson, 2005). As a result, ETFE solutions therefore initially found use on projects such as botanical gardens, zoological gardens, swimming pools, and exhibitions spaces. However, ETFE is increasingly finding its place in more traditional buildings as roofing for courtyards, shopping malls, atria and stores. The ETFE material has been used on prominent architectural projects such as the Eden Centre (Fig. 110). Previous ETFE studies have focused mainly on structural properties and related issues, while little research has been carried out in order to determine energy transmission properties and characteristics in terms of environmental building design.

transmittance through the ETFE layers, in practice ETFE foils are usually modelled as glazing units. Depending on the building use, the building design, the site, and geographical location of the building, this simplification may impact on the accuracy of the simulated building performance, as discussed in the following.

ETFE has been used for more than 25 years for transparent roofs and facade systems around the world, but only recently entered onto the world stage with the debut of the Allianz Arena for the 2006 FIFA World Cup in Germany (Fig. 111) and with the light-filled National Aquatics Center at the 2008 Beijing Olympic Games (Fig.112), both constructed of air-filled ETFE pillows. Now the material - with its diverse aesthetic and performance capabilities— is considered a material of choice for both traditional skylights and innovative building skins. Few other materials utilized as a building skin match its transparency, durability and strength.

Figure 110) Eden Project, Cornwall, Uk, 2001

Figure 111) Allianz Arena, Munchen, 2005

Figure 112) Beijing National Aquatics Center, 2008

Prior to these two projects, the most critical project relating to the technology's development was the Chelsea and Westminster Hospital in London, England (Figs. 113 & 114 & 115) designed by Sheppard Robson and completed in 1986. The Chelsea Hospital was instrumental in transitioning the use of ETFE from ephemeral programs — like exhibition, aquatic centers and zoo pavilions— to program types that had life-safety, performance and longevity concerns at the center of the system's evaluation. Additional performance testing and technical reports were commissioned during the system evaluation for this project. The success of these tests and the endorsements by leading experts that followed began to validate the use of ETFE within mainstream architecture, leading to further acceptance and awareness of the material and technology.

Today ETFE foils have penetrated the entire range of architecture programs, from hospitals to stadia and corporate complexes to highly secure governmental headquarters. Currently in North America several projects on the drawing boards will integrate ETFE foils, including a sculptural skylight designed to depict a DNA molecule at a major university medical complex and a prototype for a rooftop greenhouse that could be used on urban rooftops around the world.

Figure 113) The Chelsea and Westminster Hospital, Interior View

Figure 114) Interior View, The ETFE roof system allows maximum light transmission while retaining high insulation. Effective use of the Stack Effect enables easy ventilation of the central atrium space.

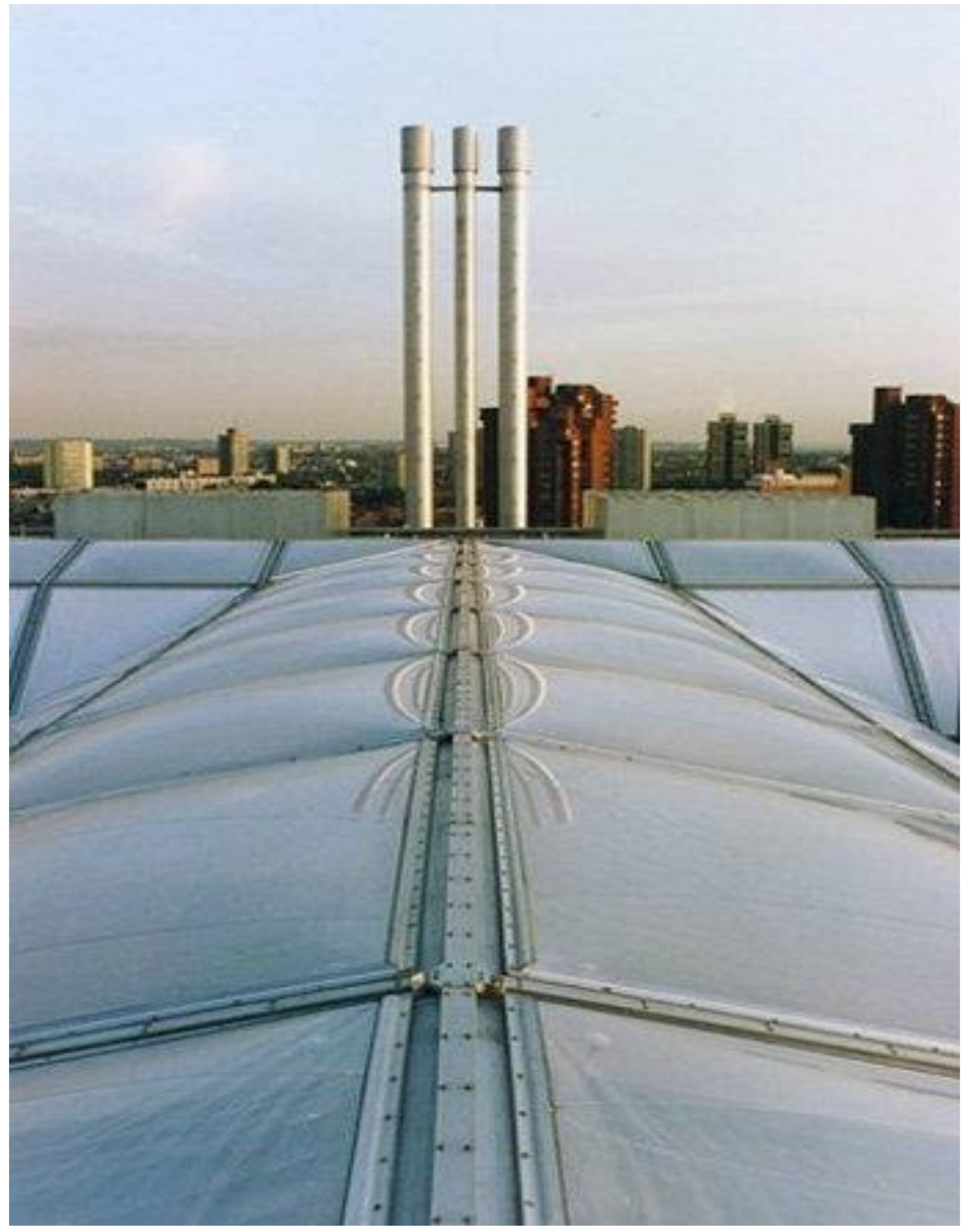


Figure 115) View from roof

ETFE Physical Properties

ETFE is distinguished from perfluopolymers (totally fluorinated polymers) as a partially fluorinated copolymer of ethylene and TFE. This chemical modification provides significantly higher strength relative to PTFE, FEP or PFA. It is less flexible than PTFE, but has superior impact strength, abrasion and cut through resistance. Addition of a third component to the chemical structure creates a modified ETFE that has lower weight per unit volume, is stiffer and tougher than PTFE, PFA or FEP. These properties allow it to withstand greater physical abuse during its lifetime. For example, glass reinforced ETFE has outstanding wear characteristics and may be used for bearing applications. ETFE is also suitable for pump impellers or moving parts of equipment that are operating in chemically aggressive environments.

Property	Value	Units	Method
MECHANICAL PROPERTIES			
Tensile Strength, 73°F	5500 – 7000 38 – 48	psi MPa	D 638
Elongation at break, 73°F	100 – 350	%	D 638 ??
Flexural Strength, 73°F			D 790
Impact Strength, Izod, 23 deg C	No break	J/m	D 256
Compressive Stress at 1% deformation,	1500 10.3	psi MPa	D 695
Yield Strength At 23 deg C	2800 19	psi MPa	
Density	1.7	gm/cu.cm	
Coefficient of friction	0.4		D 1894
THERMAL PROPERTIES			
Coefficient of Linear Expansion	9 x 10-5	K-1	
Melting Point	437 – 518 225 – 270	deg F deg C	
Thermal Conductivity	0.137 0.238	Btu·in/h·ft2·°F W/m·K	ASTM C 177
Specific Heat	0.45 – 0.48 1.9 – 2.0	Btu/lb/deg F kJ/Kg/deg K	
Heat Distortion Temperature, 66 lb/sq.in (0.455 MPa)	219 104	deg F deg C	D 648
Service Temperature	<-148 to 302 <-100 to 150	deg F deg C	
Processing Temperature	617 – 653 325 – 345	deg F deg C	
ELECTRICAL PROPERTIES			
Dielectric Strength, short time, 0.080”			
Surface Arc-Resistance	75 – 110	sec	D 495
Volume Resistivity	> 1016	ohm-cm	D 257
Surface Resistivity, @ 100% RH	> 1014	Ohm sq-1	D 257
Dielectric Constant, 60 Hz to 1 MHz	2.5	e	D150-81
Dielectric Strength	59 at 0.25 mm thick	kV mm-1	
Dissipation Factor, @ 1 kHz	0.0008		D150-81

Table 3) ETFE Physical Properties

Single Layered Application

ETFE can be applied in a single layered form and are reinforced with either wire cables, light weight steel or aluminum to maintain shape and stability.

Architects and designers are using ETFE single layer systems to create dynamic all weatherproof spaces. Because ETFE is lightweight, there is great cost savings to be had by reducing the size of the supporting framework and foundations.

The demand for economically priced materials to cover walkways is increasing, making ETFE very popular. Typical installations for single foil systems include bridging existing building, such as schools, to create dry space and covering walkways in shopping centers and transportation hubs.

With this system, there is no requirement for an air handling unit. Because the actual material has a slippery surface, dirt and algae do not stick to it, making maintenance minimal.

As ETFE is flexible, curvature can be introduced in the design of your covered space to create dramatic focal points that are functional.

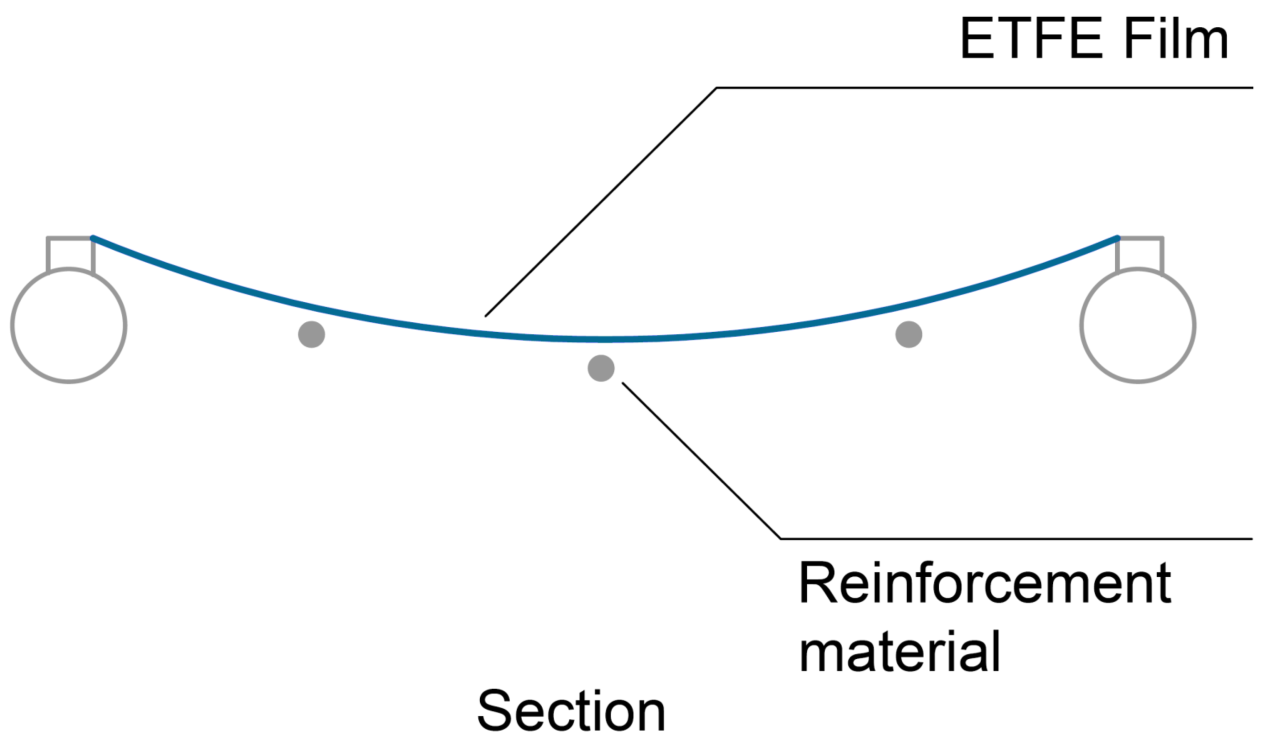


Figure 116) This configuration provides a unique visual effect, similar to the two and three layer configurations. The façade and roofing application is most common, with U values still reaching as low as 5.2 W/m²K.

Figure 117) Parc des Vergers de la Plaine, Chambourcy, France, 2012

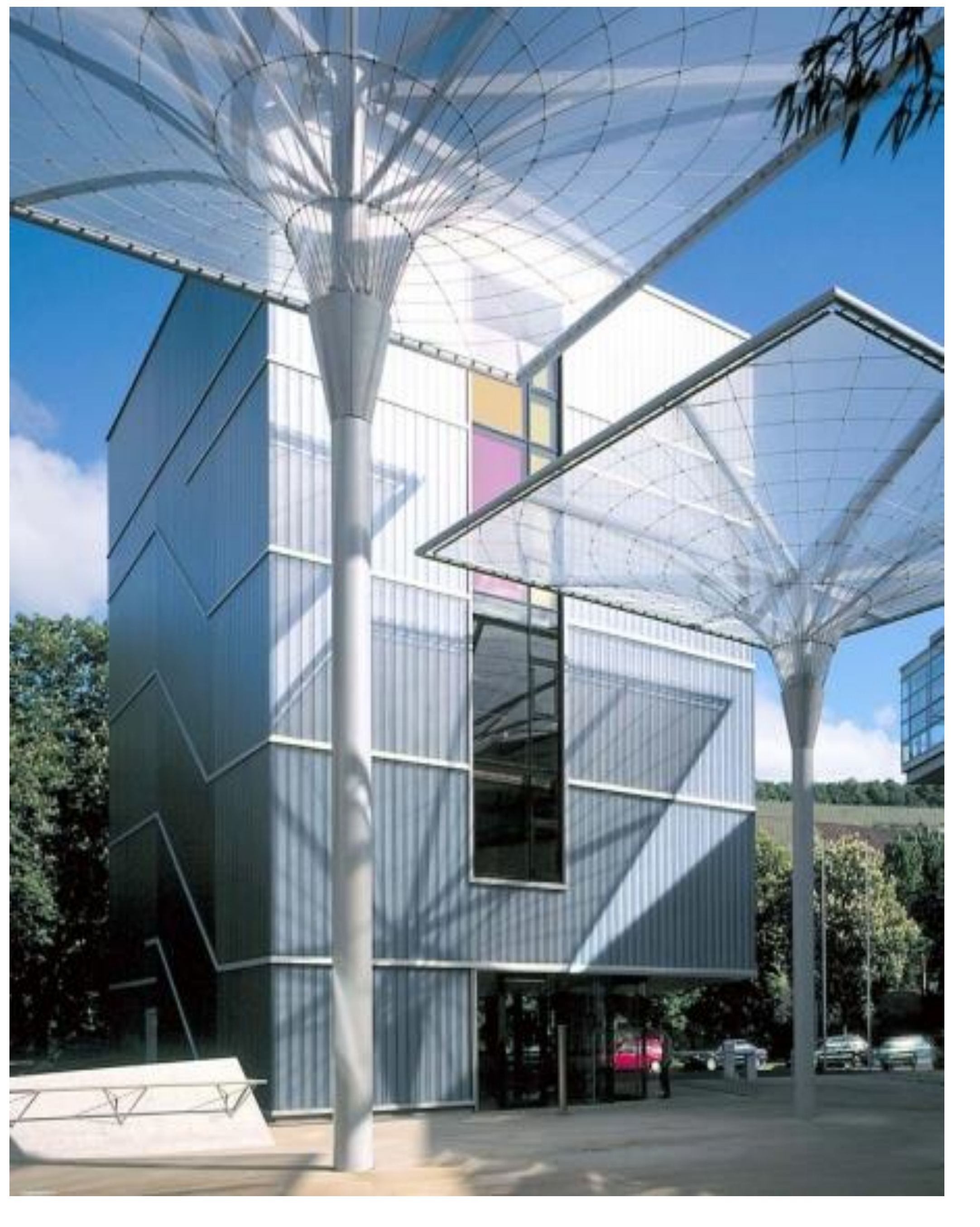


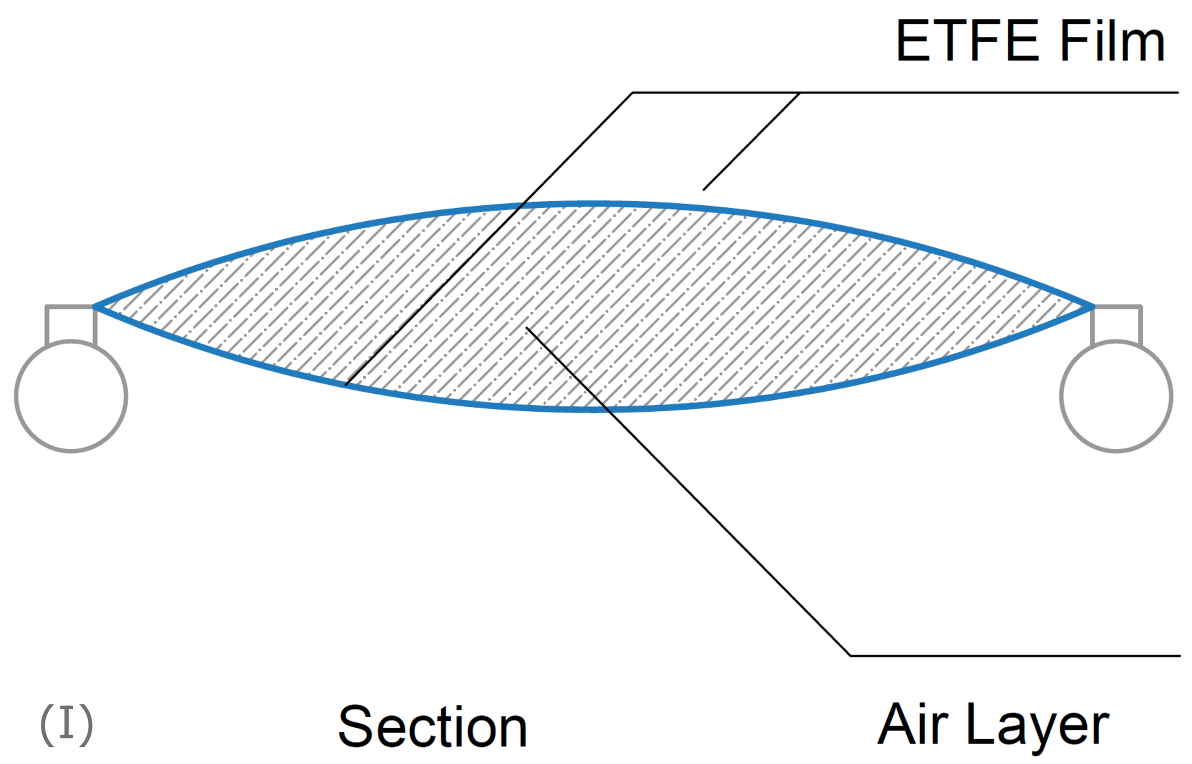
Figure 118) Funnel-shaped umbrellas for the IHK, Wurzburg, Germany, 2004

Figure 119) The Cloud, Auckland, New Zealand, 2011

Double or Triple Layered Application

In a double or triple layered application, ETFE film incorporates a pneumatic system to maintain air between 2 or 3 layers of film attached in aluminum extrusions and supported by a lightweight structure creating inflated cushions. These cushions are filled with low-pressure air, providing thermal insulation and structural stability against wind or snow loads. If needed, small cables can be used for reinforcement. Under usual loading conditions ETFE cushions can reach dimensions up to 60 m x 5 m.

When used as a pneumatic pillow, the cushion is restrained in aluminum extrusions and supported by a lightweight structure. The cushions are inflated with low pressure air to provide insulation and resist wind loads. The pneumatic construction resists external forces through the difference in internal and external pressure. Multilayered ETFE pillows also provide great thermal resistance which can be as effective as glass. Additionally, printed ETFE foil can provide target Shade Coefficients.



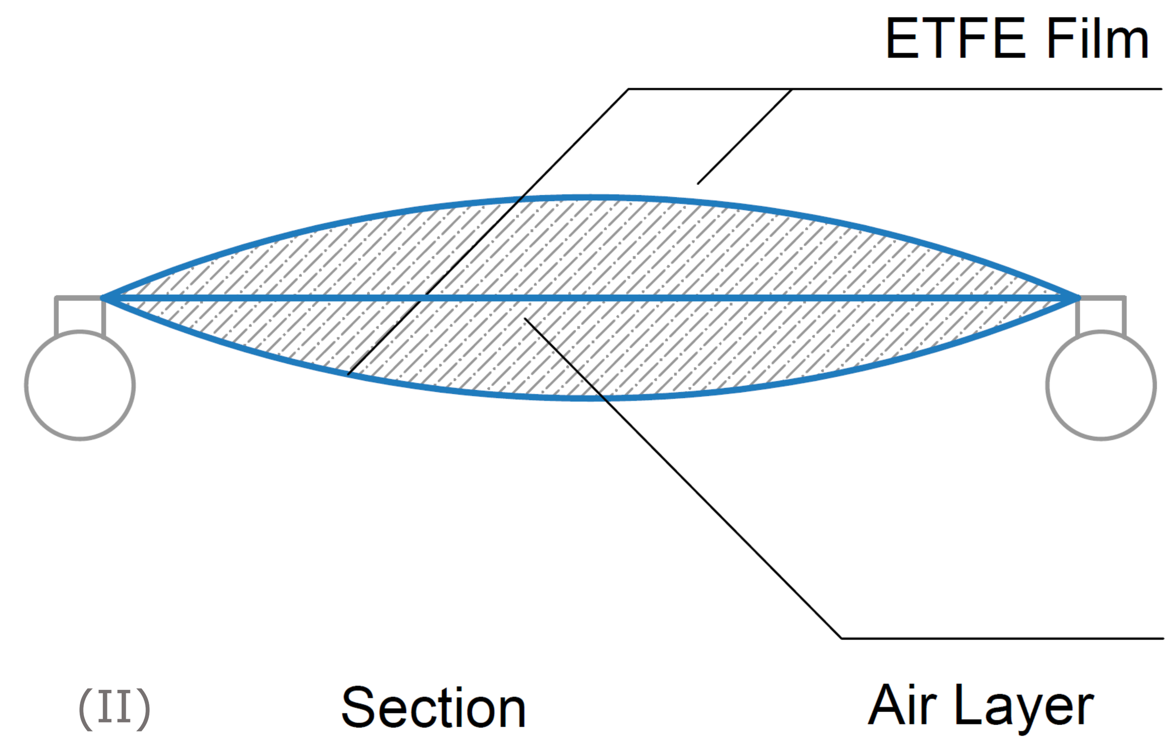


Figure 120) (I) This configuration provides efficient insulation with U values as low as 2.3U(W/m2K)

(II) This configuration provides superior insulation with U values as low as 1.5U(W/m2K).

Figure 121) Heated conservatory at the Botanical Gardens, Aarhus, Denmark, 2009

Figure 122) Media-TIC building, Barcelona, Spain, 2011

Figure 123) Residenzschloss, Dresden, Germany, 2008

Manufacturing

ETFE is not a derivative of a petrochemical. It is manufactured from fluorspar (CaF_2), trichloromethane ($CHCl_3$) – called chlorodifluoromethane (CHF_2CL) – and hydrogen sulfate (HSO_4). Chlorodifluoromethane is a raw material classified as a class II substance under the Montreal Treaty on ozone depleting substances. Class II substances are scheduled to be phased out but have a later timeline than Class I substances.

The by products formed during ETFE manufacture are calcium sulfate ($CaSO_4$), hydrogen fluoride (HF) and hydrochloric acid (HCl). The calcium sulfate and hydrogen fluoride are reused to produce more fluorspar which can be used again as in input into the manufacturing process.

The production process of ETFE-foils can be divided into three basic steps: firstly copolymerisation, secondly drying and granulation, and finally extrusion. Figure 6.29 shows the successive production steps of ETFE-foils to produce the finished product.

Copolymerization

With copolymerisation the long-chain molecules are created. In a chemical reaction the two monomer units ethylene and tetrafluoroethylene arc linked together. Catalysts crack the carbon compound of the macromolecules and hence additional monomer units can link. The product of copolymerisation is an aqueous solution.

Drying and granulation

The second production step is drying and granulation. The aqueous solution of copolymerisation is transformed into granules by separation and drying. ETFE granules are frequently generated by a granulation machine as shown in Fig.125 . The solution of copolymerisation flows over a metal sheet. The temperature of the aqueous solution drops.

(I)

(II)

(III)

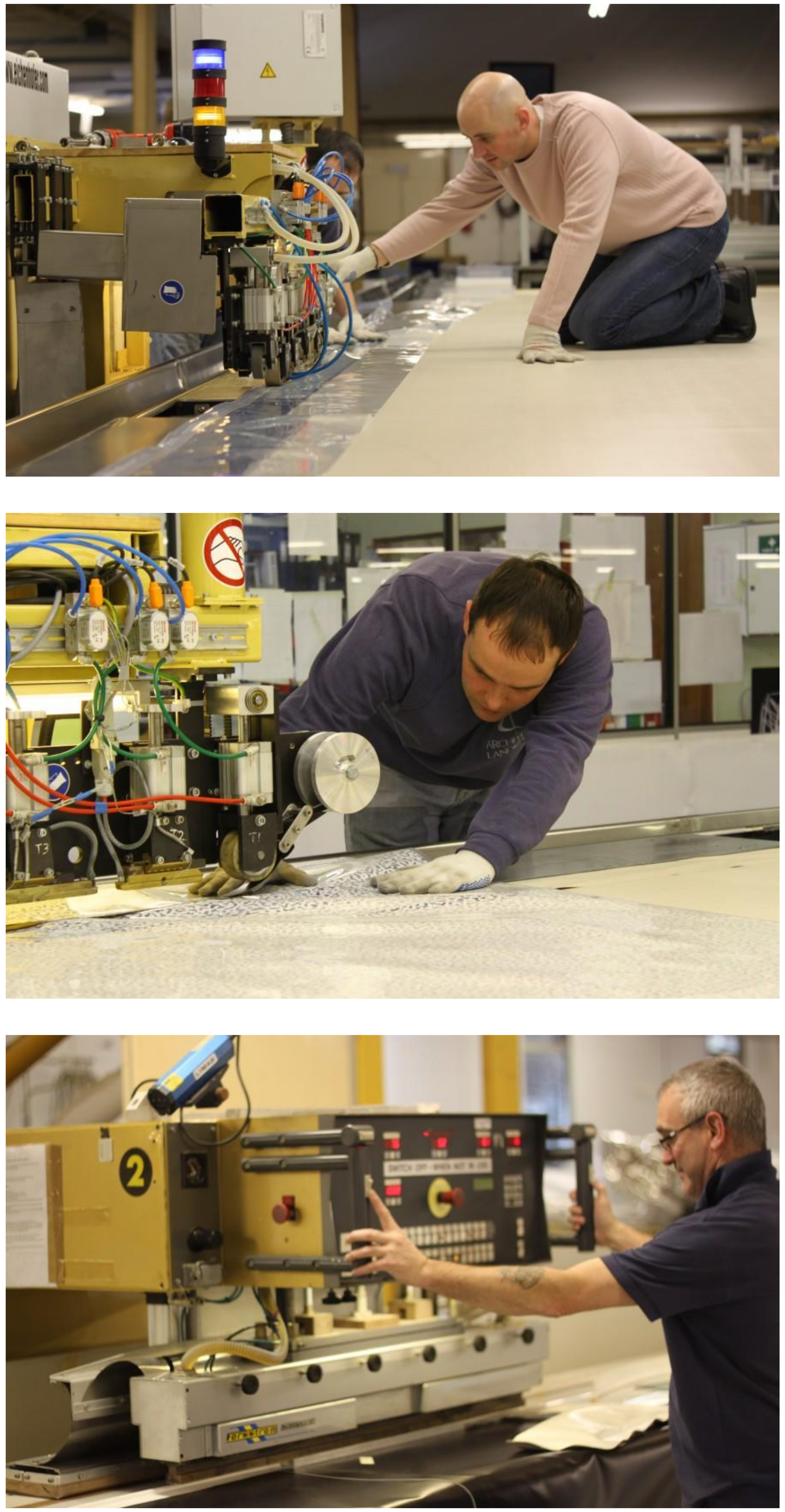


Figure 124) Preparing ETFE foils, cutting and welding

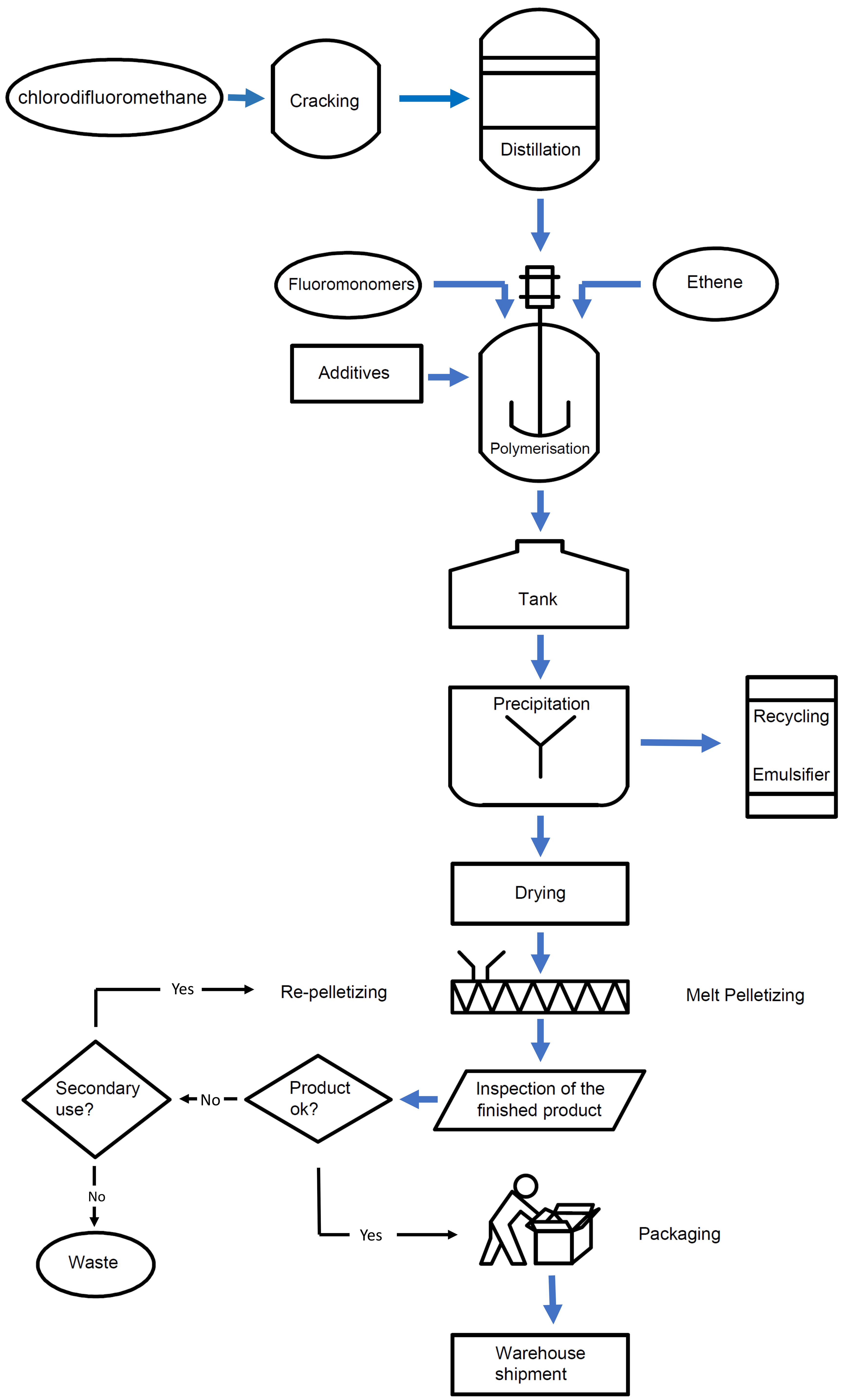


Figure 125) Flow chart of ETFE granulate production

At the end, traces of the solution are cut into pieces. The pieces are cooled, dried and finally formed into granules. The generated granules are easier to handle and easier to store than the aqueous solution of copolymerisation. At this point colored granules or granules of recycled foils could be added.

Extrusion

The final step is the extrusion of the ETFE-foil. In this step granules are processed to the finished rolled foil. The granules will be filled, e.g. into a single-screw extruder. Inside the extruder the granules melt. The screw transports the semi-fluid material with defined velocity, temperature and pressure. The forming tool at the end of the extruder consists of a nozzle with a defined gap. The thickness of the produced film depends on that gap. The width is defined by the length of the nozzles. Standard thicknesses of ETFE-foils are today 12 pm to 300 pm (0.012 mm to 0.30 mm). The width of the foil depends on manufacturer, but the foils are nowadays produced up to a width of 1.60 mm.

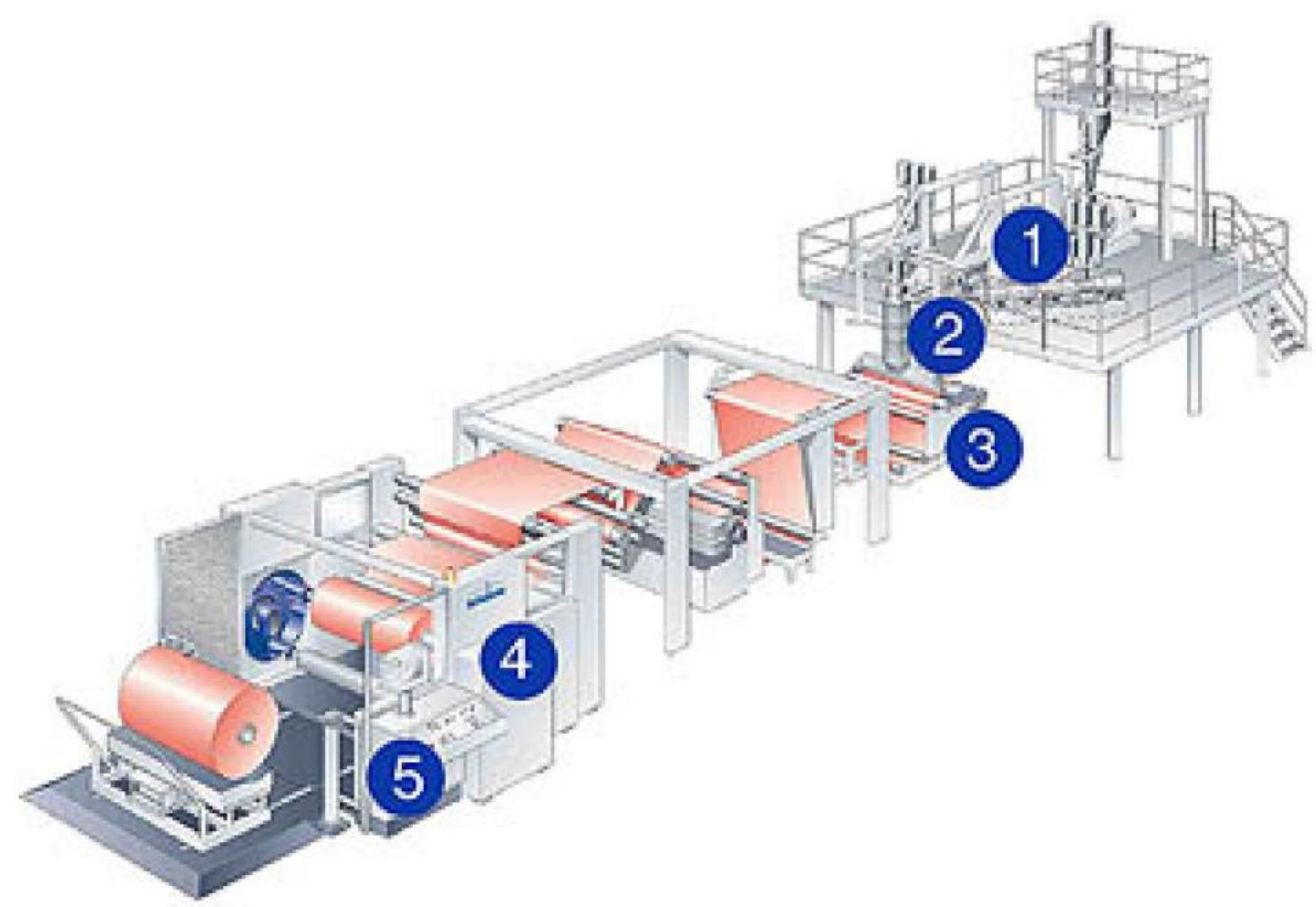


Figure 126) ETFE foil production line; 1) extruder, 2) shaping, 3) casting, 4) winder, 5) automation

Main Properties

Light Transmission

ETFE films can be highly transparent (from 90% to 95%) and allow for the passing of UVs which are responsible for the promotion of photosynthesis thus facilitating plant growth. It is also important to note that the film absorbs a large proportion of infra red light transmitted, a quality which can be exploited to improve buildings energy consumption.

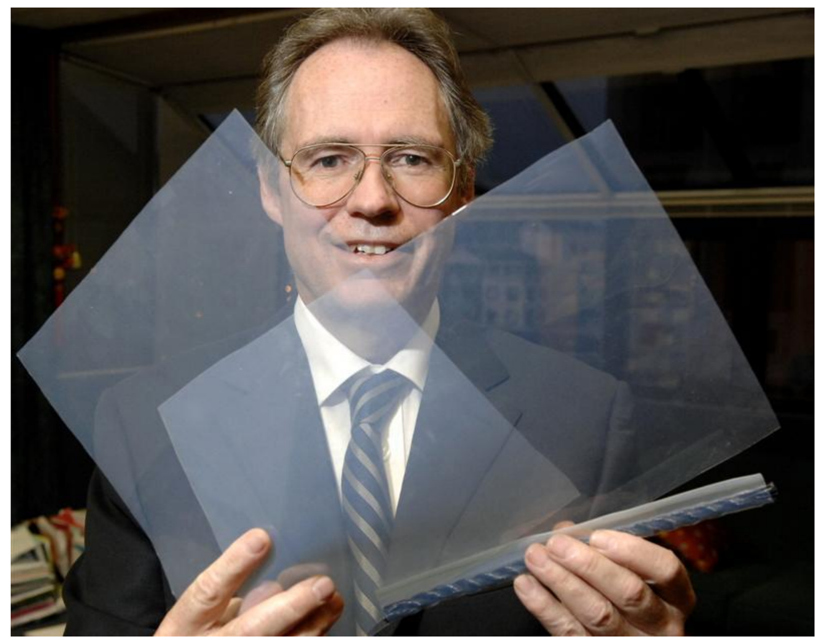


Figure 127) ETFE transparency

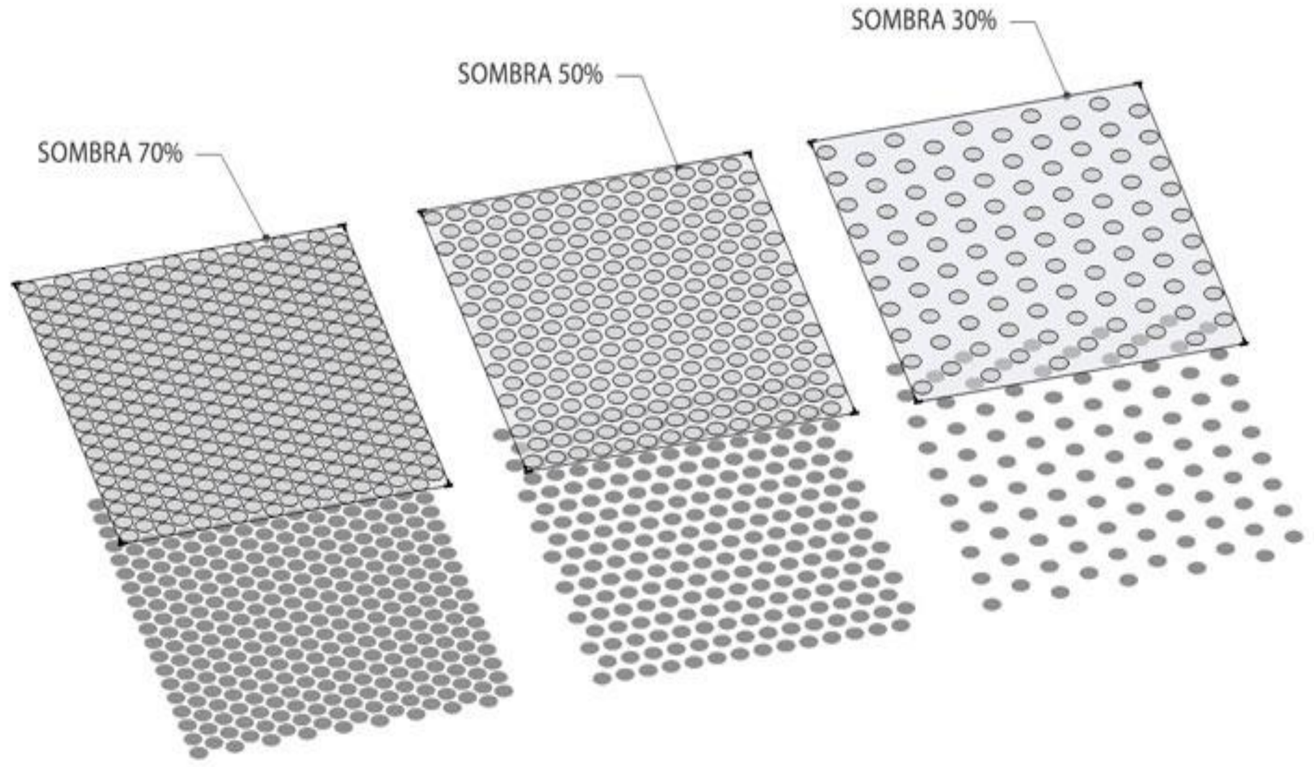


Figure 128) Different coatings for solar controls

Solar Control

As described above, the base material of an ETFE installation is very transparent, however, the ETFE Foil can be treated in a number of different ways to manipulate its light transmission properties :

- Printing: Also known as fritting, the surface of the foil is covered with a variety of patterns to reduce solar gain while retaining translucency. By varying the percentage of coverage and density of the ink, the energy transmission can be altered. Alternatively, the foil can be over printed with a number of treatments to affect transmission. We offer a standard range of over 20 standard fritting patterns to achieve this variety of light transmissions, however, bespoke patterns are available at an extra cost.
- Tinting: A selection of colored foils are also available, although less readily than the standard clear foil. Colored foils can be used alongside clear foil to incorporate branding and large scale imagery. White ETFE foil can be used to reduce glare but maintain some light transmission and insulation properties.

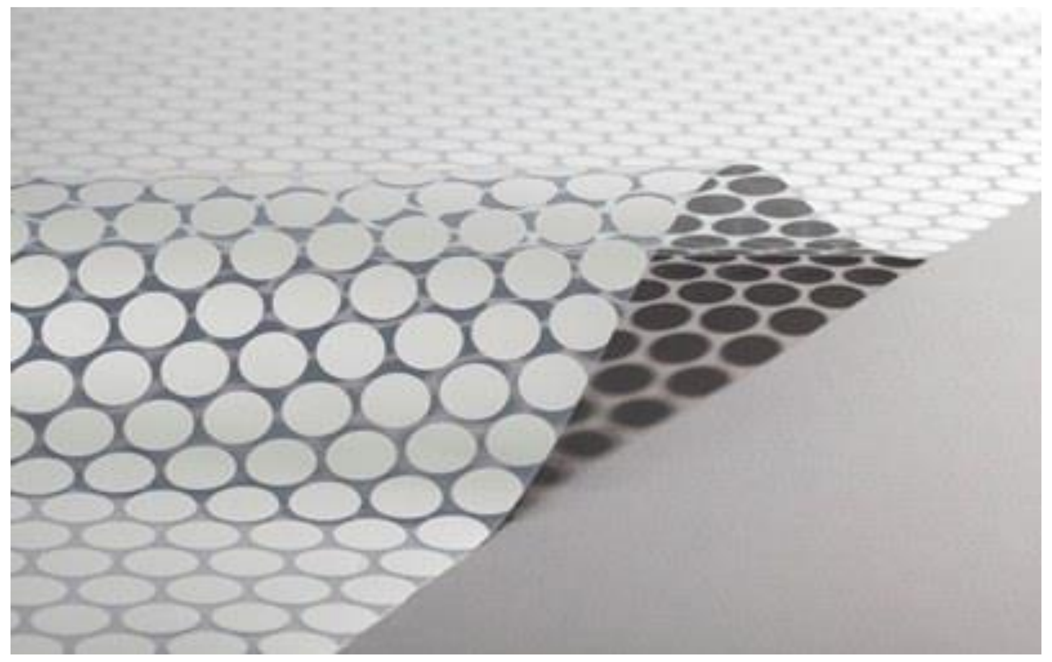


Figure 129) Partially coatings, sample photo

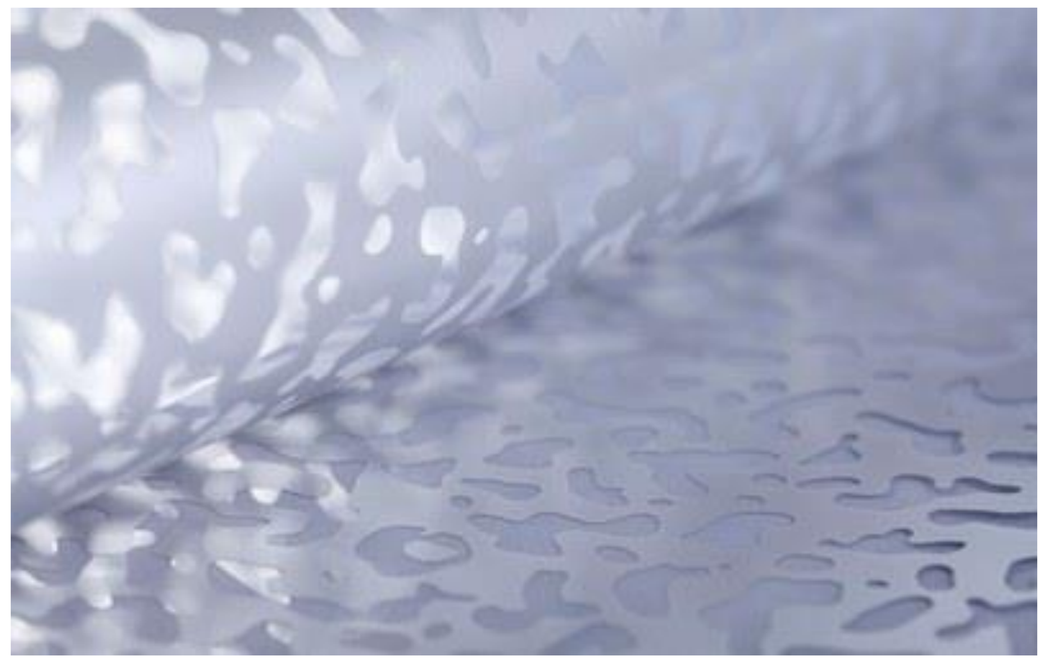


Figure 130) Partially coatings, sample photo

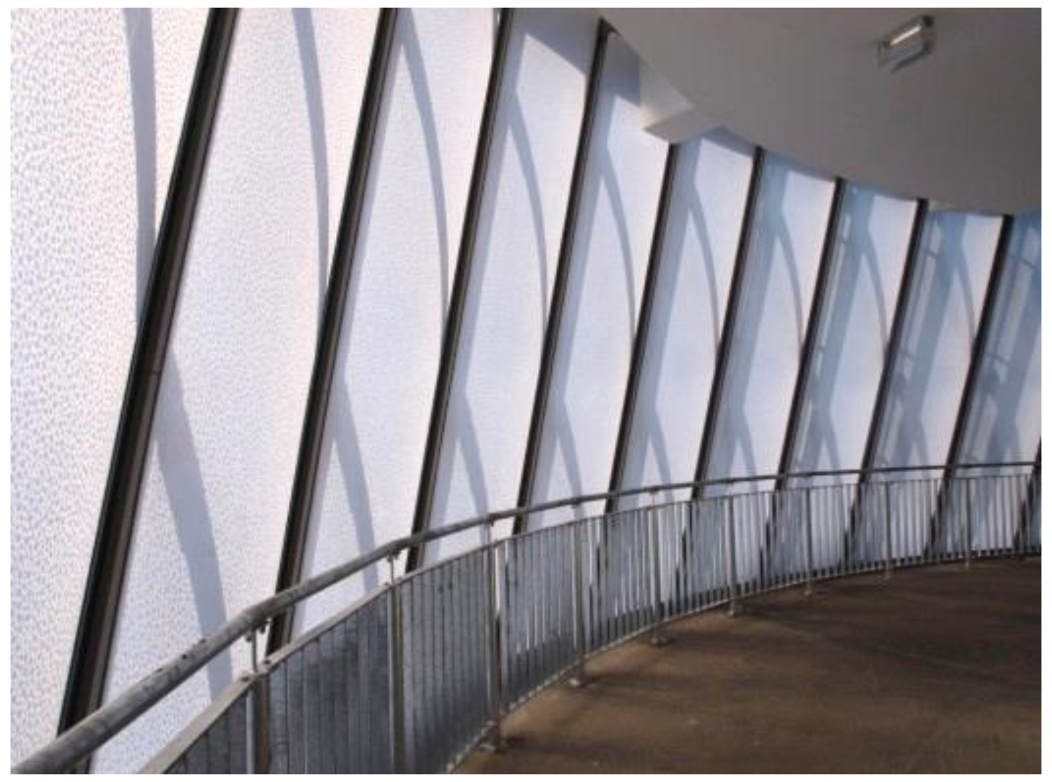


Figure 131) Hamburger Meile Mall, Hamburg, Germany, 2010
Interior View of Printed ETFE

Figure 132) Hamburger Meile Mall, Exterior View

- **Surface treatments:** Surface treatments undertaken during the manufacturing process can vary the properties of the fabric and allow us to manipulate light transmission. These treatments render the foil matt in appearance and therefore provide an excellent projection surface for light shows and images.
- **Radiation:** The foil be conditioned with a range of radiation treatments which can reduce the levels of IR and UV rays transmitting through the membrane skin.

Adding additional layers of ETFE foil to a cushion also allows light transmission and solar gain to be controlled. Multi-layer cushions can be constructed to incorporate movable layers and intelligent (offset) printing.

G Value

The G value of an installation reflects the fraction of solar energy transmittance through glazing. This is usually expressed as a percentage or a value between 0 & 1; the higher the number, the more energy is being transmitted through the glazing and the more the building will heat up.

The G value of an ETFE roof can be reduced to as little as 0.48 for a 2 layer system with a fritted top surface and to around 0.35 by using a 3 layer system. For comparison, standard glass is approx. 0.88 whereas some specially treated glass may be as low as 0.46.

Fire

The material is approved fire resistant Class 1 in Italy and B1 in Germany according to DIN 4102: extremely natural safe without any additives. Even when burning, the material shrinks, not spreading flames by falling fragments.

ETFE Foil as a material has low flammability (270C) and is considered self extinguishing. In the event of a fire, hot smoke will cause the foil to soften, fail and then shrink away from the fire source to create natural ventilation. The quantity of material used in the roof is not important in this situation the foil will not create molten drips or any fumes.

Figure 133) Fire resistant Class 1 in Italy and B1 in Germany

Acoustics

ETFE foil cushions are a relatively transparent form of roofing which means that there are minimal acoustic benefits in its natural state.

Rain noise can be suppressed using a rain attenuation layer added to the top surface of the cushions. This acts as a dampener, stopping the sound reverberating around the space below. In general, the installation of a rain attenuation layer is only necessary in exceptional circumstances. This can be retro fitted to the ETFE foil cushion system.

Sustainability

The raw material associated with ETFE is a class II substance admitted under the Montreal treaty. Unlike its class I counterparts it causes minimal damage to the ozone layer, as is the case for all materials used in the manufacturing process. The production of ETFE involves the transformation of the monomer TFE in to the polymer ETFE using polymerisation; no solvents are used in this water based procedure. The material is then extruded to varying thicknesses depending on application; a process which uses minimal energy. Fabrication of the foil involves welding large sheets of the ETFE; this is relatively quick and again a low energy consumer.

From extruding of the film to transportation to site, compared to other similar cladding material, little energy will be consumed thus reducing the overall carbon footprint. In addition to this, the nature of the product enhances the building physics through insulation and daylighting, therefore contributing to the global low energy aspect of the building.

ETFE systems are composed of "green" materials with low embodied energy and are demountable and recyclable. However, the most sustainable attribute is the system's ability to become a catalyst for holistic sustainable design, driving building performance and creating facilities that are environmentally significant and conscious. This result and the ultimate building performance a greater ecological effect than the sum of its parts. Areas that has drive these holistic sustainable opportunities include natural ventilation, reduction of structural tonnage and controlled light transmittance for daylighting.

Its low weight results in lower C02 emissions (Ref 11) and requires far less structural support than other transparent building systems such as glass. In fact the carbon footprint of ETFEis said to be 80 times lower than that of comparable transparent systems (Ref 13).

Figure 134) ETFE systems are composed of "Green" materials with low embodies energy and are demountable and recyclable

Elasticity

While ETFE films are very elastic (up to 600% at breaking point), they are still structurally resistant. The tensile strength at the limit of elasticity/plasticity is 21-23 N/mm^2 but tensile strength to breaking point is $52/Nmm^2$. For structural calculation a limit of 15 N/mm^2 is conservatively usually taken.

Fully Recyclable

Easily recyclable, waste from the manufacturing process or even old ETFE elements can be remolded into new ETFE products such as tubing components, wires or castings.

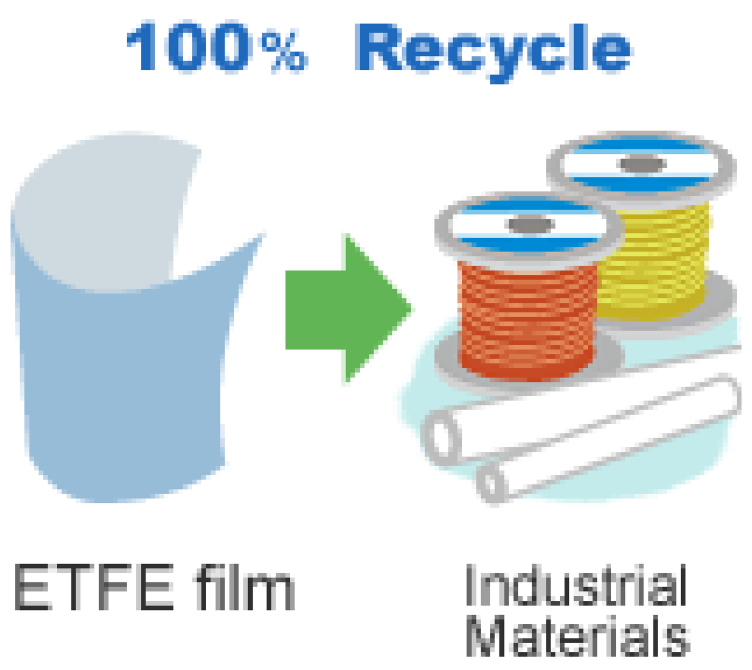


Figure 135) ETFE foils can be transformed to new products such as tubing components wires and castings.

Durability

ETFE Foil has an excellent life expectancy as it is unaffected by UV light, atmospheric pollution and other forms of environmental weathering.

While no ETFE structures have been in place for long enough to gain a true understanding of the life cycle of the foil, the material has been extensively researched and tested in a laboratory environment and out in the field. These tests have concluded that no degradation or loss of strength has occurred and there is no sign that the material will become brittle or discolor over time. As a result, it is anticipated that the material has a life expectancy in excess of 30 years.

			Value After Weathering					
Property	Unit	Original Value	1 Year	2 Year	3 Year	5 Year	7 Year	10 Year
Tensile strength (md)	N/mm^2	46.7	45.6	46.2	44.9	46	48.4	52.4
Tensile strength (cd)	N/mm^2	42.3	43.8	45.5	42.6	44.8	42.4	44.6
Yield strength (md)	N/mm^2	22.6	22.5	25.0	22.3	23.2	22.8	22.5
Yield strength (cd)	N/mm^2	18.8	21.4	22.0	–	22.3	21.0	21.5
Elongation at break (md)	%	330	340	310	345	315	325	340
Elongation at break (cd)	%	390	405	390	390	410	390	405
Tear strength (md)	N/mm^2	420	430	415	445	440	523	–
Tear strength (cd)	N/mm^2	435	425	420	480	430	531	–
Scatterered LT	%	8	8	11	9	11	11	8
Straight-lined LT	%	87	88	83	86	85	85	88
Total LT	%	95	96	94	95	96	96	96

Table 4) Weathering test on ETFE films in Arizona, USA (source Hoechst, Dyneon, 3M) md = machine direction, cd = cross direction, LT = light transmission

Maintenance / Cleaning

Due to the non-adhesive surface properties of the ETFE, deposits of dirt, dust, and debris do not stick and are washed away by the rain resulting in a "self-cleaning" effect. However, as for all mechanical equipment and their components, it is necessary to perform a yearly inspection. The inspection includes all necessary checks on the air blower system and filter replacements. The ETFE film and its attachments will also be inspected for possible damages to prevent any further deterioration.

Safety

Due to the high resistance and elasticity of the ETFE, it is an ideal building component where sudden extreme loads such as earthquakes or blast may occur. Unlike glass that will shatter and cause major concern under similar shock load situations, ETFE will either deflect under load or even in case of breakage, is unlikely to cause any major damages. ETFE is, however, not suitable as vertical railing and cannot prevent from intrusion.

a b

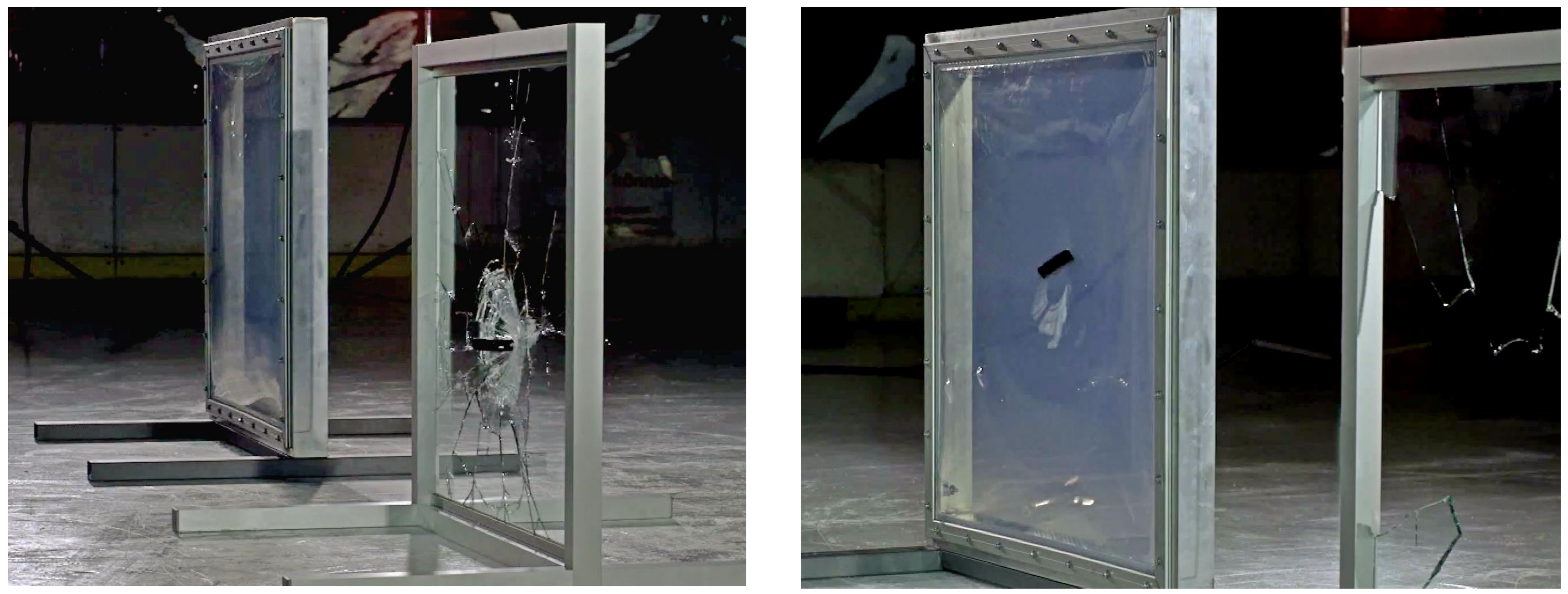


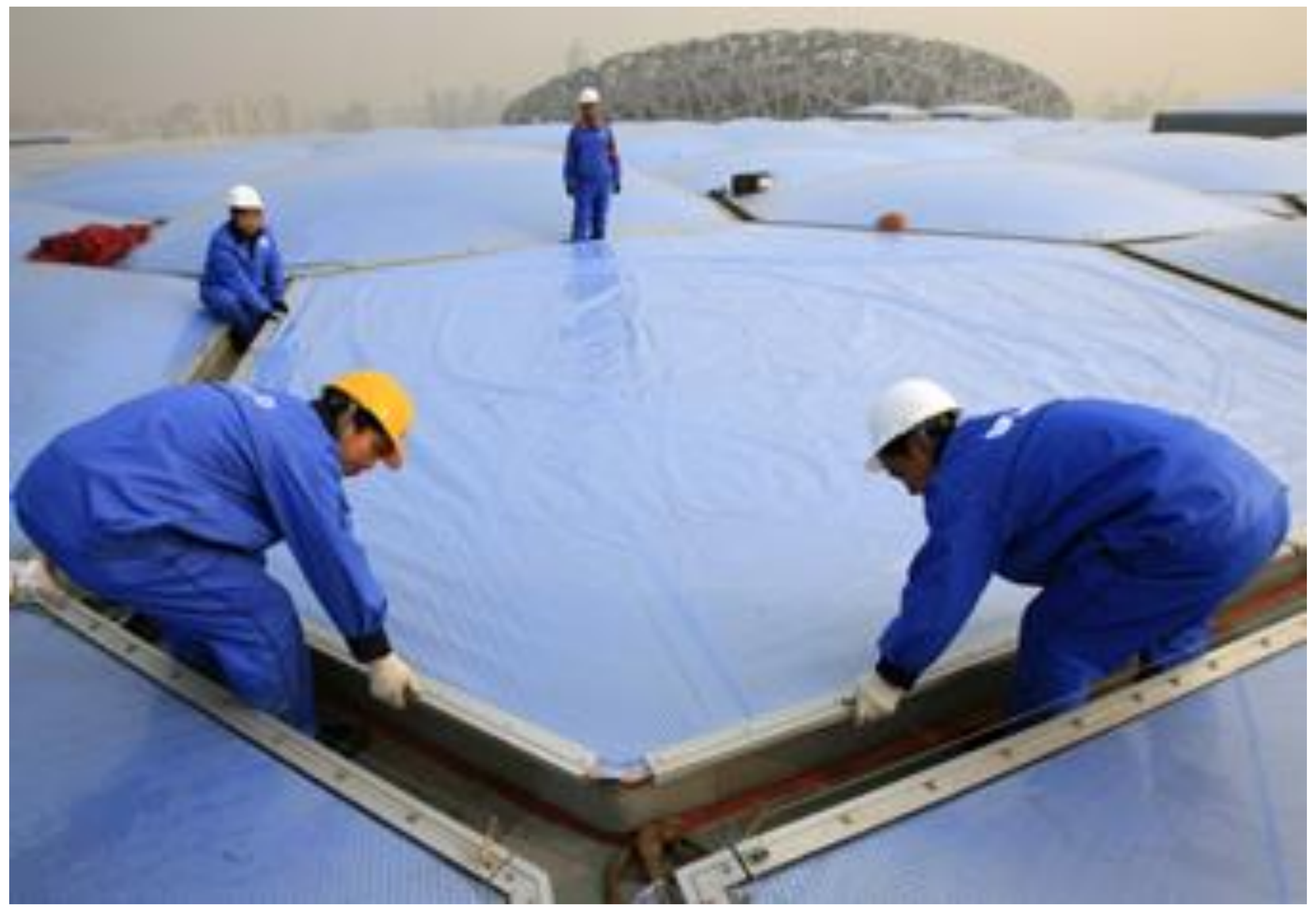
Figure 136) ETFE foil and Glass safety comparison
a: glass
b: ETFE foil

Repair and Replacement

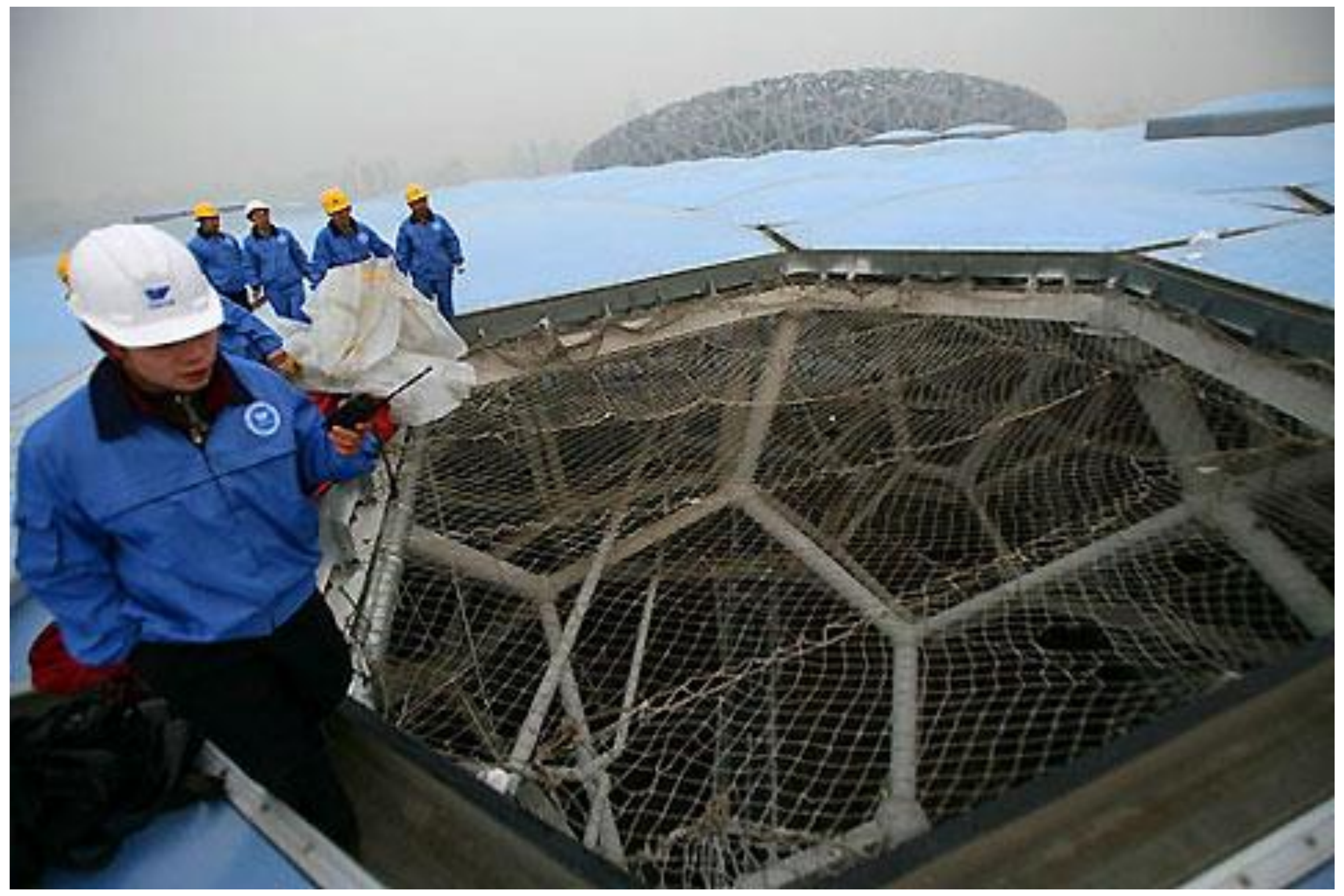
One of the outstanding characteristics of EFTE foil is its exceptional tear resistance, lack of notch weakness and stress crack concentration. Any cuts and scratches initially propagate but the material rapidly stretches and rounds out into a tough low radius area that dissipates the loads and prevents further tearing.

Minor repairs to the foil, such as a puncture hole, can be carried out in situ and within a relatively short timescale by using an adhesive ETFE foil patch. Fritted material would be used to match existing fritted oil in order that repairs do not affect the aesthetics of the structure.

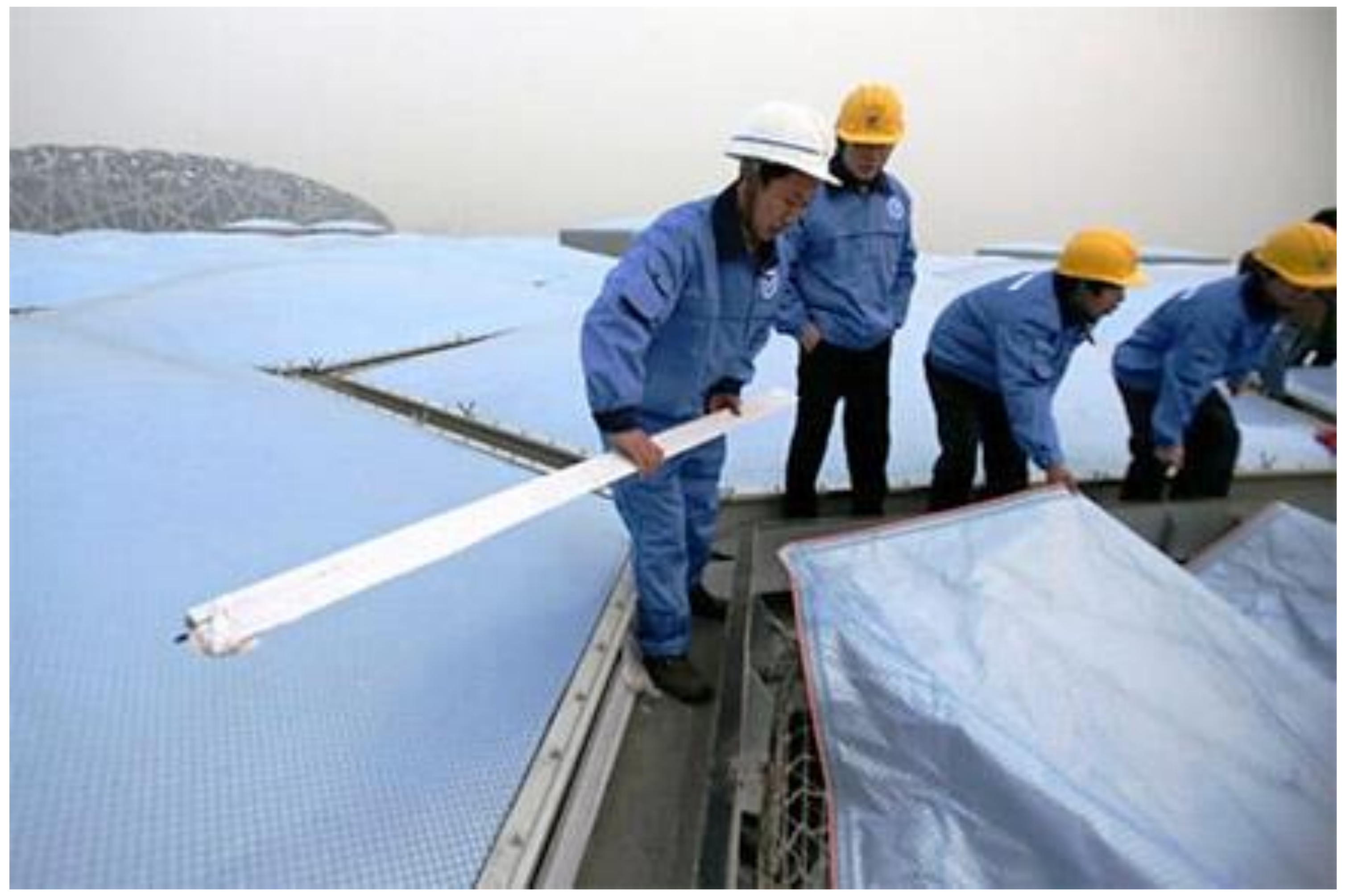
If an ETFE Foil cushion becomes more significantly damaged, an individual cushion can be easily removed and replaced with minimal disruption to the installation as a whole. The outside surface of the ETFE cushion can be accessed by technicians, using rope access techniques, from the main structural steel support. This would require the rigging of working ropes from the steel structure.



(II)



(I)



(III)

Figure 137) Replacing the ETFE cushions

Thermal Performance

Comparable to a glass system, the increased thermal performance is possible with a multi-layered system. For a double or triple layer pneumatic system, multiple layers of film are welded into panels that are inflated with low pressurized air to stabilize the film and providing the thermal property of the system.

The pneumatic system has an extreme advantage utilizing the air that stabilizes the foil as an insulator. The simple addition of layers of foils will increase the thermal performance without increasing the volume of air within the system. The typical system has three layers of foils, which is a good balance between thermal performance and optical transparency of the system, but some systems have incorporated up to five layers of foil, which almost doubles the performance from the standard three-layer system.

Weight

ETFE Foil cushions are extremely light weight weighing only 2 – 3.5 kg/m which is approximately 1% of glass structures

Cushion Size

ETFE foil cushions can be manufactured to any size and to fit any shape. Size is limited by the wind and snow loading allowed for within the design and by the orientation of the cushions i.e. whether they are installed horizontally or vertically.
As a general design guideline, rectangular cushions can span up to 3.5m in one direction and as long as required in the other direction. For triangular cushions, the size can be greater than this. If design dictates that larger cushions are required, these can be created by reinforcing the internal and external layers of the cushion by cable restraints.

Thermal Insulation

While a single ply ETFE membrane has an approximate U value of 5.6 W/m^2K, a standard three layer cushion can achieve a U value of 1.96 W/m^2K a better insulation value than triple glazing when used horizontally (glazing manufacturers figures are for vertical glazing which considerably enhances the figures). The insulative qualities of ETFE cushions can also be improved by the addition of more layers of foil (up to five in total) or by treating the foil with specialist coatings to enhance the thermal properties.

Double-glazed glass (6mm+A12mm+6mm)	2.9 W/m^2k
Double-layered ETFE Film (200μm+A300mm+200μm)	2.6 W/m^2k
Triple-layered ETFE film (200μm+A300mm+200μm+A300mm+200μm)	1.7 W/m^2k

Table 5) Thermal Insulation comparison with Glass

Cost Effect

Due to the lightweight nature of ETFE, substructure support systems and concrete foundations can be designed more efficiently.

Main Advantages

- **Transparency** Especially high light transmitting capacity of approx. 90% in the visible wavelength range (from 400 – 700 nm/UV)

- **High UV transmissibility** depending on the material thickness

- **Good thermal insulation:** U values, depending on the number of foil layers

- **G value:** between 0.10 and 0.85 depending on the design and alignment of the 'tires'

- **Low weight** of foil cushions, thereby facilitating light, intricate substructures

- **Mechanical properties:** High tensile strength/tear resistance and hail resistance

- **Flame retardant** – ETFE foils burn off without dripping

- **Low maintenance costs** due to anti-adhesive surface with self-cleaning effect

- **Interesting design options** offered by printing, e.g. shading without additional construction

- **Long service life** of at least 25 - 35 years

- **Cost savings** in comparison with conventional transparent roof constructions

- **High recyclability**

Challenges to ETFE

Though ETFE has been described as a "miracle material," it does come with some drawbacks.

ETFE is **not very soundproof** and requires very precise installation techniques. ETFE transmits more sound than glass and can be noisy for some places. Usually rain falls are problematic for ETFE. A measure of acoustic insulation is the Rw-Value or the coefficient of fading. The Rw-Value measures the capacity of acoustic insulation. A three-layered ETFE cushion has an Rw-Value f 8 dB while the Rw-Value of a double glazed glass is 42dB. However this characteristic could be a desirable attribute in some situations.

A potential danger to ETFE foils or cushions are sharp edges. Sharp points such as a bird beak can penetrate ETFE, however if the system is torn ETFE is resistant to suddenly collapse or tear propagation and the hole can be mended on site or the particular foil or cushion can be replaced.

ETFE systems obtain their integrity from an **air inflation system**. This system requires routine maintenance and service. The air has to be filtered in some way so as not to put excess moisture or debris into the system.

Even single-layer systems require great coordination of details, as the exact amount of ETFE stretch has to be considered along with the loads it is designed to withstand.

Comparison

In this section a brief comparison between ETFE and other similar materials used in the field of tensile architecture will be provided.

ETFE vs. PTFE

PTFE is constructed from carbon and fluorine atoms whereas ETFE is built from carbon, fluorine and hydrogen. Giving advantages to using both. The tensile strength of ETFE can be as much as 38% greater than PTFE, meaning ETFE material can be subjected to harsher operating conditions than its counterpart. This is why most chemical pumps are supplied in ETFE as it is a stronger material for the injection molding process they go through. However PTFE has a coefficient of friction at one-third of ETFE making it more suitable when a high flow is needed as it helps reduce pipe friction Losses. Thermal properties of both materials are also a key differentiation… PTFE can reach a maximum temperature of 327c whereas ETFE can reach a maximum temperature of 267c. This stage is critical when choosing the best suited pump; if the application needed to be pumped can reach anywhere near these temperatures it is best to choose PTFE as both materials get softer near their maximum temperature points. Furthermore, PTFE has a Limiting Oxygen Index (the minimum percentage concentration of oxygen at which the polymer will burn) greater than 95% whereas ETFE is between 30-36%, meaning that PTFE should be considered in higher oxygen environments.

ETFE Films vs. Glass

	ETFE Film			Glass	
	Single-layer	Double-layers	Triple-layers	Single	Double-glazed
Thickness/Composition	200μm	200μm+A300mm+200μm	200μm+A300mm+200μm +A300mm+200μm	6mm	6mm+A12mm+6mm
Weight (kg/m²)	0.35	0.70	1.05	15.0	30.0
Visible light transmittance (%)	90.5	82.4	75.4	88.9	79.6
Ultraviolet transmittance (%)	83.5	71.5	62.3	61.4	45.5
Heat transmittance (W/m²K)	5.8	2.6	1.7	5.8	3.3
Heat resistance	260-270℃	←	←	720-730℃	←
Acoustic transmission (under 100Hz)	3.0	4.6	unmeasured	17.7	20.0
(under 1000Hz)	12.0	12.4	unmeasured	34.3	39.2
(under 5000Hz)	23.9	33.0	unmeasured	37.3	41.0
Weather resistance	★★★	←	←	★★★★	←
Self-cleaning	★★★★	←	←	★★	←

Table 6) ETFE Film and Glass Property Comparison

Having a brief comparison between these 4 most-used tensile materials, shows a quick and understandable differences among these chooses. Some aspects are remarkable; Silicon-coated fiberglass could be used both interior and exterior while others are being used as exteriors,

Issues in Recycling PTFE

PTFE coatings can be removed with the use of aluminum oxide, metal pads, sodium bicarbonate, walnut shell, and sand blasting.

Like any other materials, recycling decreased the properties of the original material. In PTFE, many of its properties are good that it is still feasible after recycling. In some studies, 5-10% ration would still allow the material to pass off as pure PTFE. One of the main issues with recycled PTFE is that it is not applicable for long term uses.

But, to sum it all up, recycled PTFE will always have inferior properties to PTFE and cannot be consistent over time. It is always better to expect that it can be compromised and that it is priced a little lower than the original.

	Exterior / Interior	Life Expectancy	Translucency	Recyclable	Frequency of Maintenance	Cost	Fire Behavior
PVC Polyester	Exterior	★★★★	★	Yes	★★★	★★	★★★
Silicone Glass	Both	★★★★★	★★★	Yes	★★	★★	★★★★★
PTFE Glass	Exterior	★★★★★	★	No	★★	★★★★	★★★★★
ETFE	Exterior	★★★★★	★★★★	Yes	★	★★★	★★★★★

★	very poor
★★	poor
★★★	medium
★★★★	high
★★★★★	higher

Table 7) Property Comparison

9 ETFE Cushions

Foil cushions that consist of thin ETFE membranes are pneumatically pre-stressed to provide cladding for structures. Wide spans can be achieved thus allowing large spaces to be designed. The material's extremely low dead weight combined with it's high strength allows for infinite variations of the contours. ETFE cushions reduce the overall load on a supporting structure allowing for optimization of the members.

Foil cushions - pneumatically prestressed thin membrane structures made of ETFE are used in buildings as claddings with thermal properties. Due to the air buffer between various layers, foil cushions achieve very satisfying insulation properties and are used as wall or roof cover. In comparison to structural glazing, foil cushions allow larger spans in almost any shape and large transparent areas. To take advantage of the unique properties of ETFE foil claddings, examples of special and highly optimized structures are presented.

Technology

The pneumatic pre-tensioning with a low pressure air system gives the cushions a stable shape and prevents the foils from billowing and fluttering in wind conditions. The cushions are fixed by means of a continuous keder piping connected to a lightweight extrusion (fig. 145). The extrusion is bolted to the supporting structure to provide a frame onto which the cushion is mounted.

These cushions can be patterned into virtually any shape, for example the triangular and diamond shaped cushions, polygonal and so on.

The cushions are made to suit the exact dimensions of the contour. They are patterned to allow for an initial rise and dip between the upper and lower foils. After installation they are subjected to an internal pressure of typically 200 Pa, which pre-stresses and elongates the foils to give the cushions their basic shape. When short term loads are applied to the cushion one of the foil layers is further stressed, whereas the opposite foil is 'relaxed' in a way that is similar to a cross bracing consisting of pretensioned cables. If the short term loading applied exceeds the amount of the internal pressure by a factor of two, then only one of the foil layers is supporting this loading.

Figure 138) ETFE cushions, clear and fritted

In the case of long and medium term loadings, e.g., snow, it must be assumed that air will gradually be pushed out of the cushions when the load exceeds the internal pressure because the cushion is not a closed system. In such a case the foils would lie directly on top of each other and contribute to supporting the loading. The water ponding from melted snow or rain need to be considered in view of the geometry and slope of the cushions. In cases where water ponding, snow or large wind loads over stress the cushions (e.g., peripheral suction peaks) it may be necessary to support the ETFE cushions by means of thin steel cables.

Water ponding can be caused by melting snow in combination with additional rainfall. A malfunction of the inflation unit can also be a cause for rainwater collection. water ponding in the unpressurized cushions. The water ponding case is only a short-term loading condition if the analysis considers all risk circumstances correctly. The cushion’s shape will recover and the collected water will eventually drain off when the pressure-supply is restored. It is recommended to incorporate a slope for the cushions to avoid or significantly reduce water ponding issues. Valves forcing the drainage of the cushions can also be installed in some cases. It is, however, not recommended above closed spaces. The reliability of these valves may be adversely affected by leaves, ice or other debris.

It is necessary to examine the event of an Inflation unit malfunction whereby one or several cushions are in an unpressurized state (e.g. if the foil is damaged by a hurricane) when considering the structural stability. This scenario must be considered when designing the supporting structure. The resistance of the supporting structure is paramount for the structural stability of the entire building. Due to the strength of ETFE in combination with its yielding behavior (increase of gap causes an increased load bearing capacity) the supporting structure may need to have additional capacities to allow for this scenario.

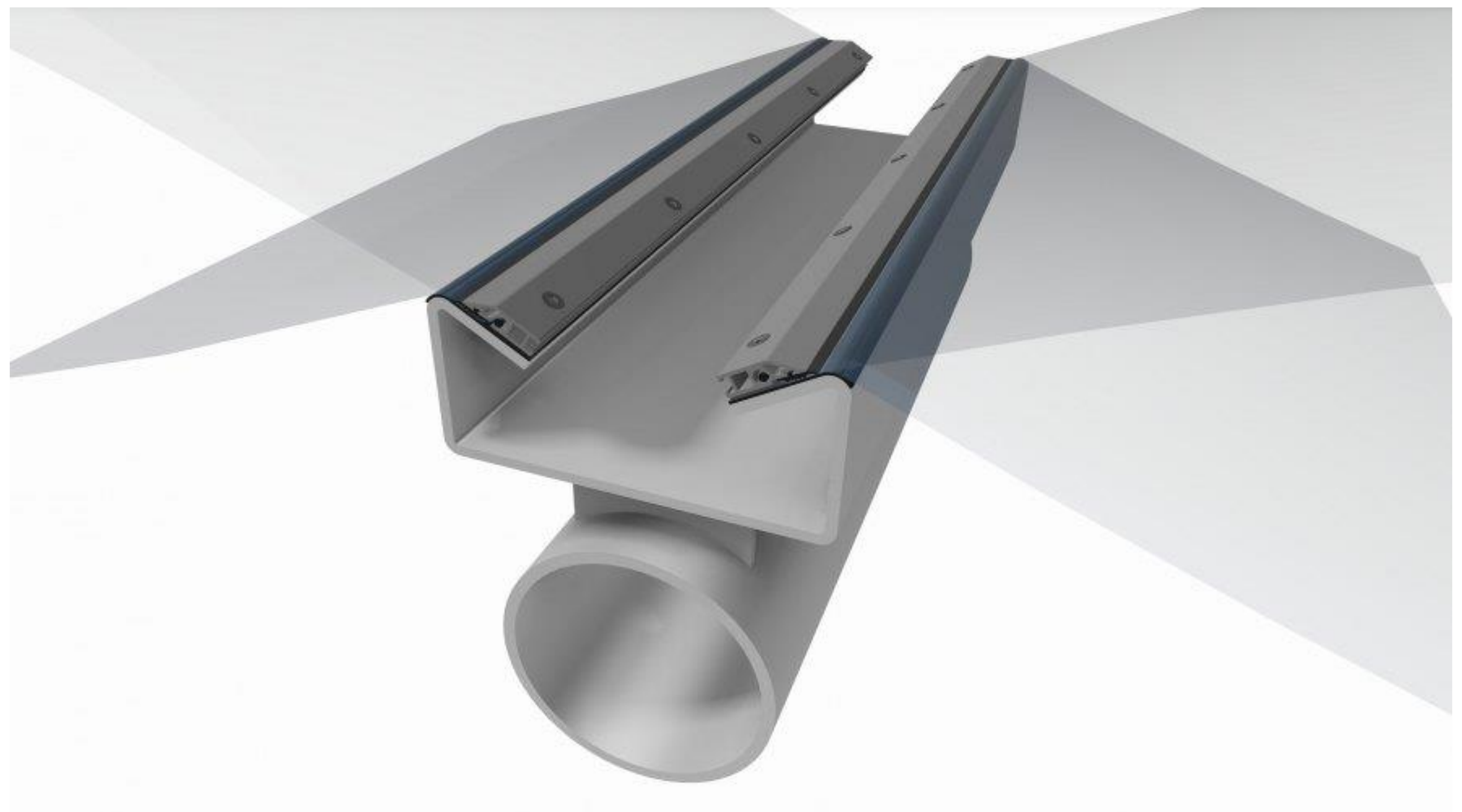


Figure 139) Standard gutter extrusion for a 2 layer ETFE cushion

(I) (II) (III)

Figure 140) Islazul Shopping Center, Madrid, Spain, 2007
Using of over 9500 m² double layer ETFE cushions for the roofing system

The extrusions and the supporting structure must be designed to be able to resist the forces that are imposed vertically on the cushion's axis, as well as for the horizontal forces arising from the cushions and cables. The reaction forces are calculated for the specific geometry and curvature including the resulting deflections. The internal pressure generates horizontal reaction forces that are to be applied permanently. Additional loads will increase the horizontal reaction forces. In general rule horizontal forces from neighboring cushions cancel each other out, so that only the frames that are at the perimeter are required to take into account the tensile forces to their full effect.


(I)

(II)


(III)

Figure 141) Villa de Laguardia Hotel, Álava, Spain
Using of 500 m² of triple-layer ETFE cushions for the roof of spa and wellness zone


(I)


(II)


(III)

Figure 142) Arena Multiespacio Shopping Center, Valencia, Spain, 2010
Using 6000 m² of double-layer ETFE cushions for the roofing system

ExCel Conference Centre is an exhibitions and international convention center in the London Borough of Newham. The center was built by Sir Robert McAlpine and first opened in November 2000. In May 2008, it was acquired by Abu Dhabi National Exhibitions Company. Phase II was completed on 1 May 2010. This expansion created The International Convention Centre London (ICC London) adding to ExCeL's event space, as well as further meeting space and banqueting facilities.

As part of the Phase 2 construction at ExCel Conference Centre, Architen Landrell was contracted to design, manufacture and install three ETFE cushion rooflights each covering an area of 25m x 25m (615sqm each) – currently the largest ETFE cushions in the world.

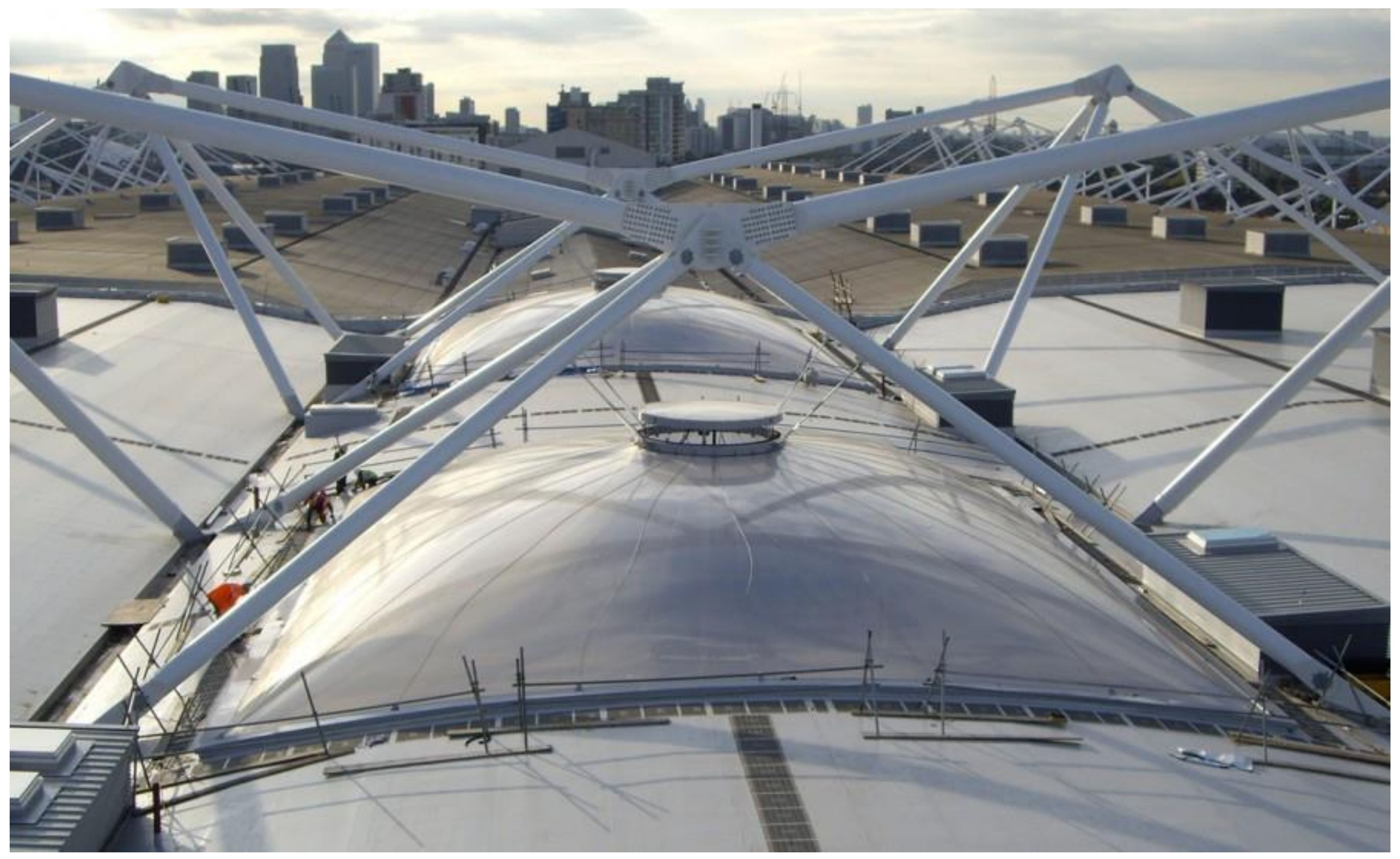
In contrast to glass or even traditional tensile fabric structures, ETFE cushions offered an exciting opportunity to integrate an element that was aesthetically different and to create an ultimately modern and clean looking space. The rooflights allow a light and open feeling to be created in the exhibition space below, let in maximum natural light and serve as a surface for internal uplighting.

As the largest individual ETFE cushions installed in the world the size of the cushions in itself posed a challenge for manufacture and installation. Nearly 2000sqm of material was patterned, cut and welded before being transported to the site for installation.

However, the real complexity of the rooflights at ExCel lay in the design development stage. Not just ETFE cushions, the rooflights are formed as a hybrid between a traditional tensile cone formed by the inside layer of the cushion and a pneumatically supported membrane formed by the upper layer.

(I)

(II)



(III)

Figure 143) ExCel Conference Center, Phase II, London, 2010

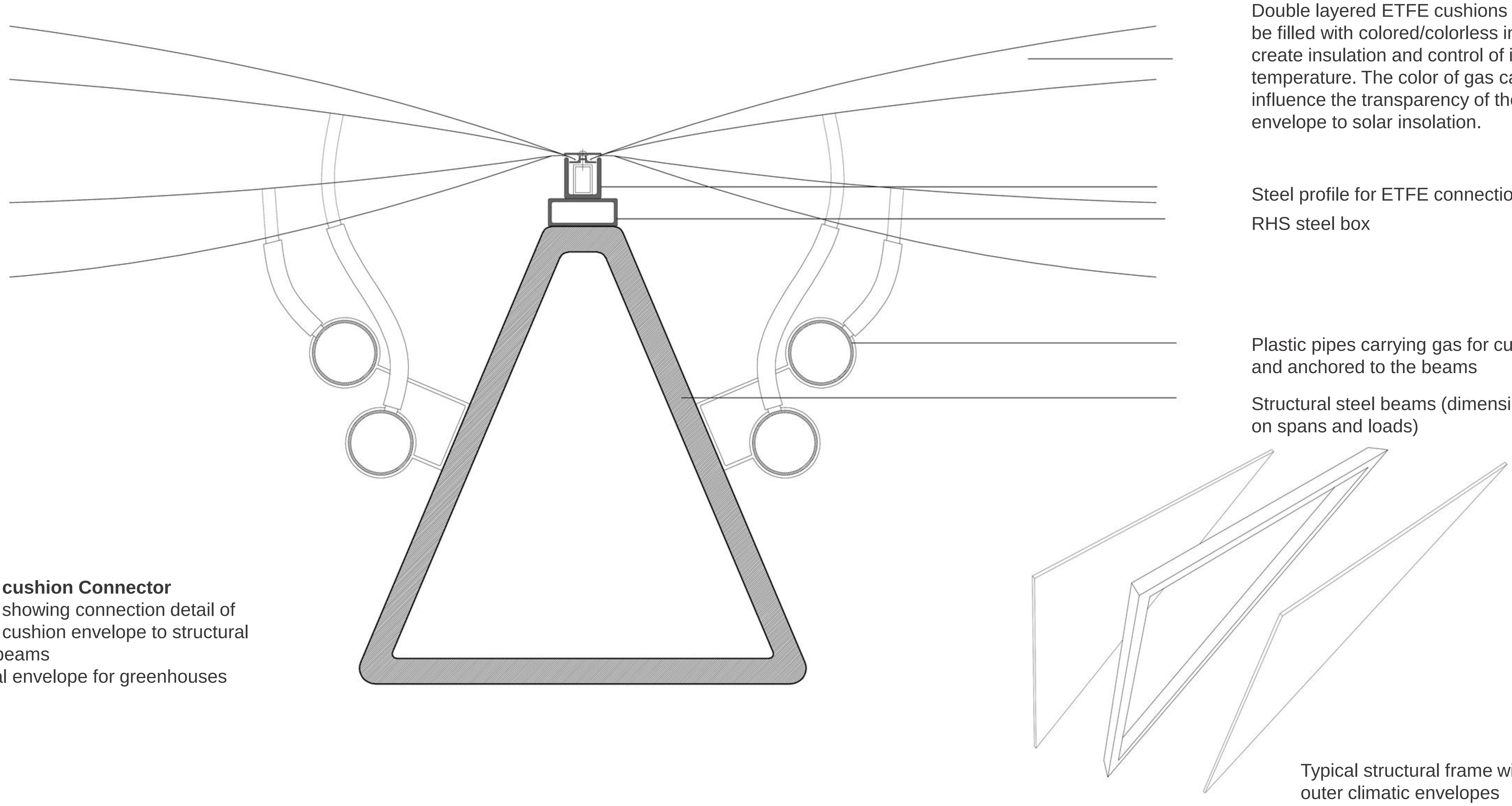


Figure 144) ETFE connectors, detail showing connection details of ETFE cushions envelope to structural steel beams
Typical envelope for greenhouses

Using currently available foil thicknesses, cushions spanning up to 4.0m wide, depending on certain parameter and situations, are possible without the need for reinforcement cables. The length of the cushions is practically unlimited. As opposed to glass, curvatures, deformations and warpages are easily achieved with ETFE cushion systems. The degree of curvature is limited to a certain extent for geometrical reasons, however, this limitation has no effect on buildability. Square, polygonal or round cushions with biaxial stress distribution allow larger spans. Even for these forms, it would be advisable to incorporate a slight slope in the arrangement of the cushions.

The flexibility of the ETFE cushions and the possibility of variable welded seams enable the cushions to be made to measure for almost any shape. This allows for a vast scope for creative design. It is possible to install ETFE cushions on “soft” supporting structures like cable net structures offering watertight building envelopes that allow movement in the structure.

Advantages compared with structural Glass Technology

- The system's low weight (particularly advantageous for refurbishment projects)
- Wider spans result in a larger transparent/translucent spaces
- Flexible 3D shaping
- Deformation is not an issue and therefore ideally suited for cable structures
- Large range of coloring and graphic printing available
- Lower cleaning costs
- Excellent UV transmission
- Very good spatial acoustics with short reverberation times
- Light weight supporting structure options possible

Disadvantages

- Poor acoustic insulation
- Maintenance of the inflation units

Foil cushions made from ETFE have been used successfully as thermally insulating building envelopes for almost 30 years. They enable large transparent or translucent areas to be created with an extremely low degree of shading from frames and supporting structures.

The flexibility of the ETFE cushions and the possibility of variable welded seams enable the cushions to be made to measure for almost any shape. Long rows of cushions that are slightly sloped longitudinally or transversely with a width of up to approximately 4 m, in conjunction with an adequate supporting structure are recommended. This design concept has been extensively applied for over 30 years and allows for economically beneficial building envelopes. Buildings that can be filled with natural light and that are a tribute to architectural expressiveness.

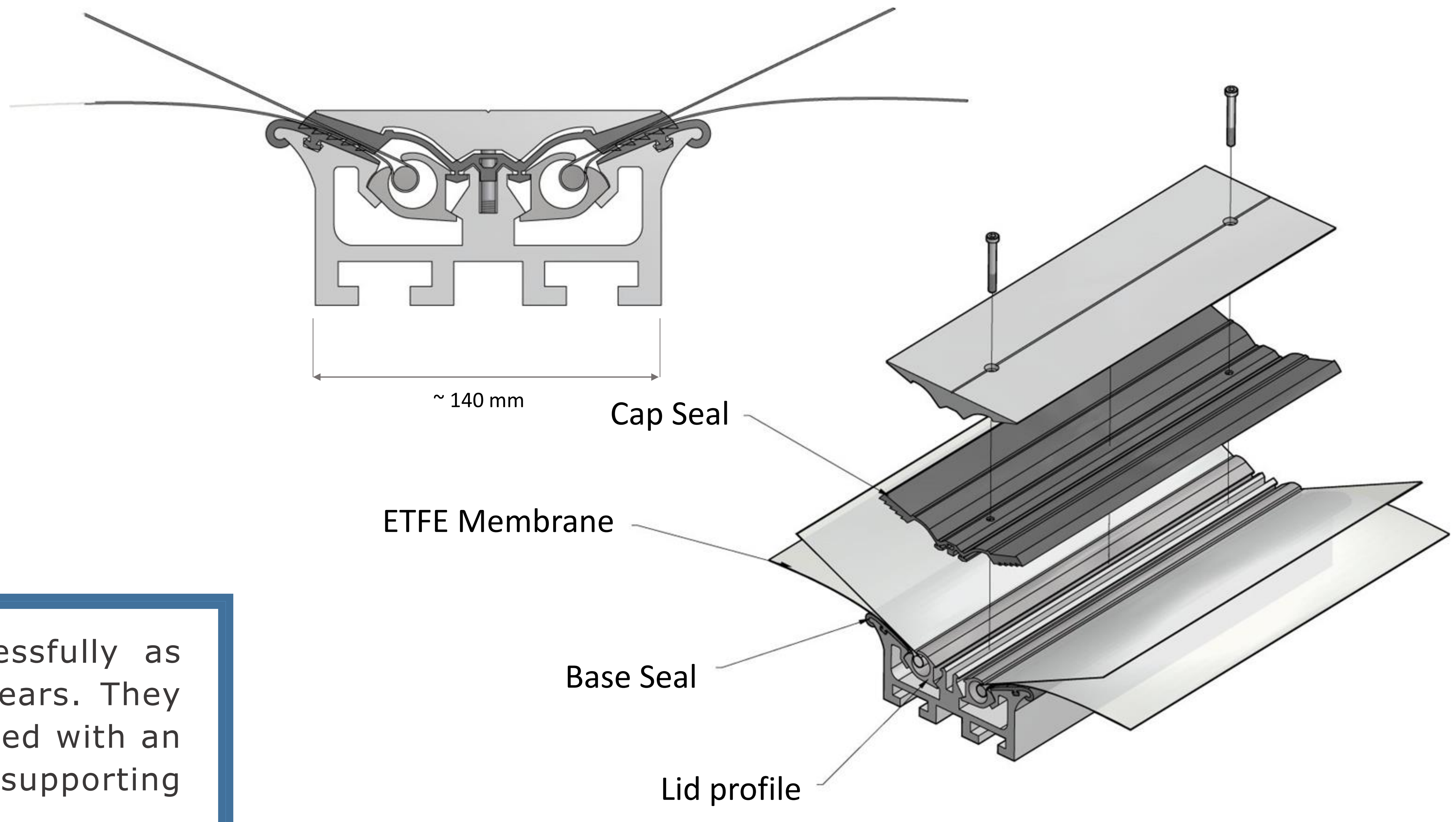


Figure 145) Typical aluminum profile for ETFE membrane cushions fixed by keder, including silicon seal

Air Inflation System / Energy Consumption

A pneumatic ETFE cushion system is generally fed by one or more inflation units. Each unit consists of two redundant blowers forming a backup system for guaranteed structural stability. The air when entering the machine will be pre-dried to avoid condensation within the cushions. A series of pressure sensors continuously monitor the internal pressure of the ETFE cushions maintaining them between 300 pa and 400 pa. In case of high wind or snow loads, sensors can automatically and continuously adapt the pressure to compensate external loading. Depending on air temperature and humidity, one unit can feed a roof of 1400 m² up to 2300 m². They are UL certified and run on an 110V or 220V power with consumption less than 1kW.

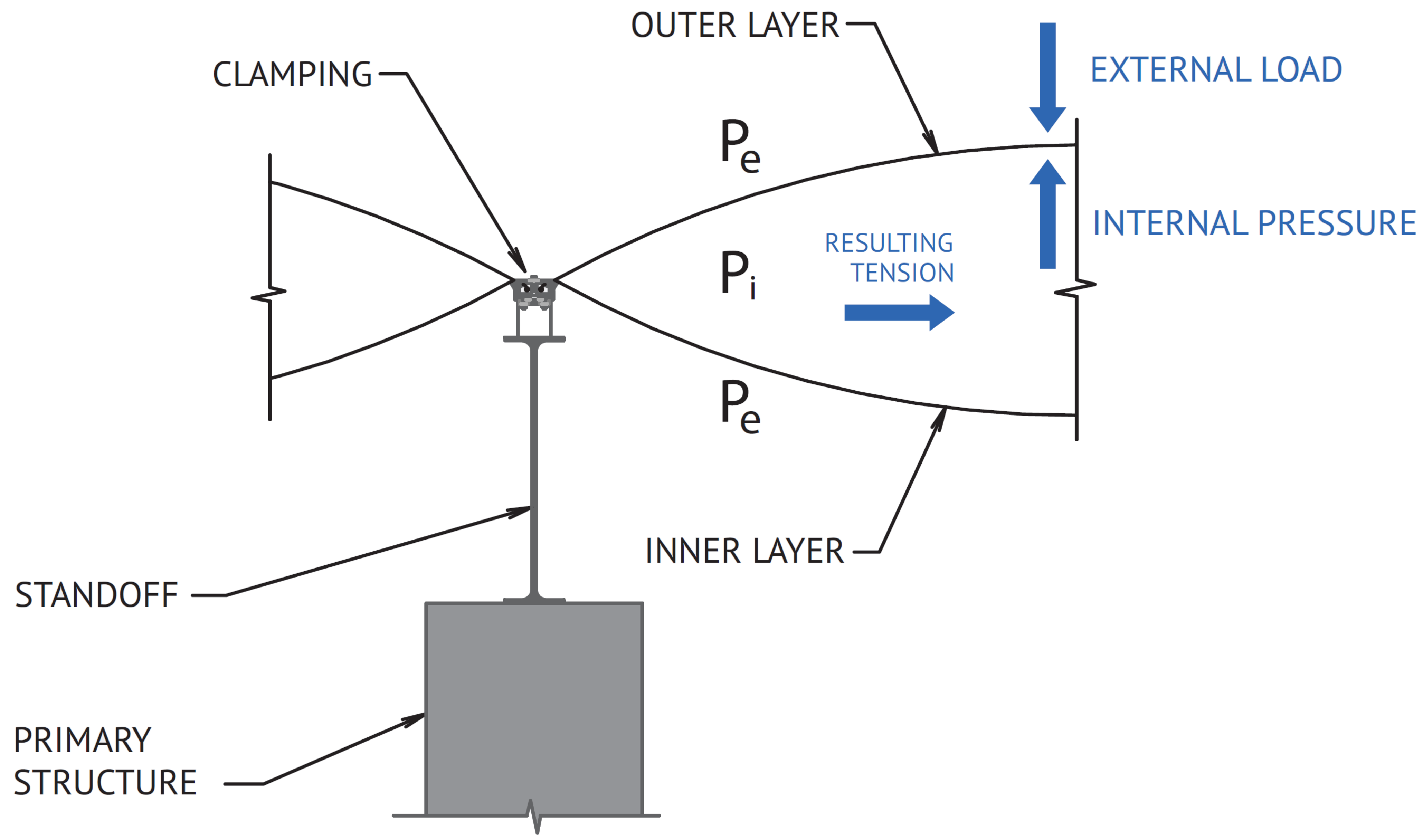


Figure 147) Internal and external loads diagram

(I)

(II)

Figure 146) Air Inflation unit

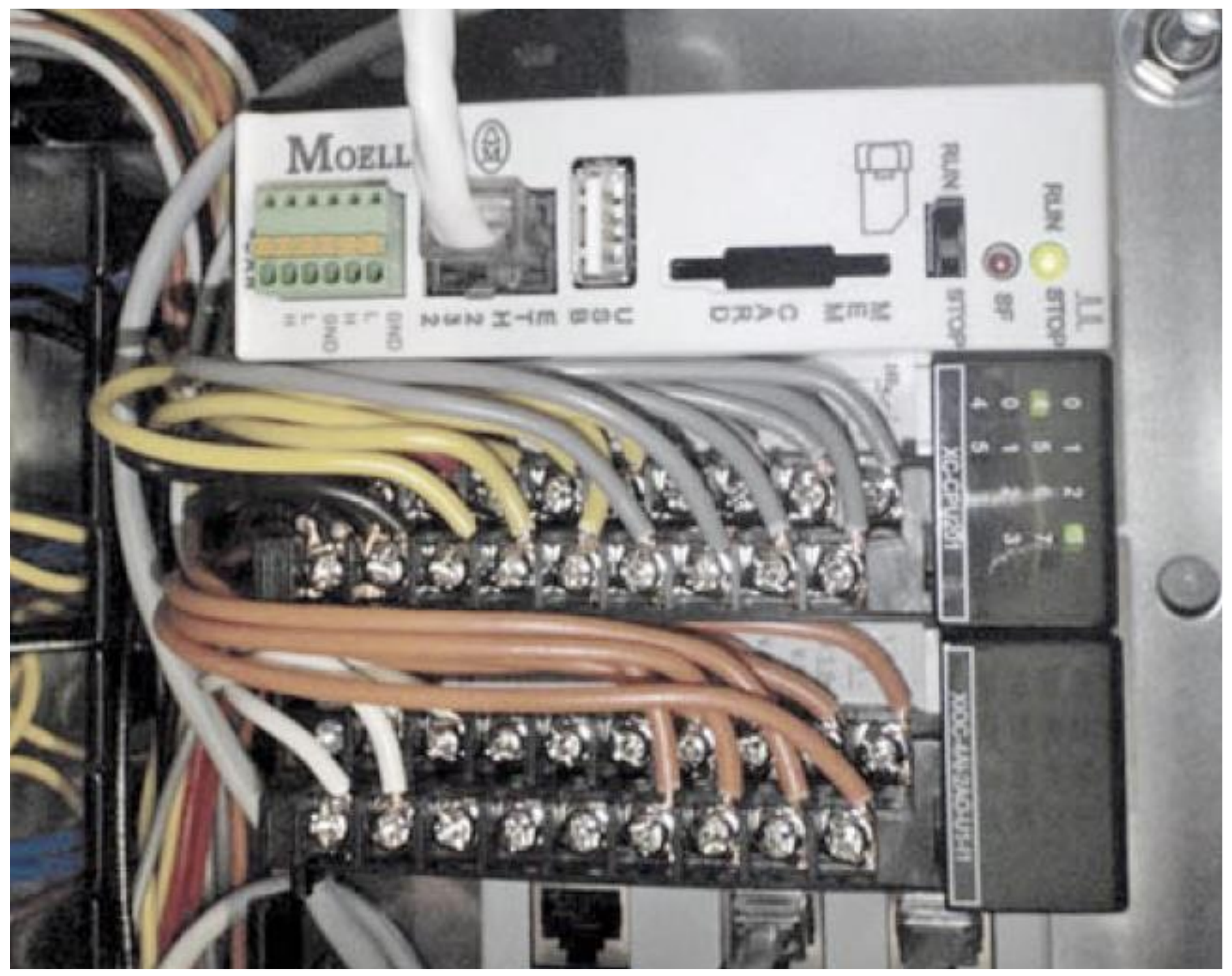


Figure 148) Inflation control system

ETFE (ethylene tetrafluoroethylene) is a lightweight material increasingly used in building applications. It has gained popularity mainly due to its daylight transmittance and the potential for energy savings. When used as cladding ETFE sheets are usually assembled into cushions, which are inflated for structural reasons. ETFE cushions can provide thermal insulation with reduced initial costs and less structural supports as compared with a conventional glazed roof. Limited research regarding the modelling of ETFE in building applications and limited availability of information on material properties led to the present study. Designers are currently facing difficulties when carrying out energy optimization studies as part of the design process. For example, since ETFE is not entirely opaque to longwave radiation, merely treating the material as a standard glass layer can lead to errors when evaluating its thermal performance. In order to enable building designers to assess the performance of these systems, maximizing performance and managing risk, it is essential to gain knowledge and develop methods to model this novel material. Here we take into account the longwave transmission properties of the ETFE material and discusses the need for a methodology for estimating surface temperatures, heat losses, and solar gains. Guidelines for integration are needed to define its properties and to evaluate performance during the building design process.

ETFE has approximately 95% light transmittance, but does not offer the clear visibility/transparency of glass (Robinson, 2005). As a result, ETFE solutions therefore initially found use on projects such as botanical gardens, zoological gardens, swimming pools, and exhibitions spaces. However, ETFE is increasingly finding its place in more traditional buildings as roofing for courtyards, shopping malls, atria and stores. The ETFE material has been used on prominent architectural projects such as the Eden Centre and the Water Cube and it is currently considered for a number of high profile international sports venues. Previous ETFE studies have focused mainly on structural properties and related issues, while little research has been carried out in order to determine energy transmission properties and characteristics in terms of environmental building design.

Modeling of ETFE in Building Simulation Tools

Implementing ETFE cushions in building design is a complicated task due to the unusual transmission characteristics of the material. Since currently available commercial software tools are not developed to take into account the longwave transmittance through the ETFE layers, in practice ETFE foils are usually modelled as glazing units. Depending on the building use, the building design, the site, and geographical location of the building, this simplification may impact on the accuracy of the simulated building performance, as discussed in the following.

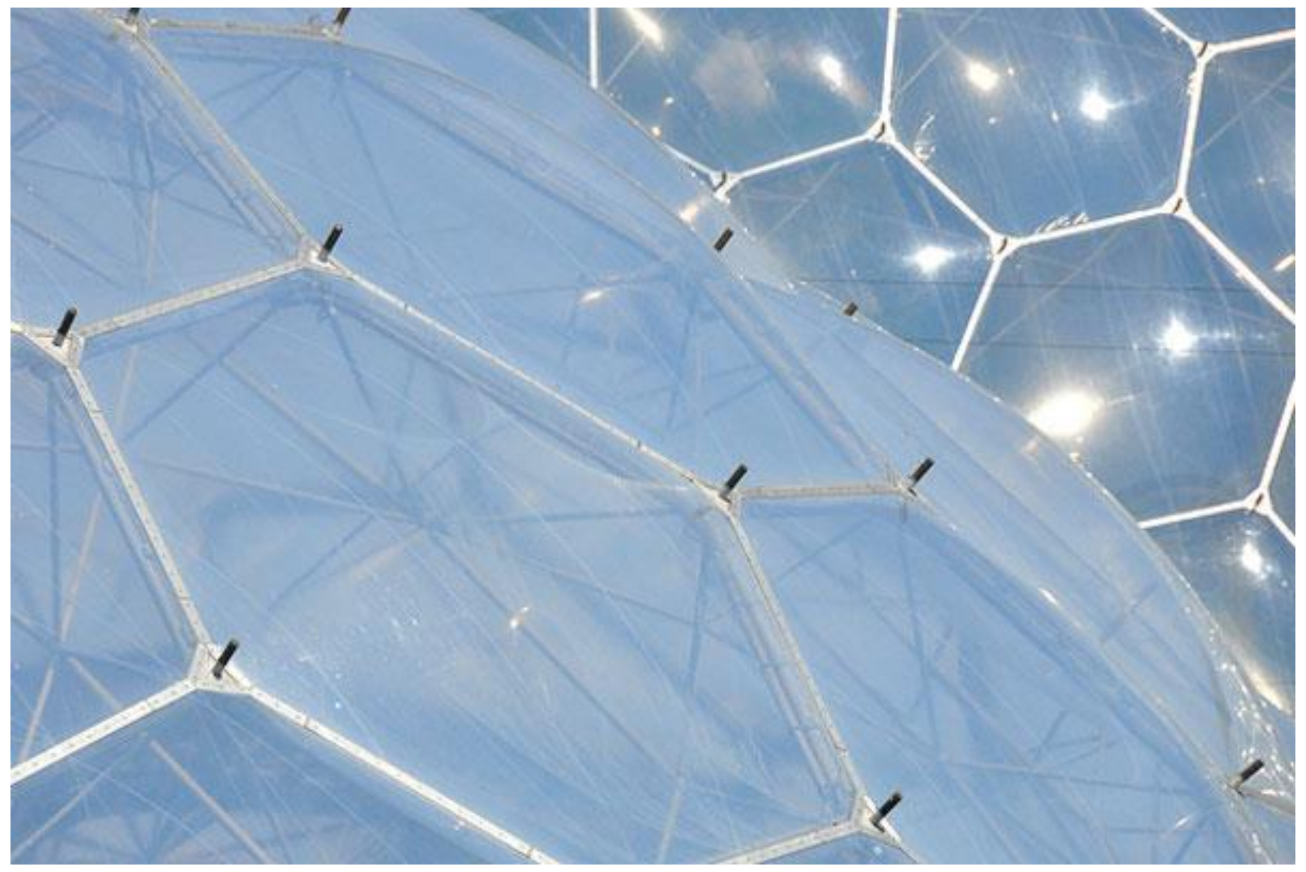


Figure 149) ETFE Cushions

Shortwave and Longwave Radiation

This section presents a brief theoretical background, in order to gain an understanding of the particular properties of ETFE and the resulting potential shortcomings of current energy modelling tools and methods.

Electromagnetic radiation is an energy form, which comprises what we refer to as heat and light. The electromagnetic spectrum is outlined in Figure 150. The term 'thermal radiation' (relating to heat transfer) ranges from a wavelength of approximately 0.1μm to 100μm and includes part of the ultraviolet (UV) and all of the visible light and infrared (IR) radiation.

All bodies emit and absorb energy in the form of electromagnetic radiation. At a given temperature, the thermal radiation emitted from a surface varies for different wavelengths. The term 'spectral' is used to indicate this dependence. The spectral distribution depends on the characteristics and temperature of the emitting surface. In order to accurately quantify radiative heat transfer, the spectral and directional effects should be taken into account.

ETFE Thermal and Optical Properties

One of the main reasons for using ETFE is the low thermal transmittance achieved for large span modules. In Table 8 a comparison of thermal transmittance (U-value) and total solar energy transmittance (g-value) of insulating glazing units and ETFE cushions is presented.

	U-value (W/m²K)	g-value
6mm monolithic glass	5.9	0.95
6-12-6 Double Glazing Unit (DGU)	2.8	0.83
6-12-6 High Performance Double Glazing Unit (DGU)	2.0	0.35
2 Layer ETFE Cushion	2.9	0.71-0.22 (with frit)
3 Layer ETFE Cushion	1.9	0.71-0.22 (with frit)
4 Layer ETFE Cushion	1.4	0.71-0.22 (with frit)

Table 8) Thermal and solar transmittance for glazing and ETFE cushions

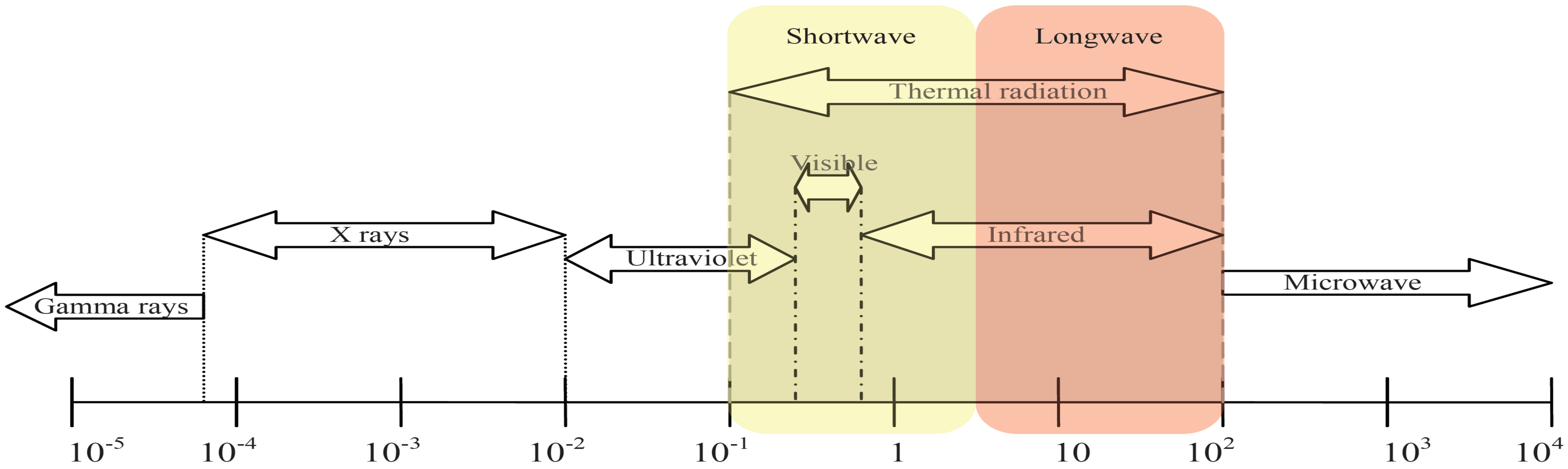


Figure 150) Bands of electromagnetic radiation spectrum

The thermal and optical properties of the ETFE cushions can be altered significantly by application of coatings, print, geometry and the build-up in which they are applied. The following two examples illustrate how energy transmission through an ETFE cushion (transmission, reflection and absorption) can be modified

- Application of a reflective frit to an inflatable intermediate cushion; the intermediate foils can be in an open or closed position allowing heat and daylight into the inner space as shown in Figure 151.

- Application of coatings (low emissivity coating in order to reduce the longwave transmission losses i.e. during a cold winter night providing lower thermal transmittance values and/or solar control coating in order to reduce the solar transmittance) as shown in Figure 152.

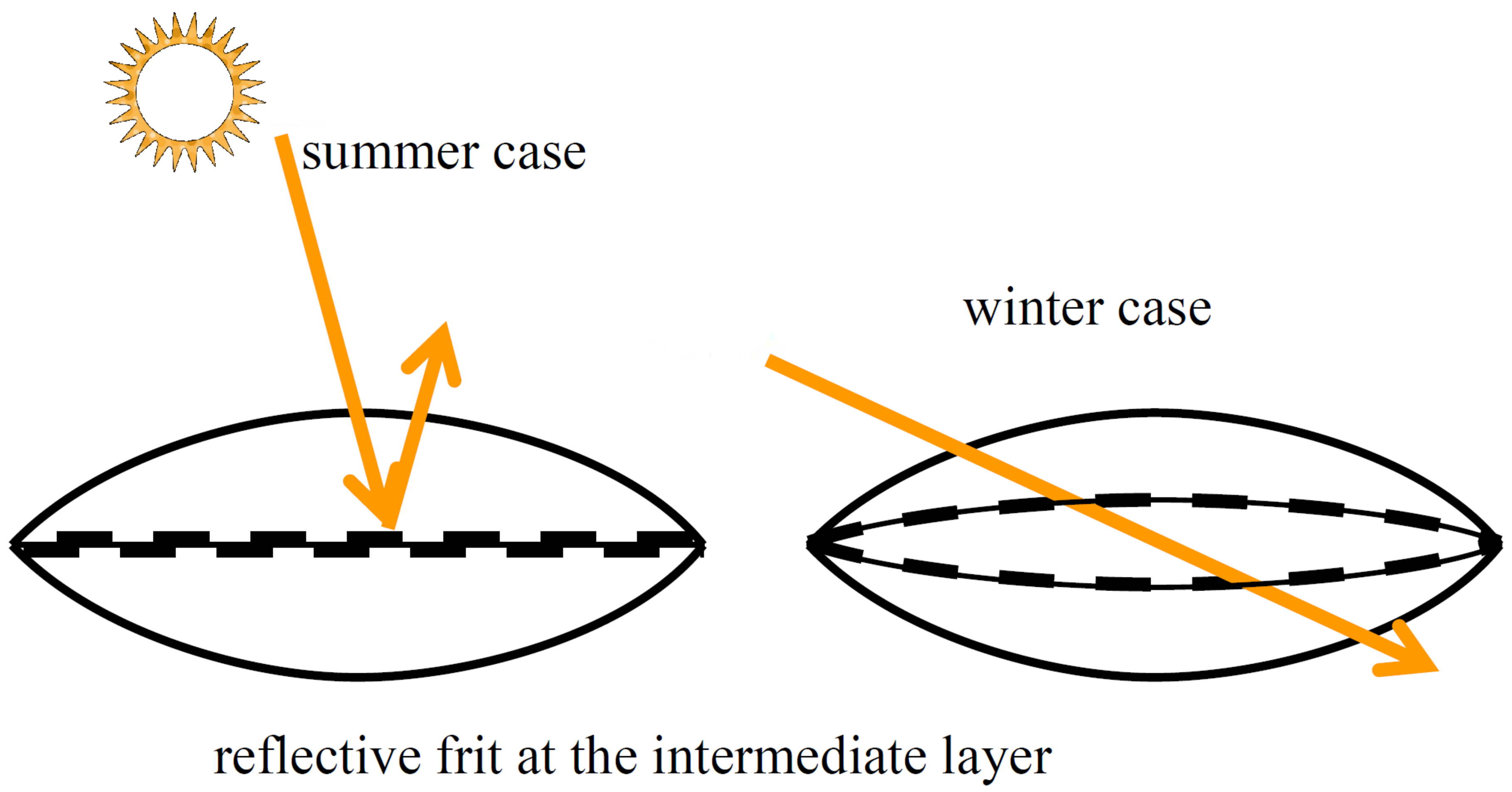


Figure 151) Frit in ETFE Cushions

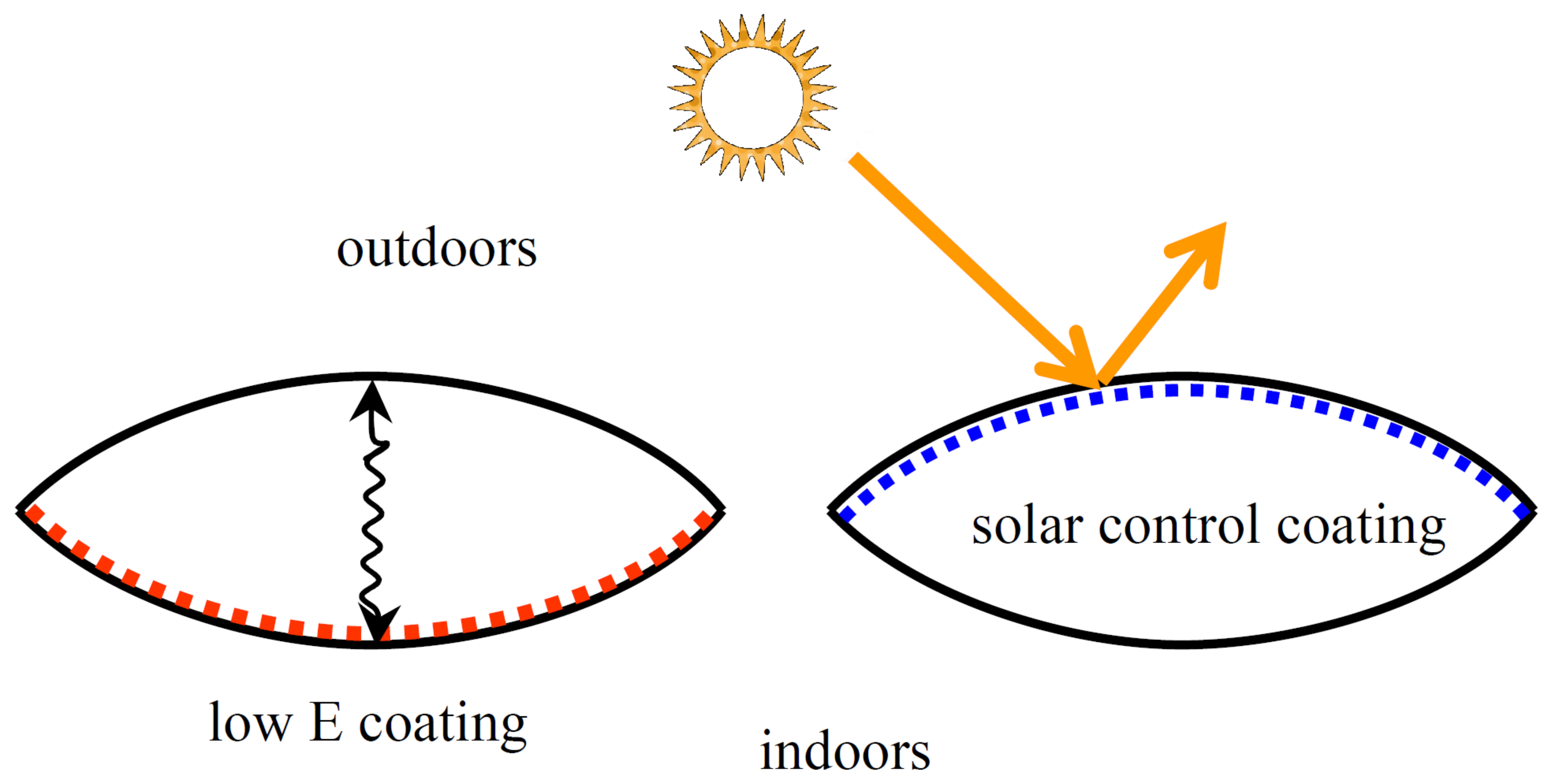


Figure 152) Coatings in ETFE Cushions

Usually ETFE cushions incorporate two or three air chambers. Convective heat transfer within these air chambers will influence the thermal performance of the cushion and estimation of U-values is generally complex. Modelling of ETFE cushions as part of building performance simulation is therefore not straightforward. The performance of the systems can be assessed by means of computational fluid dynamics (CFD) and/or by empirical (hot box) testing.

A potentially important difference between glass and ETFE is the way in which longwave radiation is blocked or transmitted. Glazing is virtually opaque to longwave radiation, while ETFE transmits part of the longwave radiation as indicated in Figure 153. It is difficult to obtain information on the physical properties of ETFE for the longwave spectrum. Precise knowledge of the ETFE spectral behavior is essential for increasing the confidence in predictions for the impact of longwave radiation on the building performance. It should be clearly stated that the information in Figure 153 is not confirmed for its accuracy and has been included for illustrative purposes only.

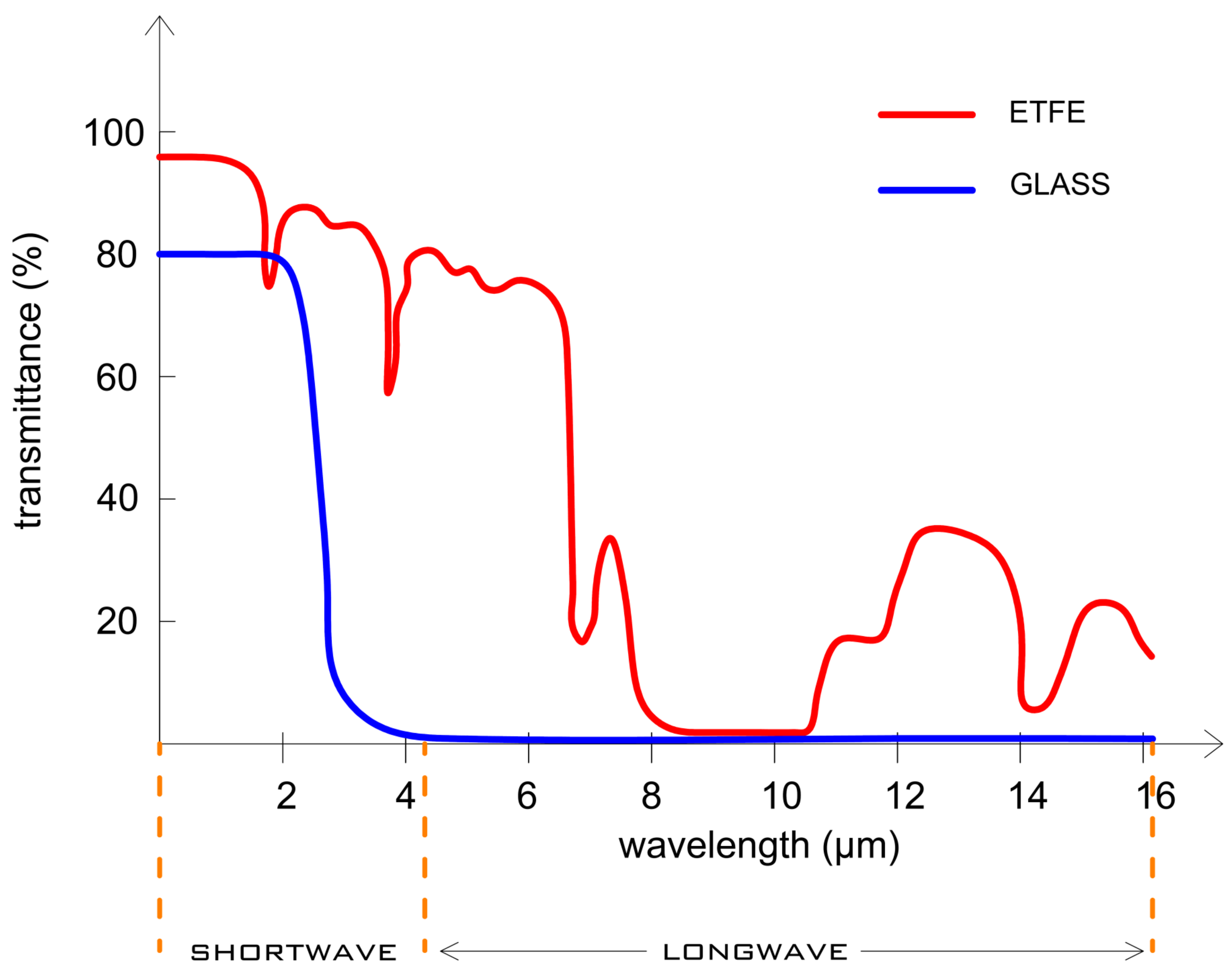


Figure 153) Spectral Transmission through ETFE and Glass

The visual light transmittance of ETFE is 94-97% with ultraviolet transmittance being in the 83-88% range. Within the visible part of the solar spectrum the frequencies are fairly evenly transmitted through the material, which means that the colors viewed through the ETFE are not disturbed.

As mentioned above, glass is practically opaque to longwave radiation. For a given glass surface, the longwave radiation emitted depends on the surface emissivity and temperature. A temperature difference between the pane and its surroundings will result in exchange of longwave radiation. In Figure 154 a comparison of the mechanism between a 'triple glazed unit' and a triple-layer ETFE cushion is presented.

- Triple Glazed Unit, exposed to solar radiation:

- Incident solar radiation reaches the 1st pane; part shortwave and part longwave radiation.

- The shortwave radiation is transmitted, absorbed, and reflected. The absorbed energy will lead to an increase in the temperature of the 1st pane. The same applies for the 2nd and 3rd pane.

- The glazing is practically opaque to longwave radiation. In terms of longwave radiation exchange, the relatively very high temperature of the sun means that the exchange is completely dominated by the incident longwave radiation from the sun. However, depending on the temperature difference between the panes and the emissivities of their surfaces, longwave radiation is exchanged between the 1st and 2nd pane similar is the mechanism between the 1st pane and the outdoor environment. Depending on the radiative temperatures of the panes and the surroundings, the net (or resulting) longwave radiation flux can be inwards or outwards.

- The resulting temperature of the panes depends on the longwave radiation exchange, convection between the panes and absorption (including the effect of multiple reflections). The total solar transmittance (g-value) of the triple glazed system is the sum of the shortwave transmitted part, the net longwave radiation emitted from the 3rd pane to the indoor side, and the energy transfer by convection from the 3rd pane to the indoor side.

• By reducing the emissivity of one of the panes (low emissivity coatings), we reduce the longwave radiative exchange and therefore reduce the thermal transmittance of the system. By filling the cavities with Argon or Krypton, we reduce the heat exchange due to convection between the panes, achieving similar results (lower U-values).

- ETFE layers, exposed to solar radiation:

• Incident solar radiation reaches the 1st layer; part shortwave and part longwave radiation

• As for the glazing system, the shortwave radiation is transmitted absorbed and reflected by the layer. The absorbed shortwave energy leads to an increase in the temperature of the 1st layer. The mechanism is similar for the 2nd and 3rd layer.

• ETFE is not opaque to longwave radiation. Therefore, when solar radiation reaches the 1st layer, part of the longwave radiation is transmitted. The mechanism of ETFE is similar to the one of glass, but in this case, a reduced part will be absorbed and re-emitted due to the transmission.

• In the case of ETFE the longwave transmittance impacts on the transmission of energy absorbed in layers (for instance a fritted layer) which is emitted and transmitted through other layers, as well situations where longwave exchange occur between inside and outside across the ETFE. The significance of these effects will vary with the environmental conditions and the properties of the ETFE build-up.

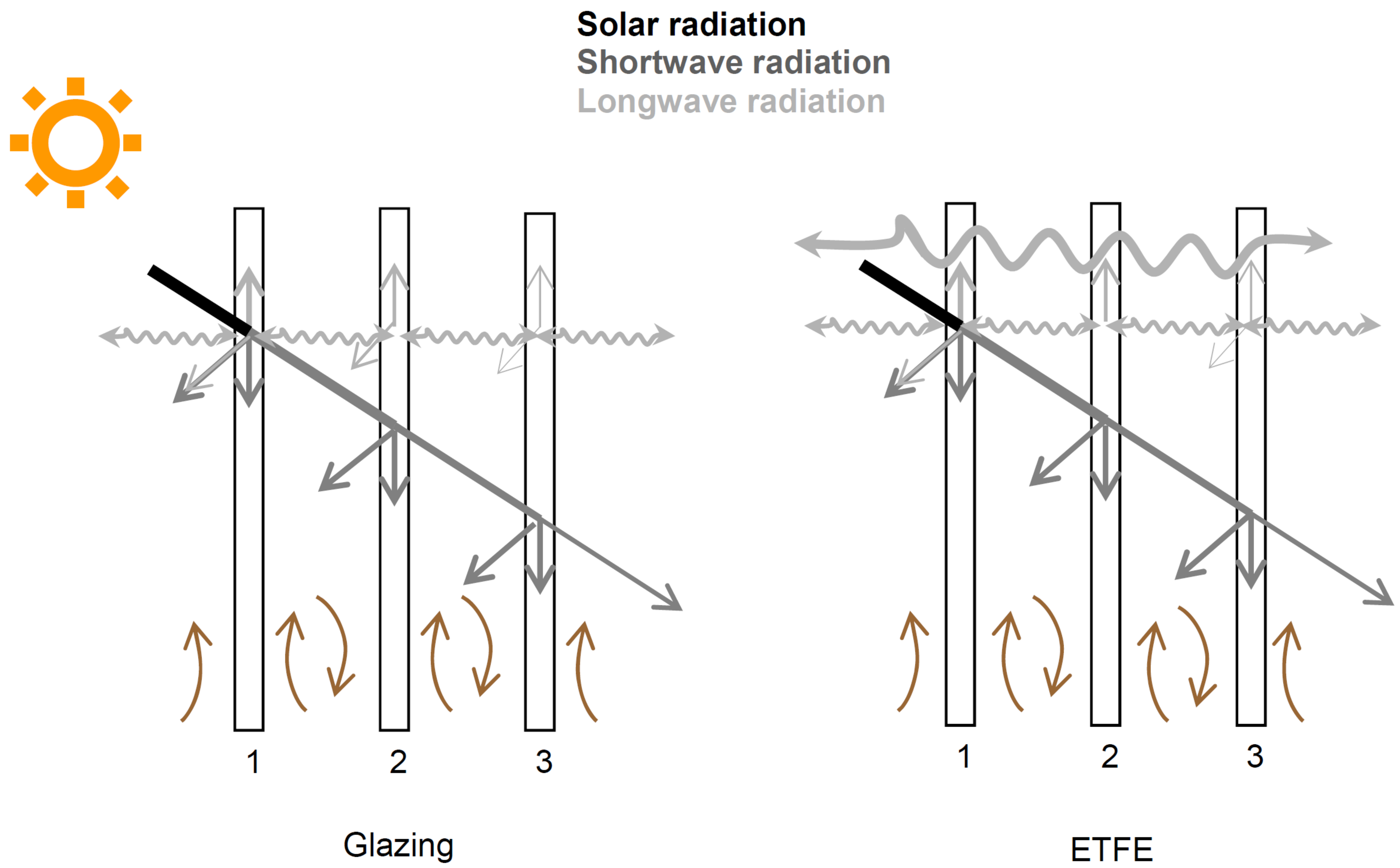


Figure 154) Mechanism of solar radiation for triple glazing and triple layered ETFE

ETFE and Longwave Transmission on Building Performance

In order to better understand the potential effect of longwave transmission on the resulting building performance, a space with a glazed roof is compared with a space with an ETFE roof for two scenarios: a cold (winter) night and a warm sunny (summer) day.

During a cold winter night with clear sky the temperature of the floor within the space will be higher than the radiant temperature of the sky. Since the indoor space will be able to transmit longwave radiation through the ETFE roof directly to the cold sky, a longwave exchange between the indoor space and the outdoor environment will take place. The resultant heat transfer depends on the temperature difference, the temperature of the ETFE layers and their longwave transmission properties. Similarly and depending on view factors, longwave radiation exchange may occur between the occupied space and the surrounding buildings.

When exposed to solar radiation, during a warm summer day, the shortwave energy transmission will typically dominate, but longwave radiation exchange will potentially affect the resulting heat transfer, depending again on the temperature differences between the different ETFE layers (which may include fritted and thus absorbing layers) the floor of the occupied space, the sky and any surrounding buildings.

Impact of Frit on Longwave Transmission

A key parameter influencing the performance of ETFE cushions is the possible presence of a fritted intermediate layer (Fig. 155). In general, the main purpose of the frit is to introduce shading and reduce the transmitted solar energy into the occupied space. The solar transmission may be variable by means of multiple fritted layers, which can be regulated to vary the combined shading effect.

During a cold night, such a frit would increase the thermal insulation, since its opacity to longwave would reduce the longwave heat transfer between the floor and the sky.

During a warm sunny day, the frit will reduce the amount of shortwave radiation entering the space; the higher the frit density, the lower the direct shortwave penetration. The frit will reflect a part of the shortwave and absorb another part increasing the temperature of the layer. A highly absorbing frit would increase the temperature of the middle layer more than a highly reflecting one, increasing the emitted longwave radiance (towards indoors and outdoors depending on the temperature differences and emissivities). On the other hand, since the frit is opaque to longwave radiation, a fritted intermediate layer would shield from transmission of longwave radiation from outdoors.

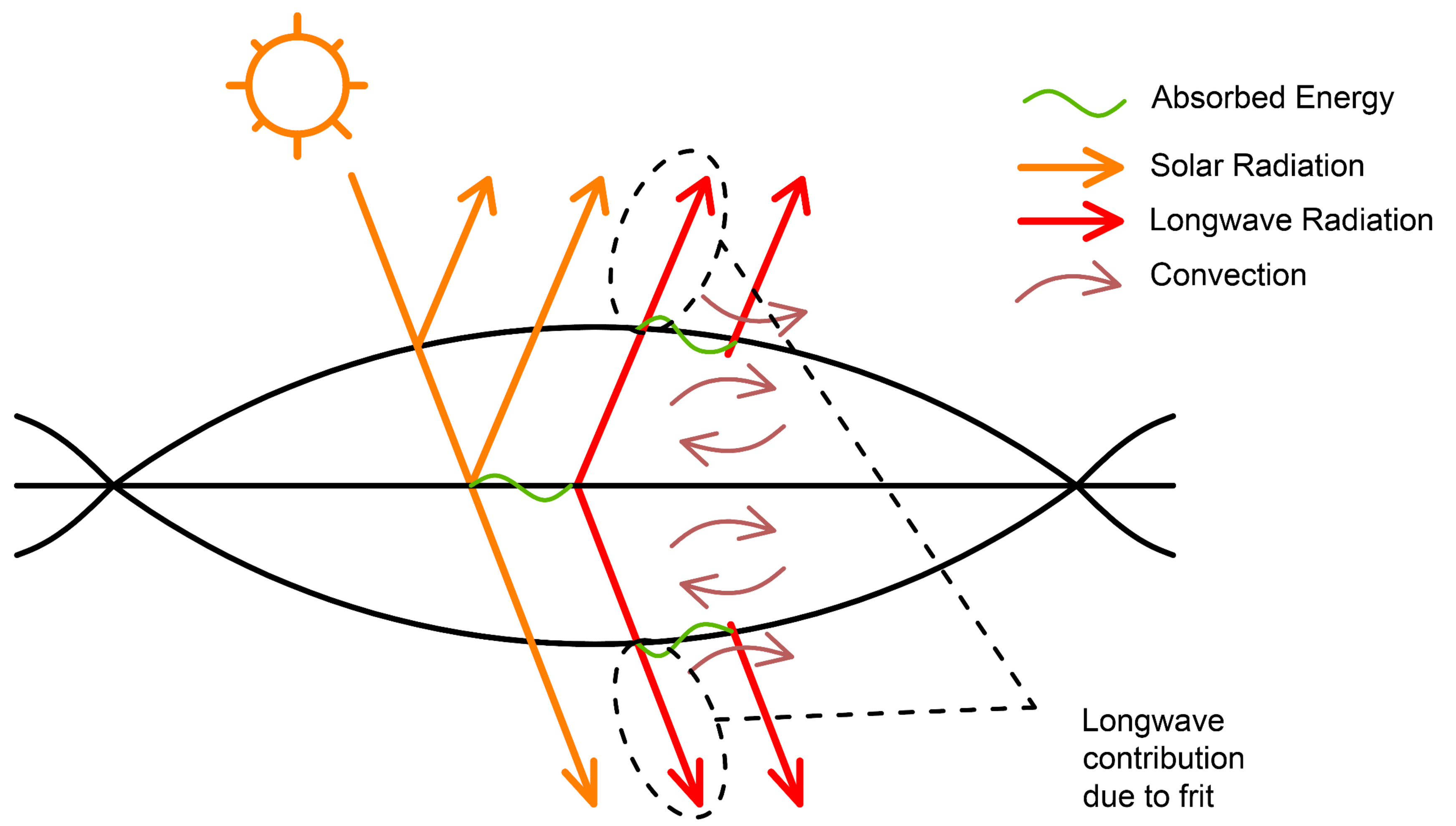


Figure 155) Impact of Fritting on ETFE performance

10 Two Analyses

Analysis 1 ETFE Membrane Pavilion vs. Traditional-Type Pavilions

In this section a study due to having a comparison between construction of an ETFE membrane pavilion and 2 traditional roof types enclosure – pitched roof and flat roof – will be discussed. Parameters like wind, snow, construction process, timing effects, cost, maintenance will be taking to account.

The location will be Milan, Italy. And all weather data and mechanical properties of materials will be provided.

The aim of this study is to study differences between setting up a conventional temporary structure like a pitched roof or flat roof pavilion and a temporary membrane structure like a tensile structure pavilion.

For the tensile structure ETFE is in interest, since this thesis is focusing ETFE as the main material, therefore all mechanical and physical characteristics of ETFE will be considered.

The weathering data such as wind is taken from the "Climate Consultant" software inputting the weather data of Milan city. Average snow loads are from weathering database existing in various forecasting websites.

This study will help understanding and having a better idea about general advantages and disadvantages of the traditional architecture and tensile architecture.

Figure 156) The study takes place in Milan, Italy

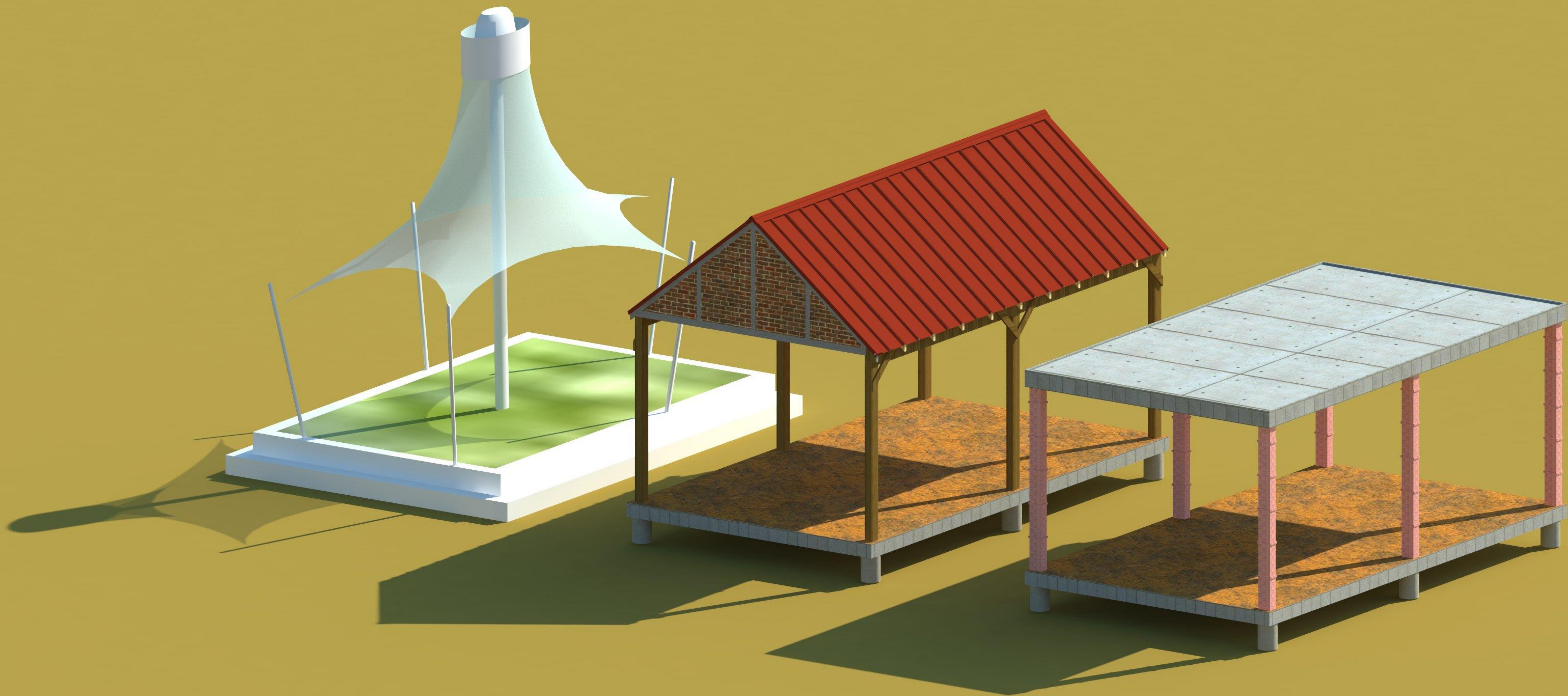


Figure 157) ETFE membrane roof vs Pitched and Flat roof

Flat-Roof pavilion

The flat-roof pavilion will consist of a rectangular shape structure with the dimension of 4.5 m x 8 m, having the area of 36 m². Six brick columns of about 2.8 m will support the rigid concrete slab roof. The concrete floor covered with finishing is about 20 cm higher than ground level.

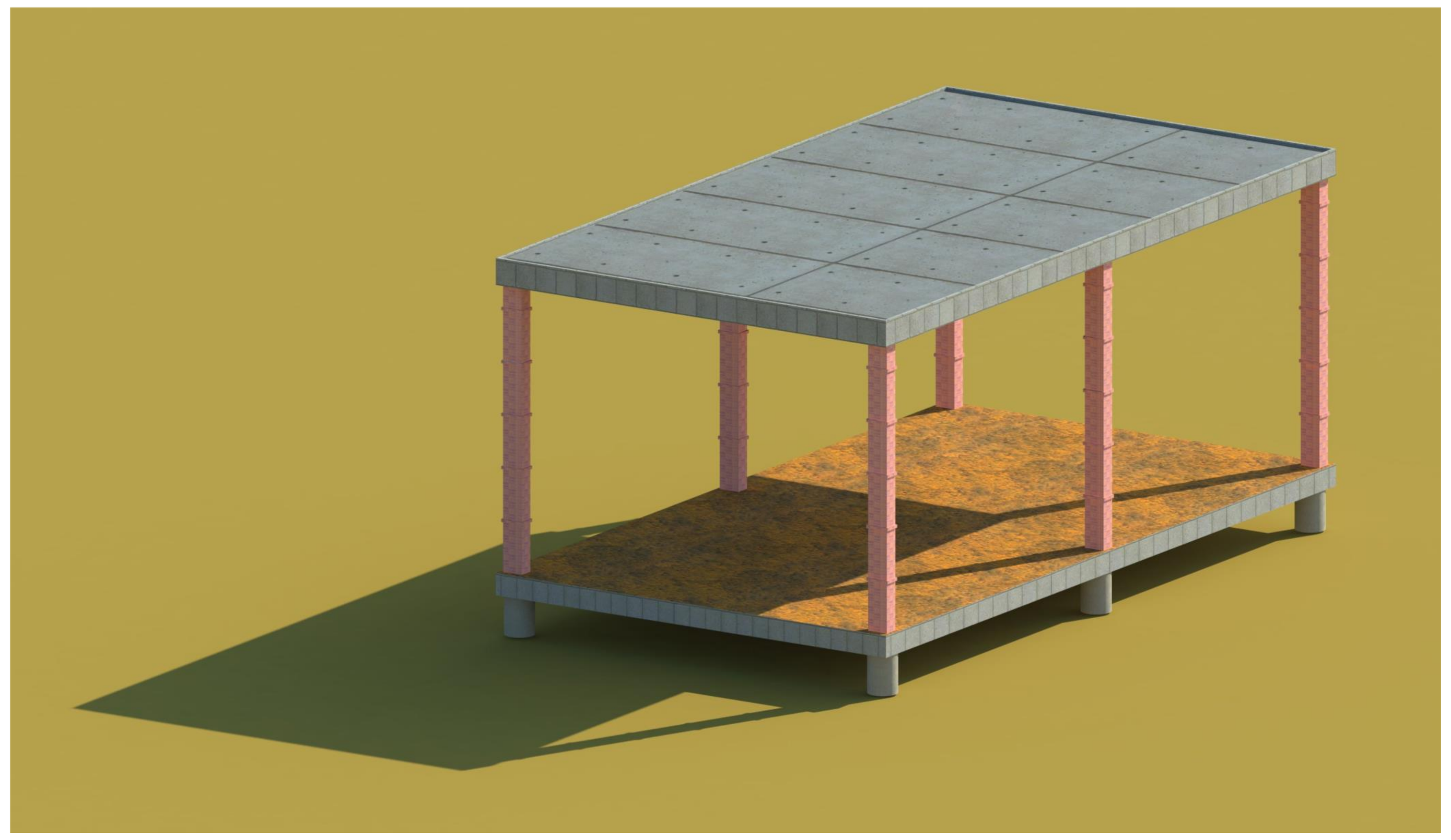


Figure 158) Flat-Roof pavilion

Pitched-Roof Pavilion

The pitched-roof pavilion will consist of a rectangular shape structure with the dimension of 4.5 m x 8 m, having the area of 36 m². Six timber columns of about 2.8 m will support the pitched wooden roof; wooden trusses also laid bellow the roof including a metal finishing over all. Bricks and steel vertical beams enclose the two sides of the pitched roof. The concrete floor covered with finishing is about 20 cm higher above the ground level.

Figure 159) Pitched-Roof pavilion

ETFE Membrane Pavilion

The ETFE membrane pavilion will consist of a rectangular shape concrete base with the dimension of 4.5 m x 8 m having the area of 36 m². The form of the tensile structure is an anticlastic form in which steel bars is supporting the tension and membrane.

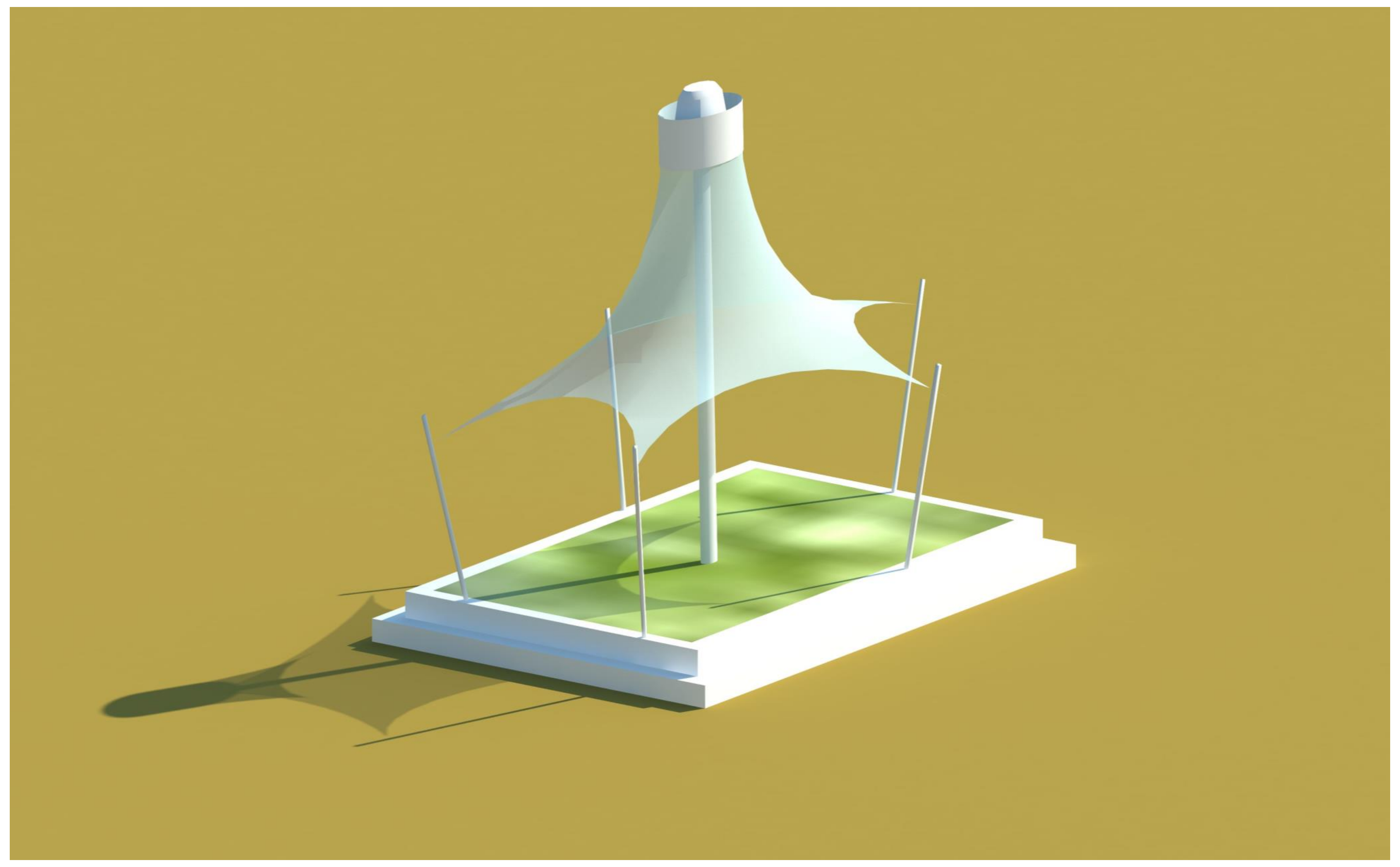


Figure 160) ETFE Membrane pavilion

Milan has a humid subtropical climate that is mild with no dry season, constantly moist (year-round rainfall). Summers are hot and muggy with thunderstorms. Winters are mild with precipitation from mid-latitude cyclones.

What is important in this study is the wind speed and snow depth, the parameters which play the main roll for dead loads over roof.

WIND: Here is shown the wind speed and direction of the wind in Milan. Data taken from "Climate Consultant"

HOW TO READ THE DIAGRAM: *The outermost ring (brown) shows the percentage of hours when the wind comes for each direction. On the next (blue) ring the height and color of the radial bars shows the average temperature of the wind coming from each direction (light blue is in the comfort zone). The next ring shows average humidity (light green is considered comfortable). The three triangles in the innermost circle show the minimum, average, and maximum velocity of the winds from each direction.*

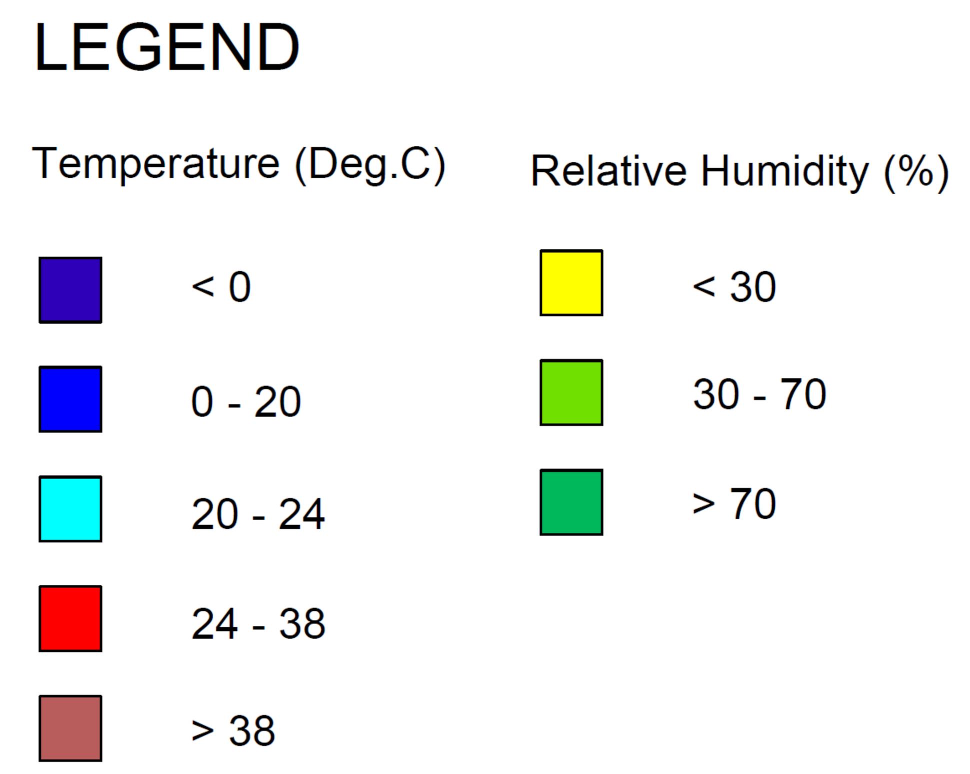


Figure 162) Legend for Wind Wheel

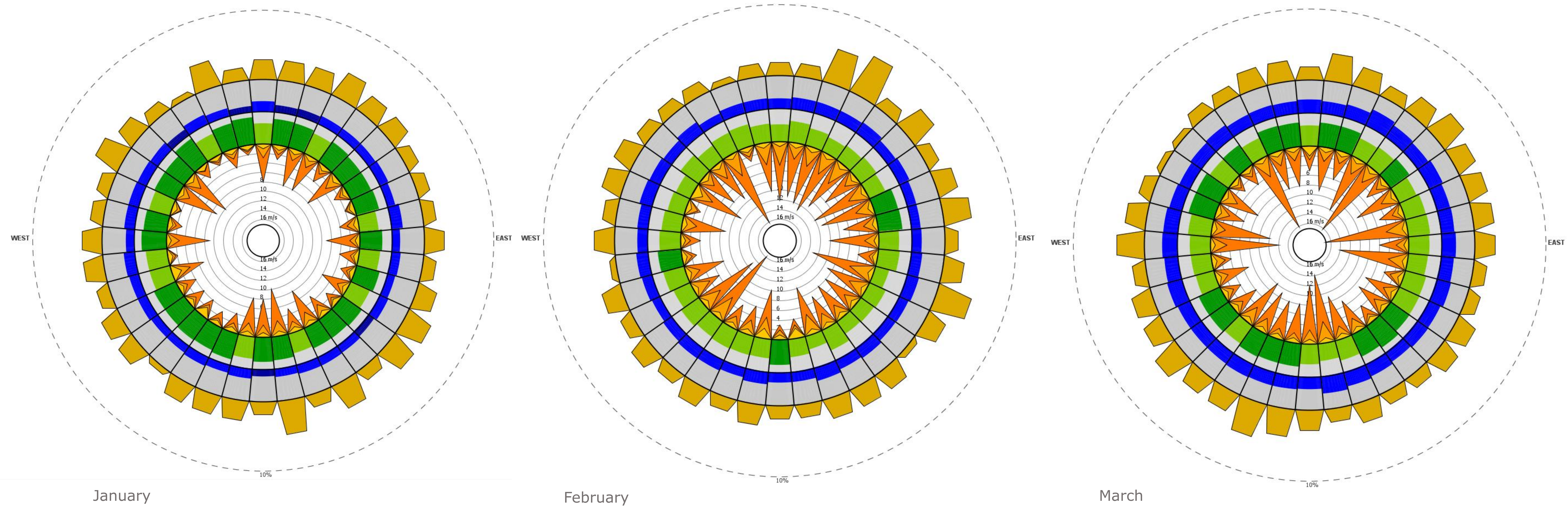
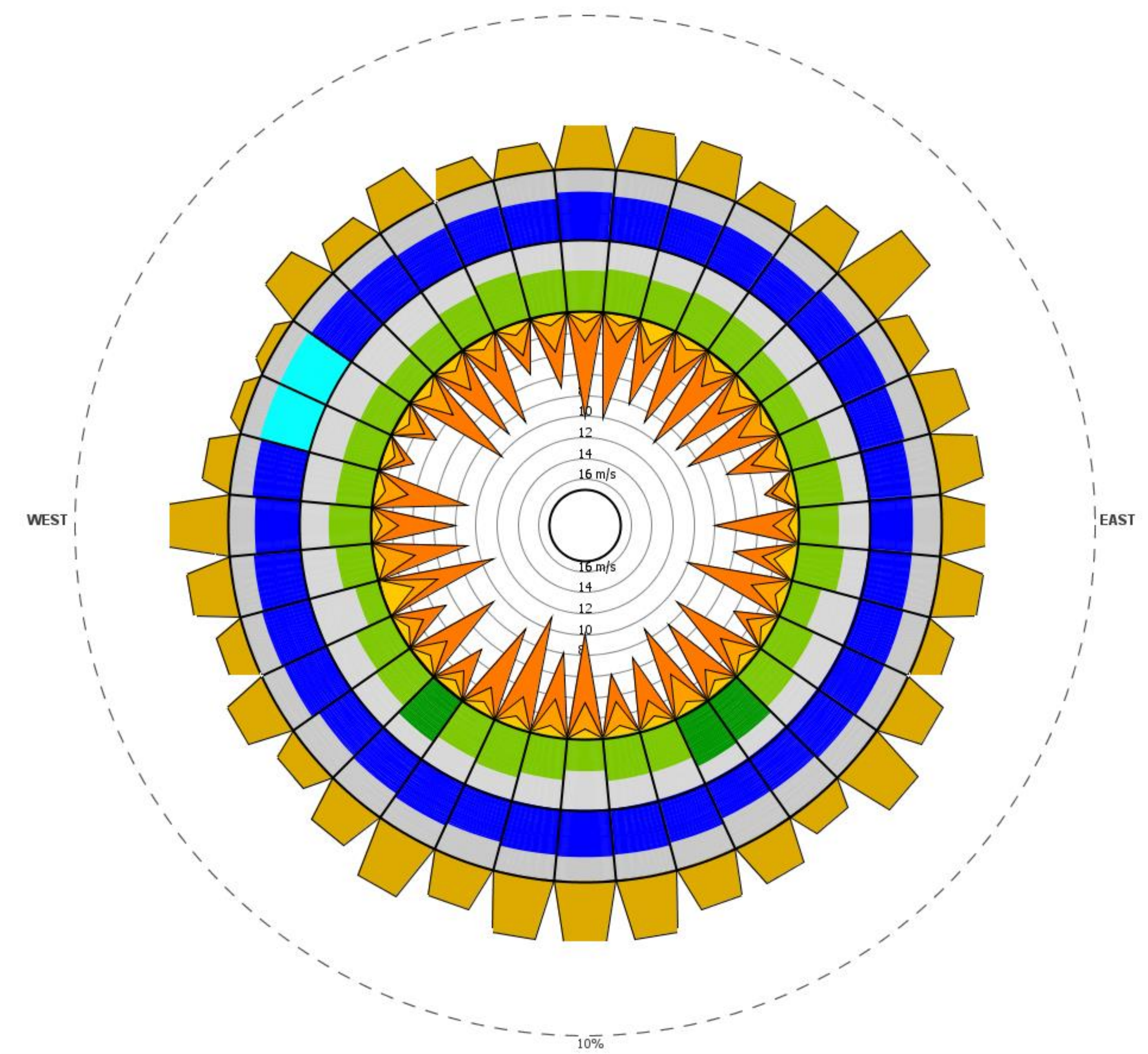
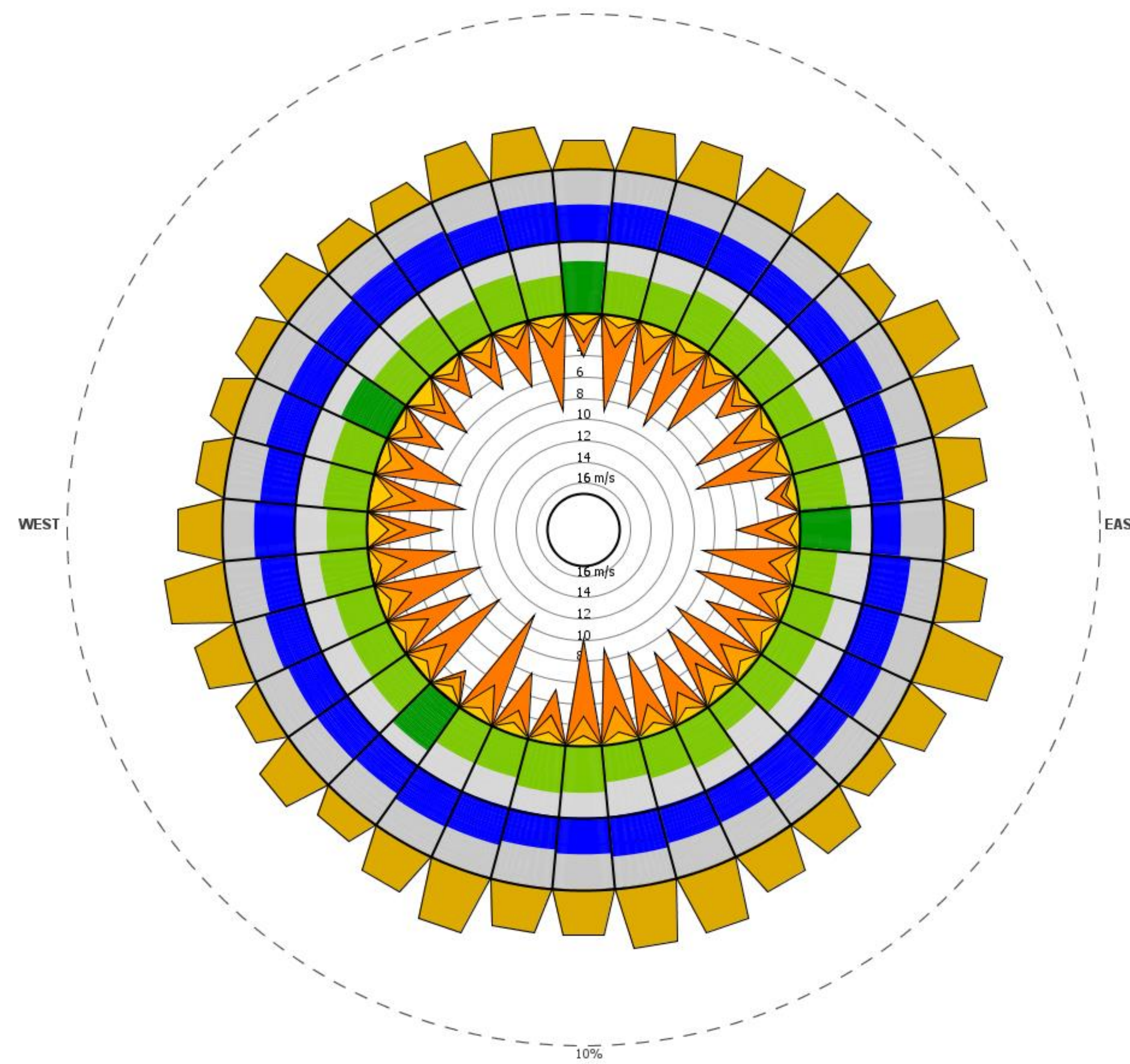


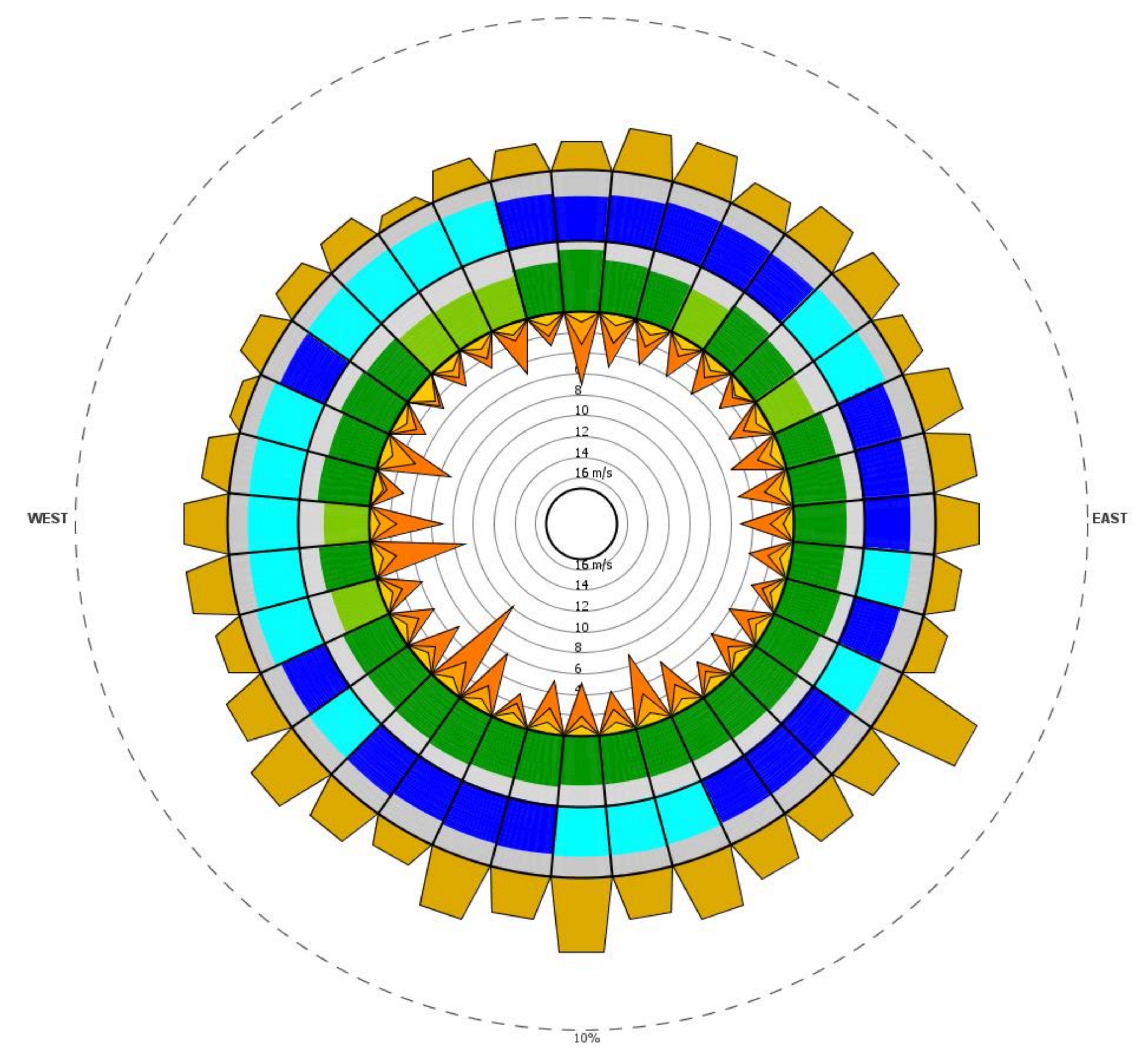
Figure 161) Speed, Direction and Temperature of the Wind according to 12 months, Milan, Italy



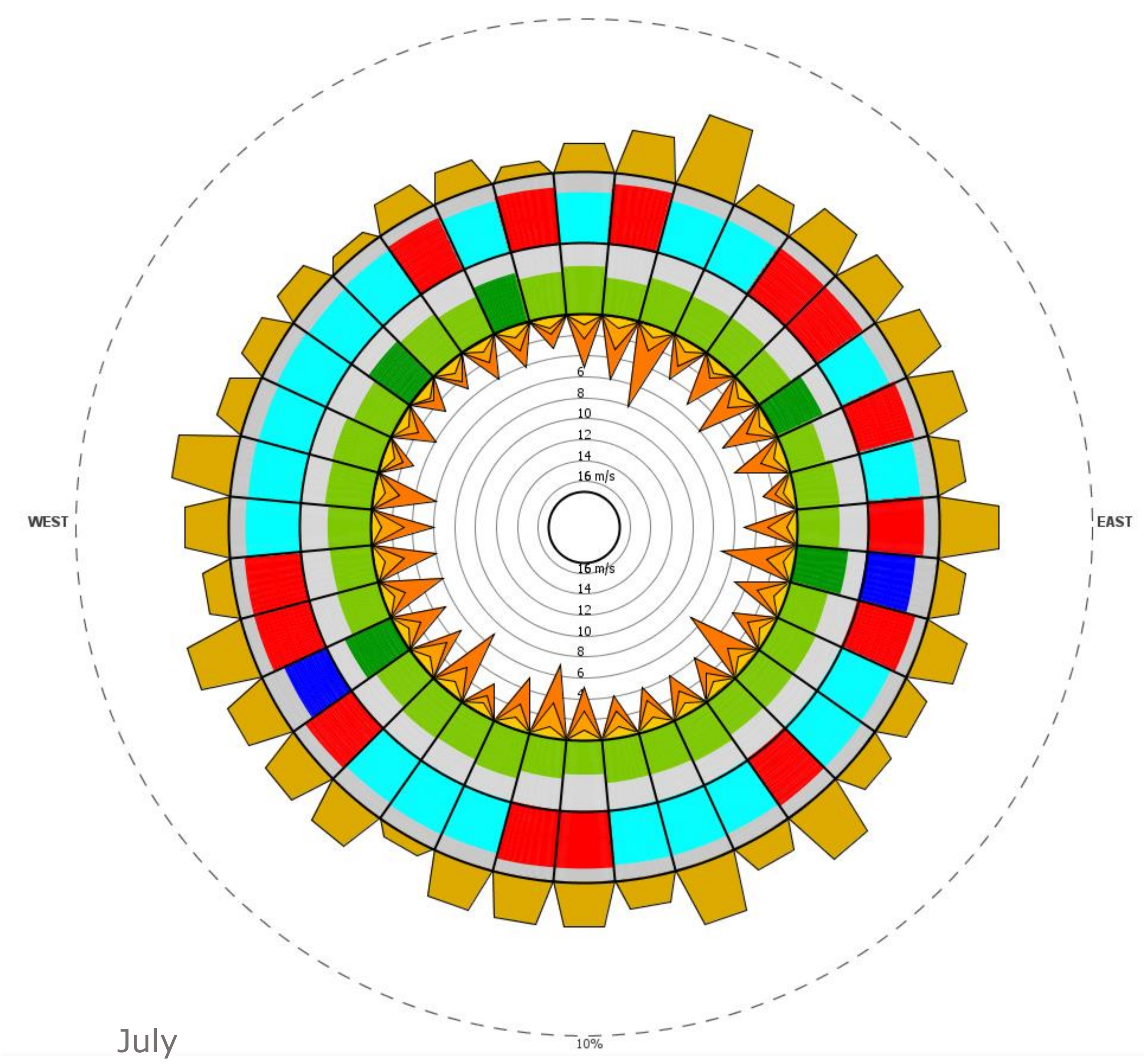
April



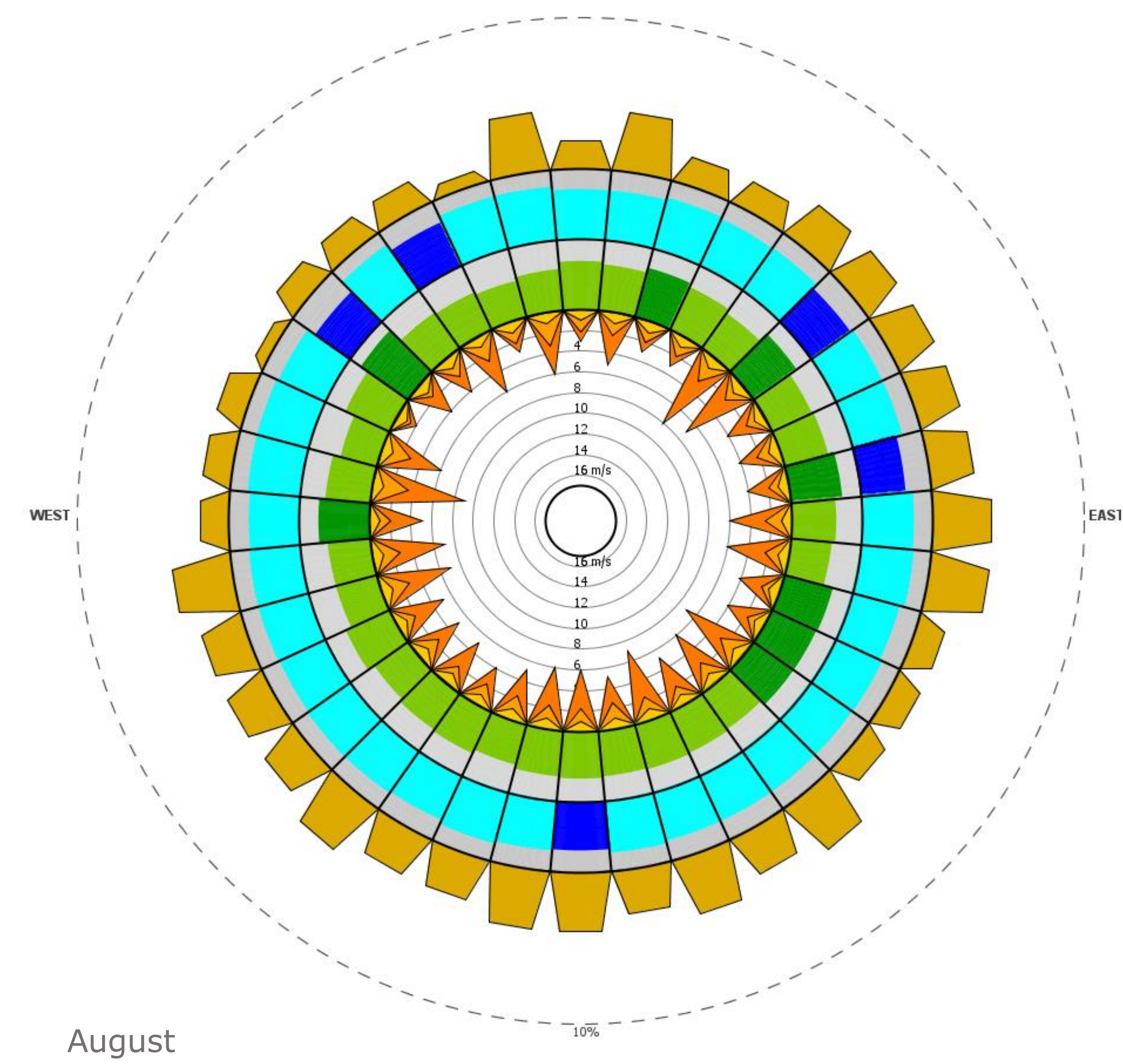
May



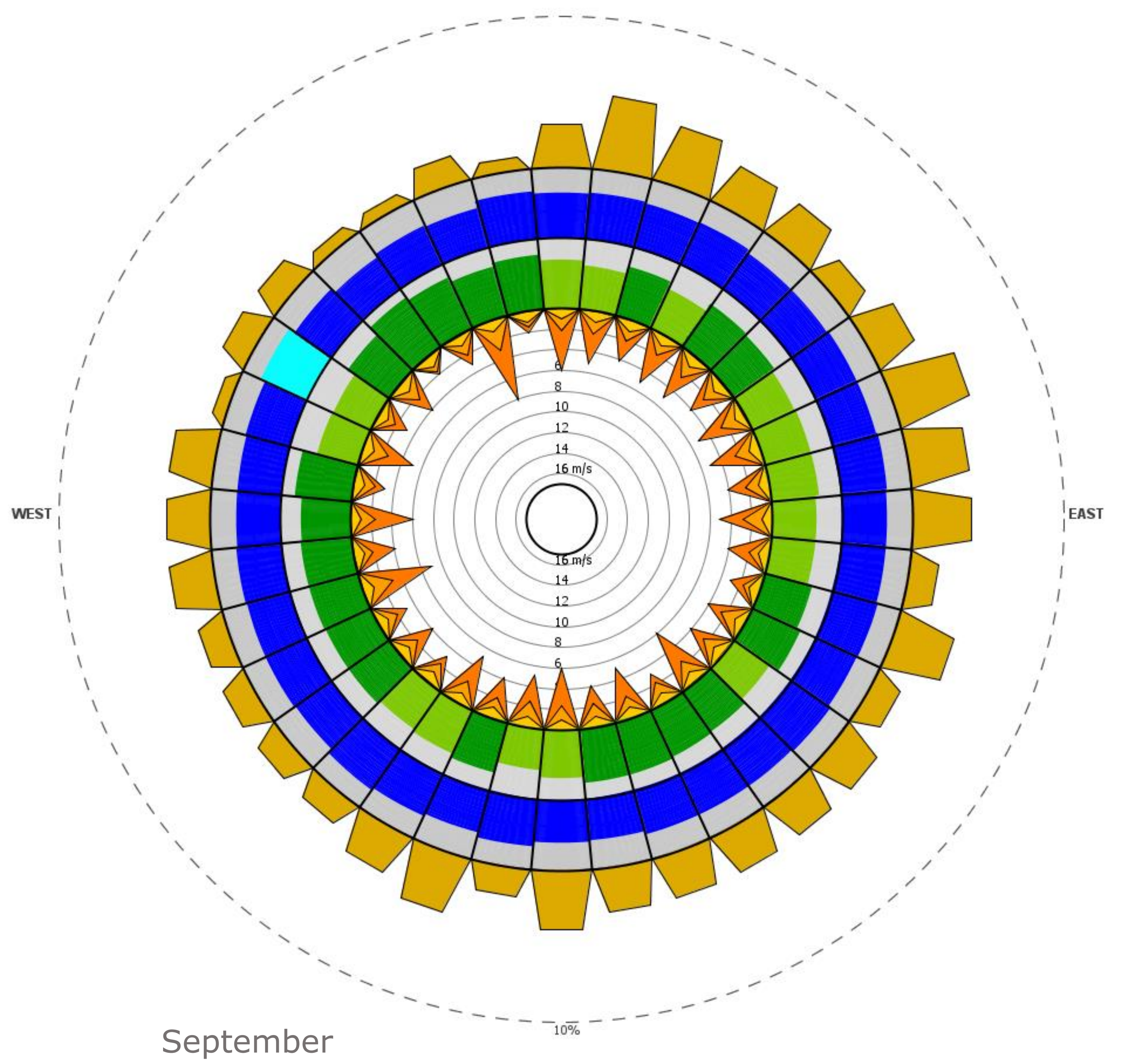
June



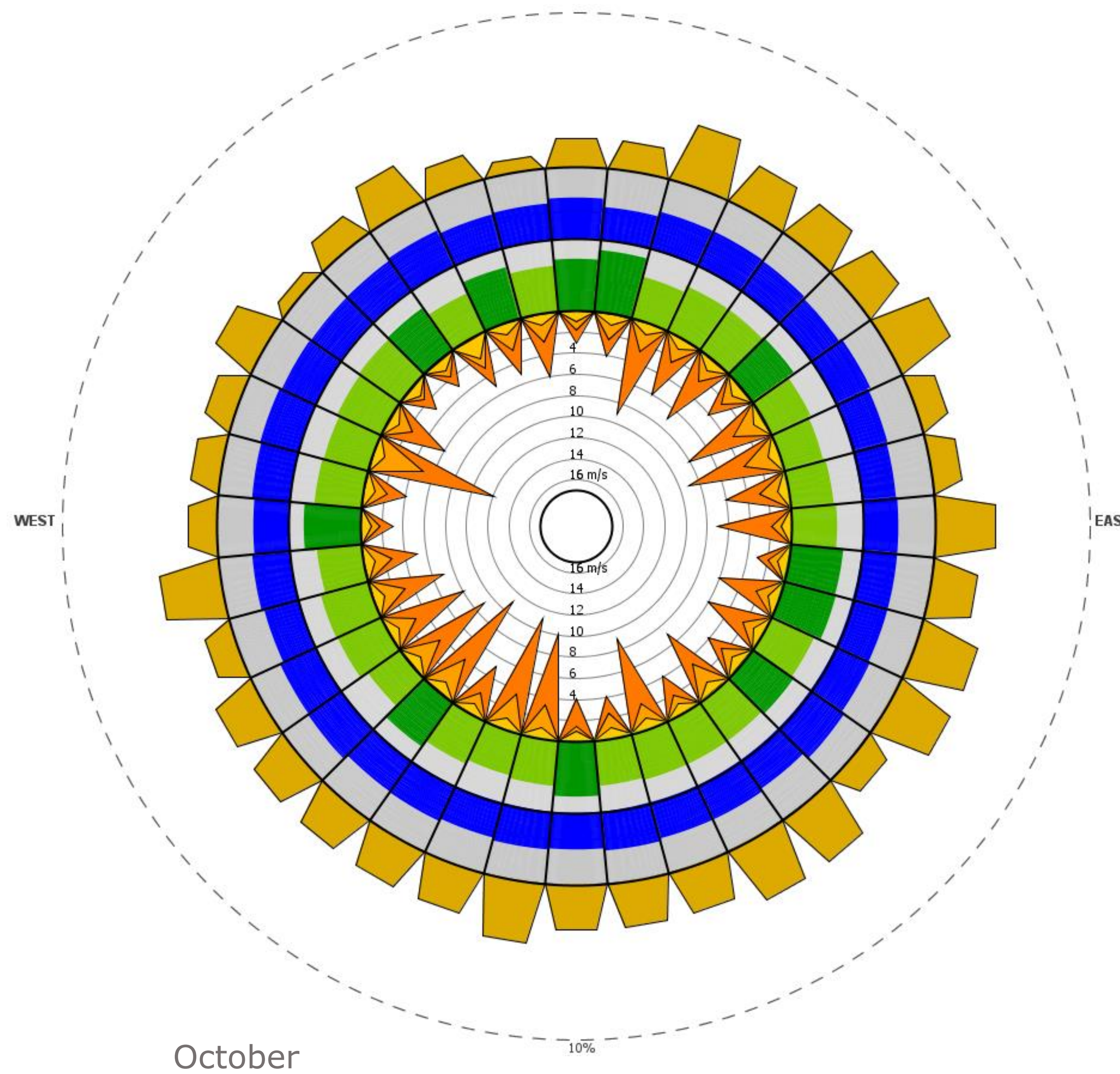
July



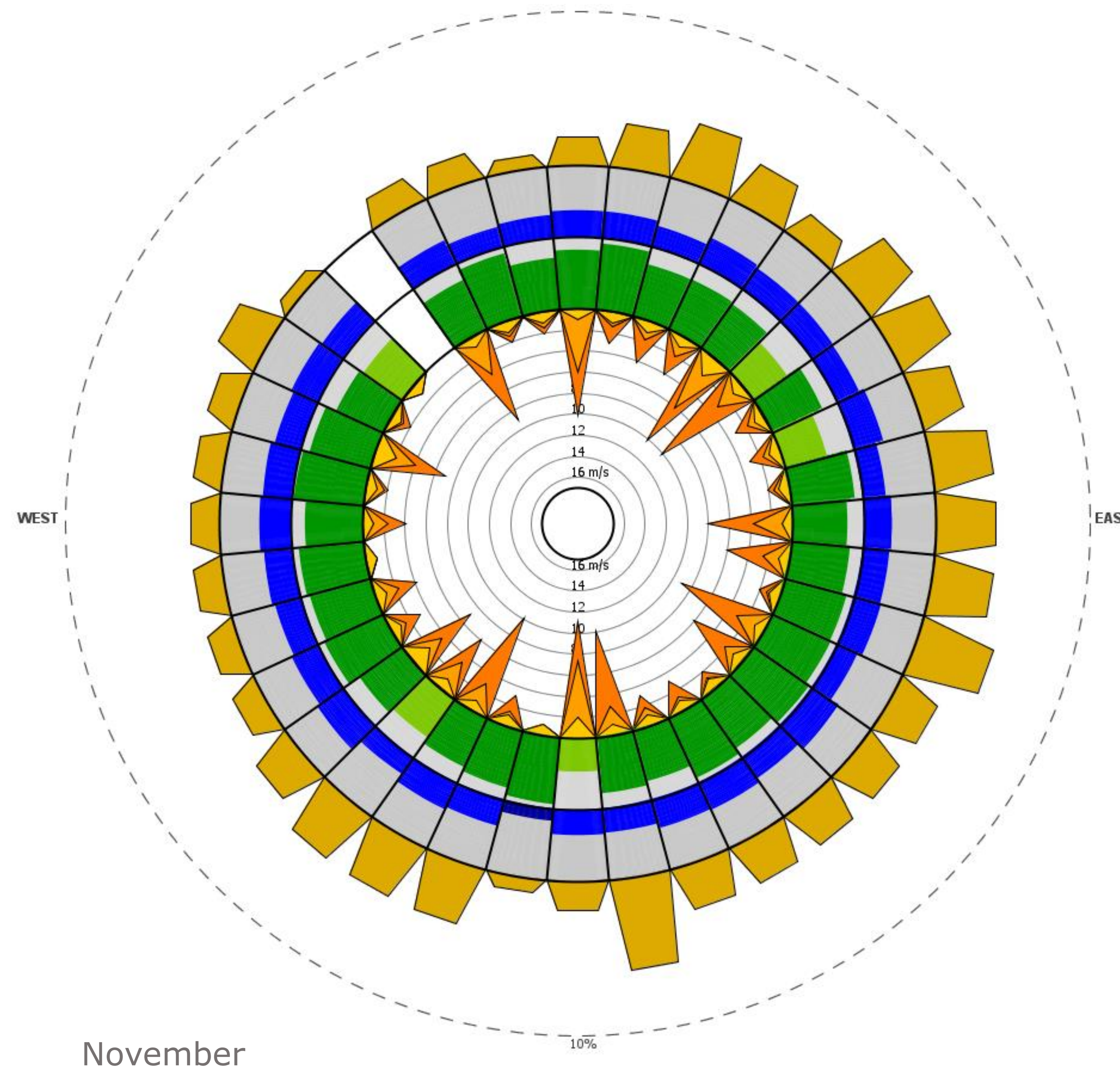
August



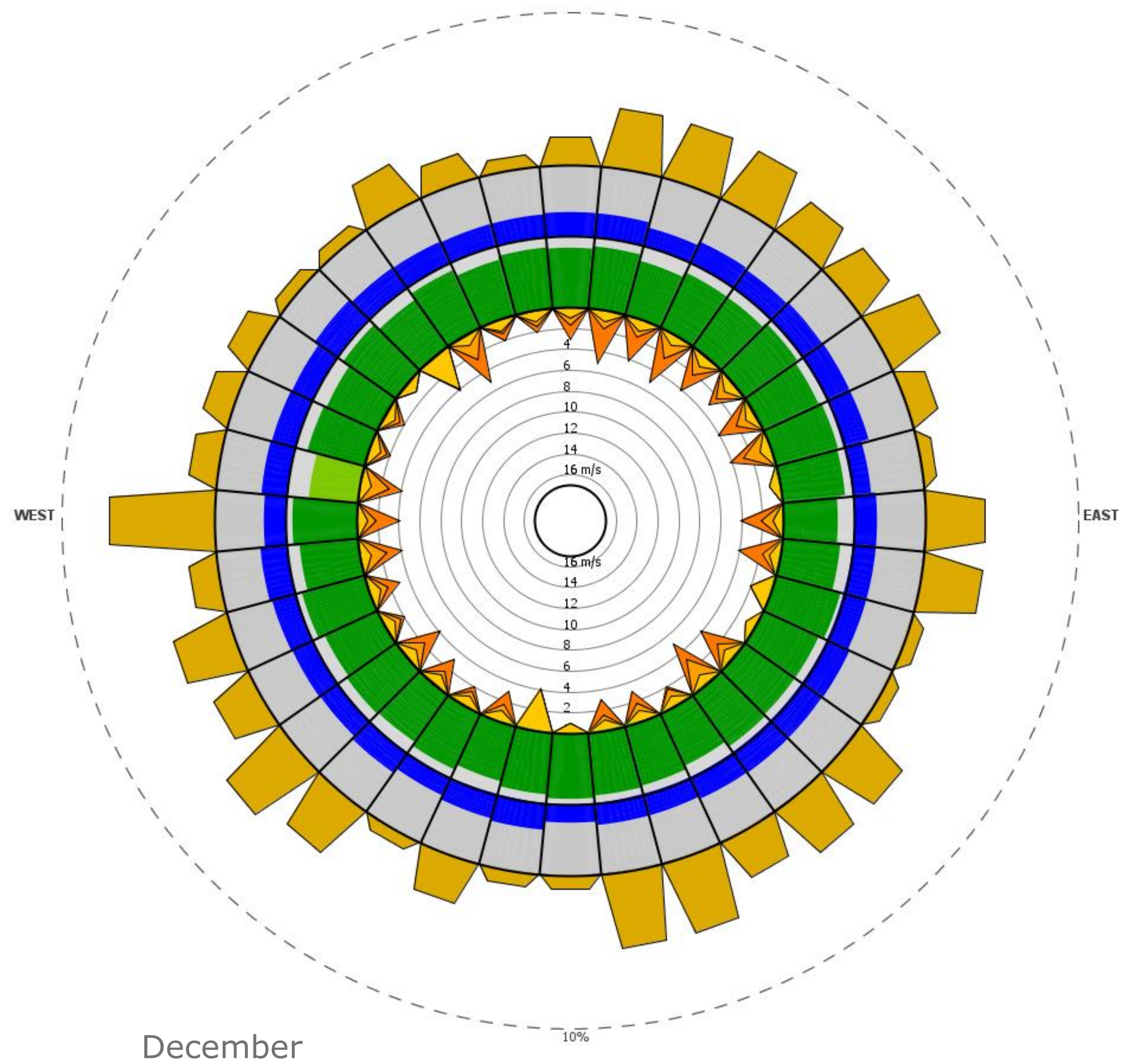
September



October



November



December

According to this data map, the annual average wind speed is below 2 m/s, and in only some exceptional occasions we have high speed data recorded which the maximum speed is related to March and will be about 16 m/s from the East.

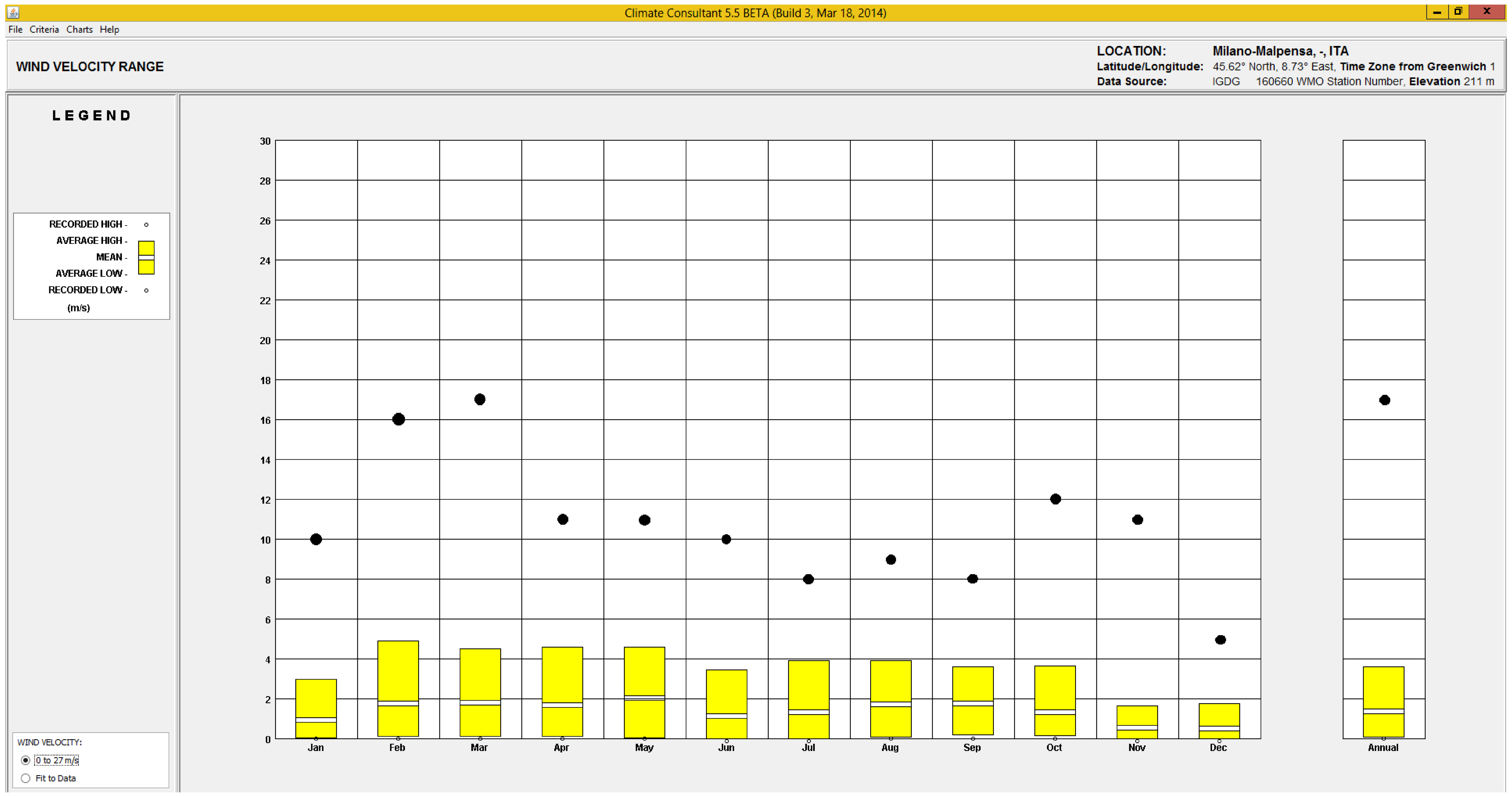


Figure 163) "Climate Consultant" Interface

SNOW: The following diagrams will show the "Probability", "Chance of snow on the ground" and "Average Snow Depth" for Milan city.

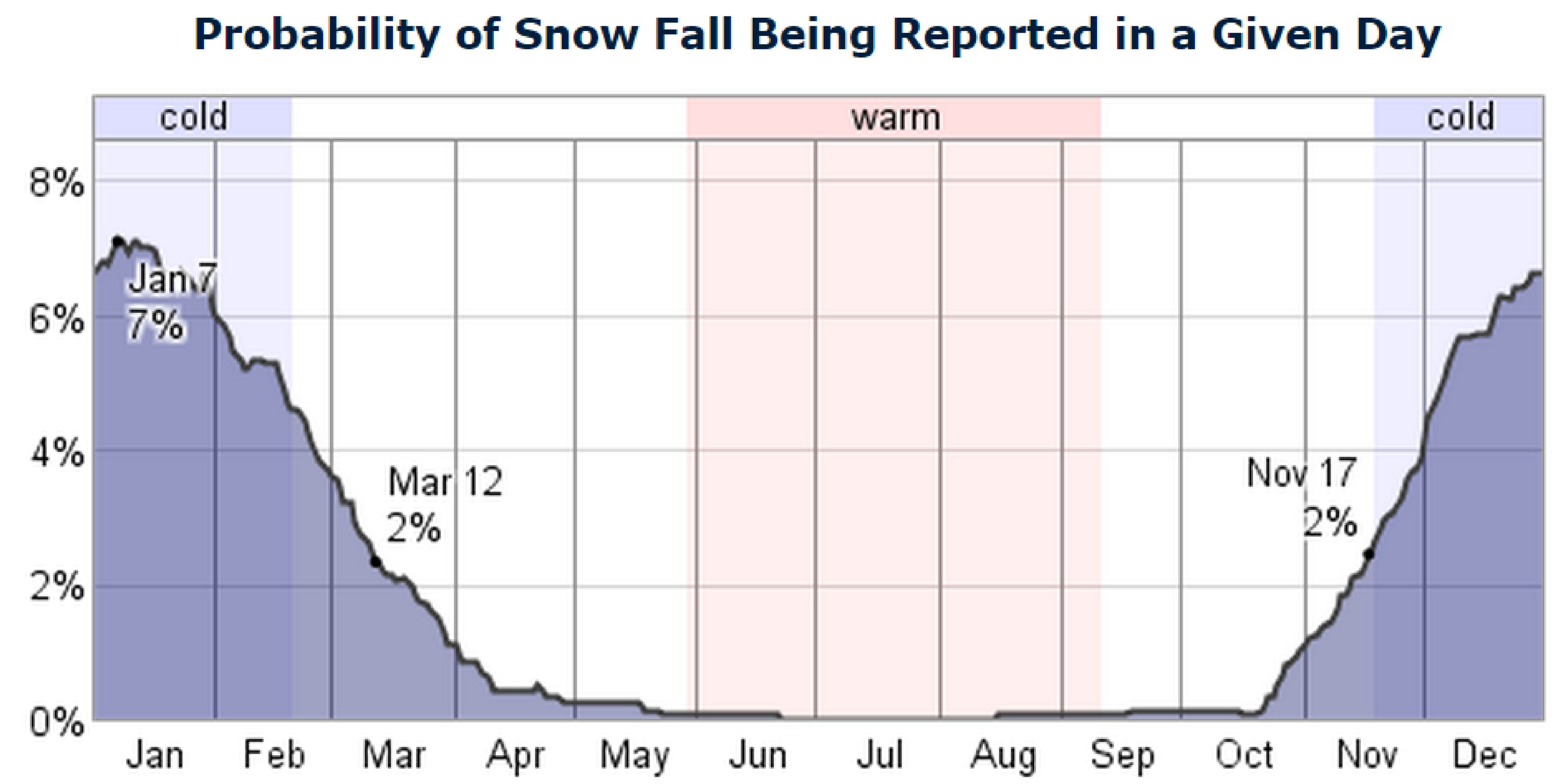


Figure 164) Probability of snow fall

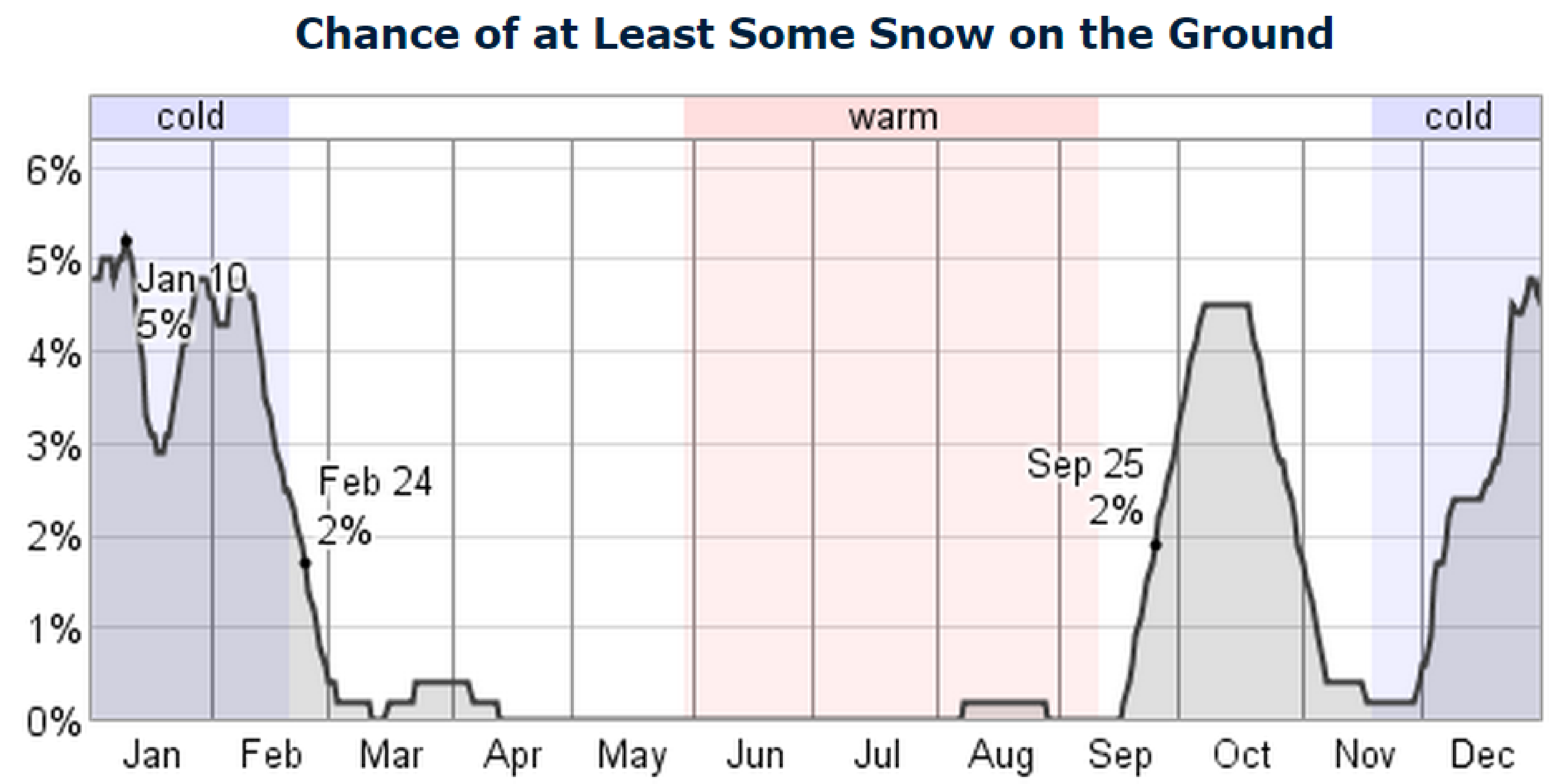


Figure 165) Chance of snow on the ground

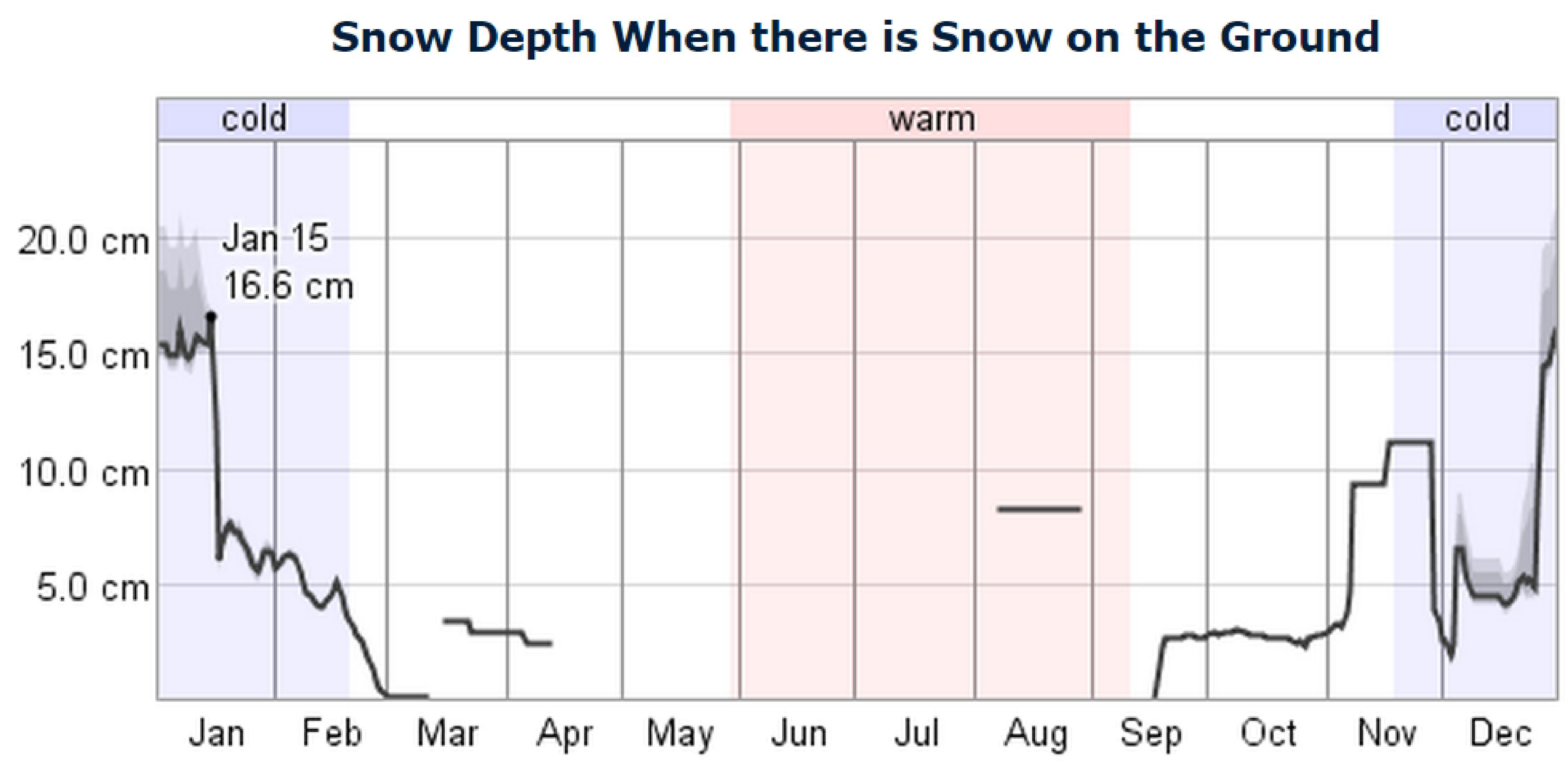


Figure 166) Snow depth

According to the data diagrams The likelihood of snow falling is highest around January 7, occurring in 7% of days. The chances of there being snow on the ground are highest around January 10, occurring 5% of the time. The snow is typically at its deepest on January 15, with a median depth of 16.6 cm; the depth exceeds 17.0 cm only one year out of ten.

Analysis Begins…

This analysis is trying to show a simple and rough comparison between the 2 traditional roof type and the tensile roof pavilions. The analysis is taking place in the simplest situation in terms of the climatic, location and surrounding conditions. The analysis will consider snow loads, wind load, construction timing, cost and maintenance. The snow and wind data are taken from the previous section. The models are reproduced in the Solidworks software in a simple shape with minimum critical requirement.

Analysis begins with snow load. In the following the calculation of snow load for the Milan considering the snow depth is shown.

The steps below show how to estimate the snow load on a roof using the ground snow load, roof properties, and formulas based on national structural engineering codes.

Roof Snow Load Calculation

Step 1 : Finding the Ground Snow Load *G*

The ground snow load is measured in pounds per square foot (psf) or (pa) over a typical patch of ground during a typical snow season. In the Milan case the Ground Snow Load would be 20 psf.

Step 2 : Finding the Exposure Factor *E*

The exposure factor is a value between 0.7 and 1.3, with low values for greatly exposed roofs, and high values for more sheltered roofs. In this case we consider the structures greatly exposed; therefore the Exposure Factor E would be 0.7.

Step 3 : Finding the Thermal Factor *T*

If the building is unheated, we use a thermal factor of 1.2. Typical occupied dwellings that are heated have a thermal factor of 1.0. For hotter, continuously heated structures such as greenhouses, use a thermal factor of 0.85. in this case we consider our roof an unheated roof; therefore the Thermal Factor would be 1.2.

Step 4 : Finding the Roof Slope Factor *R*

If the roof is sloped, you need to account for the angle and surface type to compute the roof slope factor. The roof slope factor is given by the equation :

$$R = (70 - X)/(70 - Y)$$

where X equals the angle in degrees, and Y varies by roof type:

Type A: warm roof, slippery unobstructed surface: Y = 5

Type B: warm roof, other surface: Y = 30

Type C: cold roof, slippery unobstructed surface: Y = 15

Type D: cold roof, other surface: Y = 45

In this case we consider the roof type C, because the pitched rood would be a metal sheet and therefore slippery and unobstructed.

Step 5 : Putting All Together

$$\text{Roof Snow Load} = 0.7 \times G \times E \times T \times R$$

This method will be applied to all 3 models of roofs being analyzed in this analysis

Flat-Roof Pergola Snow Analysis

Having all factors from the previous section, now the Snow Load for the Flat roof Pergola could be calculated :

R = (70 – 0) / (70 – 15)

RSL = 0.7 x 20 x 0.7 x 1.2 x 1.27 = 14.93 psf

RSL = 714.85 pa

Another way for Snow Load Calculation is to have the peak snow depth of the location (Milan) and auto calculate it by online calculation websites.

In this case the max sow depth of Milan according to previous data shown is 17 cm.

In this case the online calculation says 750 pa which is almost similar.

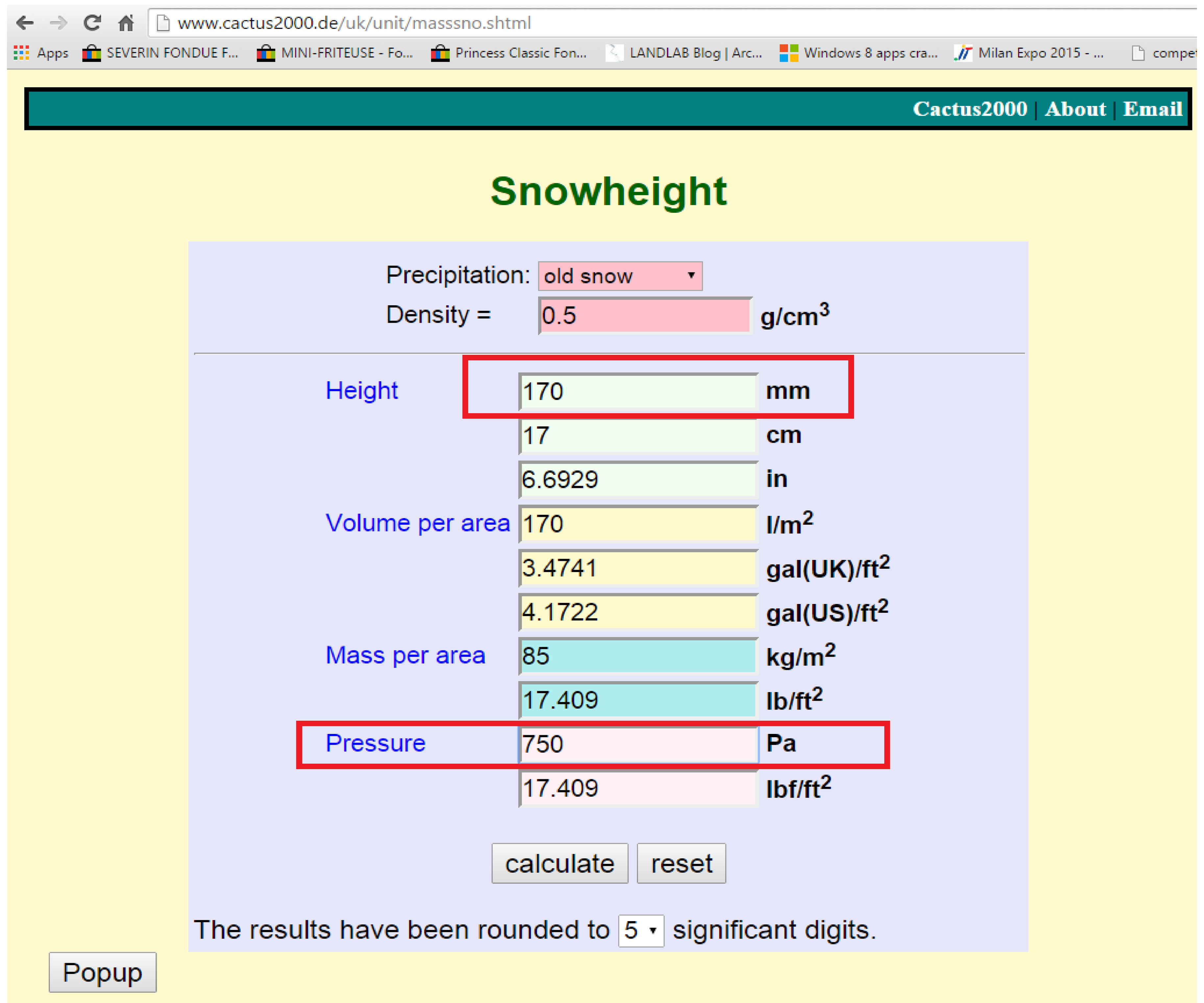


Figure 167) Snow Load online calculation
http://www.cactus2000.de/uk/unit/masssno.shtml

Now with the aim of Solidworks first we model the flat roof pergola in a simple way then try to import this load and run the analysis to the stresses and displacements.

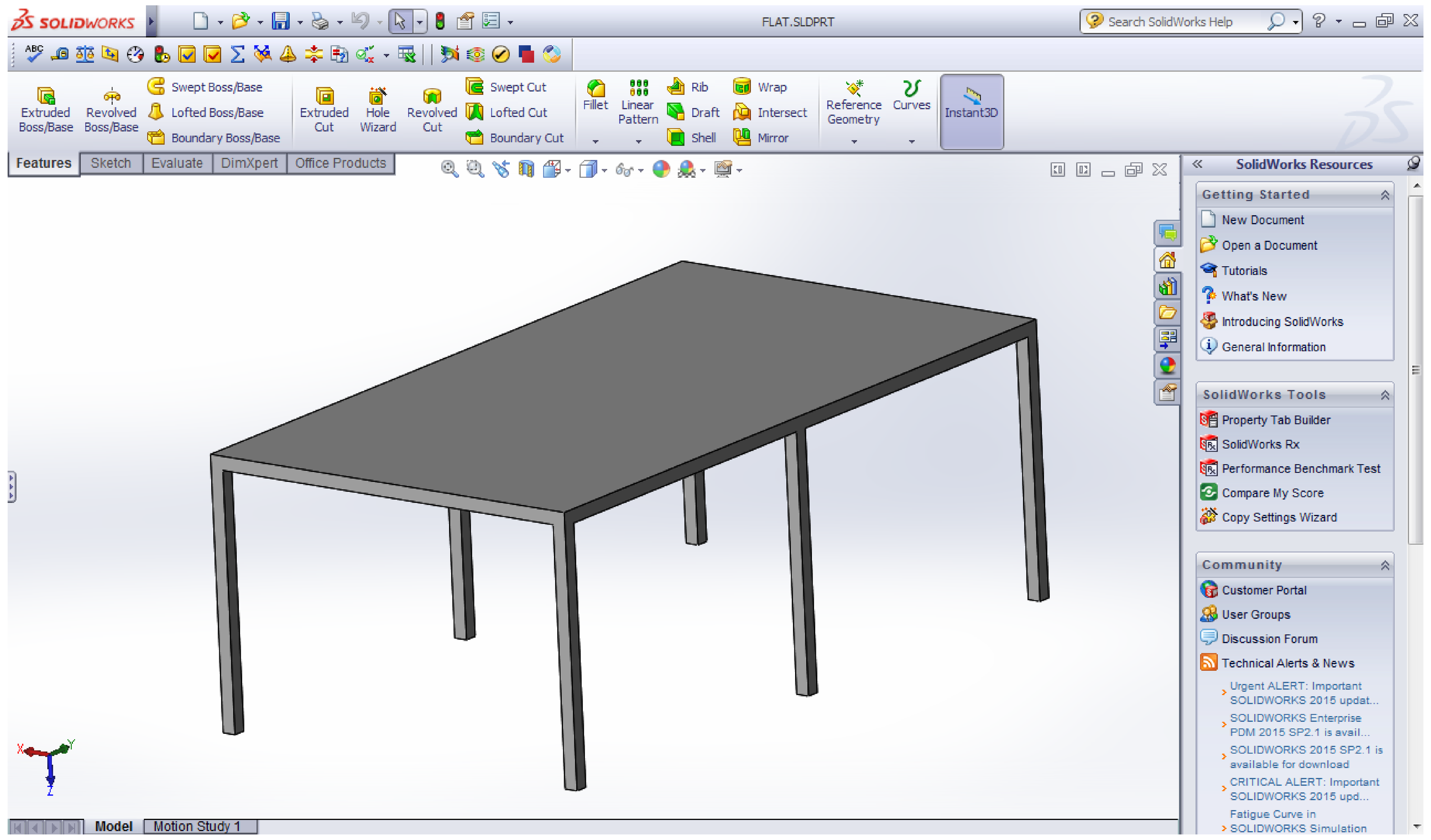


Figure 168) Axonometric view of the Flat-Roof Pavilion model

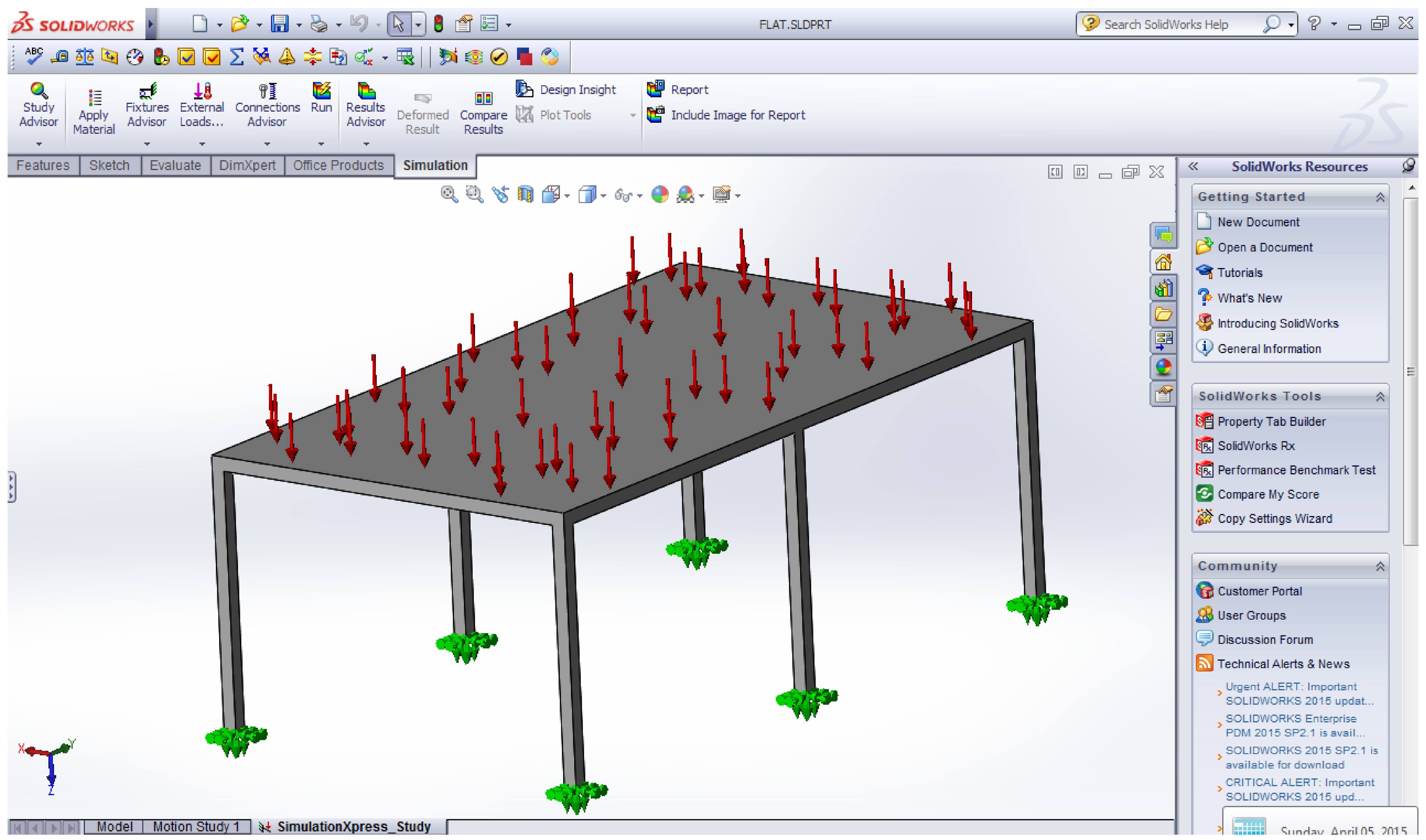


Figure 169) Applying the snow loads on the Flat-Roof Pavilion

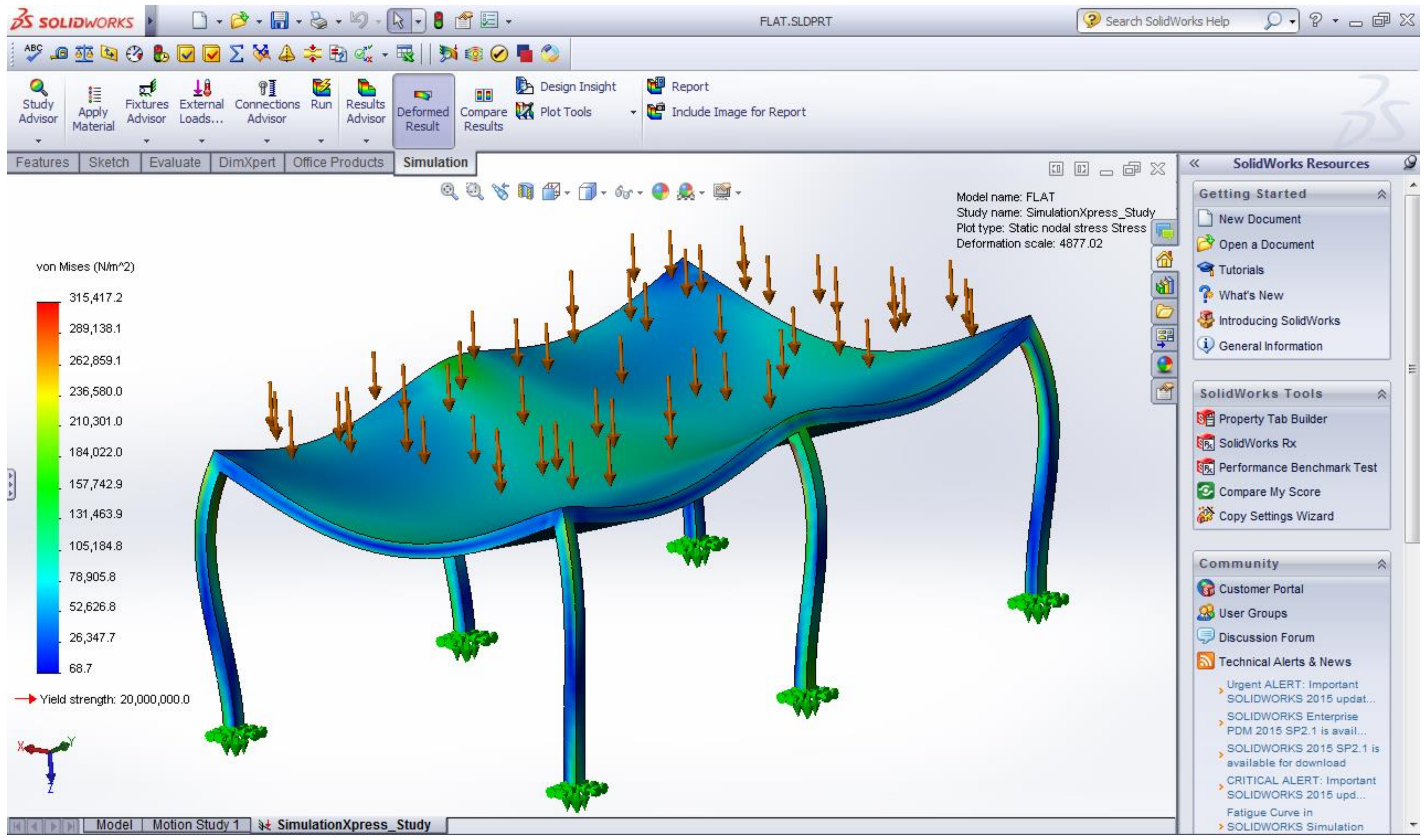


Figure 170) Stress caused by snow loads

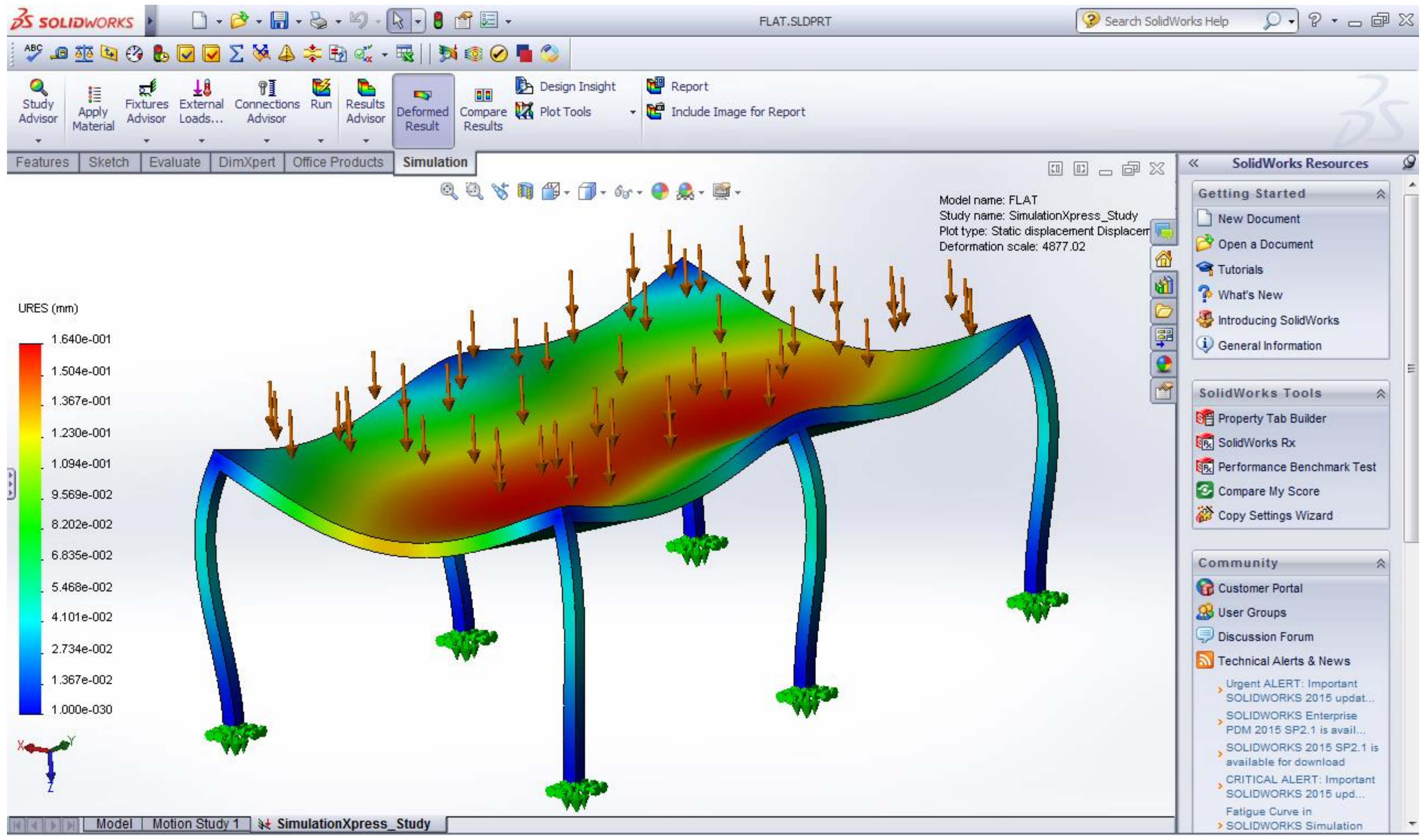


Figure 171) Displacement caused by snow loads

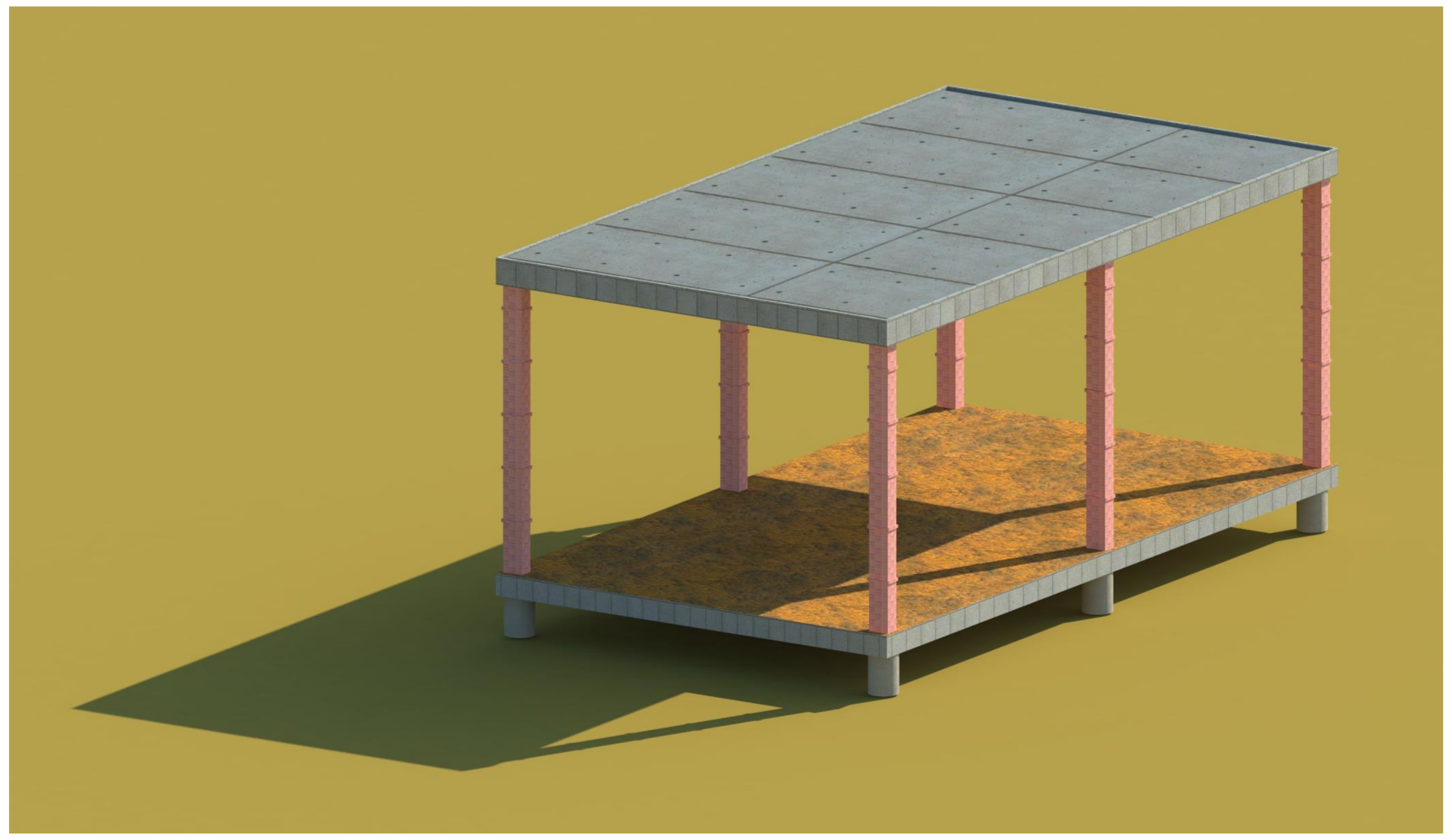


Figure 172) Flat-Roof Pavilion

Applying the snow loads and running the simulation shows the stress and displacement causing by the snow on the flat roof. The model shows that in the maximum snow load the stress would be below 300 kpa and this stress will cause the displacement around 0.164 mm. in other words it is showing that this pavilion is completely stable for this amount of snow which is the maximum rate of snow in Milan.

Flat-Roof Pergola Wind Analysis

In the previous section the wind speed and direction was discussed and as given data for the Milan the maximum wind speed was due to March for the average of 16 m/s from the direction of East. Applying this data to the wind analysis of the Solidworks giving speed and direction to the flat roof pavilion model the results are gathering in the following pictures. In this particular case the wind will affect minimum stress and turbulence to the structure. The turbulence is higher when the wind is leaving the structure.

In other words the Flat-Roof Pavilion is stable against Snow and Wind loads

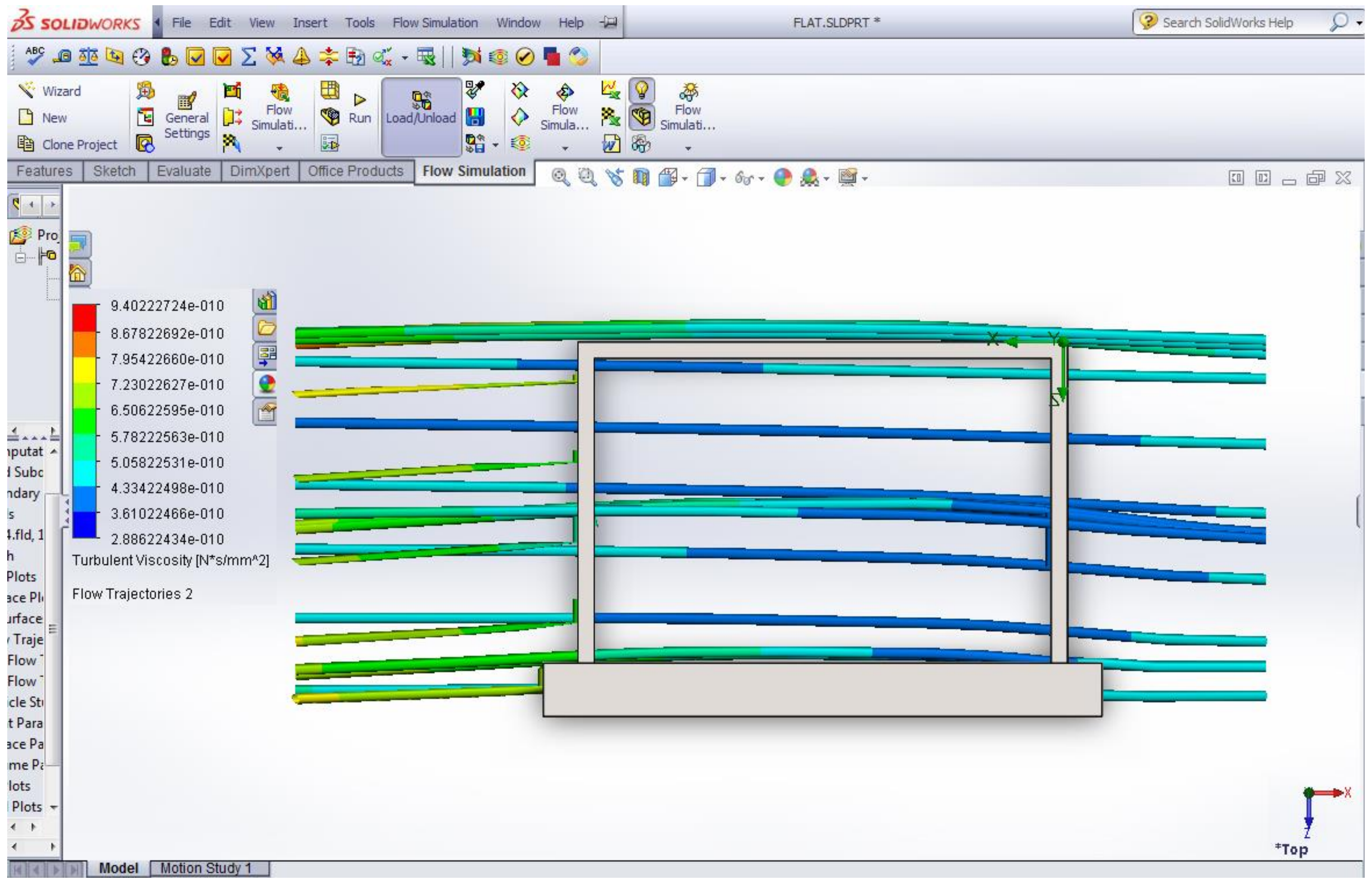


Figure 174) Turbulent Viscosity, Wind blowing from the east passing through the structure

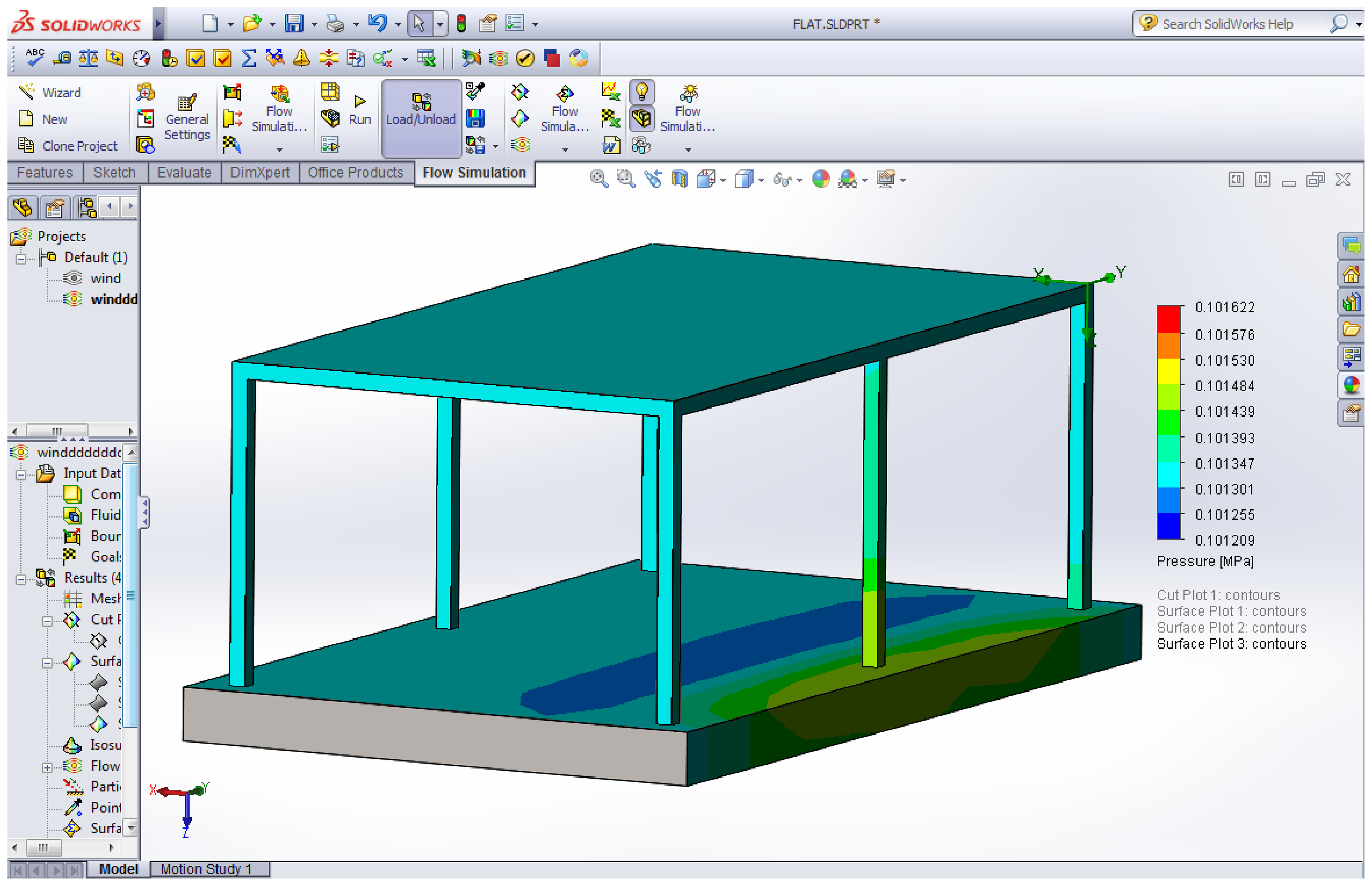


Figure 173) Wind pressure on the east side surface, 3D view

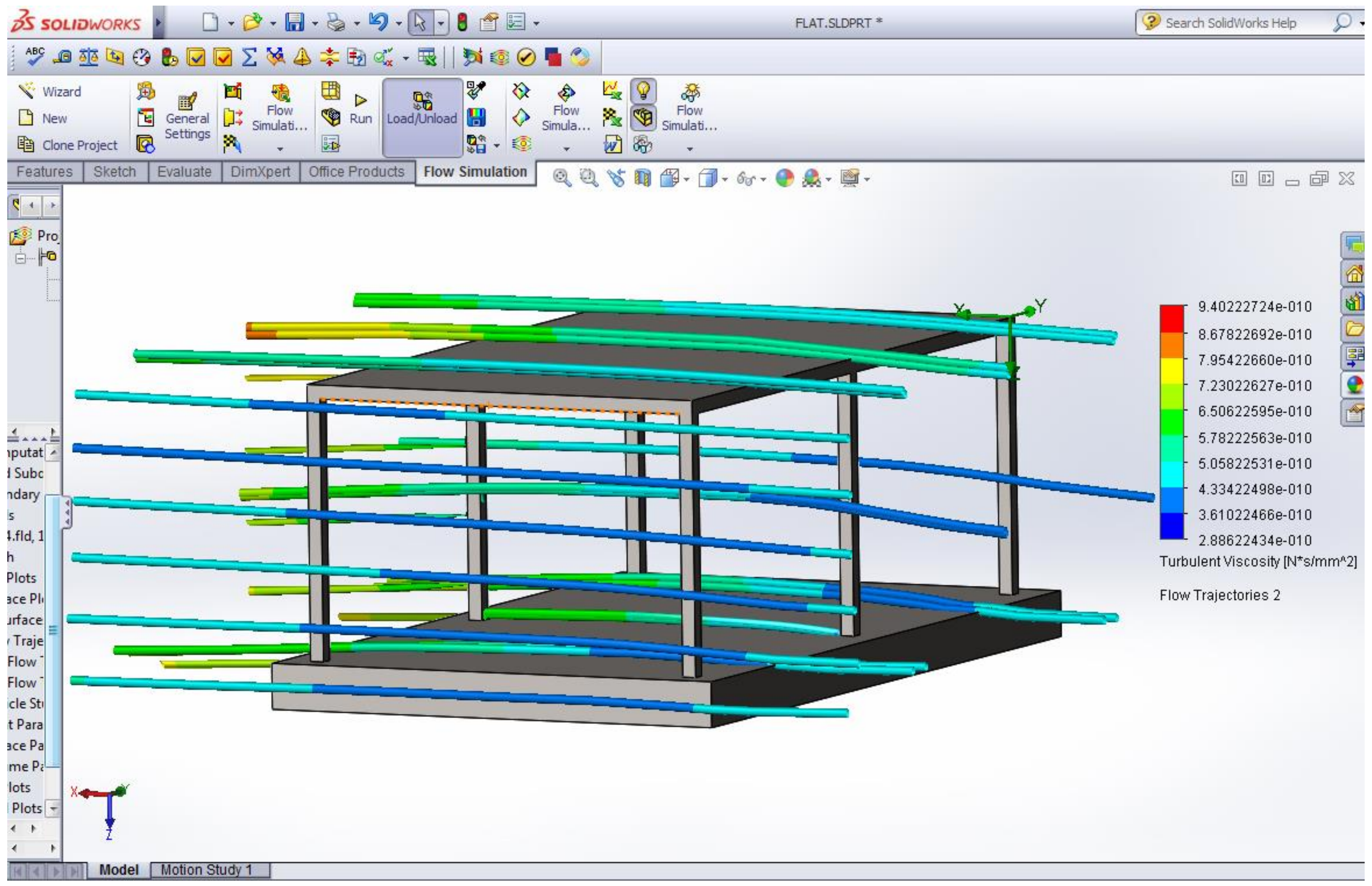


Figure 175) Turbulent Viscosity, wind passing through the structure, 3D view

Flat-Roof Pergola Cost Analysis (WBS Chart)

In this section the cost analysis will be evaluated. The **WBS chart (Work Breakdown Structure)** is provided in a rough and simple mode just in order to have an idea about the cost. The WBS chart is not accurate and the labor and mechanical costs are not included for all 3 structures. Costs are taken from "Listino dei Prezzi 2012".

WBS Code	Group of Technol. Units	WBS Code	Technological Units	WBS Code	Group of Technical Elements	WBS Code	Technical Elements	WBS Code	Technical Detail	list of cost	list code	Cost items	U.m.	Q	Unit Cost	TOTAL Cost
.00	PLELIMINARY ACTIVITIES	.00.00	PRELIMINARY GROUND WORKS	.00.00.00	EXCAVATION	.00.00.00.00	Earth moving for foundations and cellar			http://www.barrie.ca/assets/engineering/	23mRow	Cost including excavator renting and the excavation itself (labor) in cubic meter	m^3	5m x 8.5m x 0.2m = 9 m^3	7.51 eur	67,59 eur
.01	STRUCTURE	.01.00	Foundations	.01.00.00	Direct foundations	.01.00.00.00	Concrete Foundation Slab 150 mm		Concrete slab 150 mm Thermal resistance : 1.43 m^2K/W	http://www.mybuilder.com/	Sw1066	Cost including the concrete itself and the cost of laying	m^3	5m x 8.5m = 42.5 m^2 x 0.15 m = 6.4 m^3	120 eur	768 eur
		.01.01	Frame	.01.01.00	Vertical frame	.01.01.00.00	Stuctural brick column square		Rectangulare brick column 21cm x 21cm	http://www.alibaba.com/product-gs/865814884/200mm_Stuctural_Pillar_square_tube.html	A106	Stuctural square brick column , the cost doesn't include labor fees	Ton	0.96 Tons	500 eur	480 eur
						.01.01.00.01	Mortar		Used for ceramic tiles 10 mm 1 part lime to 3 parts well-graded sharp	http://www.bolton.ac.uk/Quality/QAEContents/	COARSE STUFF	A basic ready-mixed mortar containing well-graded sharp sand and sieved, mature lime putty. Suitable for bricklaying	m^3	0.2m x 0.2m x 0.1m x 240 = 0.96	62 eur	59 eur
.02	ENCLOSURE	.02.00	Lower horizontal enclosure	.02.00.00	Ground floor	.02.00.00.00	Concrete floor Slab		Concrete slab 150 mm Thermal resistance : 1.43 m^2K/W Thermal	http://www.mybuilder.com/	Sw1066	Concrete slap using for flooring membrane	m^3	4.5m x 8m = 36 m^2 x 0.15 = 5.4 m	120 eur	648 eur
		.02.01	Upper enclosure	.02.01.00	Flat Roof	.02.01.00.00	Concrete floor Slab		Concrete slab 150 mm Thermal resistance : 1.43 m^2K/W Thermal Conductivity : 0.28 W/mK Specific Heat : 836.8 J/kgK	http://www.mybuilder.com/	Sw1066	Concrete slap using for Roofing	m^3	4.5m x 8m = 36 m^2 x 0.15 = 5.4 m	120 eur	648 eur
.03	FINISHING	.03.00	Internal Finishing	.03.00.00	Floors	.03.00.00.00	Floor of the inner space of pergola		Ceramic tiles 20 mm	http://www.alibaba.com/product-detail/concave-surface-homogeneous-unpolished-ceramic-tiles_60056528941.html	Q6P988	concave surface homogeneous unpolished ceramic tiles 40x40	m^2	36 m^2	4 eur	144 eur

Total : 3,200 eur

Table 9) WBS chart for Flat-Roof Pergola

*** Please note that the WBS chart represents only the material costs of the project excluding equipments and labor fees.**

Pitched-Roof Pergola Snow Analysis

Having all factors from the previous section, now the Snow Load for the Pitched-Roof Pergola could be calculated :

R = (70 – 30) / (70 – 15) (30° slope)

RSL = 0.7 x 20 x 0.7 x 1.2 x 0.72 = 8.5 psf

RSL = 406 pa

It is also possible to calculate it online having the snow depth of 17 cm for Milan, but this time the result should be multiplied by cos of the pitched roof angle, which in this case is 30°.

750 pa x cos(30°) = 375 pa

Which is almost equal to 406 pas calculated above.

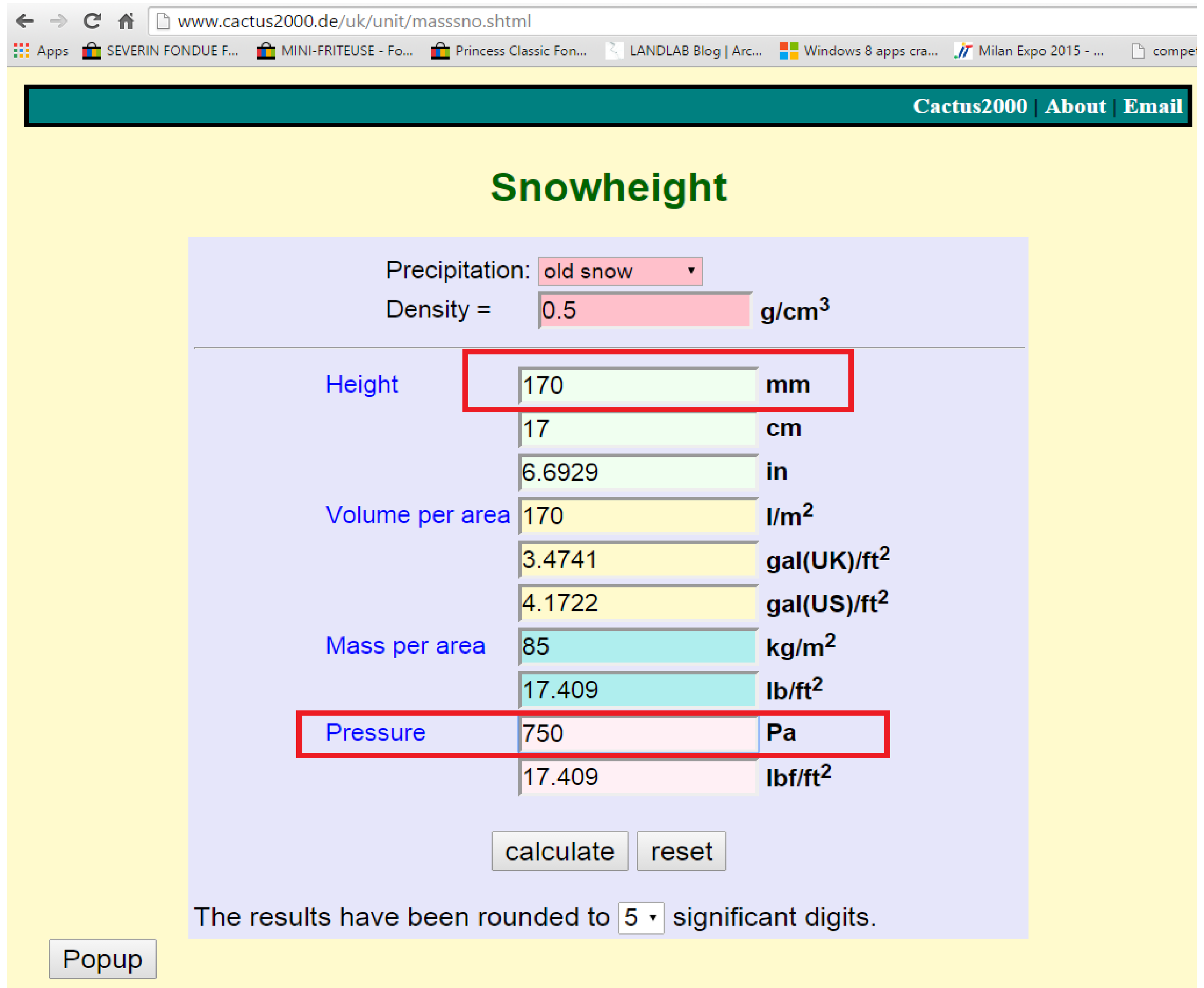


Figure 176) Snow Load online calculation
http://www.cactus2000.de/uk/unit/masssno.shtml

Now with the aim of Solidworks first we model the flat roof pergola in a simple way then try to import this load and run the analysis to the stresses and displacements.

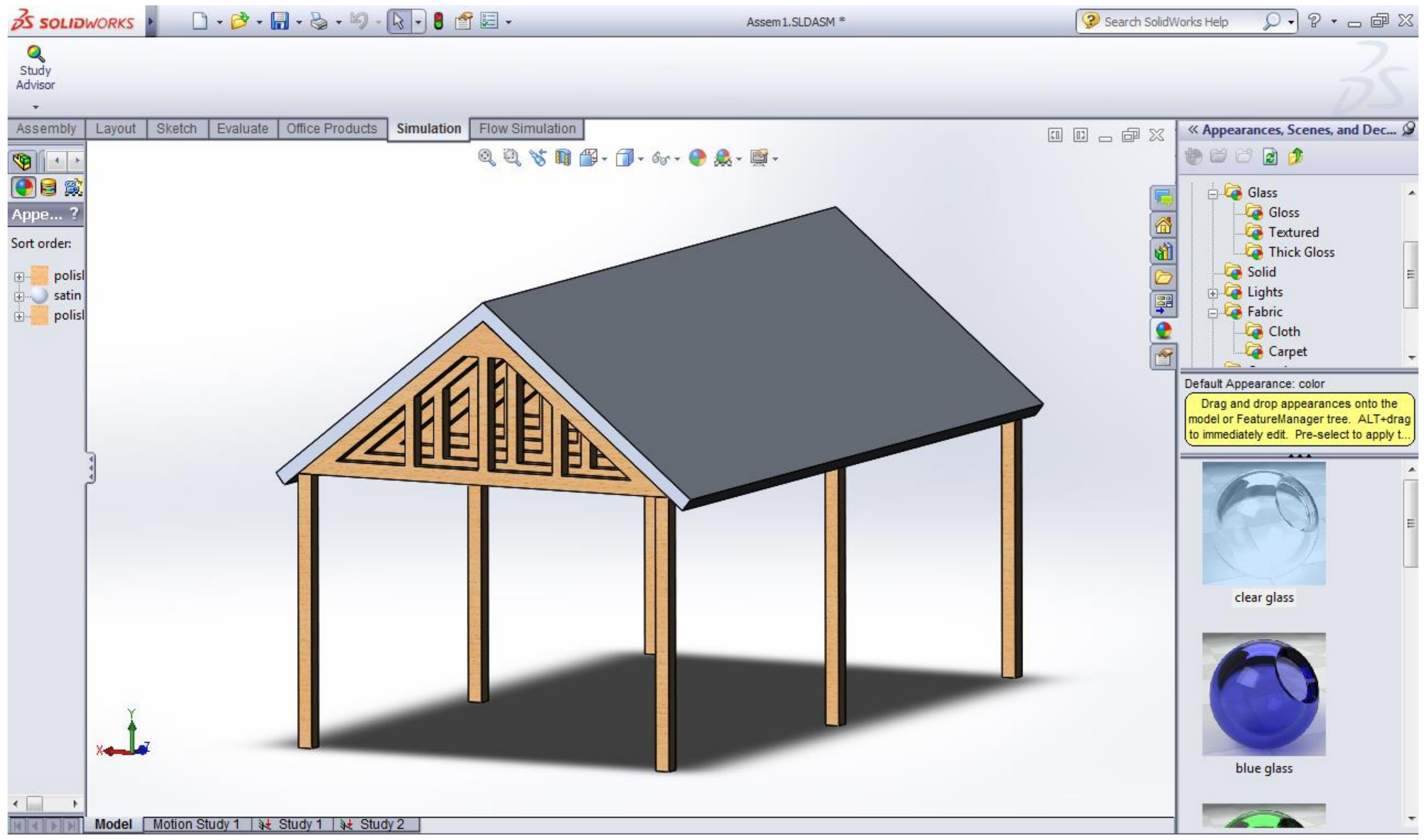


Figure 177) Axonometric view of the Pitched-Roof pavilion model

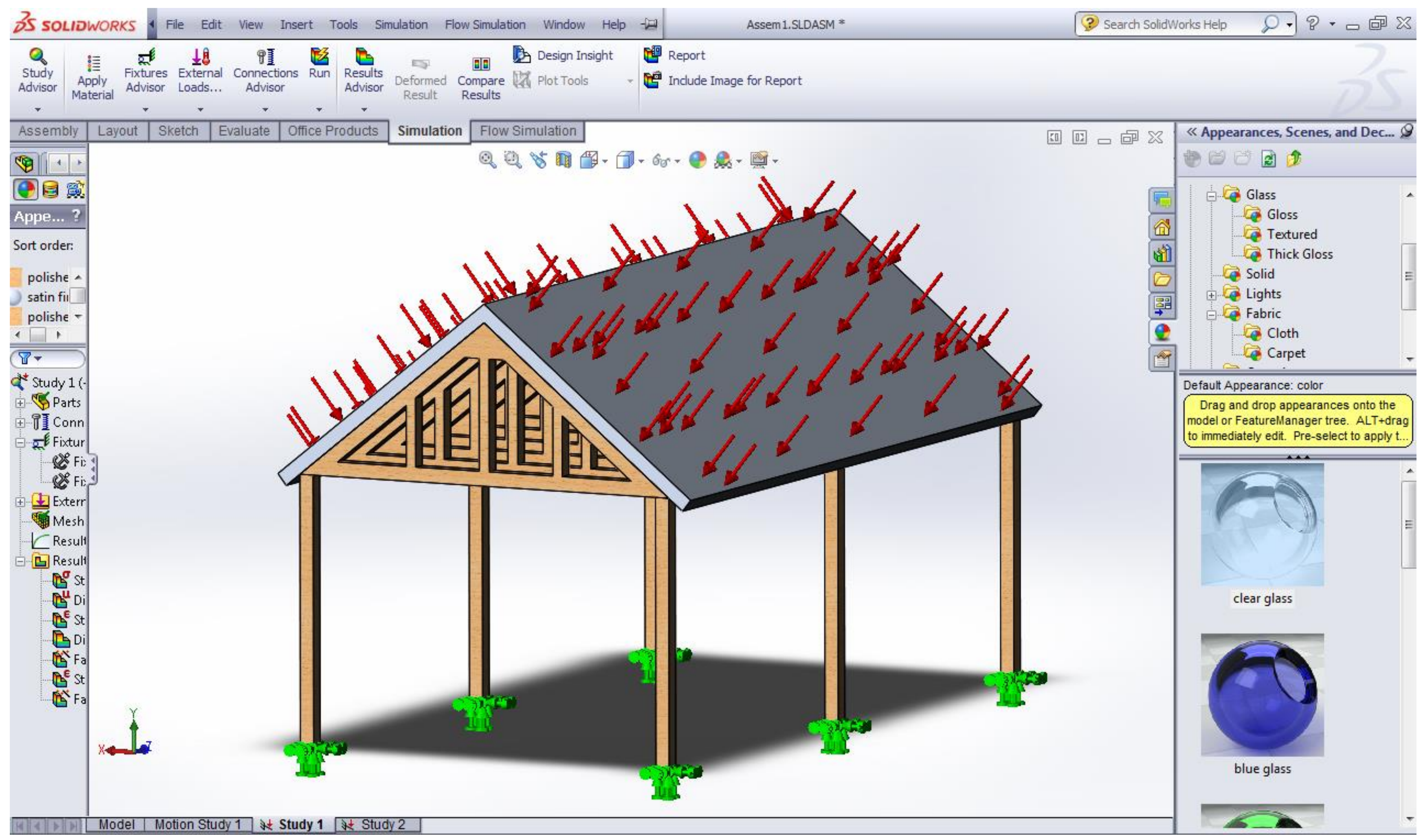


Figure 178) Applying the snow loads on the Pitched-Roof pavilion

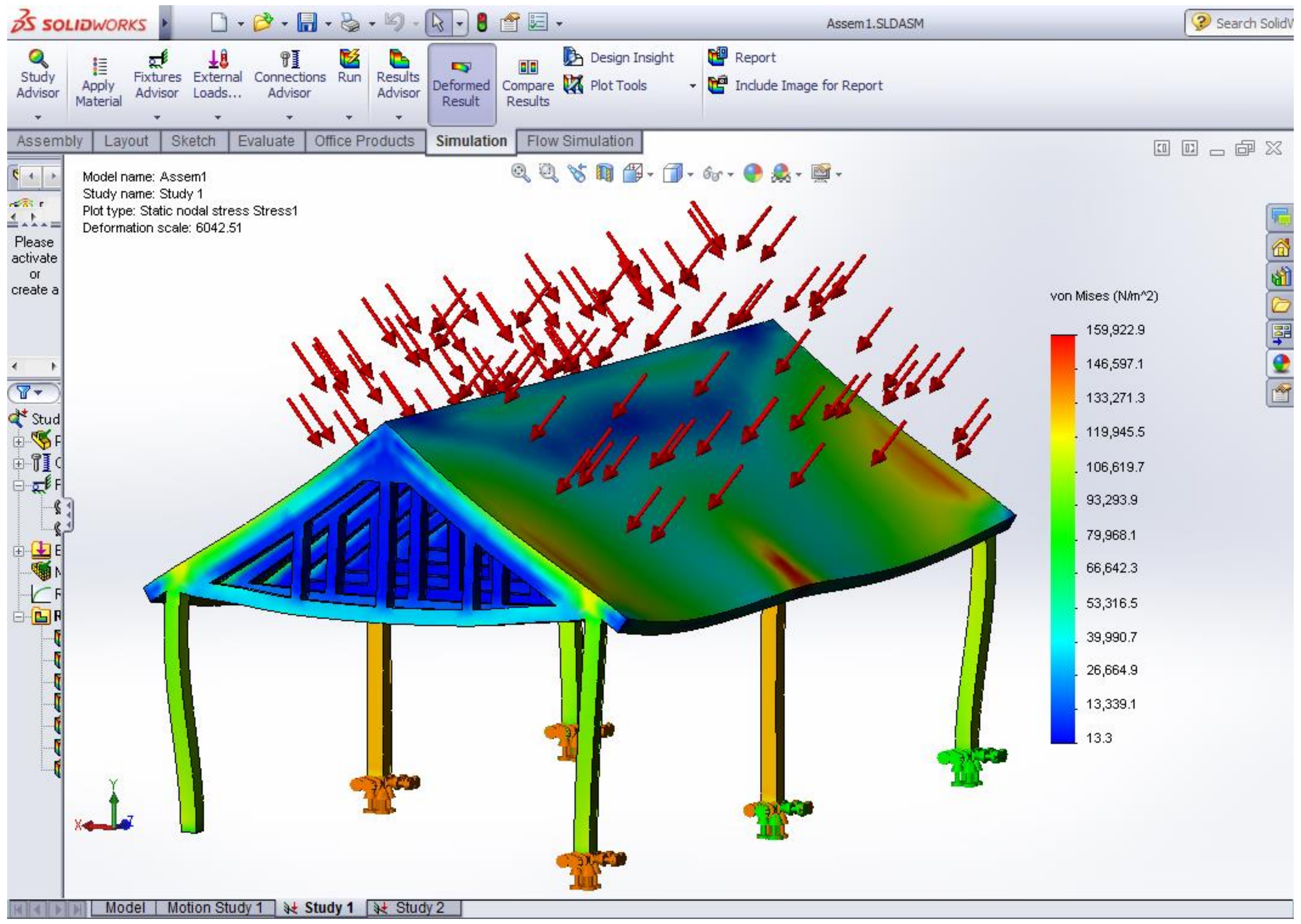


Figure 179) Stress caused by snow loads

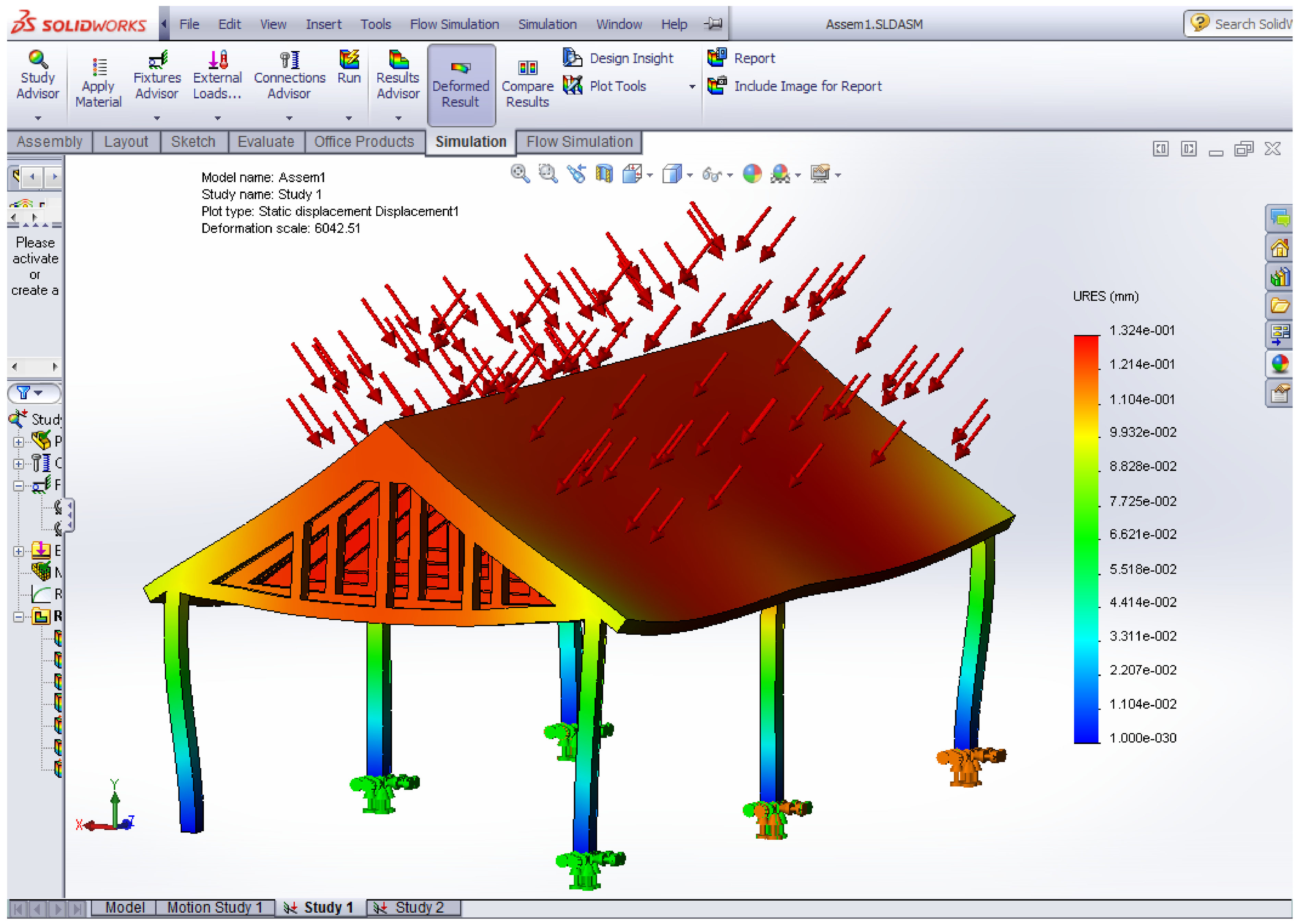


Figure 180) Displacement caused by snow loads

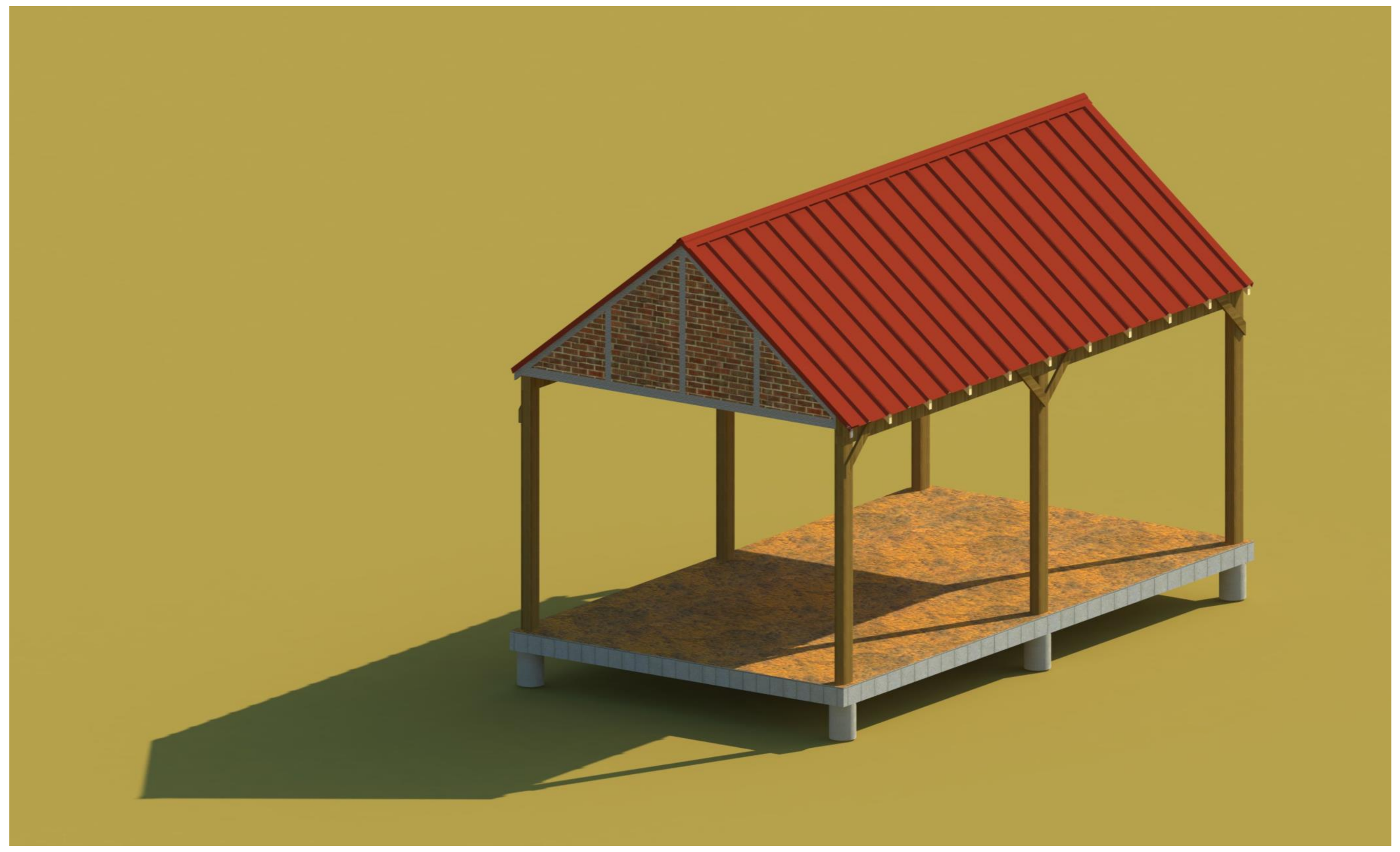


Figure 181) Pitched-Roof Pavilion

Applying the snow loads and running the simulation shows the stress and displacement causing by the snow on the pitched-roof. The model shows that in the maximum snow load the stress would be below 160 kpa and this stress will cause the displacement around 0.132 mm. in other words it is showing that this pavilion is completely stable for this amount of snow which is the maximum rate of snow in Milan.

Pitched-Roof Pergola Wind Analysis

In the previous section the wind speed and direction was discussed and as given data for the Milan the maximum wind speed was due to March for the average of 16 m/s from the direction of East. Applying this data to the wind analysis of the Solidworks giving speed and direction to the Pitched-Roof Pavilion model the results are gathering in the following pictures. In this particular case the wind will affect minimum stress and turbulence to the structure. The turbulence is higher when the wind is leaving the structure. The maximum pressure causing by this wind would be 0.1 Mpa.

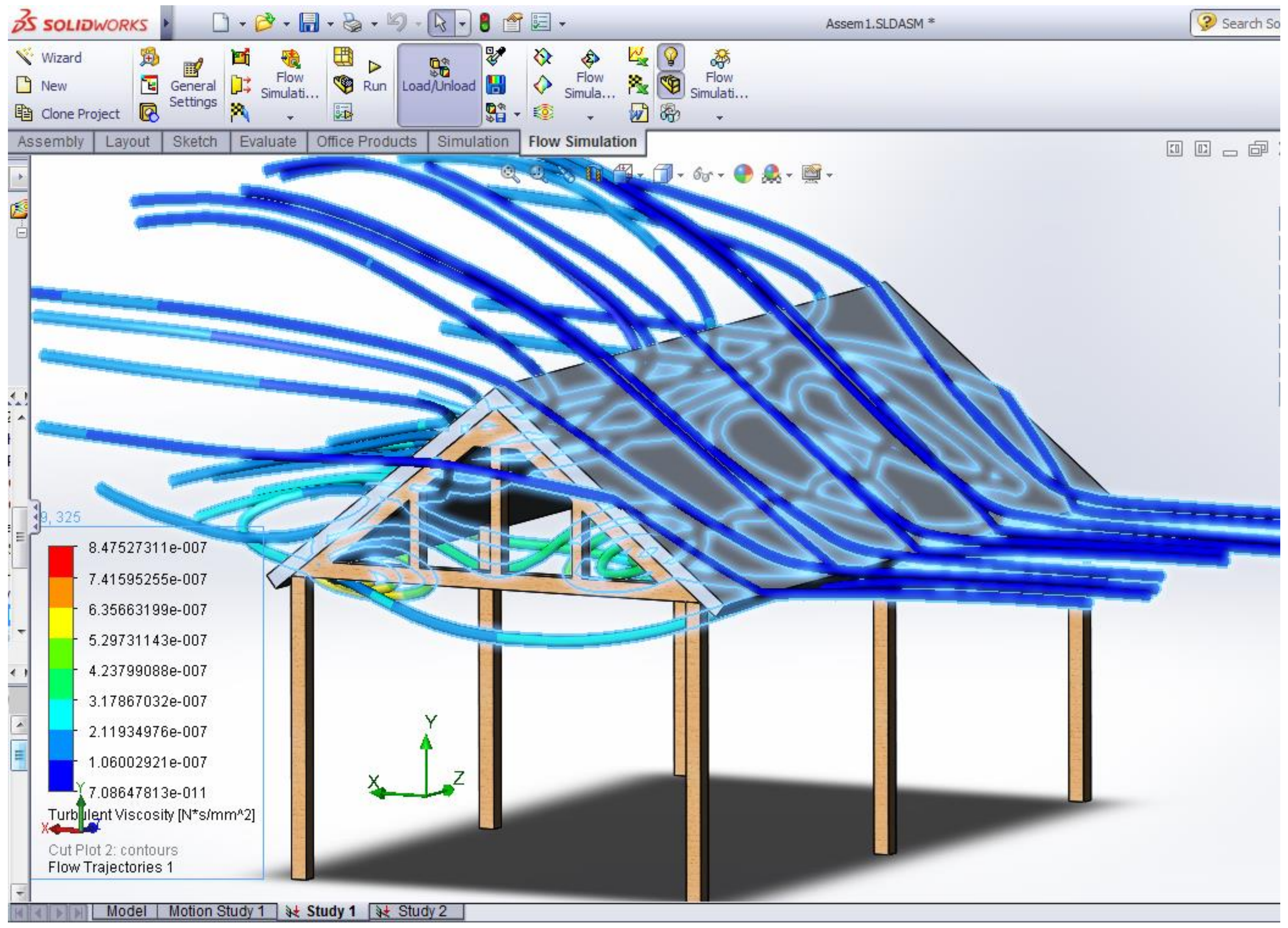


Figure 182) Turbulent Viscosity, Wind blowing from the east, 3D

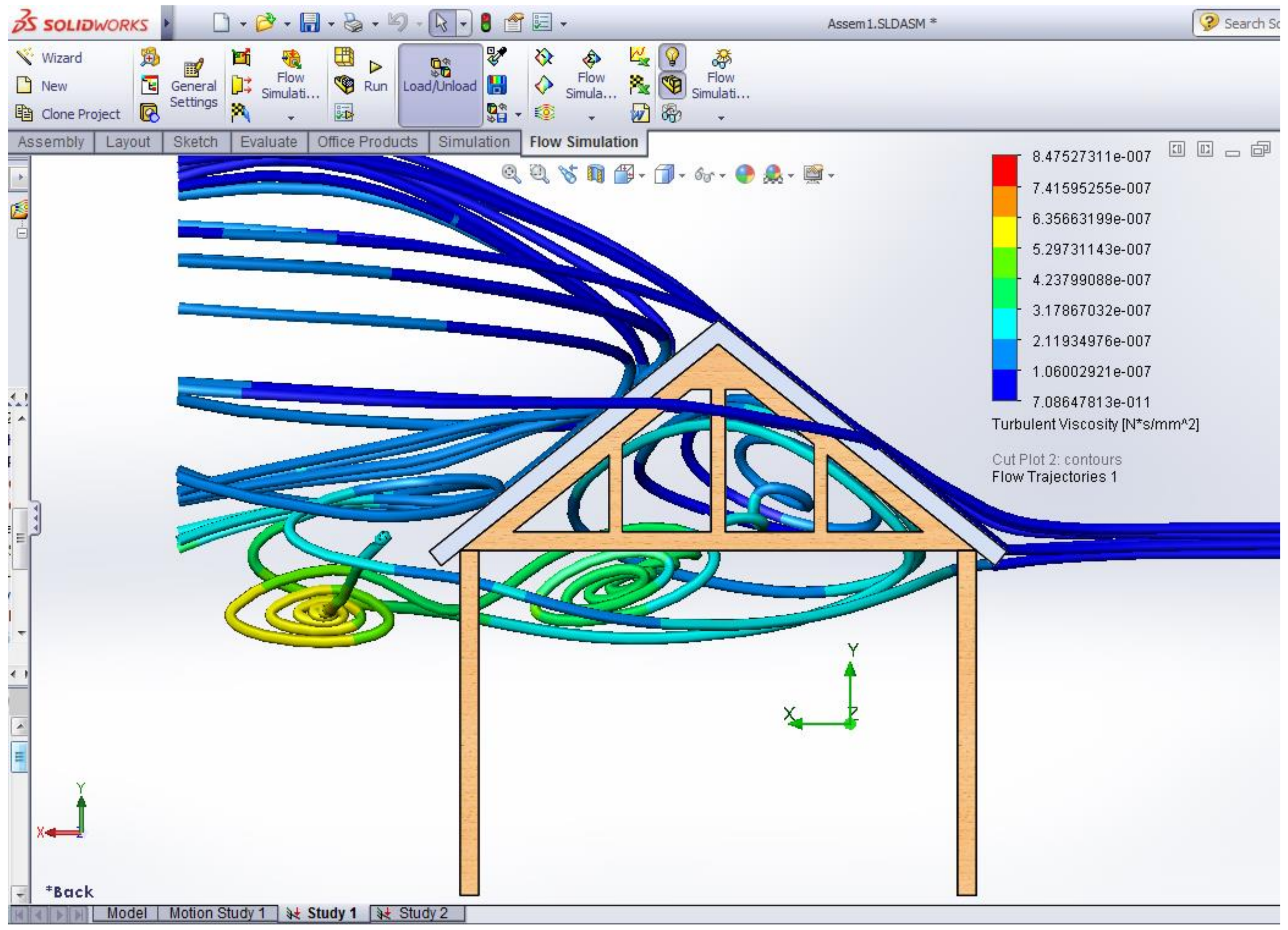


Figure 183) Turbulent Viscosity, Wind blowing from the east

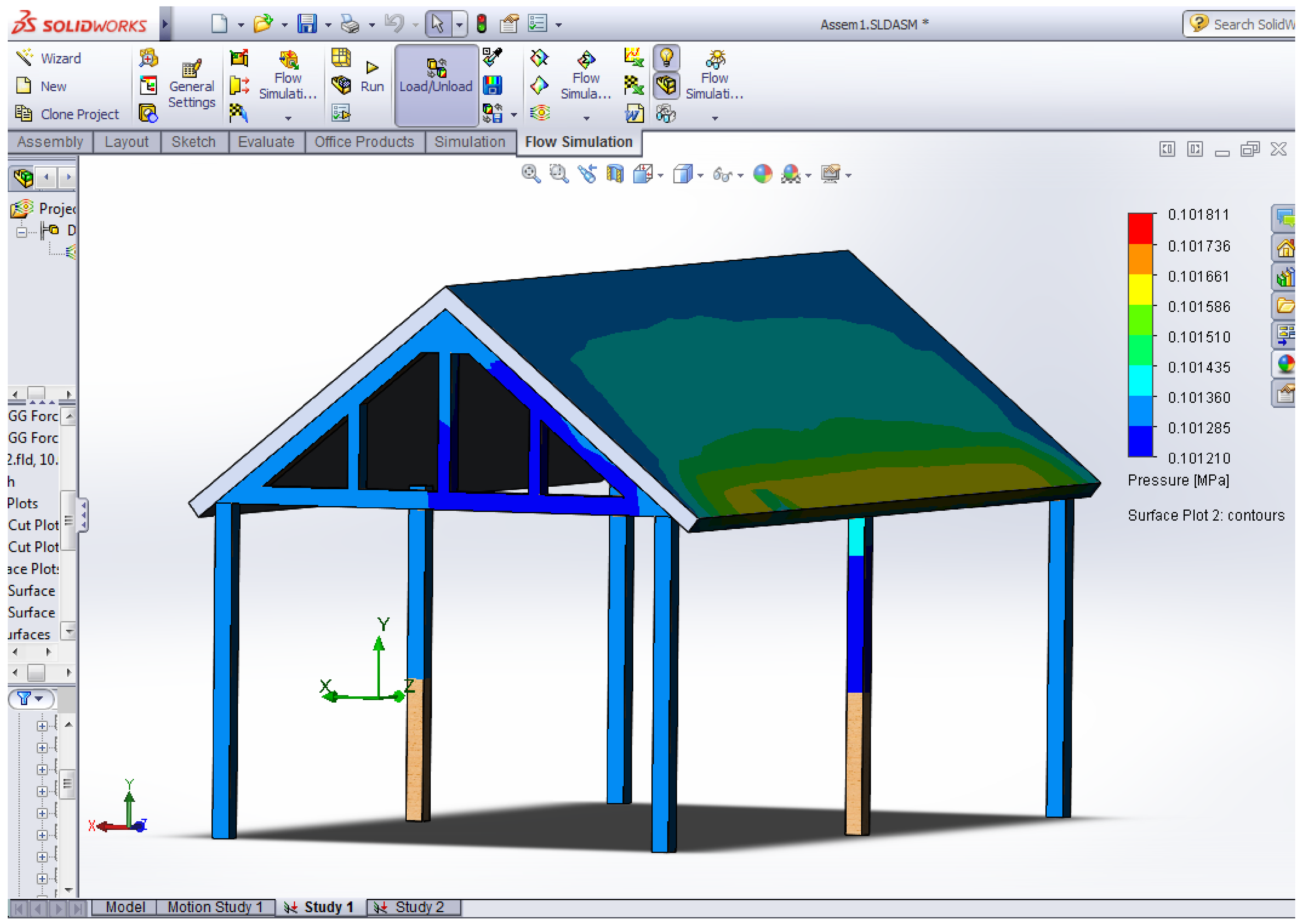


Figure 184) Wind Pressure on the east side surface, 3D

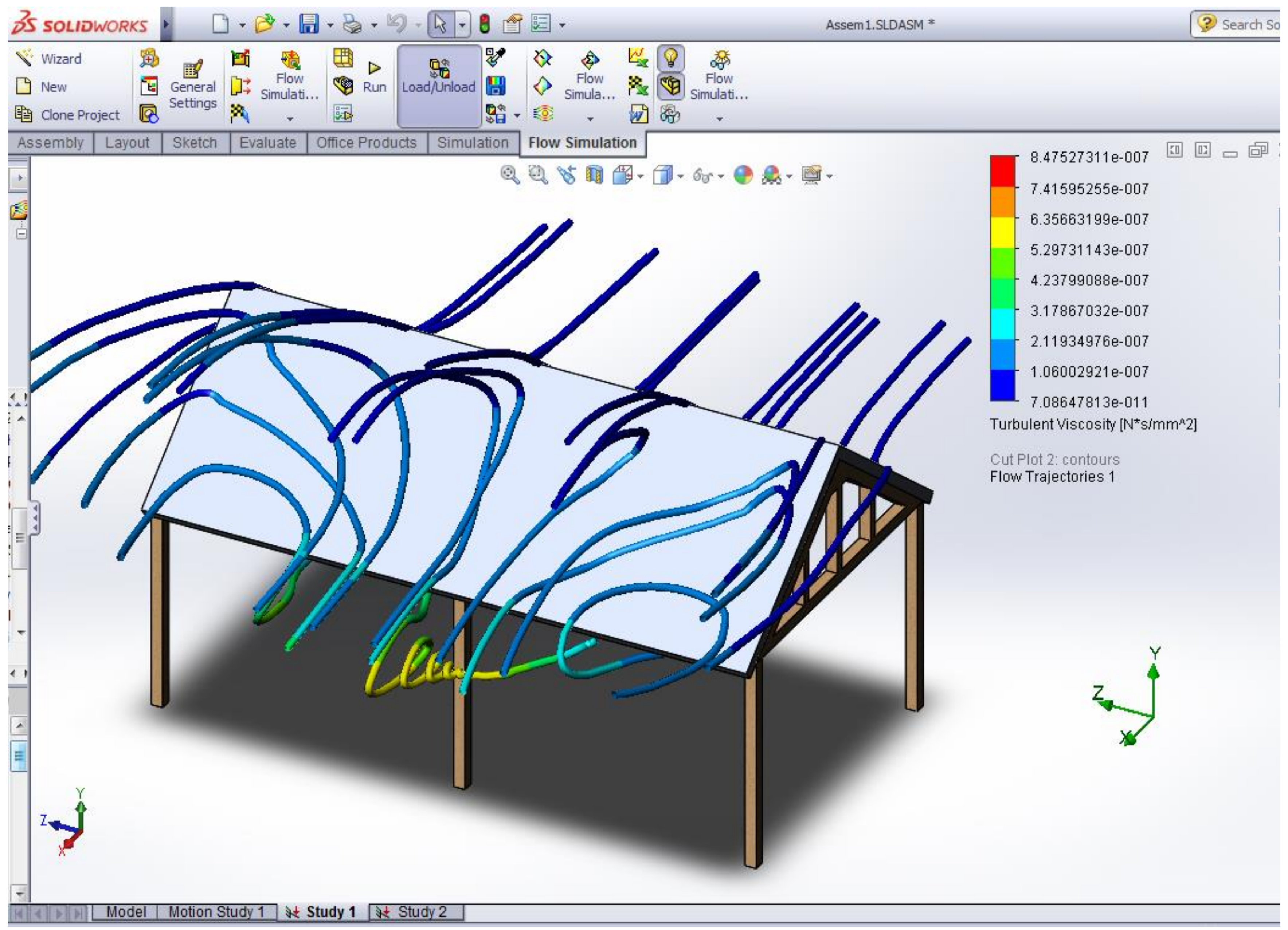


Figure 185) Wind leaving the structure causing turbulent, 3D

Pitched-Roof Pergola Cost Analysis (WBS Chart)

In this section the cost analysis will be evaluated. The **WBS chart (Work Breakdown Structure)** is provided in a rough and simple mode just in order to have an idea about the cost. The WBS chart is not accurate and the labor and mechanical costs are not included for all 3 structures. Costs are taken from "Listino dei Prezzi 2012".

WBS Code	Group of Technol. Units	WBS Code	Technological Units	WBS Code	Group of Technical Elements	WBS Code	Technical Elements	WBS Code	Technical Detail	list of cost	list code	Cost items	U.m.	Q	Unit Cost	TOTAL Cost
.00	PLELIMINARY ACTIVITIES	.00.00	PRELIMINARY GROUND WORKS	.00.00.00	EXCAVATION	.00.00.00.00	Earth moving for foundations and cellar			http://www.barrie.ca/assets/engineering/	23mRow	Cost including excavator renting and the excavation itself (labor) in cubic meter	m³	5m x 8.5m x 0.2m = 9 m³	7.51 eur	67,59 eur
.01	STRUCTURE	.01.00	Foundations	.01.00.00	Direct foundations	.01.00.00.00	Concrete Foundation Slab 150 mm		Concrete slab 150 mm Thermal resistance : 1.43 m²K/W Thermal Conductivity : 0.28 W/mK Specific Heat : 836.8 J/kgK	http://www.mybuilder.com/	Sw1066	Cost including the concrete itself and the cost of laying	m³	5m x 8.5m = 42.5 m² x 0.15 m = 6.4 m³	120 eur	768 eur
		.01.01	Frame	.01.01.00	Vertical frame	.01.01.00.00	Stuctural column		Rectangulare wooden column 20 cm x 20 cm	http://www.alibaba.com/product-detail/PP-plastic-coated-Supply-wide-application_60012953928.html	A106	Structural wooden columns , the cost doesn't include labor fees	Ton	0.5 Tons	500 eur	250 eur
.02	ENCLOSURE	.02.00	Lower horizontal enclosure	.02.00.00	Ground floor	.02.00.00.00	Concrete floor Slab		Concrete slab 150 mm Thermal resistance : 1.43 m²K/W Thermal Conductivity : 0.28 W/mK Specific Heat : 836.8 J/kgK	http://www.mybuilder.com/	Sw1066	Concrete slap using for flooring membrance	m³	4.5m x 8m = 36 m² x 0.15 = 5.4 m	120 eur	648 eur
		.02.01	Upper enclosure	.02.01.00	Pitched Roof	.02.01.00.00	Aluminuim Sheet		Aluminum roof shingles 1mm thickness	http://www.alibaba.com/product-detail/aluminum-roof-shingles_1744272117.html	1C.10.250.0060.b	Single layer aluminium sheet using for the exposed pitched roof	m²	44.6 m²	10 eur	446 eur
						.02.01.00.01	Wooden Truss		Used for roofing system	http://www.mybuilder.com/	Sw1066	Wooden truss system for roofing enclosure	m³	0.72	500 eur	360 eur
.03	FINISHING	.03.00	Internal Finishing	.03.00.00	Floors	.03.00.00.00	Floor of the inner space of pergola		Ceramic tiles 20 mm	http://www.alibaba.com/product-detail/concave-surface-homogeneous-unpolished-ceramic-tiles_60056528941.html	Q6P988	concave surface homogeneous unpolished ceramic tiles 40x40	m²	36 m²	4 eur	144 eur

Total : 2,683 eur

Table 10) WBS chart for Pitched-Roof Pergola

*** Please note that the WBS chart represents only the material costs of the project <u>excluding</u> equipments and labor fees.**

ETFE-Membrane Pergola Snow Analysis

Calculating snow load for a tensile structure is not as easy as a traditional roof like we did before. ETFE is slippery and even some where the slope is even more than the pitched roof we analyzed before. But in order to have an idea about the tensile strength of ETFE, we consider the snow load for the traditional flat roof for this analysis, which is even more than the snow load for the Pitched-Roof Pergola.

in other words we consider the 714.85 pa for this analysis.

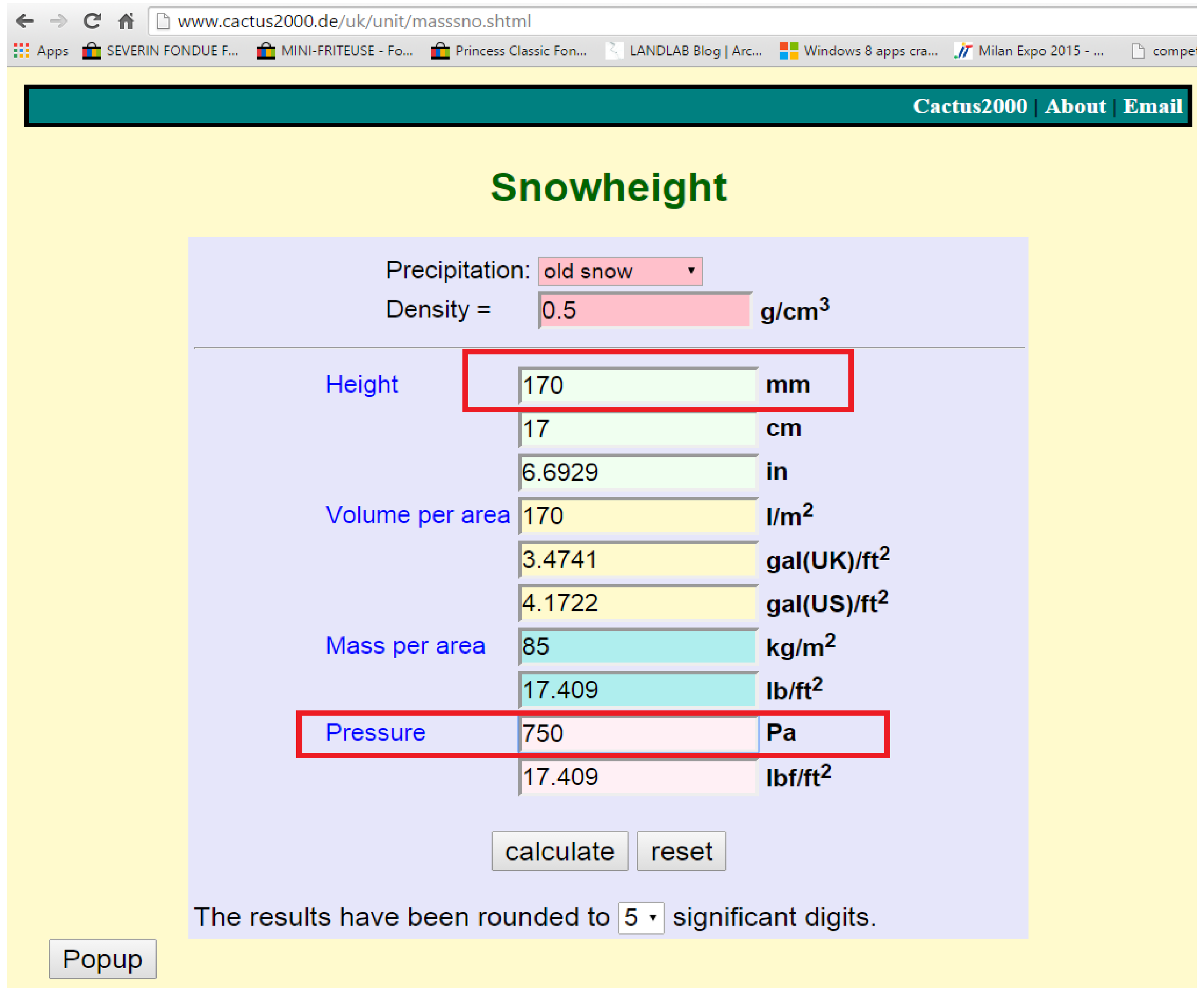


Figure 186) Snow Load online calculation
http://www.cactus2000.de/uk/unit/masssno.shtml

Now with the aim of Solidworks first we model the flat roof pergola in a simple way then try to import this load and run the analysis to the stresses and displacements.

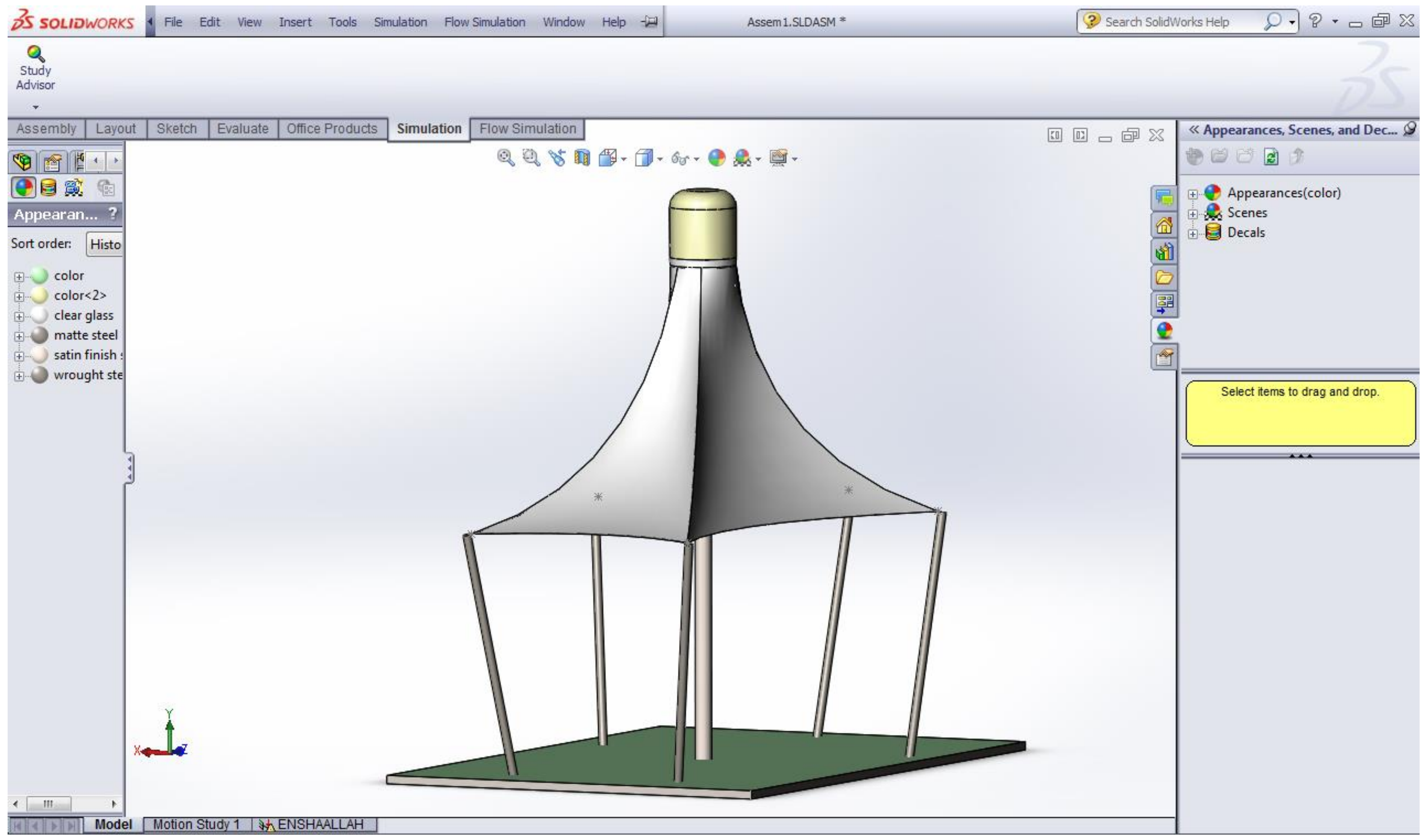


Figure 187) Axonometric view of the ETFE Membrane pavilion model

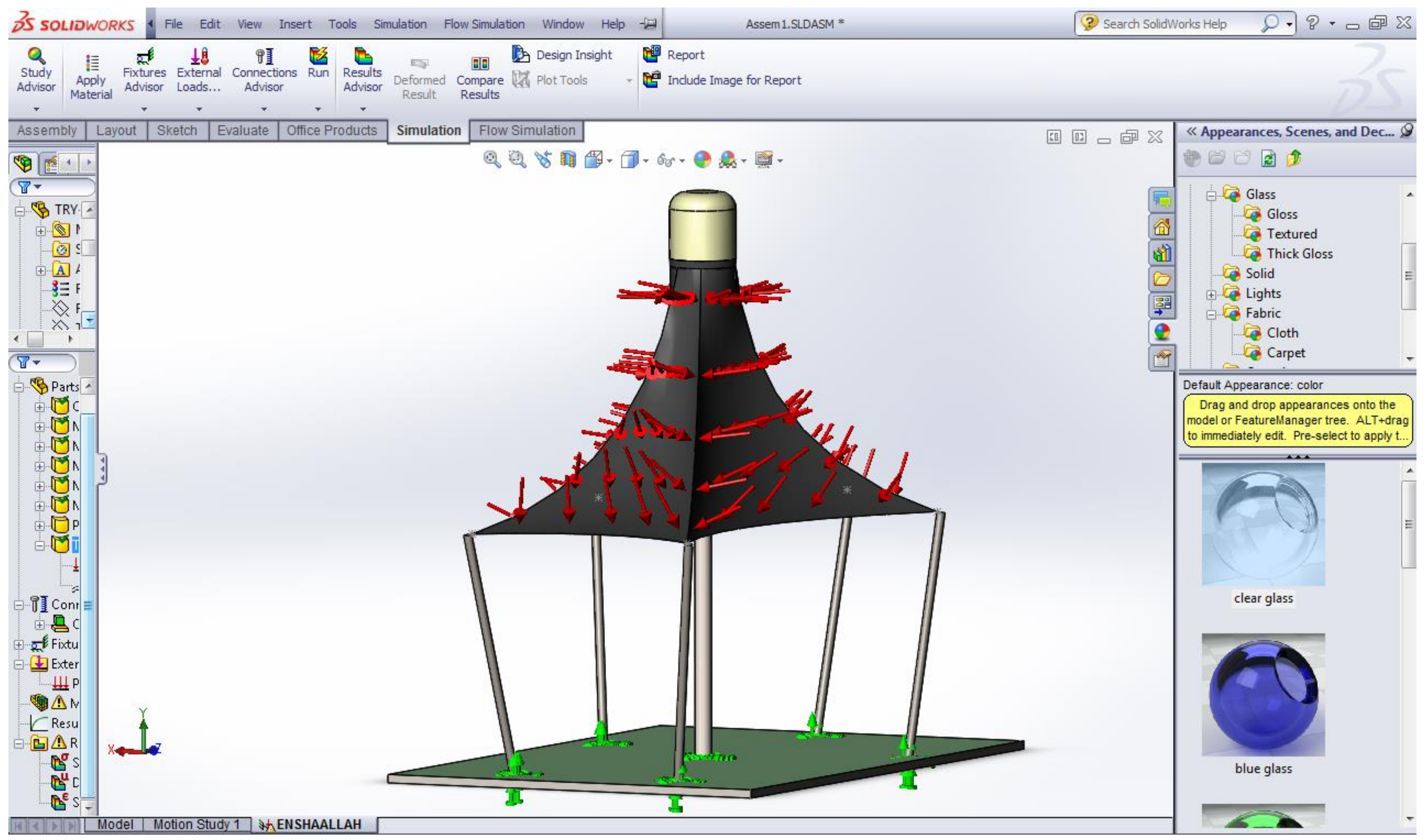


Figure 188) Applying the snow loads on the ETFE Membrane Pavilion

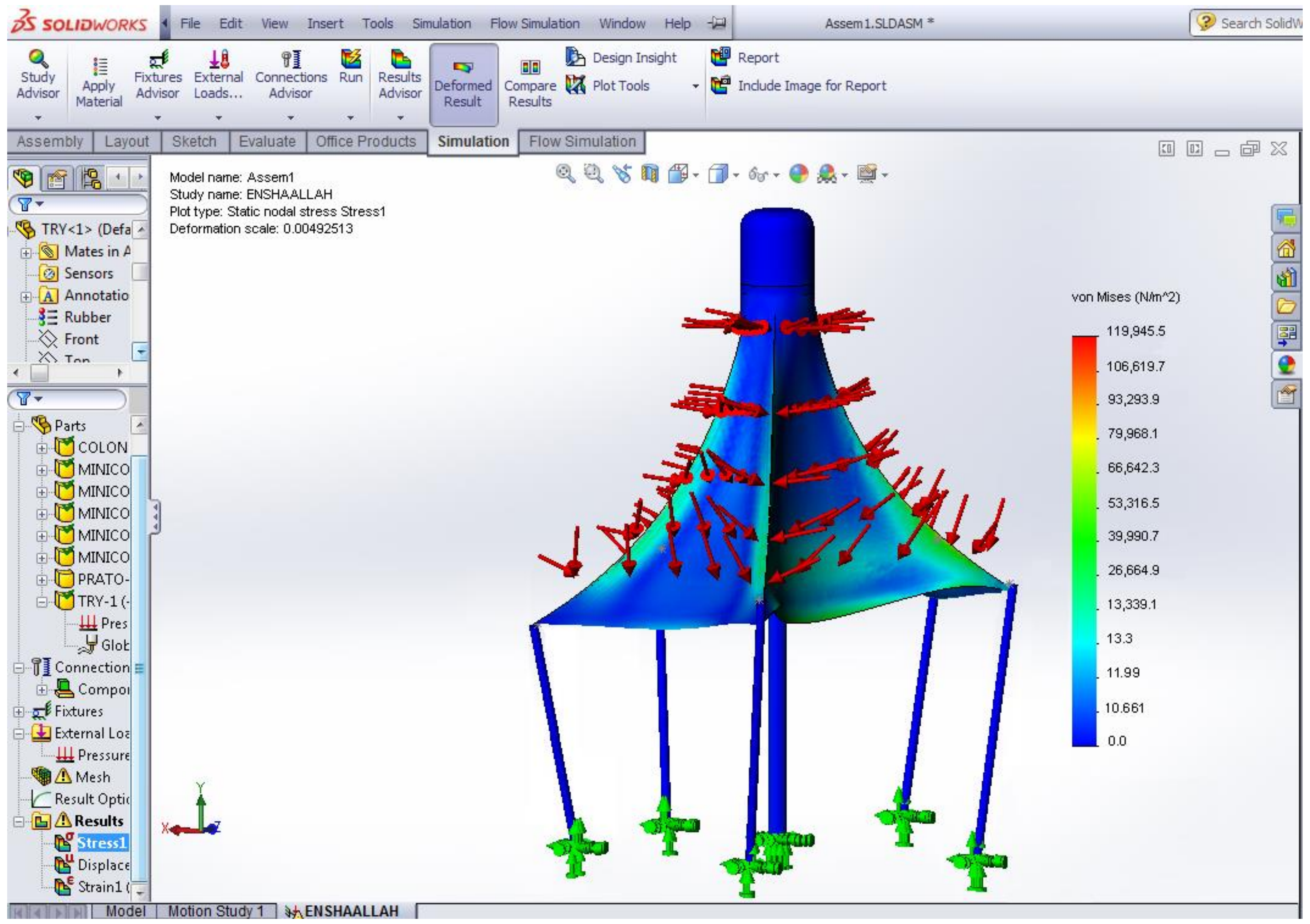


Figure 189) Stress caused by snow loads

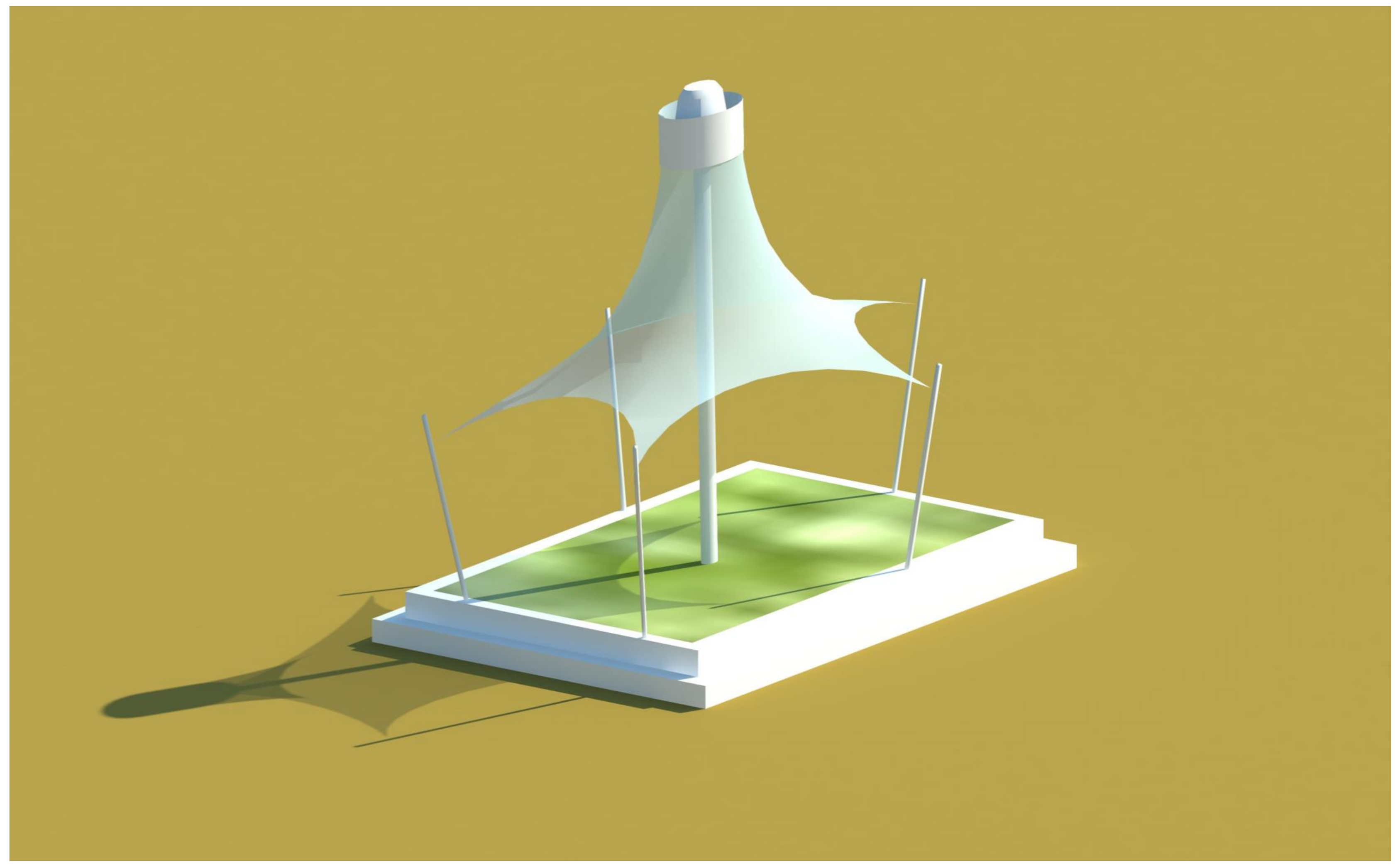


Figure 191) ETFE Membrane pavilion

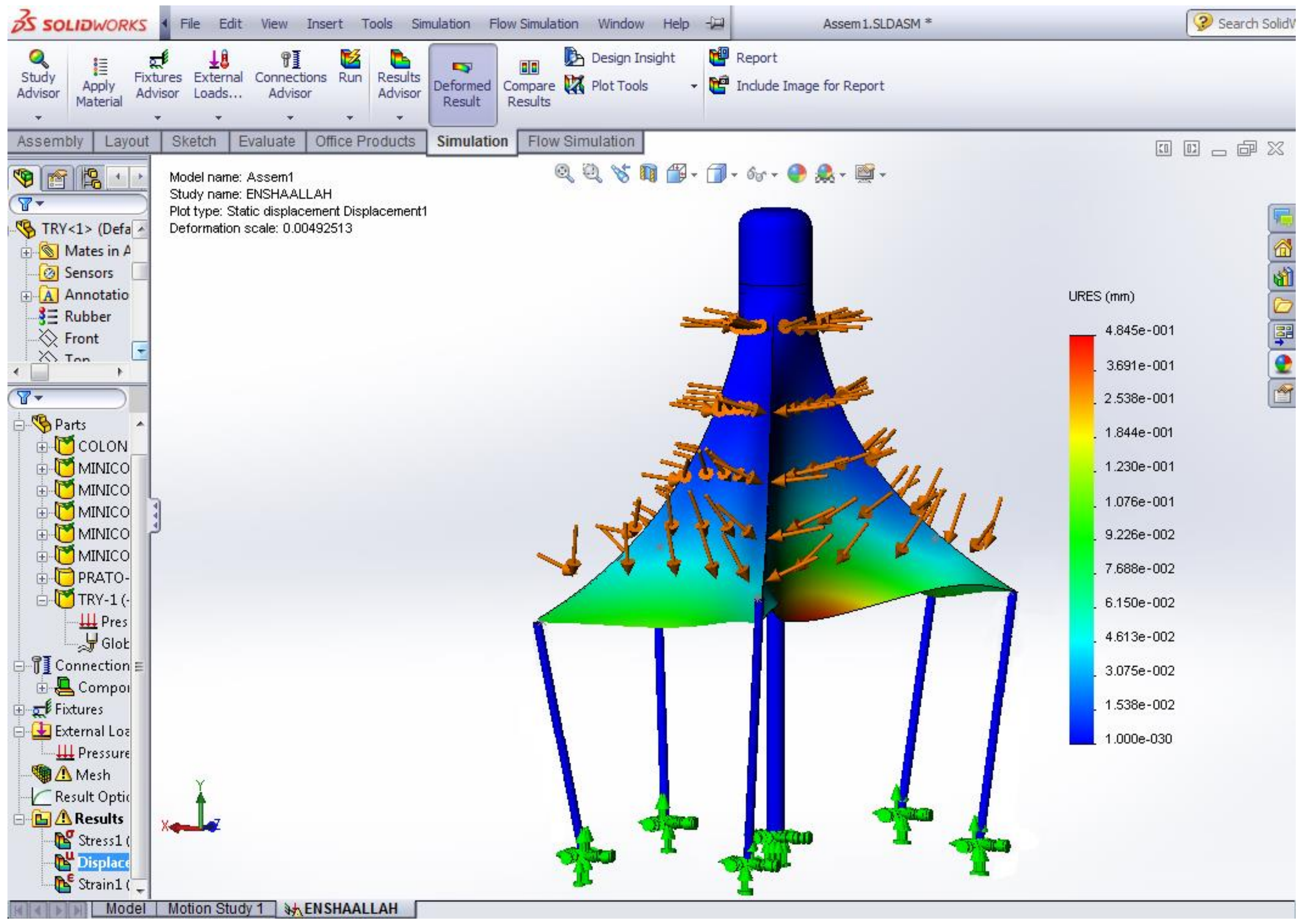


Figure 190) Displacement caused by snow loads

Applying the snow loads and running the simulation shows the stress and displacement causing by the snow on the ETFE Membrane Pergola. The model shows that in the maximum snow load the stress would be below 120 kpa and this stress will cause the displacement around 0.484 mm. in other words it is showing that this pavilion is completely stable for this amount of snow which is the maximum rate of snow in Milan.

ETFE-Membrane Pergola Wind Analysis

In the previous section the wind speed and direction was discussed and as given data for the Milan the maximum wind speed was due to March for the average of 16 m/s from the direction of East. Applying this data to the wind analysis of the Solidworks giving speed and direction to the flat roof pavilion model the results are gathering in the following pictures. In this particular case the wind will affect minimum stress and turbulence to the structure. The turbulence is higher when the wind is leaving the structure.

In other words the ETFE-Membrane Pavilion is stable against Snow and Wind loads

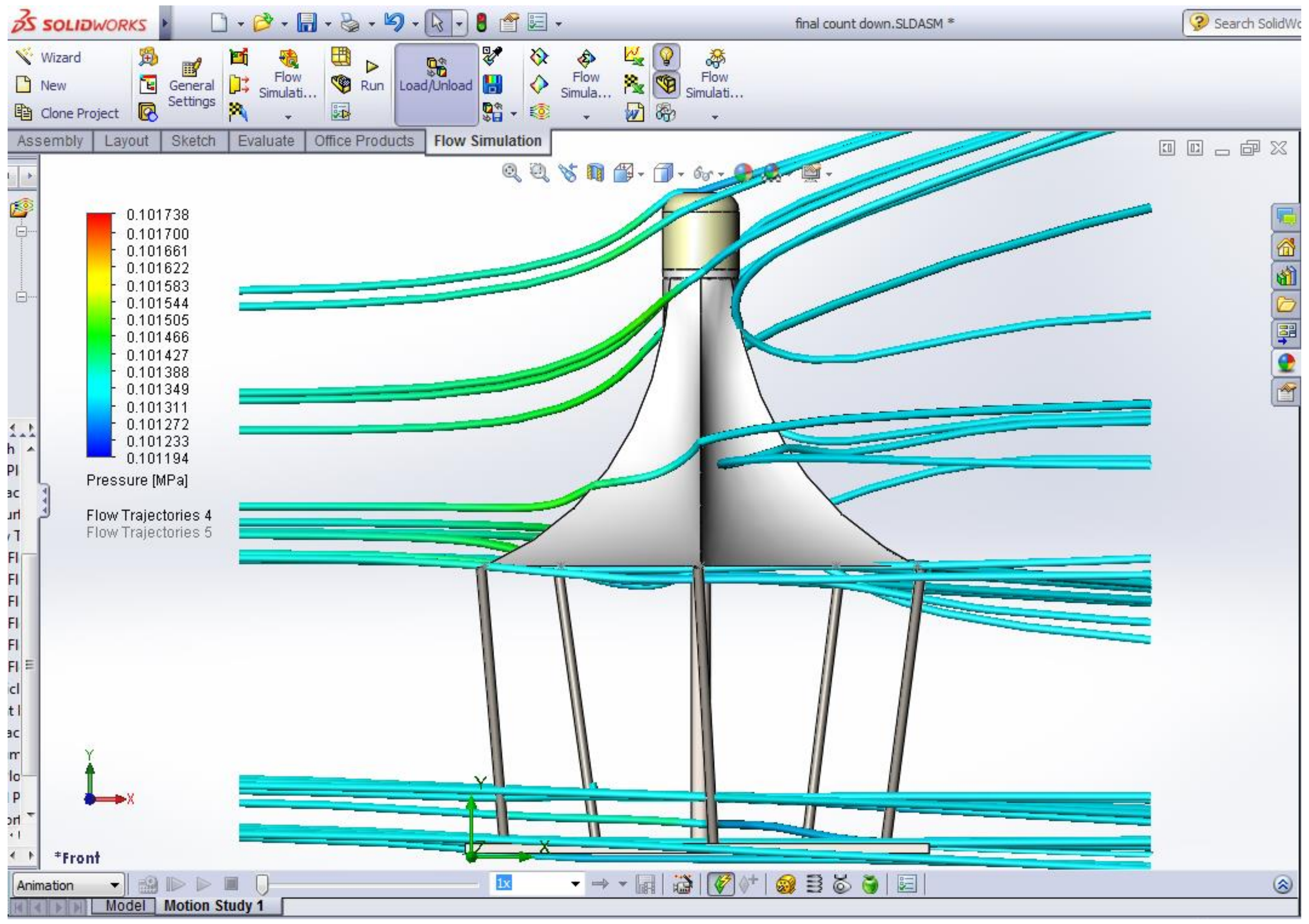


Figure 193) Turbulent Viscosity, Wind blowing from the east passing through the structure

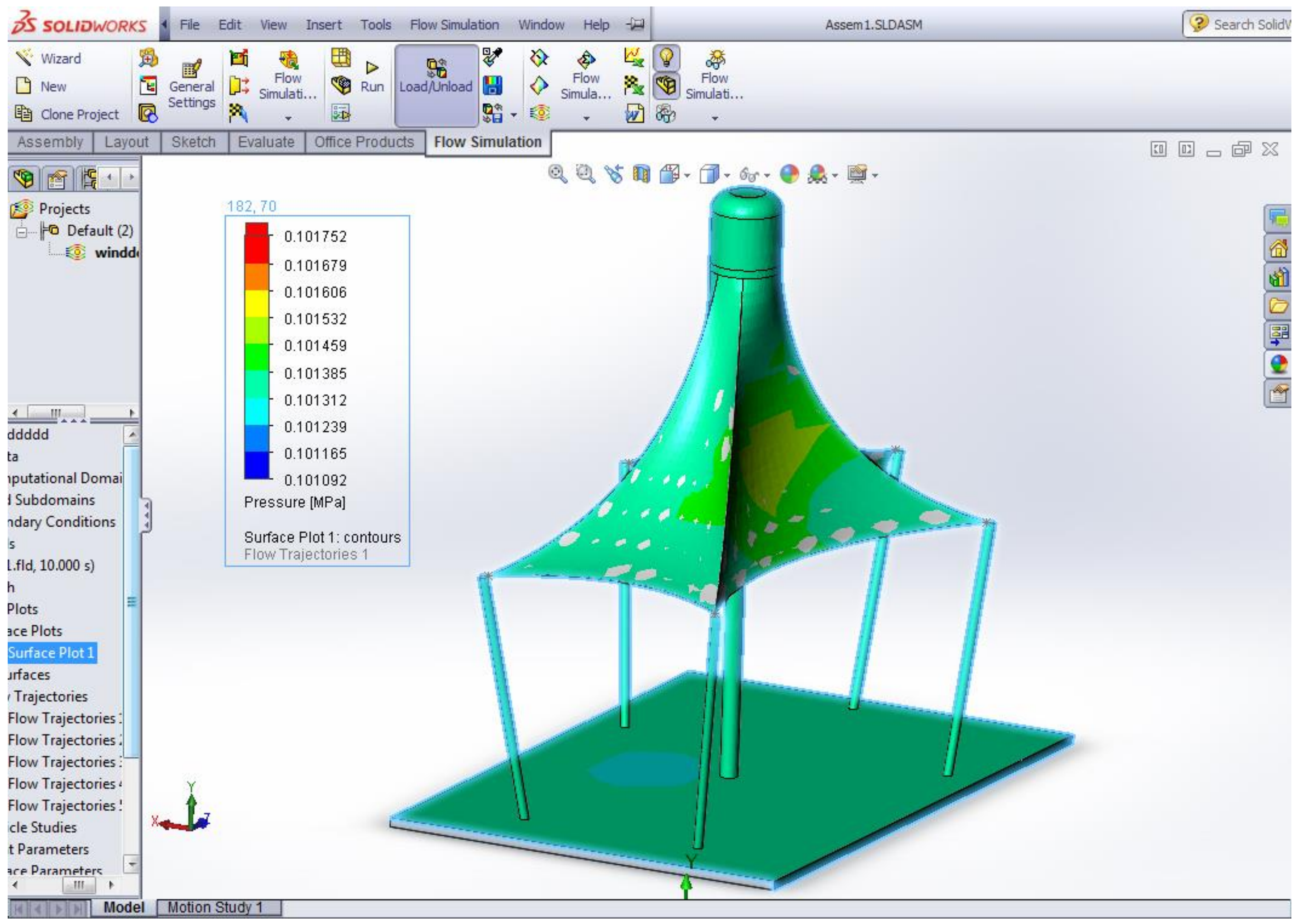


Figure 192) Wind pressure on the east side surface, 3D view

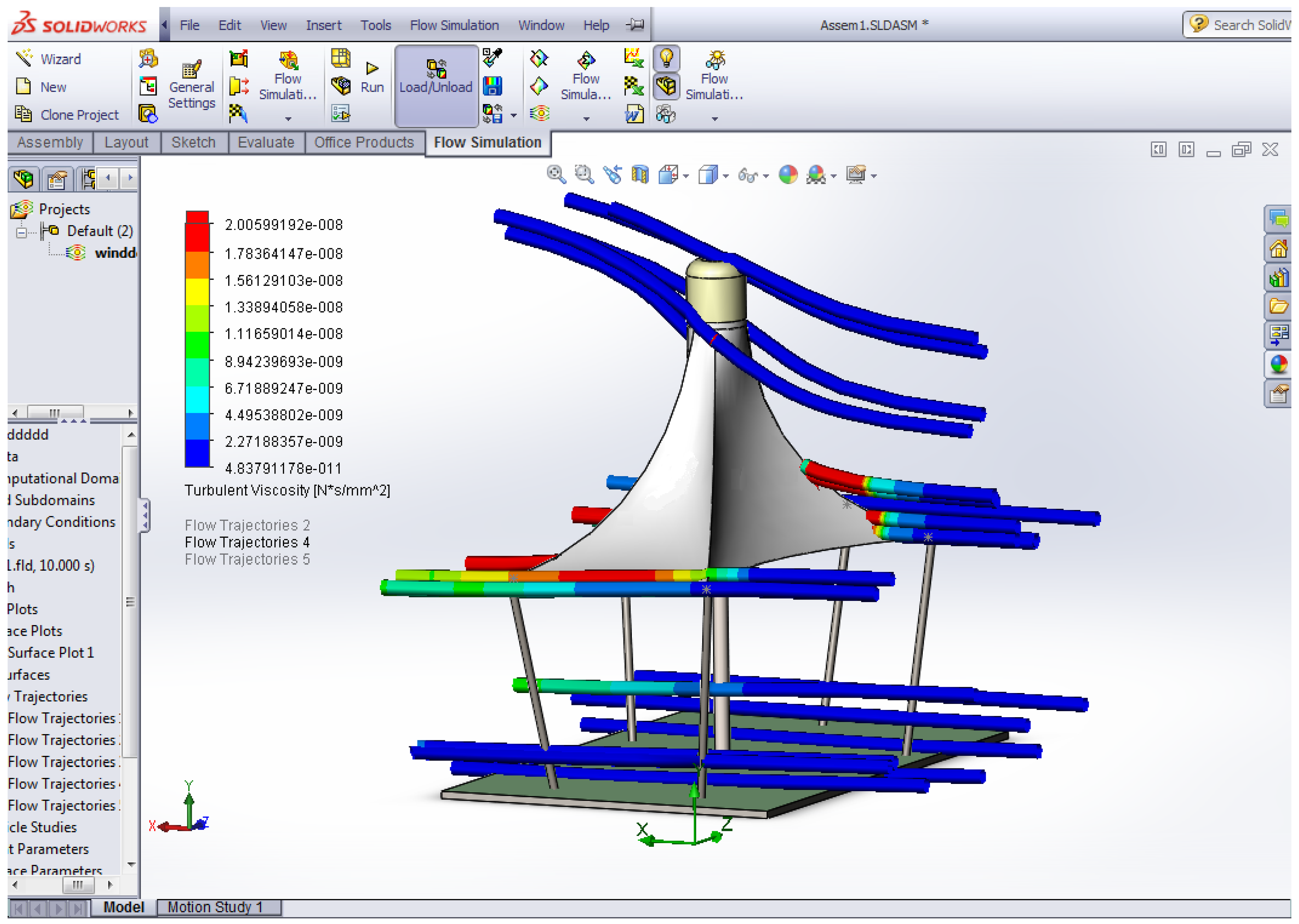


Figure 194) Turbulent Viscosity, wind passing through the structure, 3D view

ETFE-Membrane Pergola Cost Analysis (WBS Chart)

In this section the cost analysis will be evaluated. The **WBS chart (Work Breakdown Structure)** is provided in a rough and simple mode just in order to have an idea about the cost. The WBS chart is not accurate and the labor and mechanical costs are not included for all 3 structures. Costs are taken from “Listino dei Prezzi 2012”.

WBS Code	Group of Technol. Units	WBS Code	Technological Units	WBS Code	Group of Technical Elements	WBS Code	Technical Elements	WBS Code	Technical Detail	list of cost	list code	Cost items	U.m.	Q	Unit Cost	TOTAL Cost
.00	PLELIMINARY ACTIVITIES	.00.00	PRELIMINARY GROUND WORKS	.00.00.00	EXCAVATION	.00.00.00.00	Earth moving for foundations and cellar			http://www.barrie.ca/assets/engineering/	23mRow	Cost including excavator renting and the excavation itself (labor) in cubic meter	m^3	5m x 8.5m x 0.2m = 9 m^3	7.51 eur	67,59 eur
.01	STRUCTURE	.01.00	Foundations	.01.00.00	Direct foundations	.01.00.00.00	Concrete Foundation Slab 150 mm		Concrete slab 150 mm Thermal resistance : 1.43 m^2K/W Thermal Conductivity : 0.28 W/mK Specific Heat : 836.8 J/kgK	http://www.mybuilder.com/	Sw1066	Cost including the concrete itself and the cost of laying	m^3	5m x 8.5m = 42.5 m^2 x 0.15 m = 6.4 m^3	120 eur	768 eur
		.01.01	Frame	.01.01.00	Vertical frame	.01.01.00.00	Stuctural column galvanize tube		Circle steel column Ø7cm	http://www.alibaba.com/product-detail/Top-quality-metal-mold-round-bar_1443321505.html?s=p	A106	Ø7cm Stuctural Pillar circle galvanize tube , the cost includeس labor fees	Ton	0.09 Tons	2000 eur	180 eur
.02	ENCLOSURE	.02.00	Lower horizontal enclosure	.02.00.00	Ground floor	.02.00.00.00	Concrete floor Slab		Concrete slab 150 mm Thermal resistance : 1.43 m^2K/W Thermal Conductivity : 0.28 W/mK Specific Heat : 836.8 J/kgK	http://www.mybuilder.com/	Sw1066	Concrete slap using for flooring membrance	m^3	4.5m x 8m = 36 m^2 x 0.15 = 5.4 m	120 eur	648 eur
		.02.01	Upper enclosure	.02.01.00	Tensile Roof	.02.01.00.00	ETFE		Transparent or fritting ETFE film	Ipw Milan 2011	1C.10.250.0060.b	Isolamento termico a parete o intercapedini perimetrali, realizzato con lastre di schiuma poliuretanica prodotta con gas senza CFC e HCFC, rivestite sulle due facce con cartoncino	m^2	26.8 m^2	2 eur	53,4 eur
						.02.01.00.01	Cable and Joints and clamps		Used for membrane material	http://www.alibaba.com/product-detail/Preformed-Dead-end-Clamp-For-Short_60006509559.html	Sw1066	Cost including the the clamps,joints and steel cables	set	6 sets	50 eur	300 eur
.03	FINISHING	.03.00	Internal Finishing	.03.00.00	Floors	.03.00.00.00	Floor of the inner space of pergola		Ceramic tiles 20 mm	http://www.alibaba.com/product-detail/concave-surface-homogeneous-unpolished-ceramic-tiles_60056528941.html	Q6P988	concave surface homogeneous unpolished ceramic tiles 40x40	m^2	36 m^2	4 eur	144 eur

Total : 2,160 eur

Table 11) WBS chart for ETFE Membrane Pergola

*** Please note that the WBS chart represents only the material costs of the project excluding equipments and labor fees.**

Construction Timing

Construction projects are all about timing. From the moment a new facility is conceived by a client to the day its doors are opened, there is a delicate play that unfolds over the course of weeks and months. Building projects can take weeks, sometimes years, depending upon the scale of construction. If builders don’t keep timing in mind throughout the entirety of a project, it can mean disastrous results for the project, as well as the image and brand of the builder.

In this analysis we aim to explain a general overview about the construction time. For the Flat-Roof and Pitched-Roof pergolas the situation is more or less clear, since they are traditional shapes. Here we explain a brief phrase about the process of setting up the ETFE-Membrane pergola in our case study.

Setting up a tensile structure is much more faster than traditional structures if every thing is well-arranged. I this case the pergola is a High-Point form and the construction process is shown in the figures in front.

Excluding the curing time for the concrete which is used for the flooring, (which may take up to 4 days and is equal for the three of them), the other timings for our tensile pergola is extremely faster. The need of an truck crane is needed to lift the main mast and the other five vertical columns. In contrast the construction of the flat roof pergola with concrete columns or with brick one also the pitched-roof one is time consuming much more than the ETFE-membrane pergola.

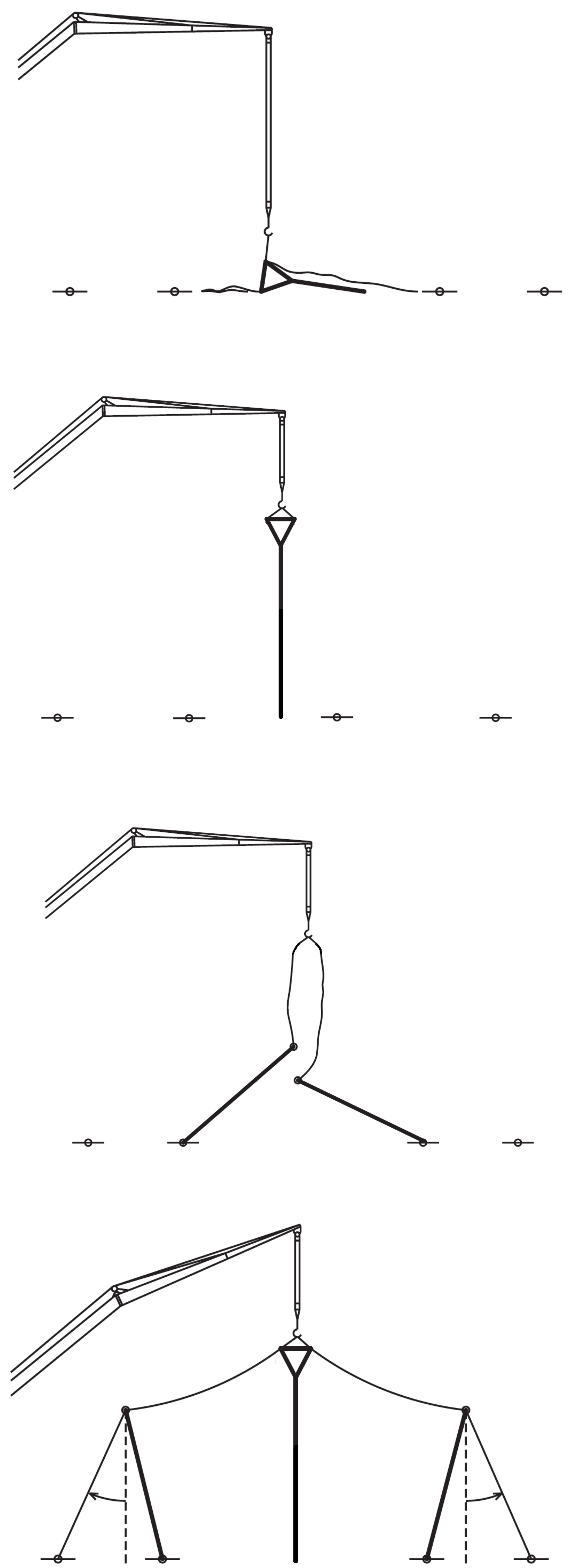


Figure 195) Using crane to set up the main mast and columns

The Main Conclusion

The aim of this analysis was not proofing that these three different structures will remain stable, without collapse and failure. Of course in the situation of Milan which is not a critical weathering behavior these structures will remain perfectly. The aim is to proof that if Timing, Cost, Retractability, Transparency, Sustainability, Embedded energy are an issue, then definitely ETFE Tensile Membrane Structure will be your choice.

As said before construction timing of the tensile structures are much more less than traditional structures, in terms of preparing, transportation times, and building and setting up processes.

Cost is also an issue, for this particular example maybe there is not a huge difference between their cost (although ETFE membrane structure is least among them) but in larger projects it will become a significant difference which no one can deny.

Retractability is also highlighted. When you build up a traditional structure it won't be disassembled, in the best situation some elements could be reused or recycled but you can not move the structure in terms of location. But in tensile structure this matter is not a big problem.

An ETFE membrane structure is almost transparent (more than 90%), this characteristic could be a benefit or a negative point. When ETFE film is used as a cover the attention should be paid about the sun. of course an ETFE membrane pergola in Saudi Arabia is not a good choice, but in the locations where gentle sun rays are welcome this could be a good choice having a panoramic view of the sky having the sun with you.

Sustainability is another issue for discuss, knowing how much material is needed for traditional structures comparing with tensile structures will give an idea about which one is more sustainable. The materials used in production process to energy needed for transporting them to the site and finally giving the shape of this structure is comparable to the traditional manufacturing processes. Therefore the embodied energy for the tensile structures are much less than the traditional ones; plus the recyclability of the tensile materials are near 100% while the traditional materials acting in another way and finally the CO_2 footprint will be reduced due to these facts. Here is a table provided to show the summary of this analysis in order to understand better the idea.

	ETFE	Flat Roof	Pitched Roof
Structural Stability Location: Milan	✓	✓	✓
Construction timing	👍👍👍	👍	👍
Cost	$	$$$	$$$
Retractability	yes	no	no
Transparency	yes	no	no
Sustainability	👍👍👍	👍	👍

Table 12) Conclusion table for the Analysis 1

Aesthetic Point of View

Tensile membranes enable architects to express their creative side to the hilt, the organic forms, curvy shapes and all their interesting forms trying to appeal your conscious, imagine yourself standing in front of these 3 types of pergolas, and you'll be asked to enter only and only one of them and spend some time there with your friends to talk, what will you choose?!

The non-conventional roof types of tensile structures are still new to the eye and still there is much more opportunities waiting for this new type of structure.

Using curvy shapes or curvy lines in every drawing make it more likable and more interested. Anthony Gaudi stopped using linear lines in his architecture over 100 years ago, and this is what makes his architecture unique and different till now, what is called Art Nouveau (New Art).

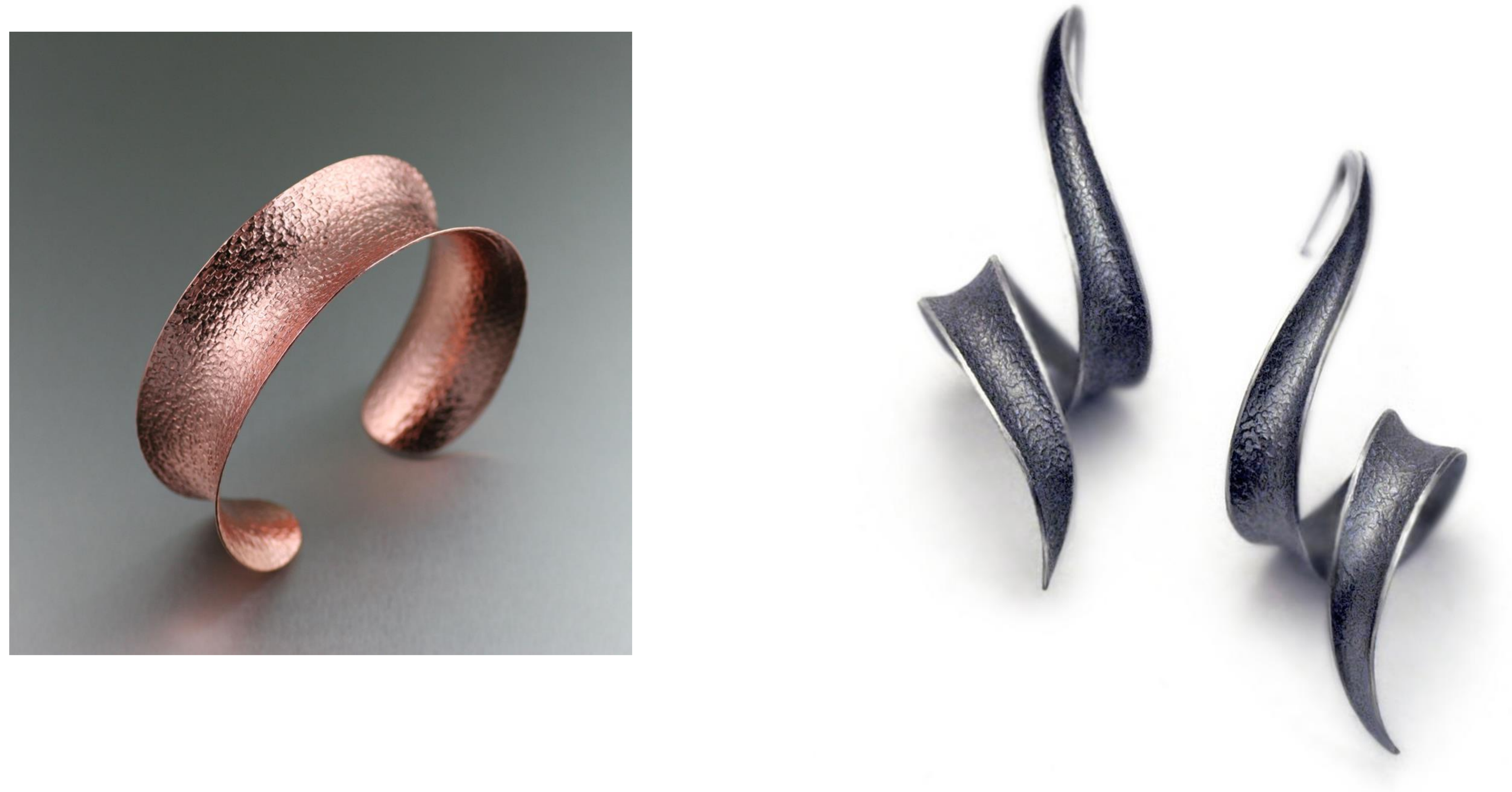


Figure 196) Anticlastic jewelleries

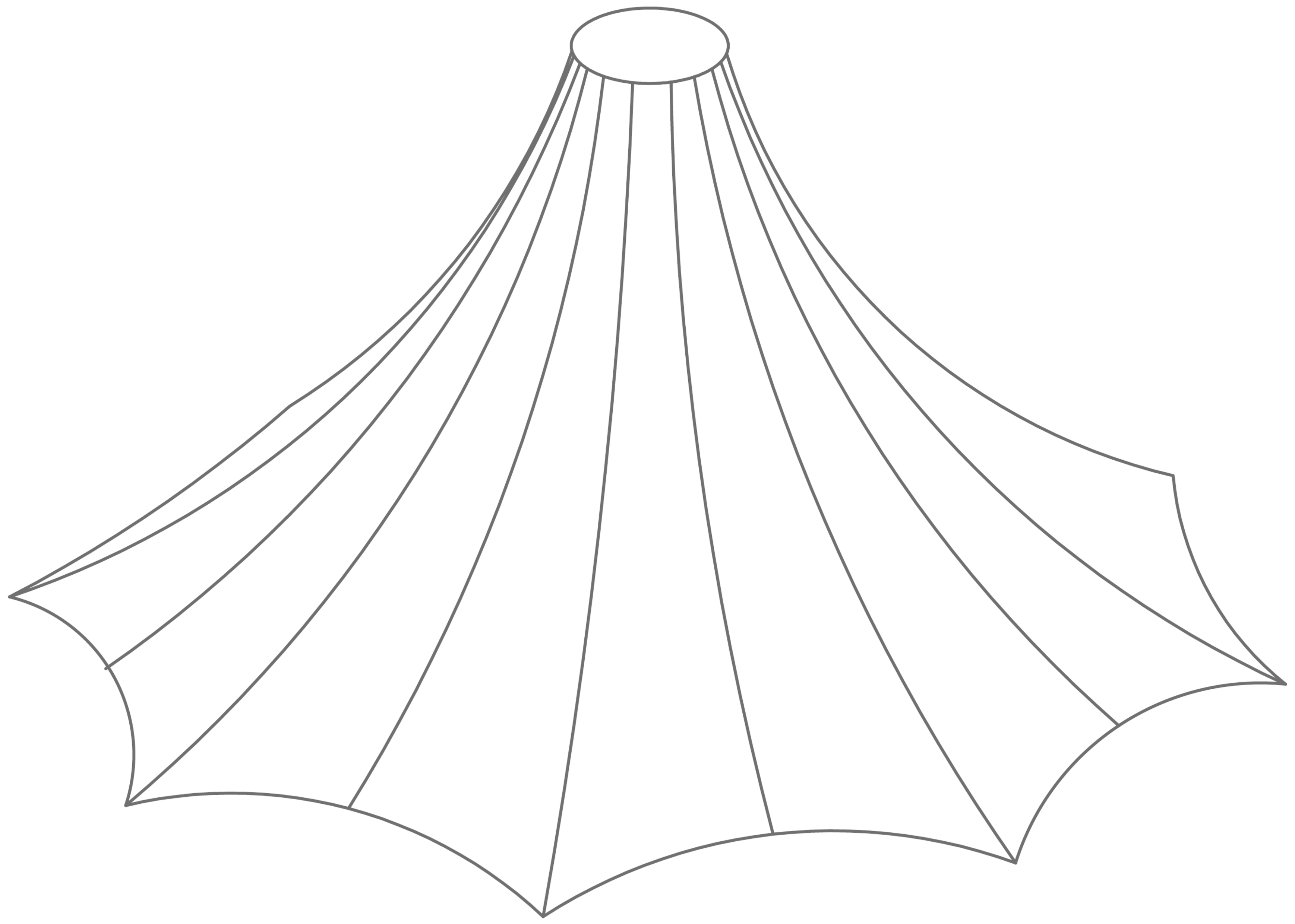


Figure 197) Conic Anticlastic Form

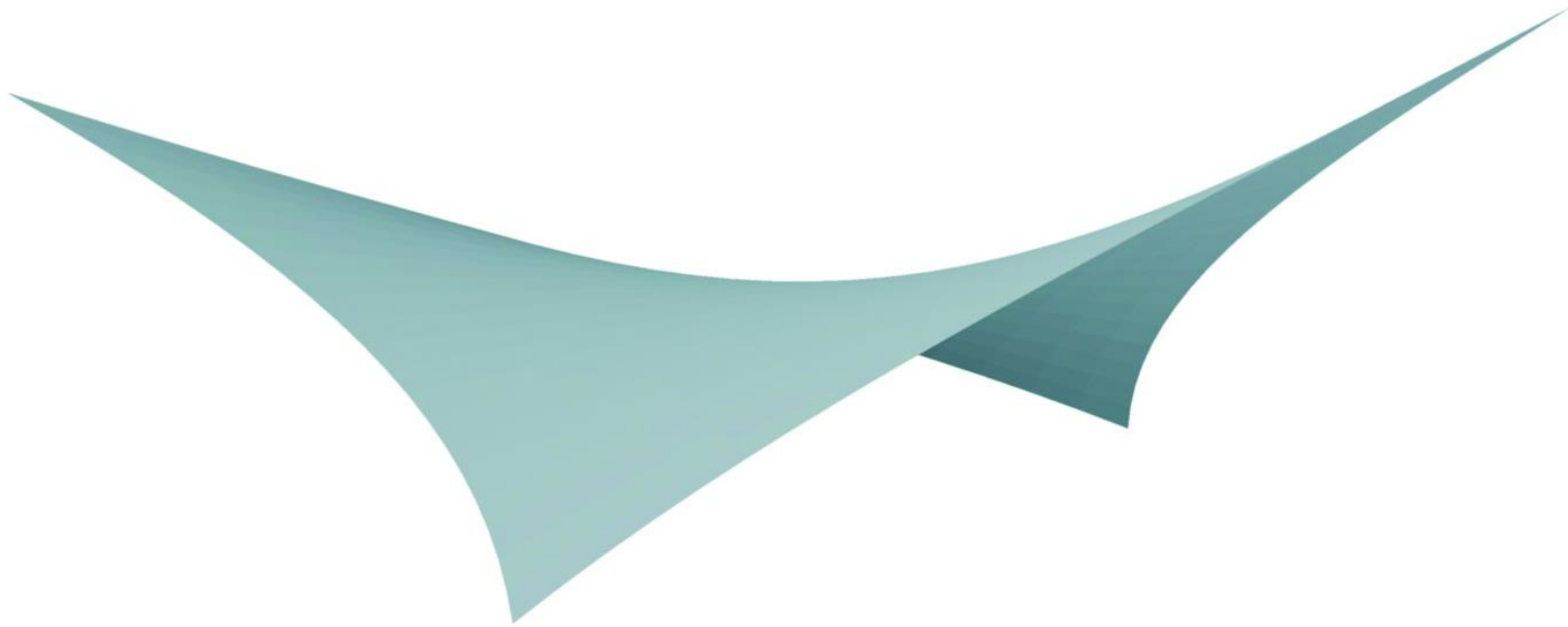


Figure 198) Hypar Anticlastic Form

Analysis 2 Quantifying the Impact of a Longwave Transmission through an ETFE Roof

Accurate assessment of ETFE systems and their impact on building energy performance (including thermal comfort) is currently not possible due to (a) uncertainty regarding longwave physical properties of ETFE and (b) dynamic building performance simulation software tools do not take into account the spectral properties of ETFE in the underlying calculation methods.

However, in order to assess the effect of longwave transmission and investigate whether the current practice of modelling the ETFE as glass significantly impacts on the simulated building performance, a preliminary study was carried out for a summer scenario. This case was divided in three parts :

- Comparison of the relative effect of heat transfer by convection and longwave radiation

- Estimation of expected maximum ETFE layer temperatures

- Development of a simplified mathematical model based on heat transfer balance for each layer

The simplified mathematical model was developed in order to estimate the effect of longwave radiative transmission through an ETFE cushion. The study was carried during the early design stage of a stadium project. The main objective was to evaluate whether the longwave contribution affects substantially the simulated building performance and therefore, whether, consequently, it should be included in the dynamic thermal model. The ETFE cushions were modelled as a roof and the calculations were carried out for the project design summer conditions.

The heat flow model for the ETFE cushion was developed by taking into consideration the heat balance for each of the component ETFE layers. For each of the layers the radiative and convective heat transfer were included in the heat balance (including the transmitted radiation). The main output of the developed model were the ETFE layer temperatures and the roof element heat fluxes. This output is purely indicative and serves to assess the impact of longwave radiative transmission properties on the resulting thermal performance of the element.

The Assumptions and Constraints Incorporated Into the Simplified Model:

- The model deals with a single roof element; therefore, wall effects are not included.
- Linear radiation heat transfer coefficients were assumed. The same coefficients were used for all layers of the cushions irrespectively of their temperature. This potentially leads to underestimation of emission from hot surfaces and overestimation of radiation from cold surfaces.
- The air temperature within the cushion is taken as the mean temperature of the two adjacent layers.
- The sky radiation temperature and the outdoor dry bulb temperature are assumed the same (humid conditions).
- The indoor mean radiant temperature is assumed identical to the indoor dry bulb temperature.
- The layers have a longwave reflectivity of 0 and a longwave emissivity of 1.
- The amount of incoming solar radiation absorbed by the ETFE layers is assigned explicitly to each layer (see Figure 8).
- The ETFE layers in the build-up all have the same transmittance. The ETFE longwave transmittance was arbitrarily set to 0.2 (while the corresponding transmittance of glass is 0.0)
- This approach does not account for any longwave absorption of interlayer shading. The effect of the intermediate layer frit on the longwave transmission was not accounted for.

For comparison the performance of glass and ETFE systems have been calculated for particular environmental conditions, chosen to represent a roof solution with a fritted interlayer in a hot humid climate.

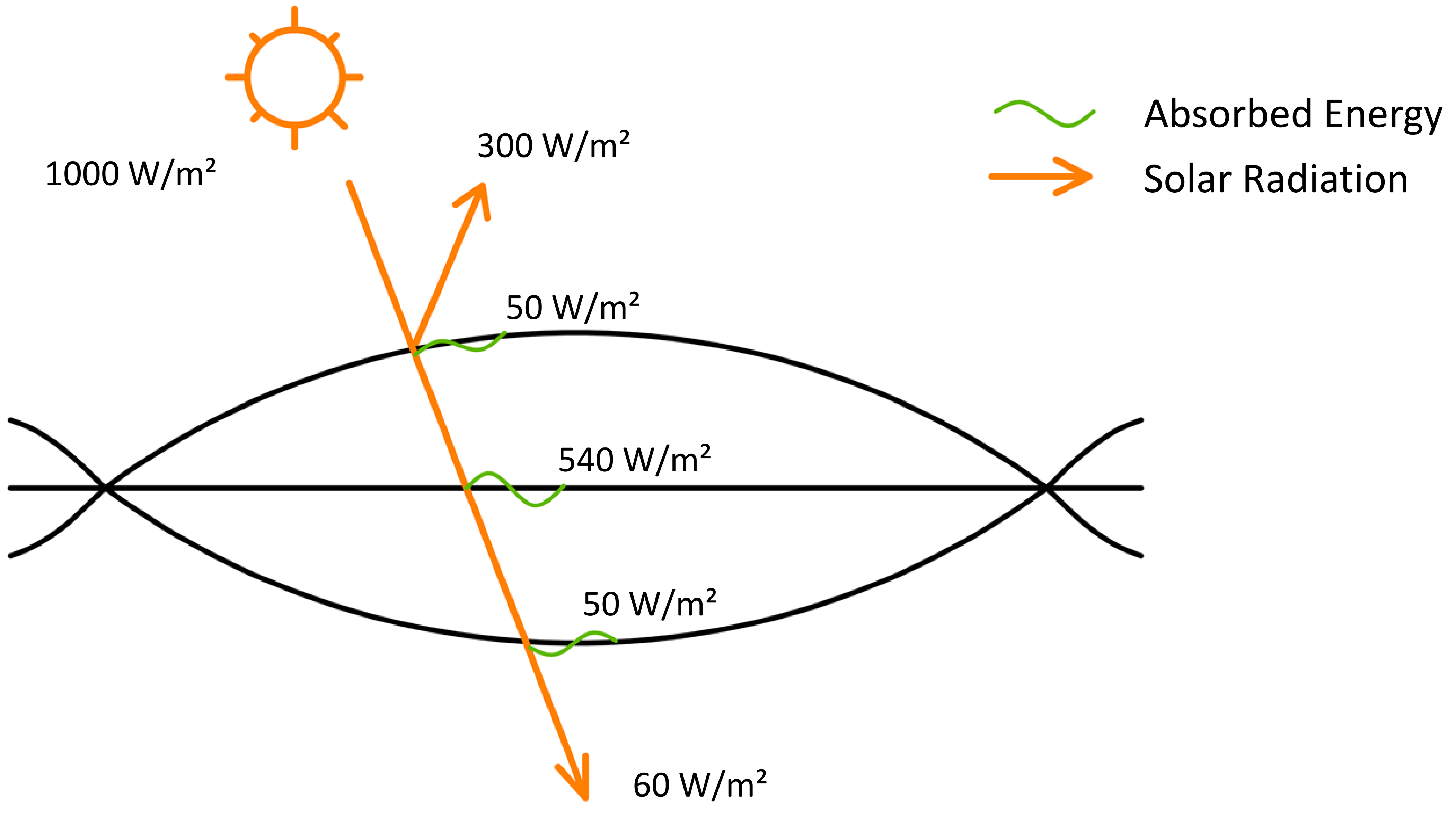


Figure 199) Boundary conditions for mechanical model of the roof

Table 13 presents the heat fluxes to the internal environment and the temperatures of each layer within the glazing and ETFE system given by the simplified model.

The Main Conclusion

- The ETFE construction has a 12% increase in the longwave heat flux from the element when compared to a glass construction.
- The ETFE construction has a 2% increase in the total heat gain through the element.
- In a scenario with solar radiation, the effects of longwave transmission through the ETFE are not considered significant (especially when considering the errors that may occur by inaccurate input in the thermal models).
- For other configurations and different environmental conditions, the longwave transmission is likely to have a more significant impact on the simulated thermal performance of ETFE building elements. A particular condition where the simulated performance of ETFE may be significantly different to that of glazed systems is that of radiation from the indoor side to a cold sky at night. The magnitude of this impact has not yet been specifically investigated but will be the subject of further research and simulation activities.

	GLASS	ETFE
Longwave radiative gain [W/m^2]	195	218
Convective gain [W/m^2]	73	56
Total gain [W/m^2]	328	334
External layer temperature [°C]	48	45
Interlayer temperature [°C]	81	74
Internal layer temperature [°C]	58	53

Table 13) Heat fluxes and temperature for simplified glass and ETFE model

11 ETFE Case Studies

1. Eden Project

Location: Cornwall, UK
Date: 2001
Architect: Nicholas Grimshaw and Partners
Engineer: Anthony Hunt and Associates

Figure 200) Exterior View

Initially conceived as a UK Millennium Project for the public, the Eden Project has grown to become not only a tourist attraction, research and educational tool, but one for generations to come. From the start, the mission of the Eden Project has been to "promote the understanding and responsible management of the vital relationship between plants, people, and resources, leading towards a sustainable future for all." The idea for the three biomes was thought up by Tim Smit who had worked on and was largely responsible for the successful restoration of The Lost Gardens of Heligan. This time his focus was to create something new, starting from scratch, that would amaze future generations. This structure aimed to educate visitors about the importance of a sustainable environment through the study and education of plants. To achieve this goal, Tim teamed up with the internationally known sustainable architecture firm of Nicholas Grimshaw and Partners. Together they explored many innovative ideas for the creation of the world's largest biome.

The strict criteria for such an innovative structure created many design challenges. First, the structure was to be the world's largest plant enclosure. This involved coming up with a design scheme that could span for great distances without the use of a single internal support. Second, the structure must be as light as possible. This was needed for transportation reasons primarily because all the materials would have to be brought in from other cities, a long distance away. In addition, a lighter structure would put less stress on the soil and allow for smaller footings and less site impact. Last, the enclosure must be ecologically friendly helping it to be used as an educational demonstration of sustainability. Grimshaw's solution to this challenge was to look at nature. He got his inspiration from looking at the honeycomb of bees and even the multifaceted eyes of a fly. These creatures used their surroundings most effectively to create a very strong, yet light-weight, solution. In addition, a geodesic dome-like structure would be able to conform to the expanding and contracting contours of the clayey soil.

Figure 201) Top View

This structure, bubbling above the surface of the pits of a former quarry, comprises 2.2 hectares of growing space for plants in rainforest and Mediterranean conditions. Nicholas Grimshaw's successful Millennium Project sits on the site in the form of eight domes of varying sizes, interlinked, lining the foot of a cliff. The isolated uneven site and the need to create optimum conditions for photosynthesis required a lightweight solution that wouldn't need bespoke parts or cast deep shadows.

Inspired in part by the geodesic structures of Buckminster Fuller, the Eden Project's domes are an economic way of enclosing large amounts of space and unlike traditional greenhouses the design uses panels that are made of two layers of ethylene tetrafluoroethylene (ETFE) foil, a plastic instead of heavier glass. Tubular steel hexagons join up to create the frame of each dome, the size of each hexagonal element contracts and decreases in accordance with the size of the dome. ETFE proved easier and quicker to cut than glass to span the different sizes of hexagonal panels.

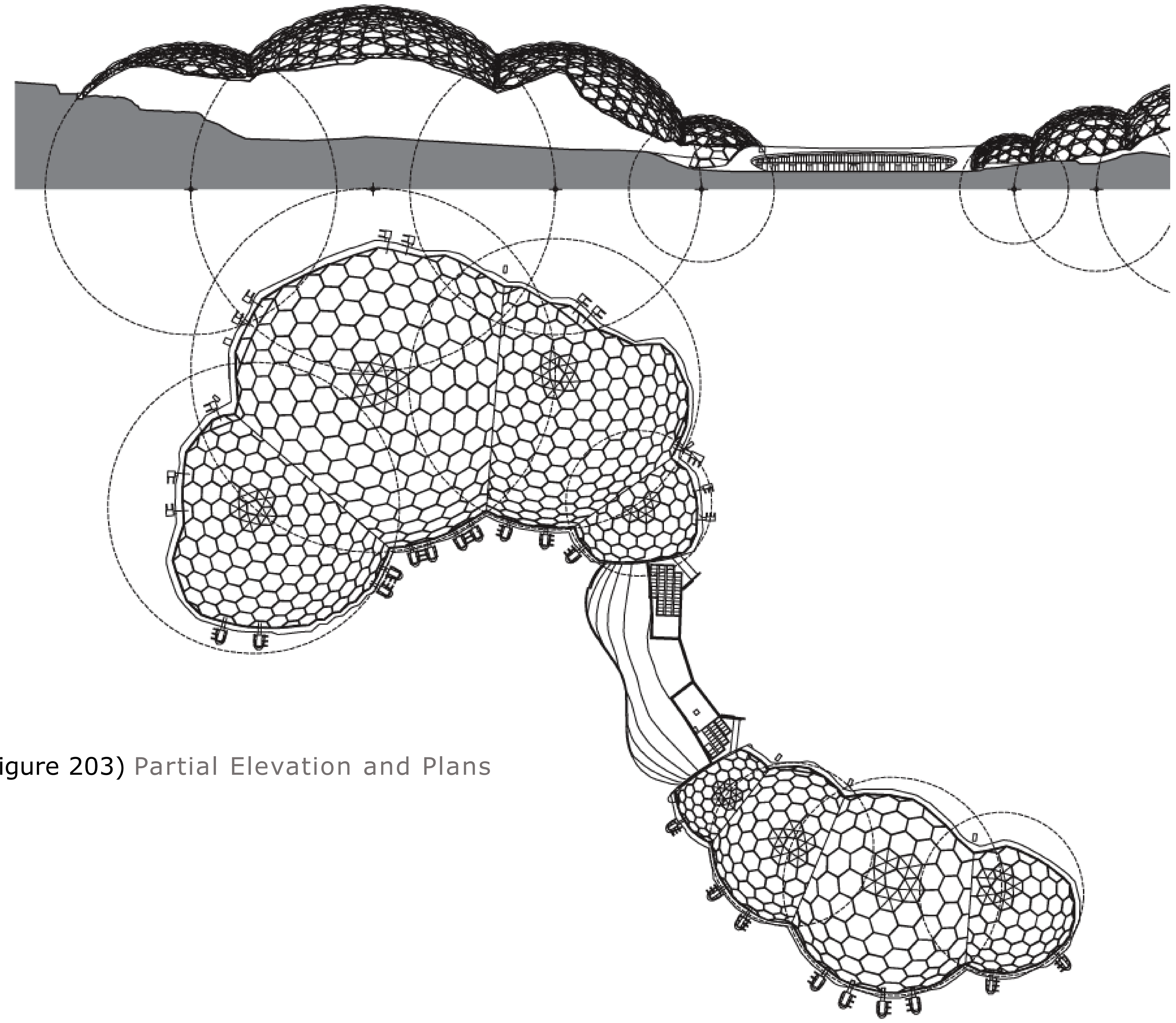


Figure 203) Partial Elevation and Plans

Figure 202) Inside looking out

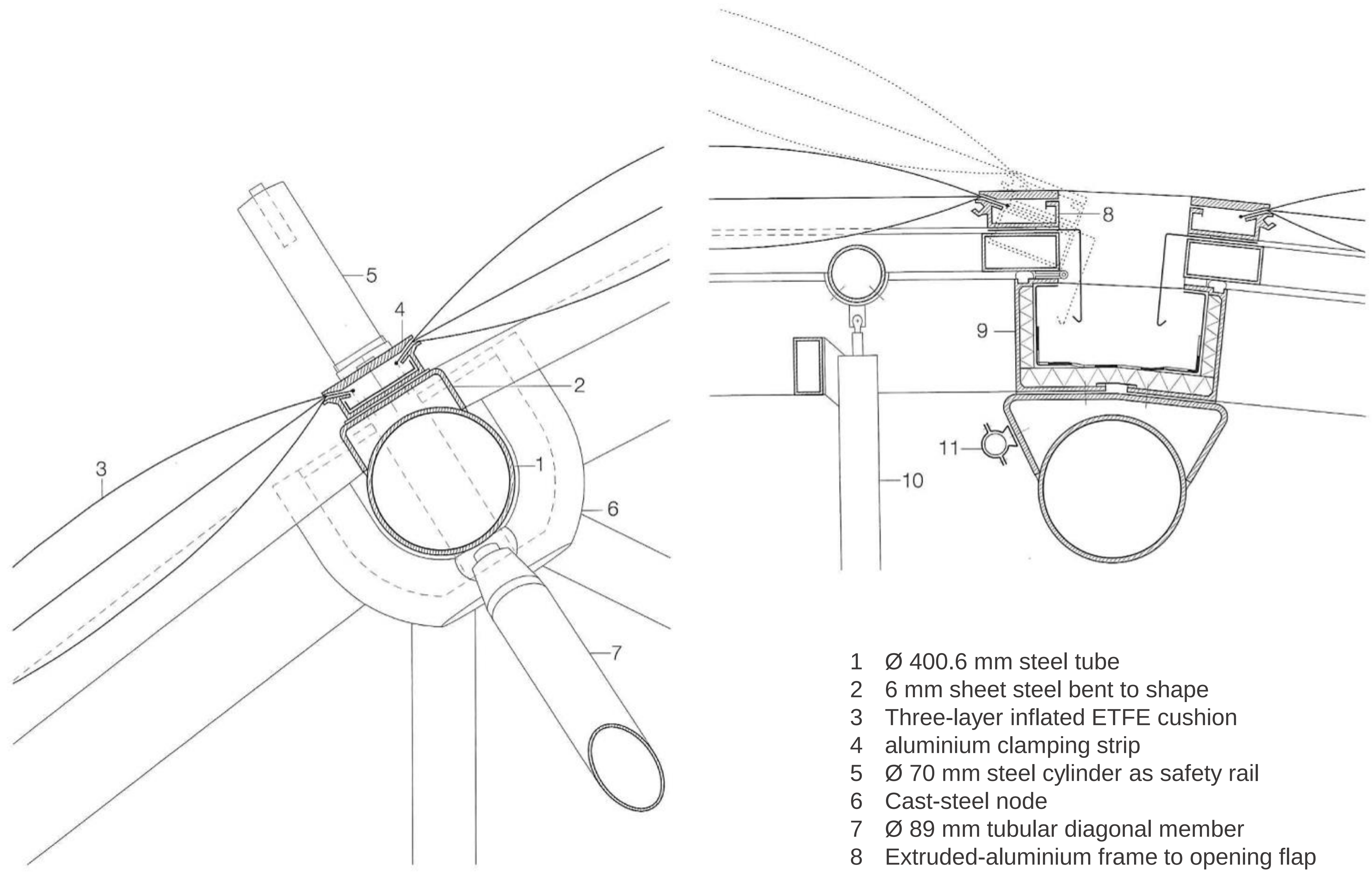
The more than 800 hexagon elements are covered by air filled cushions. These cushions are made of transparent EFTE (Ethyltetrafluorethylene) foil. The basic material is between 50 μm and 200 μm thick with a width of 1.5 m. The foil material was cut and welded. The normal cushions are made up of three layers. The top and bottom layer form the cushion and carry the loads. An additional layer between them has the function of enhancing the temperature insulation and also dividing up the airspace in case of leakage. In areas of high local wind suction the outer surface of the cushions was strengthened by using two layers of foil.

Ventilation: To achieve the tropical climate inside the domes, a special ventilation system had to be used. The required openings were determined by Ove Arup & partners , London. On top of each of the 8 domes are vent openings. The 5 hexagons surrounding the top pentagon were divided into 3 triangles so that each dome has 30 openings operated by remote control. These windows are also covered by triangular air cushions.

The substructure consists of rectangular hollow sections 140 x 70 mm. For the air inlet glass lamella windows are arranged around the edge of the domes (Fig. 204). Warm air can be blown inside the domes using heaters. Each dome also has some doors for maintenance and emergency exits only. The access for visitors is through the link building only. For maintenance the vents on top of each dome has a cat walk.

Figure 205) Interior View

Figure 204) Ventilation pipes



1 Ø 400.6 mm steel tube
2 6 mm sheet steel bent to shape
3 Three-layer inflated ETFE cushion
4 aluminium clamping strip
5 Ø 70 mm steel cylinder as safety rail
6 Cast-steel node
7 Ø 89 mm tubular diagonal member
8 Extruded-aluminium frame to opening flap
9 Thermal insulation, steel section; composite sheet-metal and plastic-sheet gutter
10 Pneumatically operated cylindrical opening shaft
11 High-pressure-air tube for operating flap

Figure 206) Cushion details

Most of the steel structure was manufactured in the MERO workshop close to Wuerzburg in Germany. Only the arches and support point were fabricated elsewhere. The manufacturing of the MERO beams and nodes was done using a computer aided machine. The end plate and support brackets of the top chord beams were welded by hand. Each element and node has it's unique number which remained the same during the design, manufacturing and erection phase.

For corrosion protection all steel elements are hot dipped galvanized. Due to their sizes the segments of the arches were galvanized by a company in France, which has one of the biggest galvanizing tubs in Europe. The bowl nodes made out of cast iron GGG40, were also galvanized. With a general inspection every two years, the steel structure is designed to be maintenance free for 30 years.

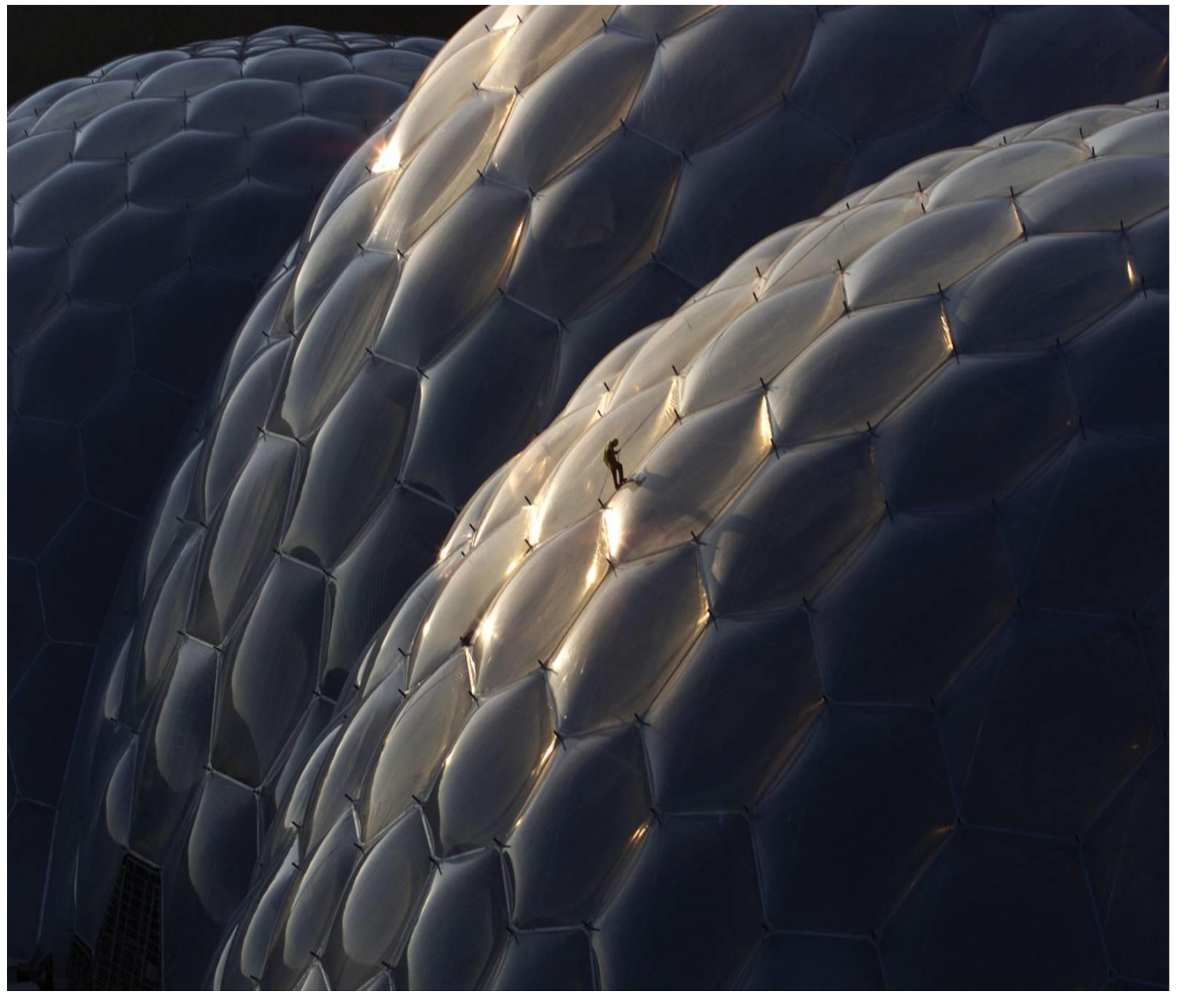


Figure 207) Exterior view

Figure 208) Night exterior view

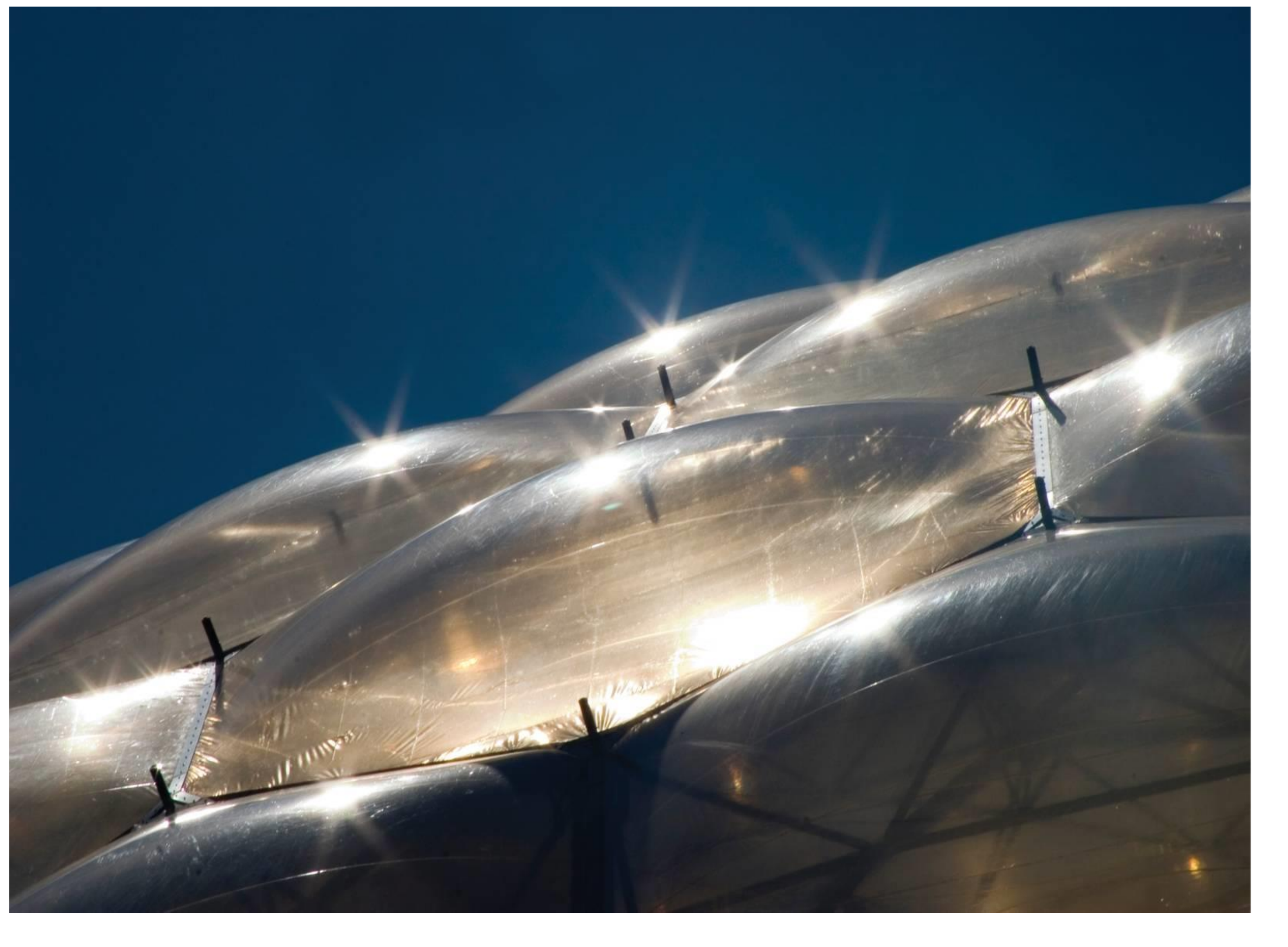
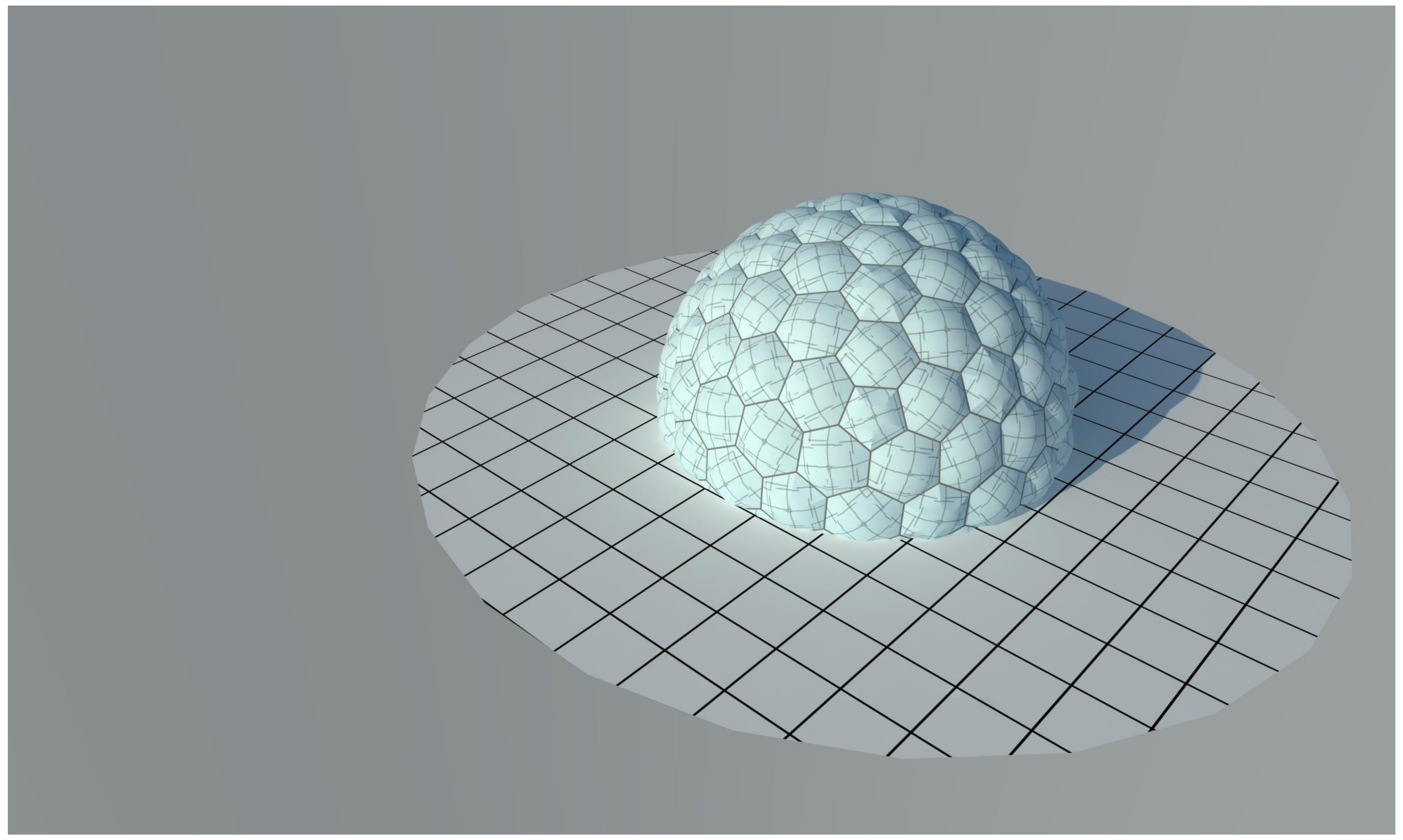


Figure 209) ETFE cushions

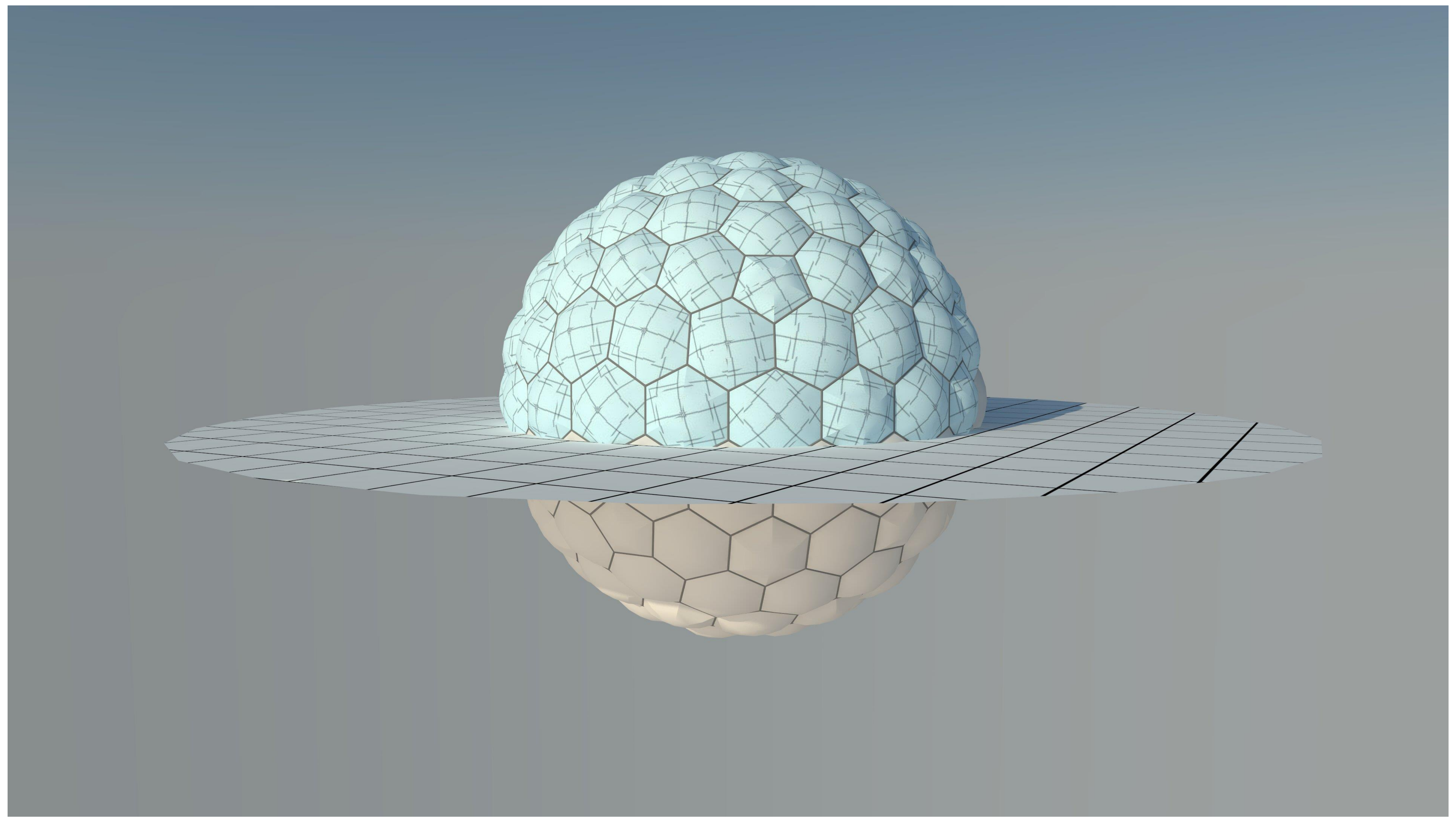
Figure 210) Ventilation openings

The idea was all about spheres, not the whole but half of the sphere, as shown in the renders below.

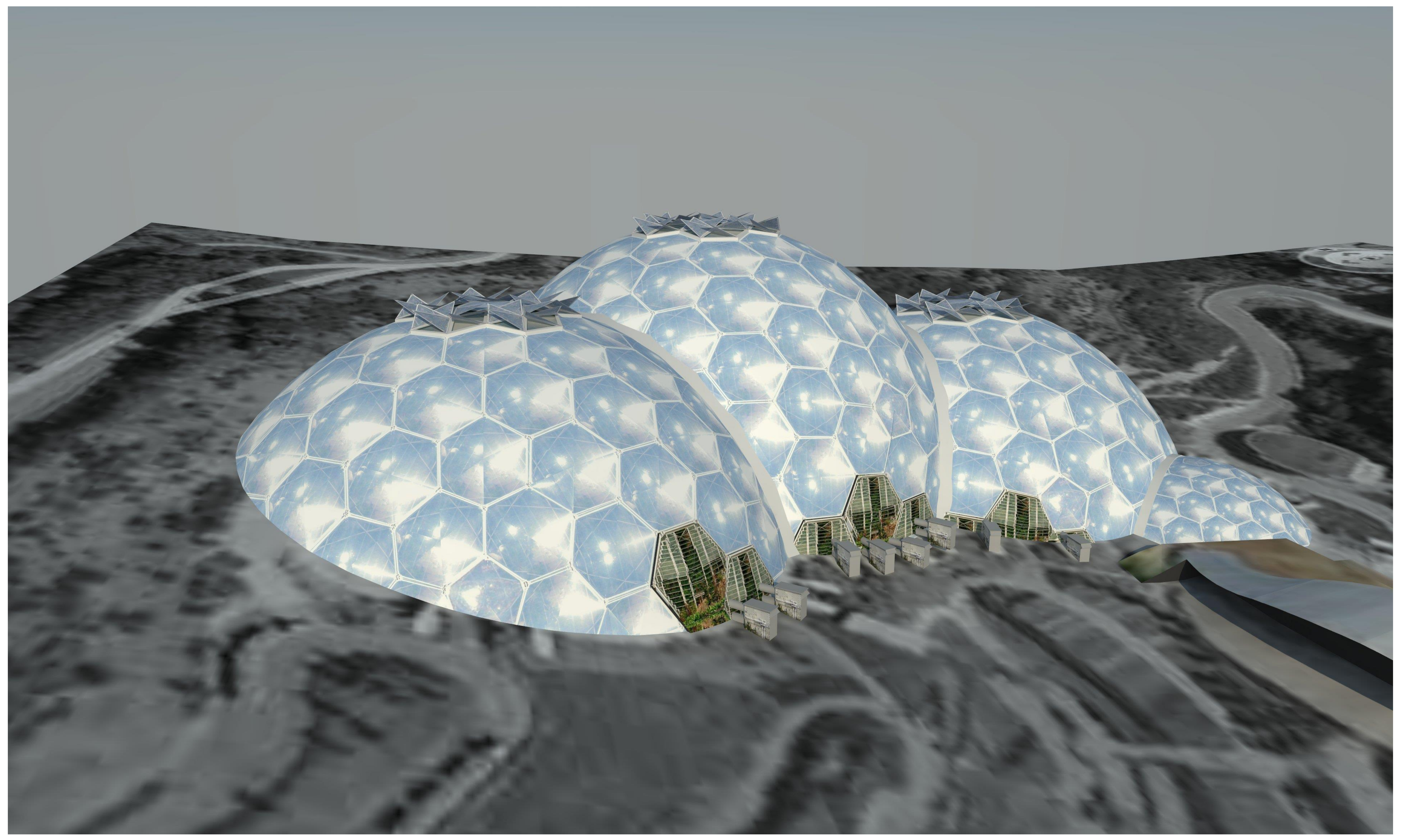
The organic inspiration for an organic use. The biggest greenhouse in the world which creates a covered artificial jungle.



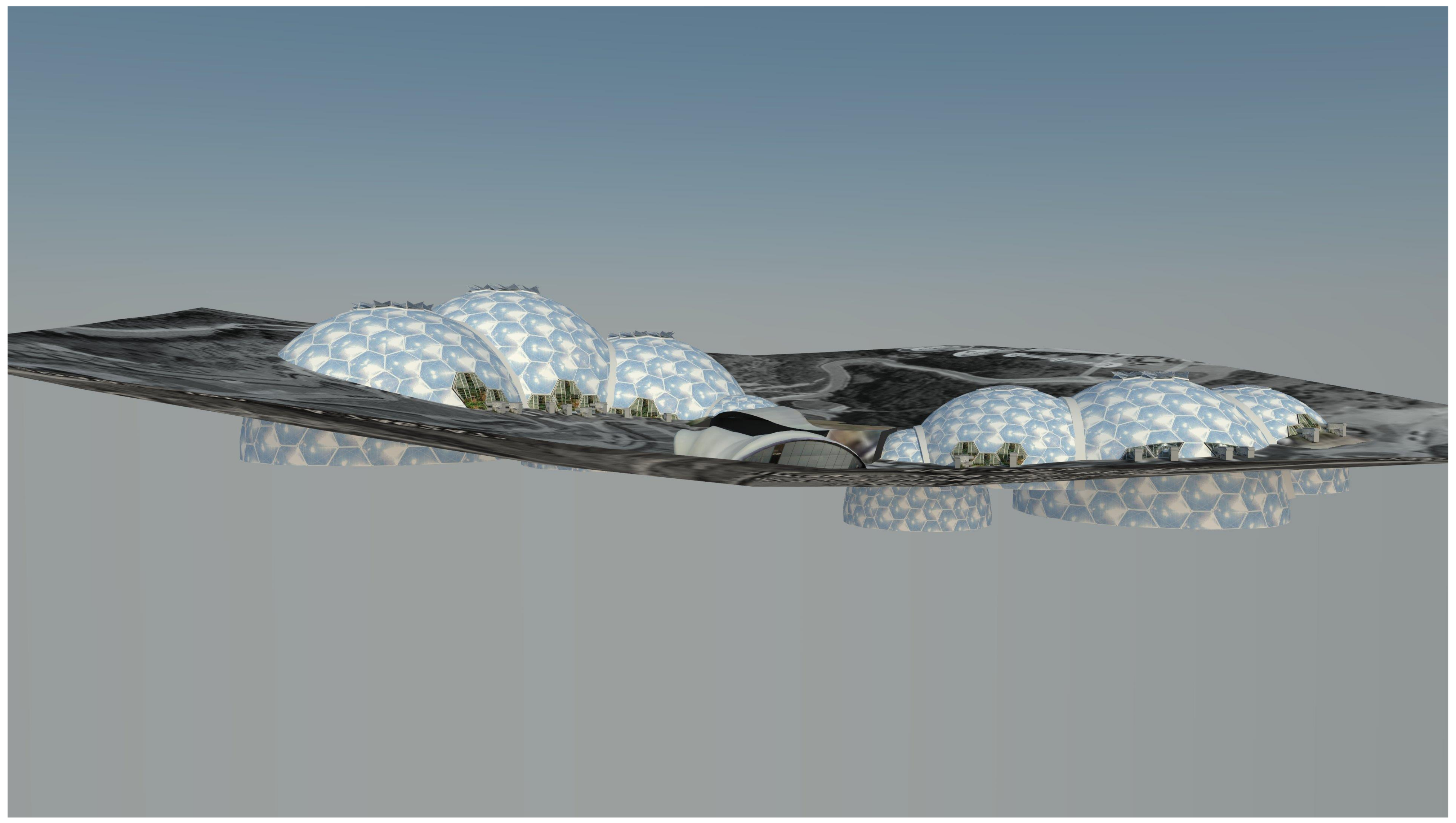
(I)



(II)



(III)



(IV)

Figure 211) Eden Project, renders

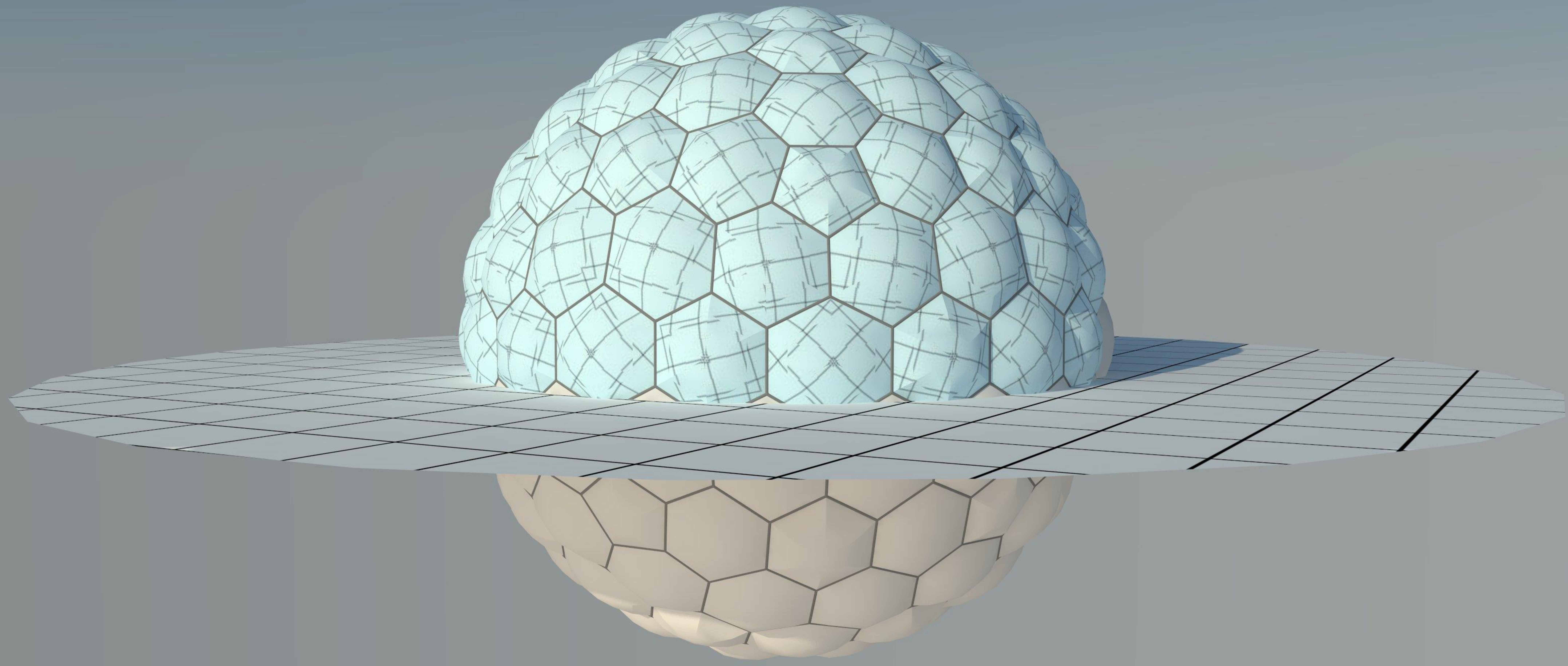


Figure 212) Eden Project, renders

Figure 213) Eden Project, renders

Figure 214) Eden Project, renders

Figure 215) Eden Project, renders

2. Allianz Arena Stadium

Location: Munchen, Germany
Date: 2005
Architect: Herzog & de Meuron
Engineer: Ove Arup & Partners

Figure 216) Allianz Arena Football Stadium

The Allianz Arena replaced Munich's old Olympiastadion. First plans for a new stadium were made in 1997, and even though the city of Munich initially preferred reconstructing the Olympiastadion, they eventually went ahead with the clubs' proposal for an entire new stadium.

Construction of the Allianz Arena started in October 2002, with a total investment in the project of €340 million.

Most distinctive part of the ground are almost 3,000 ETFE-foil 'air panels' that cover facades and roof of the ground. With its immense size exterior cladding is the largest foil construction in the world. Each of the panels, also known as cushions, may be lightened in three colors – blue, red and white. Blue are used mostly for TSV 1860 games, red for Bayern matches and white for other events, though the configurations tend to be mixed. This plays an important role however, because one of this stadium's challenges was to combine colors of both football clubs without antagonizing fans of one another. For this reason the ground is greyish when not used and takes colors for specific events. This solution has also been copied, most known example of which is New Meadowlands in East Rutherford.

The stadium can change into three basic colors: white, blue, and red (and a mixture of these). The stadium contains lights of variable color that are inserted in the façade. The outside material of the stadium is made of transparent elements. They cover the entire structure (made of reinforced concrete) that supports the tiers from the bottom up to the top where imposing supporting beams hold the roof of the stadium.

The external façade of the arena, with its 2,760 diamond-shaped cushions made of 0.2mm thick ETFE foil, makes a memorable first impression, particularly when lighted at night in one of the team colors (red for FC Bayern, blue for TSV 1860, or white for the German National Team).

“The proposal of Herzog & de Meuron Architekten, with its striking lighting concept, was immediately selected,” stated Peter Kerspe, CEO of Allianz Arena Muenchen Stadion GmbH. “The stadium is purpose-built for soccer and is not allowed by the city of Munich to promote concert events or other arena-type shows. We do host a large variety of smaller events and had a full house for public viewing of the European Champions League Final. There were some setbacks along the way, but the stadium is a big success. It was built on schedule and within its budget. Additionally, our finances are very solid—we have a turnover of ~ €50 million per year and will have paid the total investment back in the next 10 years.”

ArupSport was jointly responsible for the competition architectural design, design development for the planning submission, and subsequently for the preparation of production information for the viewing bowl. ArupSport was also responsible for the overall structural design for the competition and planning stages, and Arup GmbH for the on-going design of the substructure, frame, and seating bowl.

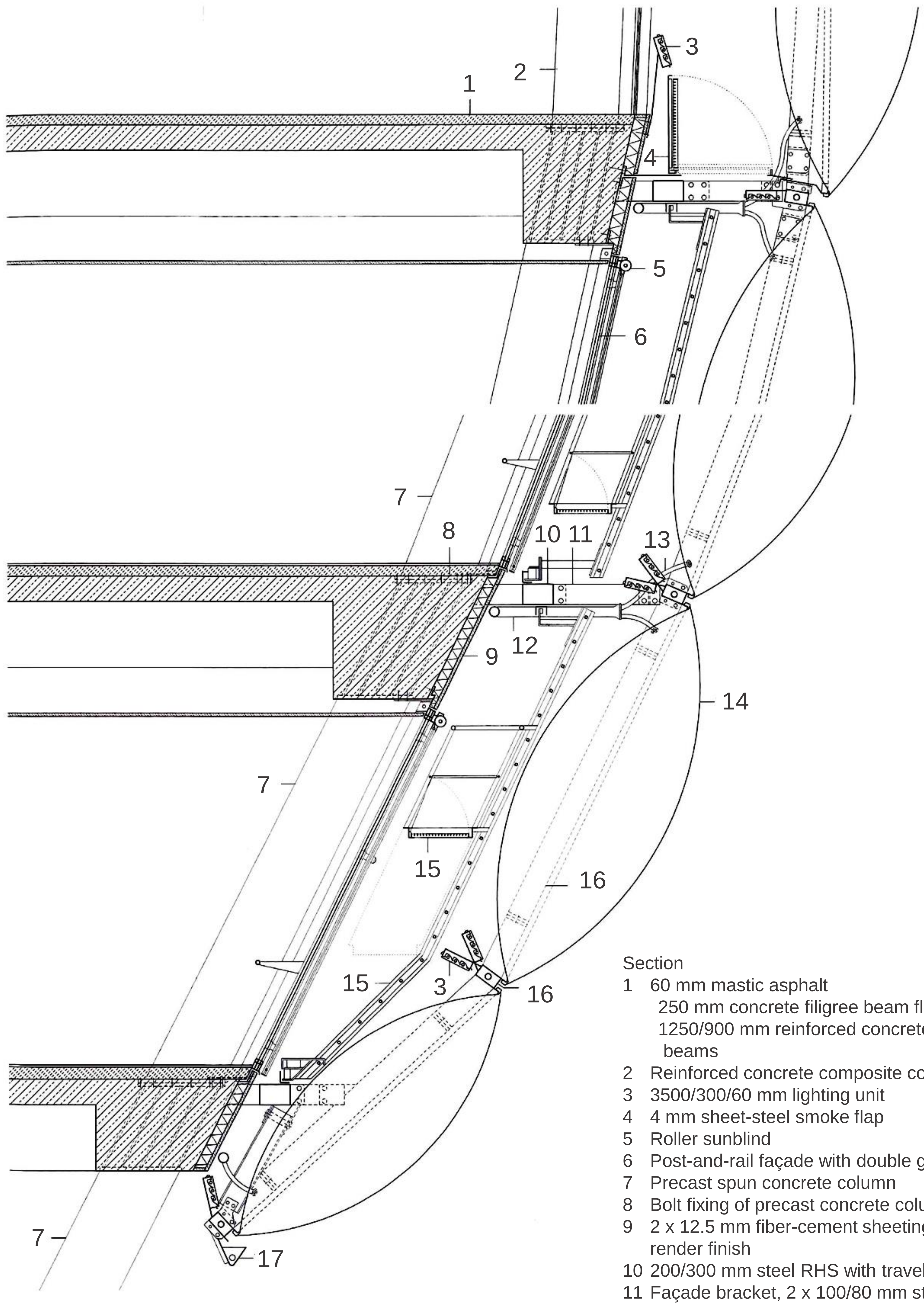
Figure 217) Top view

Figure 218) Three different colors: Red, White, Blue

The roof of the Allianz Arena consists of 2,874 air cushions and has a total surface area of 64,000 square meters. This is the world’s biggest roof made of foil. The foil is only 0.2 mm thick and up to 98% UV-permeable. Each cushion has a surface area of approximately 35 square meters, although none of the honeycombs made of ethylene tetrafluoroethylene has precisely the same shape. Giant fans underneath the stadium pump up the cushions and ensure that there is always an adequate supply of air available. If the blower fails and water collects during the resulting cooling process, a type of valve opens at the lowest point so that the moisture can flow away before the mass of water overloads the roof

The covering area of the building is split up in the roof consisting of two-layered white and transparent foil cushions as well as the façade with foil cushions whose outside is printed. The printing resp. coating was necessary, because the soccer clubs using the stadium would like to make its façade illuminated by the individual club colors during the soccer matches. This will be achieved by means of spotlights installed at the inner side of the facades. Covering the stadium with foil cushions guarantees the best possible protection of all spectators from weather impacts such as snow and rain.

Figure 219) ETFE membrane



Section
1 60 mm mastic asphalt
250 mm concrete filigree beam floor
1250/900 mm reinforced concrete floor beams
2 Reinforced concrete composite column
3 3500/300/60 mm lighting unit
4 4 mm sheet-steel smoke flap
5 Roller sunblind
6 Post-and-rail façade with double glazing
7 Precast spun concrete column
8 Bolt fixing of precast concrete column
9 2 x 12.5 mm fiber-cement sheeting with smooth render finish
10 200/300 mm steel RHS with traveler
11 Façade bracket, 2 x 100/80 mm steel flats
12 100 mm dia. Air duct to façade
13 50 mm dia. Polythene air tube
14 Cushion, 0.2 mm ETFE sheeting
15 Ladder of travelling system
16 Secondary construction
120/220 mm steel RHS
17 6 mm galvanized sheet-steel gutter

Figure 220) Facade details

The stadium construction began on 21 October 2002 and was officially opened on 30 May 2005. The primary designers are architects Herzog & de Meuron. The stadium is designed so that the main entrance to the stadium would be from an elevated esplanade separated from the parking space consisting of Europe's biggest underground car park. The roof of the stadium has in-built roller blinds which may be drawn back and forth during games to provide protection from the sun.

Figure 221) ETFE foils being installed

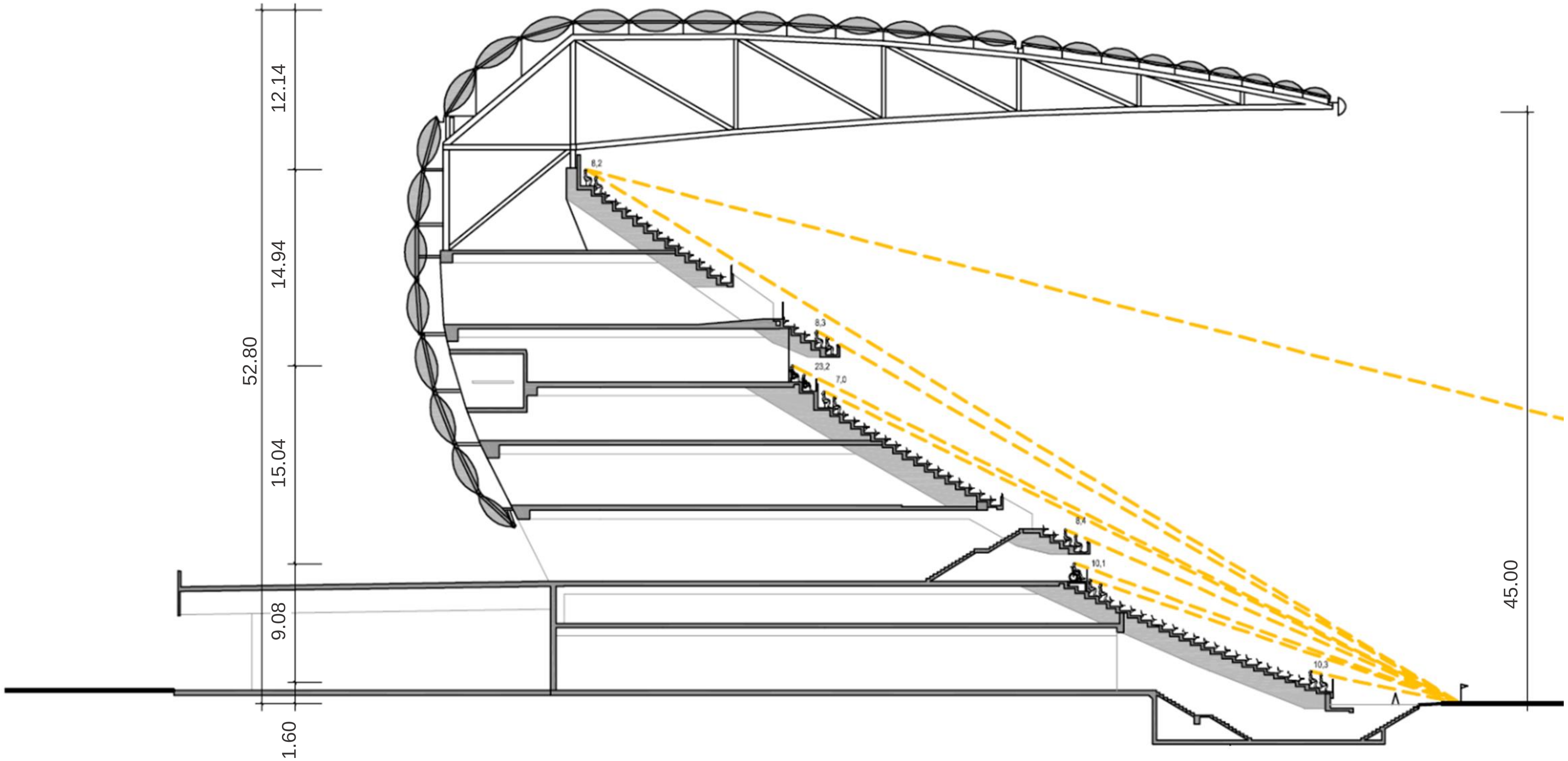


Figure 222) Section

3. Beijing National Aquatics Center

Location: Beijing, China
Date: 2008
Architect: Heerzog & Meeuron ArupSport
Engineer: CSCEC, CCDI

Figure 223) Exterior view

Located on the west side of Landscape Avenue in the Olympic Green and to the west of National Stadium (Bird's Nest), it contains the official 2008 Olympics swimming facility. The construction started on December 24th, 2003 and was finished on January 1st, 2008. It measures 177 meters long, 177 meters wide, and 30 meters high and covers an area of 62,950 sq. meters. It has four floors: one at street level, two above, and one below. Its floor space reaches 79,532 sq. meters, while the below street level area is no less than 15,000 sq. meters. The one below served as the service area during the Olympics. The first floor is for tourists. The auditorium is on the second floor with 6,000 fixed seats (2,000 of which are movable), and 11,000 temporary seats. The third floor is strictly for business.

The design combines modern technologies with Chinese traditional values. In tradition, Chinese conceptualized a square Earth and a round Heaven, and this formed the design's central theme. Moreover, the cube shape dominates ancient urban buildings. Its design is of traditional style to meet all its functional requirements.

Designed by Chinese and Australian, it is the first building in the world built upon "the soap bubble" theory, and sports a polyhedral steel-framed structure.

The ETFE (the ethylene-tetrafluoroethylene copolymer) membrane insulates it. This advanced membrane structure is formed by 3,065 bubble-like pneumatic cushions of all sizes. It becomes the first large-scale public project coated with the membrane, and it also has set up a new world record for its massive deployment. It looks like a huge blue box, from which it takes its nickname: the Water Cube. It is blue in order to reflect sunlight. It shines in the sunlight like a pearl in water. From the inside, you may discover that the pneumatic cushions of all sizes are just like sea bubbles. Various high technology and green technology are present in its construction. Popular Science magazine chose it the Best of What's New of 2006.

In July 2003, the Water Cube design was chosen from 10 proposals in an international architectural competition for the aquatic center project. The Water Cube was specially designed and built by a Consortium made up of PTW Architects (an Australian architect firm), Arup international engineering group, CSCEC (China State Construction Engineering Corporation), and CCDI (China Construction Design International) of Shanghai. The Water Cube's design was initiated by a team effort: the Chinese partners felt a square was more symbolic to Chinese culture and its relationship to the Bird’s Nest stadium, while the Sydney based partners came up with the idea of covering the 'cube' with bubbles, symbolizing water. Contextually the cube symbolizes earth whilst the circle (represented by the stadium) represents heaven. Hence symbolically the water cube references Chinese symbolic architecture.

Comprising a steel space frame, it is the largest ETFE clad structure in the world with over 100,000 m² of ETFE pillows that are only 0.2 mm (1/125 of an inch) in total thickness. The ETFE cladding allows more light and heat penetration than traditional glass, resulting in a 30% decrease in energy costs.

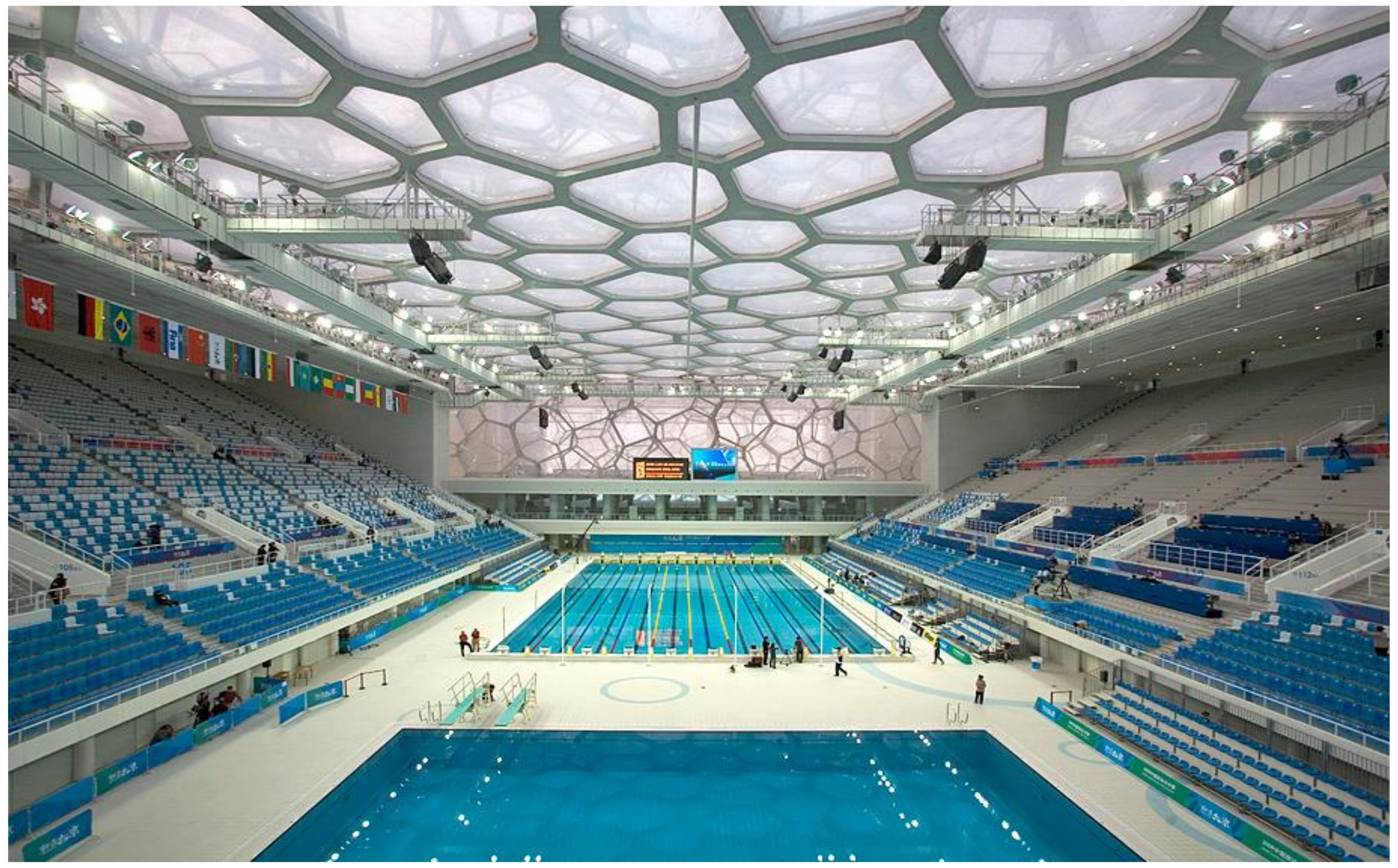


Figure 224) Interior view

Figure 225) Exterior night view

The daylight allowed into the cube saves up to 55% on the lighting energy required for the leisure pool hall.

There are two parts to the Water Cube's structural framework – internal and external. The external structure forms the actual roof, ceiling and walls and comprises a flat web of rectangular boxed sections. These sections are then clad with the inflatable material transparent ETFE.

The internal steel frame is based on the unique geometry of biological cells or soap bubbles. Ove Arup and PTW based this "soap bubbles" structural concept on a solution from two Irish professors of physics at Trinity College, Dublin, known as the Weaire-Phelan structure, whereby a recurring pattern of polyhedrons is packed together to occupy a three dimensional space in the most efficient way possible.

Over 22,000 stainless steel members form the sides of these "bubbles", which are welded at the joints to more than 12,000 spherical steel nodes. The benefit of this frame design, as well as resembling water bubbles, is that it is ideally suited to the seismic conditions found in Beijing.

There were a lot of myths about the use of ETFE, regarding the material growing mold and being ineffective in muting external noise, which had to be dispelled. PTW managing director John Bilmon and his team put the claims to bed by conducting extensive tests and making some adjustments to the material that would reduce the acoustic impact of outside noise. The material was also shown to be superior in terms of lighting and thermal efficiency, and will protect the internal steel members from exposure to the harsh chlorinated aquatic environment – preventing their corrosion.

The building's envelope required 100,000m² of ETFE, making it the largest ETFE structure in the world. The ETFE used was produced by Vector-Foiltec of Germany and Yuanda Group of Shengyang, China.

The venue's design as an enclosed swimming gymnasium could have led to high humidity. This was addressed by taking a new approach to the air conditioning system. A stringent temperature and humidity control system, and a recycled hot water system were incorporated into the design. These help to air-condition the public area and the swimming pool. Indoor and outdoor air recycling systems, solar energy systems and deck ventilation systems maintain a comfortable climate and humidity of 50%-60% in the venue.

Figure 226) Structure

Figure 227) ETFE membrane

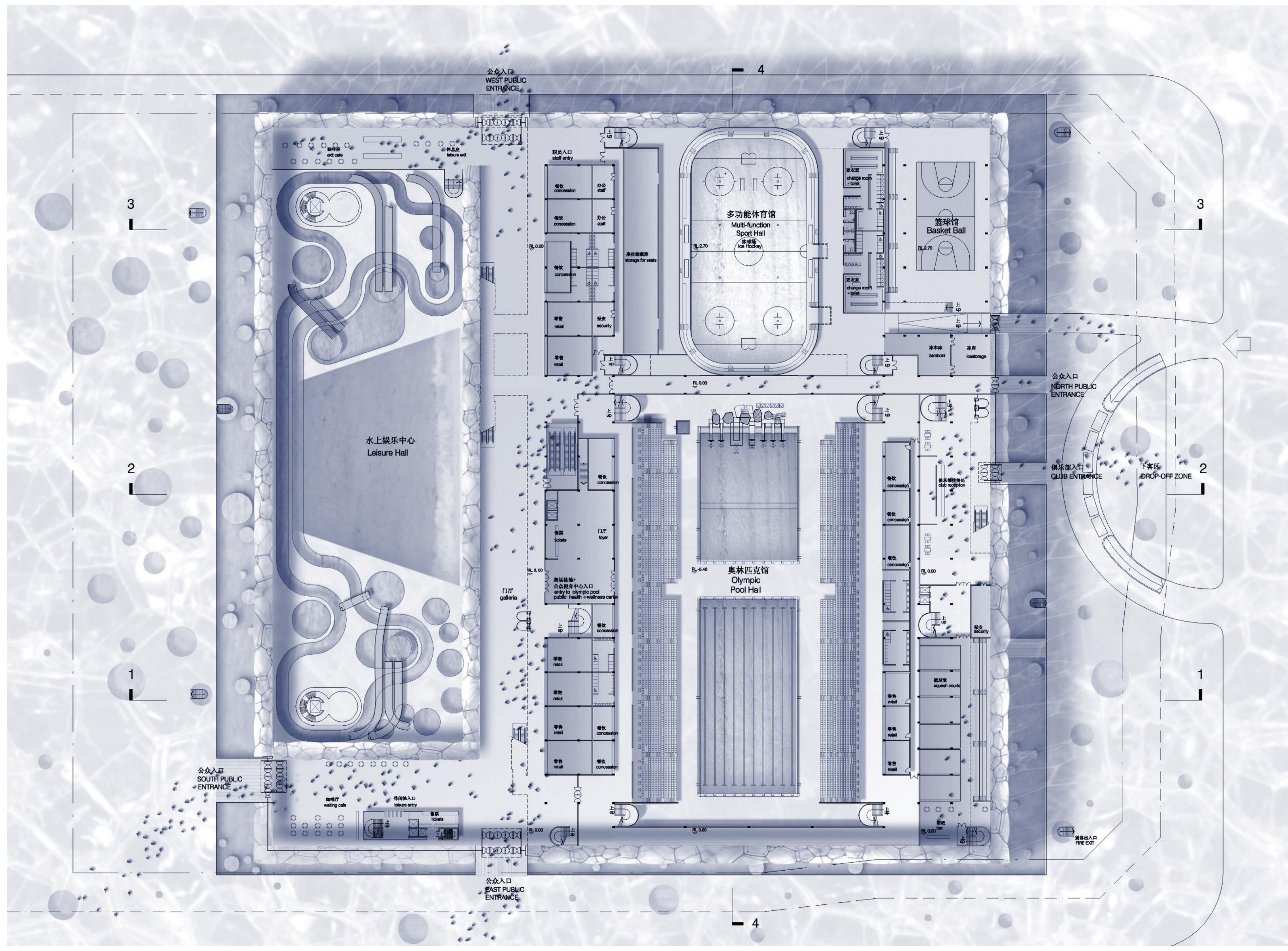


Figure 228) Plan

“The building acts like an insulated greenhouse,” says Bilmon “We’ve considered the impact of solar rays hitting the building and capturing the energy created by the solar rays and reusing that within the building. The energy savings may be second to none in the world.” In fact, according to PTW, 90% of the solar energy falling on the ETFE cushions is trapped within the structural zone and used to heat the pools and interior.

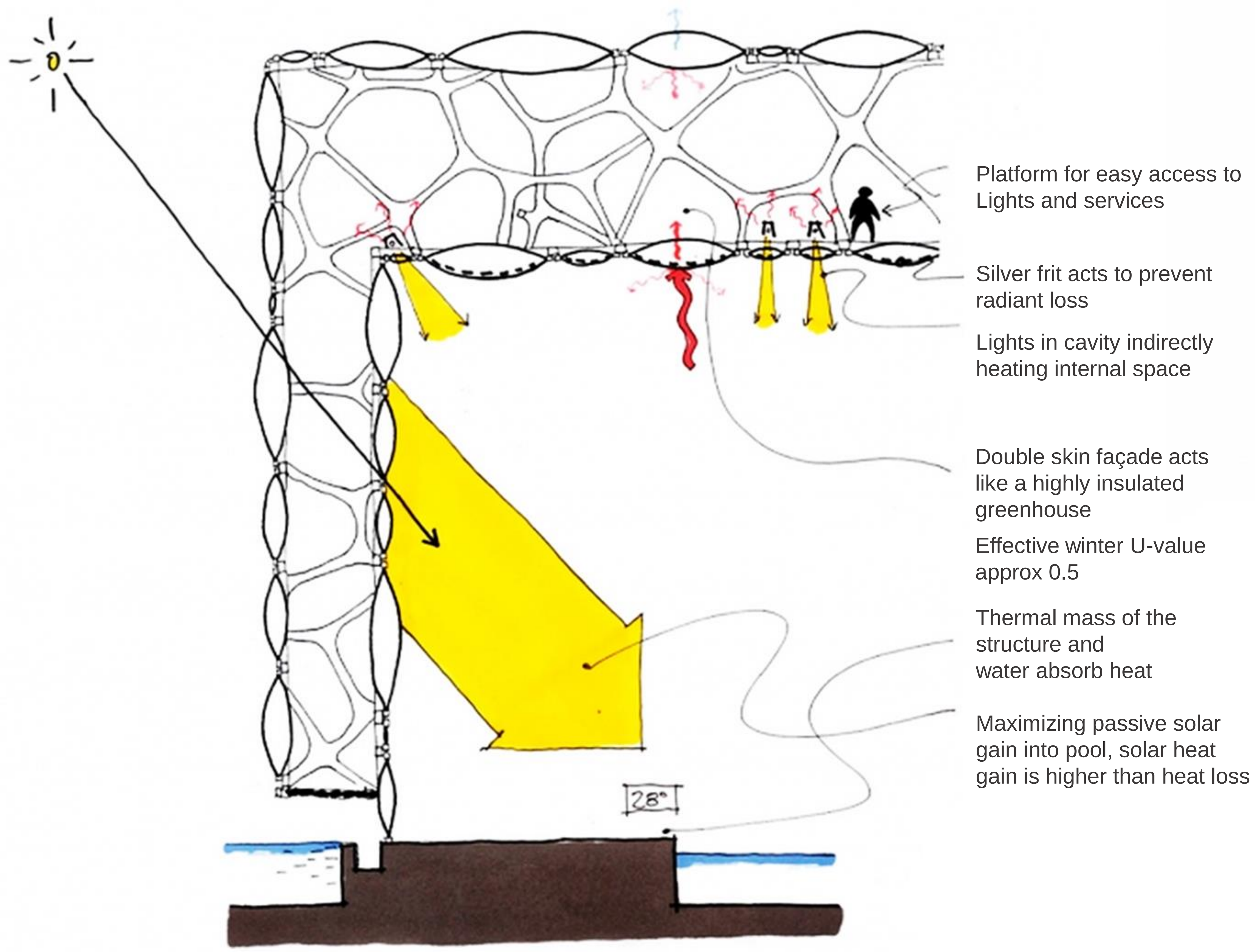


Figure 229) Winter energy performance

Vented cavity Winter

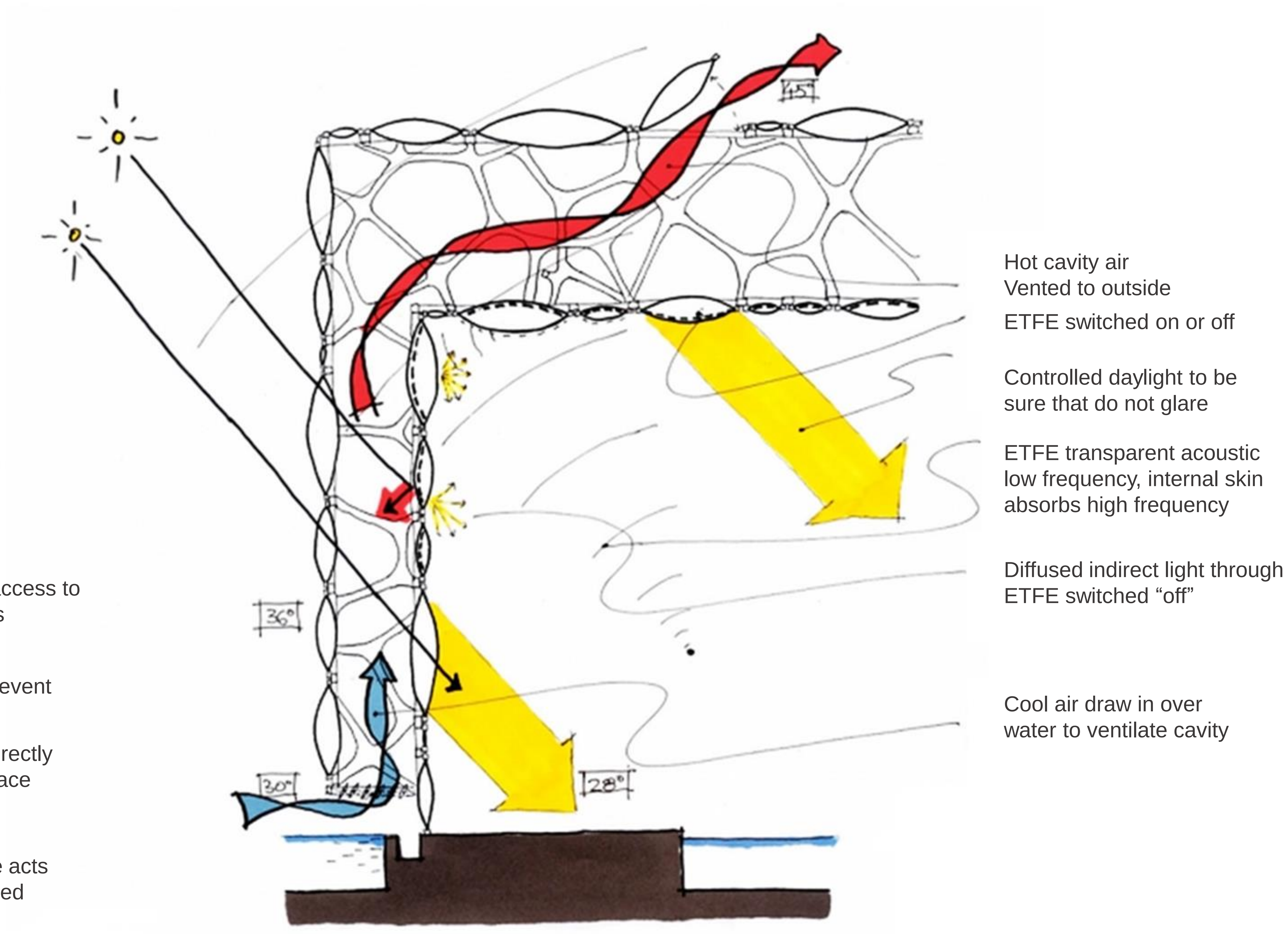


Figure 230) Summer energy performance

Vented cavity Summer

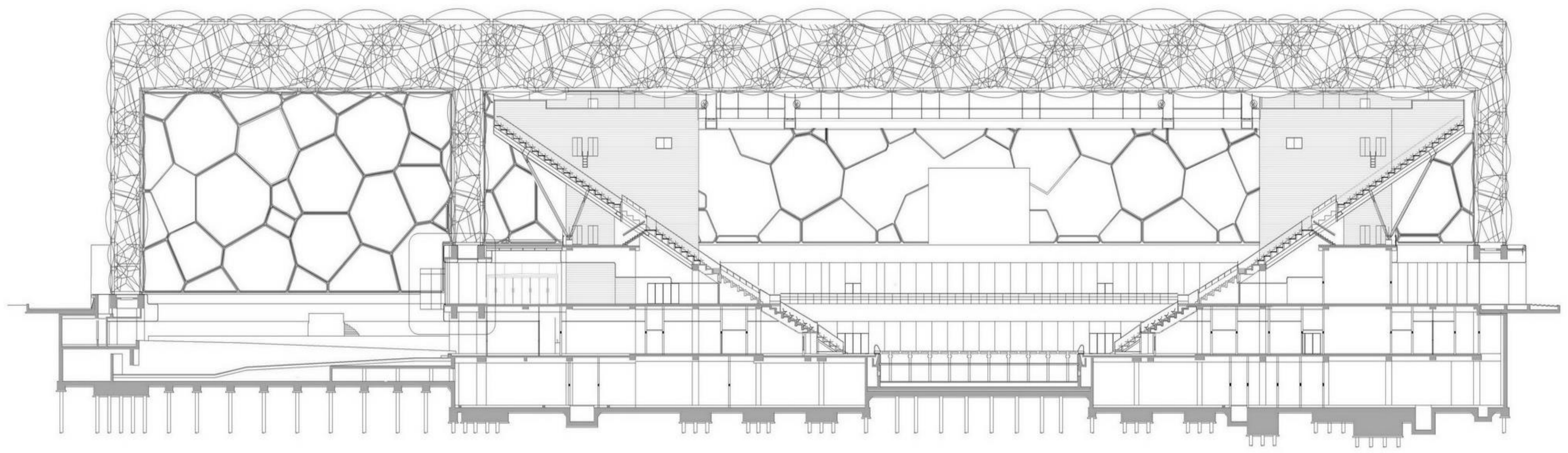


Figure 231) Section

THE APPLICATIONS OF ETFE MEMBRANE GAS PILLOW STRUCTURE IN WATER CUBE"

Engineering overview: The National Aquatics Center is one of three landmark buildings in the 2008 Beijing Olympic Games, so it is also the only one building designated by the Beijing Municipal Government which is donated by the patriotic personages of Hong Kong, Macao and Taiwan. During the Olympic Games, swimming, diving, synchronized swimming and other games was hold in this venue. After the Olympics game, here will become a multifunctional water sports center where will be holding international events, but also can provide water recreation, sports, leisure and fitness services to public. The National Aquatics Center is located in the Olympic Park Area B, the southwest corner of the Olympic central area. The project covers an area of 62828m2 and construction area is 79532m2 (excluding underground garage) (Sun *et al.*, 2008). The building eaves are height of 31 m and the basement area is 177 m×177 m and has standard seats 17,000 and 11,000 temporary seats (will be removed after the game). This project is a premium sports building and the design life of the main structure is 100 years.

Preparation Before Construction :

• **Water cube data:** The ETFE membrane structure of the National Aquatics Center is produced by German FOILTEC and Shenyang Yuanda Aluminum Industry Engineering Co., Ltd. co-production. Winding and bottom chords of the roof are covered by ETFE membrane gas pillow structure including the same four walls (inside and outside) and two interior partition walls (inside and outside). Among them, the roof covering area (gas pillow area) is 58757.48m^2 and the exterior cladding area is 34687.81 m^2 and the interior wall coverage area is 9382.80m^2. Total is 102828.09 m^2. The quantity of the roof gas pillow is 803, 734 of the ceiling, 1436 of wall and 126 of bubbles. Total is 3099 as shown in Table 14.

Figure 232) Exterior View

Coverage area of ETFE (/m^2)	100,000
The total number of ETFE (num)	3099
The type of shape ETFE (num)	24
The single largest area of ETFE (/m^2)	90
The layers of ETFE (num)	3 (wall side), 4 (roof, ceiling)
The color of ETFE	Blue(wall side); transparent(others)
The working pressure of ETFE (/pa)	500
The number of air pump (num,/m)	18, 12000 m

Table 14) Basic data of ETFE in "Water Cube"

• **Analog installation:** In order to learn the pillow installation characteristics of the ETFE membrane structure gas better. The Yuanda Company (ETFE project team members) make fifteen steel structure gas pillow in accordance with the ratio of 1:1 in Shenyang, through which workers can experience the real installation process. These gas pillows can be installed in the position of the steel facade, roofing and ceiling and this installation program can be effective technical training for construction workers such as: transport of materials, sub-structure installation and other aspects. During the process of 500 m^2 template construction, the FOILTEC technicians train the construction workers hand by hand. The Model is shown in Fig. 231.

The major technical difficulties about "Water Cube"

• **Construction technology of the roof gas pillow:** The traditional construction facilities of roofing ETFE in foreign is construction network. The disadvantage of this construction process is that: a long Installation time, which was very convenient, low efficiency of construction. When the construction workers stand on a soft, flexible online, they stand instability and cannot walk easily. So using this construction process, the project cannot guarantee the requirements of the construction schedule. Since this construction method is never used in the country and there is certain insecurity. Therefore, it is difficult to get the recognition of the safety supervision department. In order to further improve the speed and security of the installation of roof gas pillow. Using installed gutter cover all the roof with the safety net, so that everywhere is the size of the enclosed cavity. Three platforms were erected in the roof and set the channel between the platform and gas pillow parts, therefore the channel was set on both sides of each 2.4 m by 1.5 m high railing, last two wire ropes were pulled as a fence between the rails for safe. As installing the roof gas pillow, worker standing 400 mm wide and 240 mm high gutter expand their air pillow and placed it on the safe network. Before installing, workers untied the connecting ropes between the nets and the gutters, until removed the safety net for all.

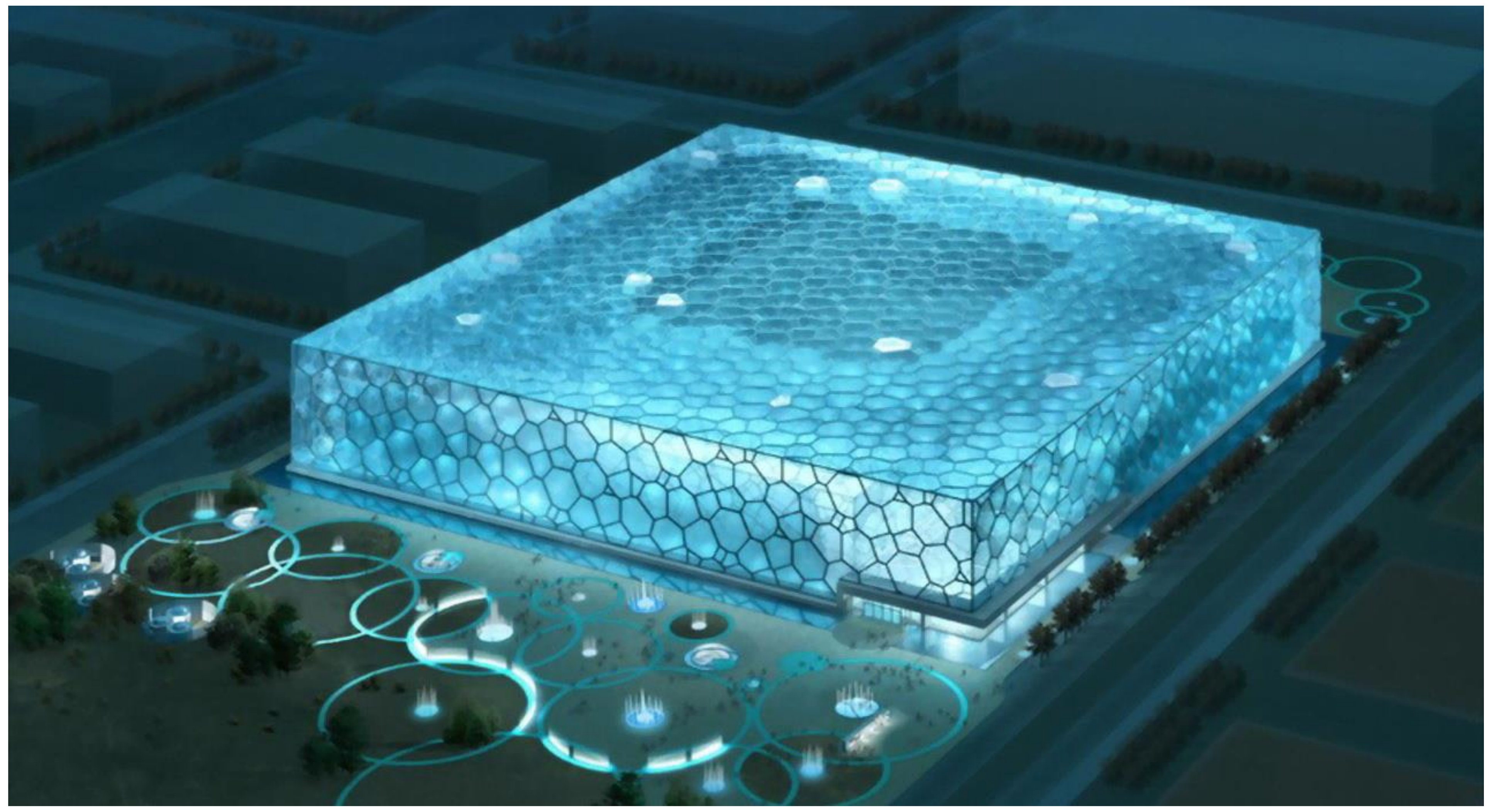


Figure 233) National Aquatics Center Model

Figure 234) ETFE Cushions, real samples

• Inflation system design: The inflation system of this project consists of eighteen permanent air pumps, eight on facade and roof and ceiling are five, weight of 540 kg. The facade air pumps are located in the basement. The roof and ceiling of the air pumps are placed in the upper surface of the core tube. There is no inflatable pillow on the top of core tube, so the position of the air pump has no relationship with premises roof lower chord. Air pump input some pressure air through the main pipeline into inflation system for all parts of inflatable gas pillow. Each inflatable pump is composed of two fans, a drying unit and four air regulators and each of inflatable pumps is to be controlled by their own control means as an independent working device.

• Condensation and prevent: Natatorium normal used in the winter, even if the air conditioning system is under normal operating conditions and the temperature and humidity of the museum respectively be controlled at 28 C°, about 70%, then the dew point temperature correspond to 21.9 C°. According to the original design, the heat transfer coefficient of the natatorium roof double-layer ETFE membrane is 0.8 W/m^2K and then the temperature of the layer below is 23 C°, so it should be able to avoid the occurrence of condensation. But when the museum air conditioning system does not work, one hand, due to the continuing wet bulk of the museum water, the air humidity is further increased and on the other hand because the air-conditioning stop running, the museum temperature drops, resulting in membrane surface temperature drop. So as below a museum air dew point temperature, the condensation will be inevitable. Especially in the cold winter night, the next morning, the museum air relative humidity is highest, however, the temperature is lowest and so the condensation is most likely to occur at this time.

Figure 235) The building’s form is inspired by the natural formation of soap bubbles.

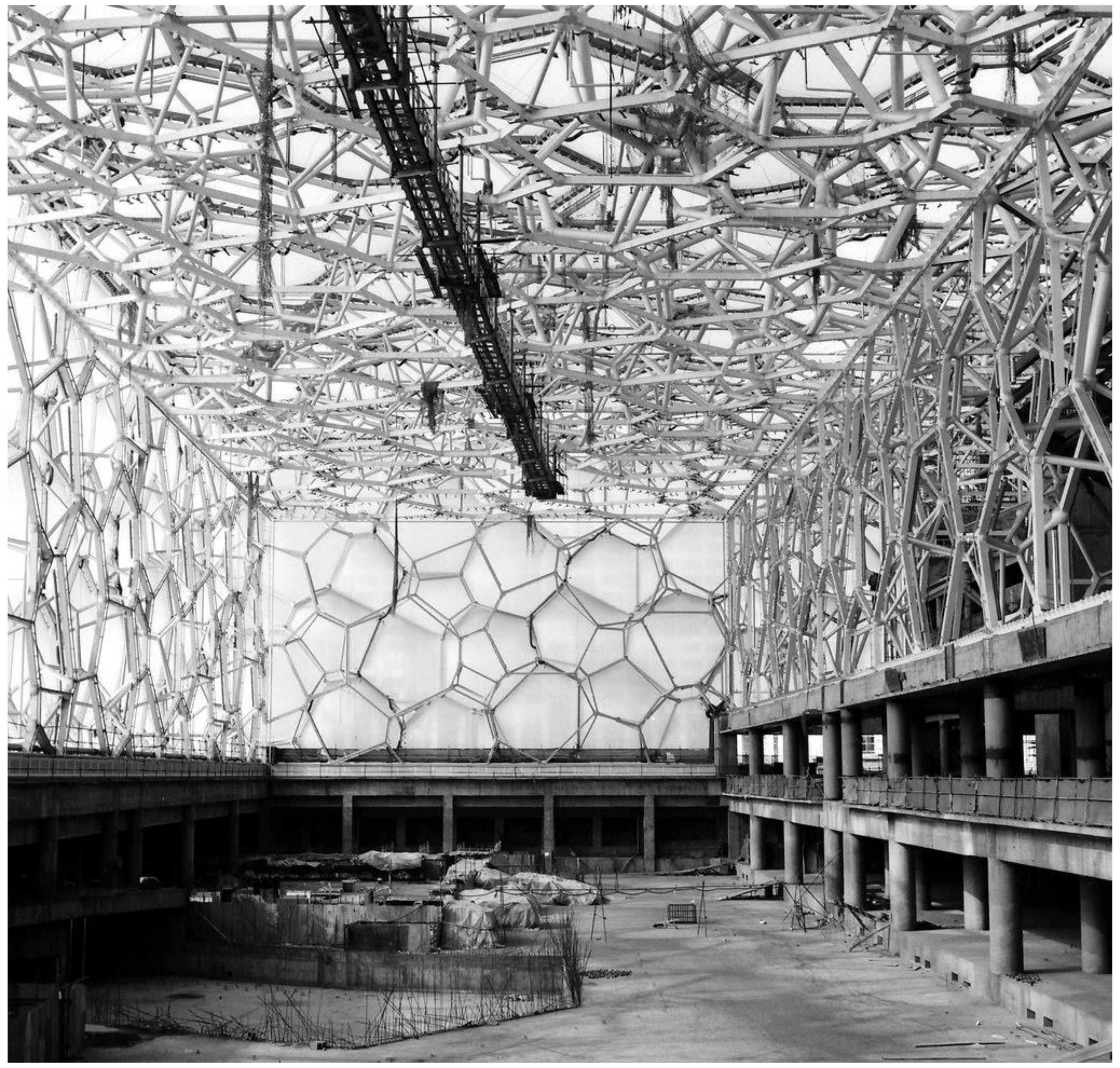


Figure 236) “Water Cube” under construction

12 Major Tensile Architecture Case Studies (Non-ETFE Projects)

1. Laboratories for M&G Ricerche, Venafro

Location:	Vanafro, Italy
Date:	1992
Architect:	Samyn et Associe's
Engineer:	IPL and Setesco
Membrane:	PVC-Coated Ployester

The chemical research 'tacky for M&G Ricerche, designed by the Belgian architect and engineer Philippe Samyn, was completed in Vanafro, Italy in 1992. The building incorporates a single-skin membrane envelope to house a combination of offices, laboratories, plant and test rigs, where research for the Sinco group is carried out. Conventional concrete and blockwork construction is used to form separate enclosures within the membrane envelope. Within these structures are housed facilities with subdivided spaces, which require various degrees of environmental control. The decision to cover all the facilities with a membrane structure allowed the construction period to be reduced to 10 months, and has resulted in the creation of a temperate environment at low cost.

Roof Structure: In order to enclose the maximum usable volume, the white PVC coated polyester membrane is supported by six steel horseshoe arches. These three-dimensional tubular steel trusses are maintained transversely by pre-stressed steel cables, which are attached to inverted steel pyramids on the underside of the horseshoes, giving clearance from the curvature of the membrane. The arches increase in size from the two ends, giving a maximum height of 16 m in the center. This extremely lightweight steel structure is composed of 1764 steel tubes cut into 441 different configurations, and was realized with the aid of fully automated shop drawing procedures and construction methods.

Figure 237) Exterior View

By keeping the interior construction completely separate from the external skin, the problems of connecting the curved forms to the rectilinear construction are avoided. However, to provide direct daylight and to afford views out, glazed screens have been incorporated behind the scalloped edges of the membrane at ground level. These are connected to the edges of the main membrane by transparent PVC closing flaps. The steel arches are themselves covered with a transparent PVC membrane which is pre-stressed in triangular panels by means of metallic disks and tension cables. The use of transparent membrane in this manner allows direct sunlight to penetrate to the center of the plan and aids the legibility of the steel supporting structure.

Building Site

The building is situated like an island in the middle of a rectangular pool and follows the outline of the foundations of a convent which once occupied this site; of the original buildings on the site a chapel and a dry-stone masonry aqueduct still exist. The artificial lake serves as a fire well and cools and animates the environment through natural evaporation and reflections.

Membrane

The membrane material of the roof is a PVC-coated polyester fabric with a tensile strength of 150 kN/m in warp and weft (fill) direction, which is equivalent to a type-4 membrane in the German classification. The membrane is prestressed between the arches and the edge cables connecting the arch feet. The edge cables are run in membrane sleeves reinforced by webbing. At the arch supports they are connected with an adjustable connection made from a perforated flat steel plate. Along the arches the membrane is connected adjustably through a garland cable with top and bottom cornerplates and threaded U-bolts. For waterproofing a membrane apron is connected to the roof membrane on the outside by a zipper along the edge cable and is clamped to the steel arch alone the bottom chord tube. The arches are covered by a transparent, prestressed plastic sheet, thus weather-protecting them economically and simultaneously keeping the arches visible and transparent. The PVC-sheet is stabilized in the triangular bays formed by the arch diagonals ,by a system of steel disks and prestressed ties.

Façade

Behind the edge cables, there are planar, glazed and arched facade elements. The connection between the roof membrane and the half-arches of the facade consists of a flexible PVC membrane apron, fixed between the upper edge of the facade and the edge cable, which can be tensioned by a horizontal lacing. In the end bays of the membrane the space is closed by a transparent membrane tensioned between roof membrane and floor slab.

Services

Lighting The truss arches are covered with a clear transparent PVC-membrane, providing additional natural lighting from above and keeping the arch structure visible at the same time. Cover strips and aprons are also made from transparent PVC-sheet. Due to the translucent membrane work is possible by day without artificial lighting. At night the building is lit by indirect halogen lighting against the roof membrane radiating from the balustrades of the lab buildings.

Ventilation

For functional and safety reasons, the large air volume under the membrane roof must be airtight. By means of a simple ventilation system (on one longitudinal side the :up.* air comes in and on the other side the exhaust air is extracted), through shading by the roof membrane and due to the lake, an air-conditioning was not required despite the high outside temperature. The inside temperatures correspond to ones under a free standing, naturally ventilated tent, i.e. the outside air temperature in the shade. Offices and lab spaces have independent air-conditioning

Functions

This space lit by the translucence of the roof membrane and through the glazed edge openings houses research areas. The spaces at the gable ends between the side membrane and research spaces serve as common rooms and reception areas for visitors. The floor space totals 2700 m².

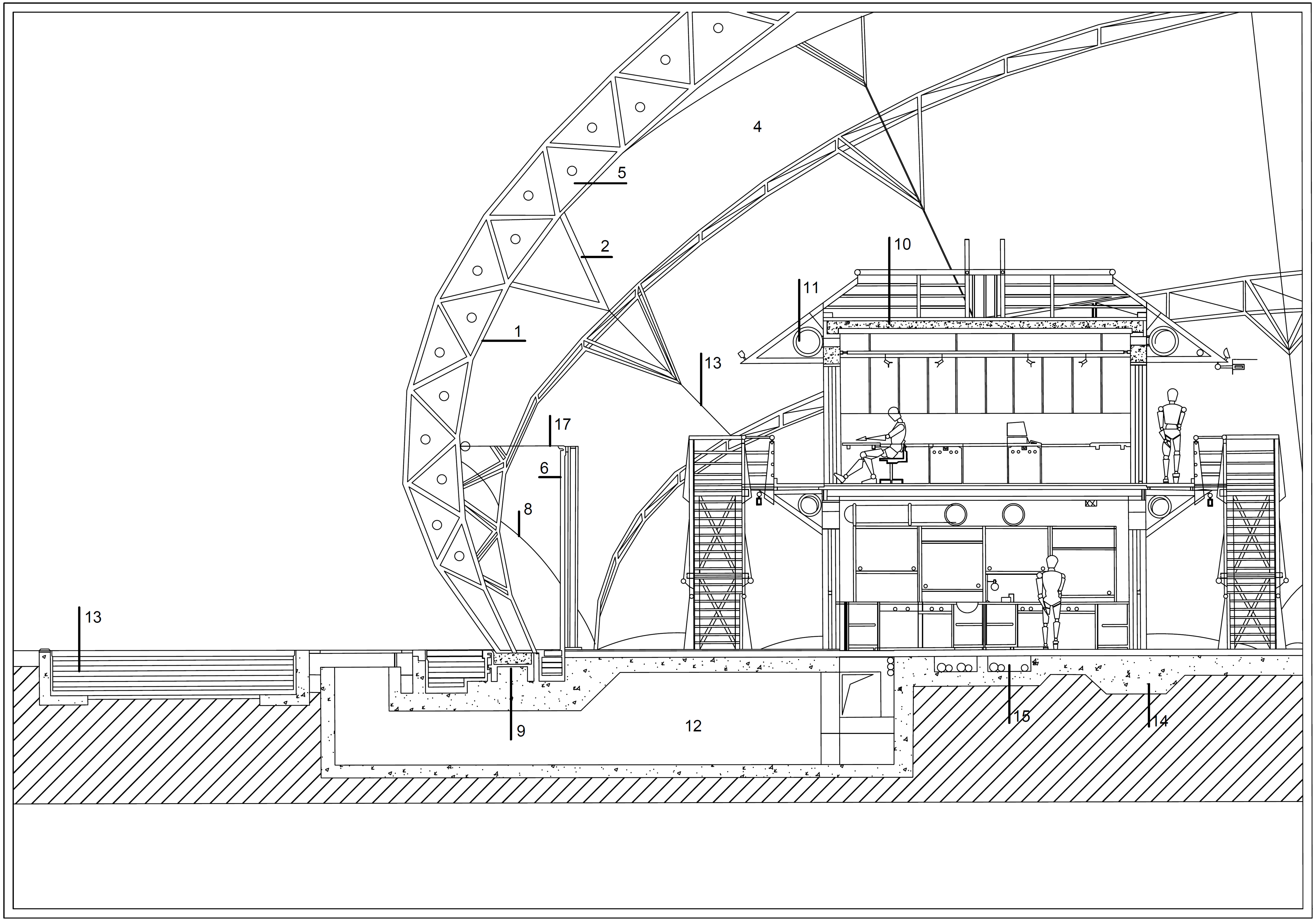


Figure 238) Detailed section through laboratories and underground ventilation duct
1 truss arch, steel tube, 2 pyramid-shaped steel tube outrigger for stabilizing cable, 3 stabilizing cable, 4 roof membrane, 5 transparent PVC sheet covering stabilized with steel disks and ties, 6 free-standing façade element, 7 horizontal façade apron, 8 membrane edge with edge cable, 9 reinforced concrete arch support and foundation, 10 lab buildings, 11 installation ducts, 12 ventilation duct, 13 pool basin, 14 reinforced concrete slab with strip foundation, 15 floor ducts

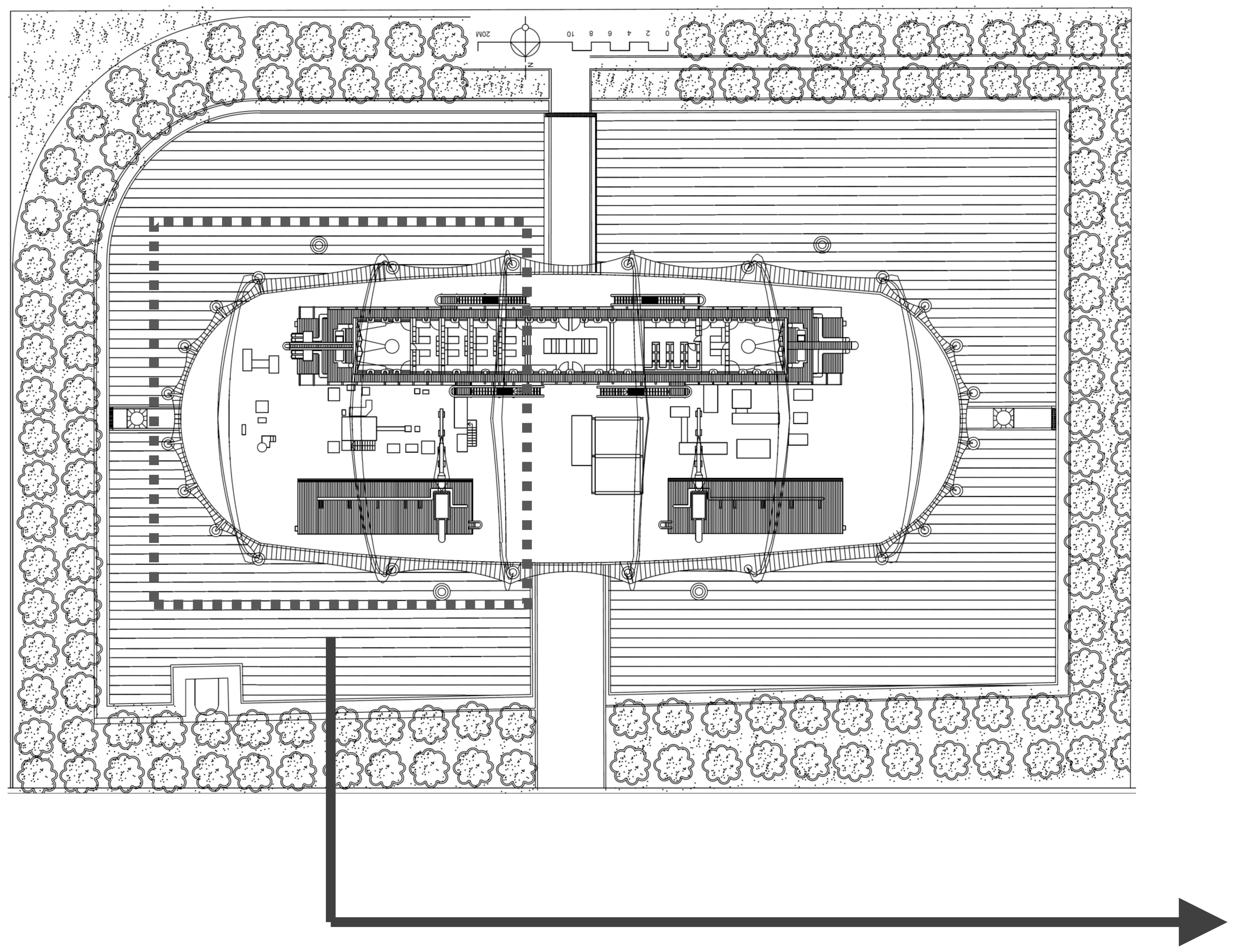


Figure 239) Plan View

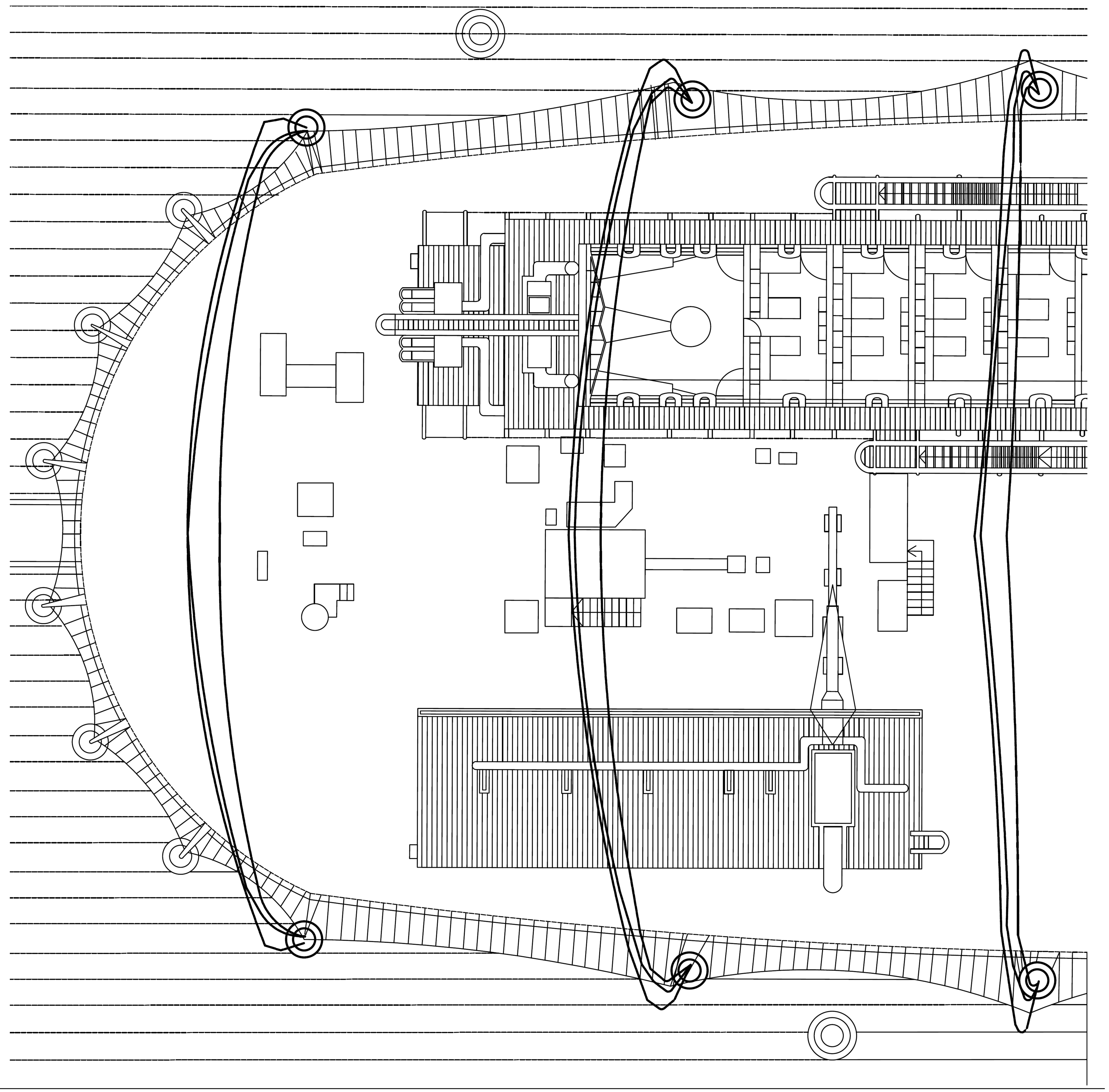


Figure 240) Zoomed View

Arches

Six arches carry the roof membrane; they are three-chord lattice arches in the a basket (three-center) arch. Their triangular cross section varies over the arch length, with a maximum size at the apex, and tapers toward the arch support. They consist of 1764 single tubes in 441 different lengths and configurations. The arches are joined by six prestressed cables under the membrane. These stabilizing cables are connected to the arches through pyramid-shaped outriggers to stay clear of the membrane curvature.

Environmental Aspects

The project at Vanafro demonstrates how a membrane envelope may be used to create a more temperate environment, within which a diverse range of activities can be accommodated. By surrounding the building with a lake, the designers have further reduced the environmental demands. In the hot Italian summer the lake helps to lower the direct outside air temperature. To further cool the internal spaces, air is drawn into the building via underground shafts and through air intake vents that are flush with the surface of the pool, causing the air entering the building to be cooled without the need for air-conditioning. Furthermore, by setting the building in a lake the architects avoided some of the potential security problems caused by bringing the membrane down to ground level. And the chance of the membrane being touched or damaged by passers-by has been reduced.

Figure 242) View from internal balcony

Figure 241) Interior View

Figure 243) Glazed Scallops allow views out

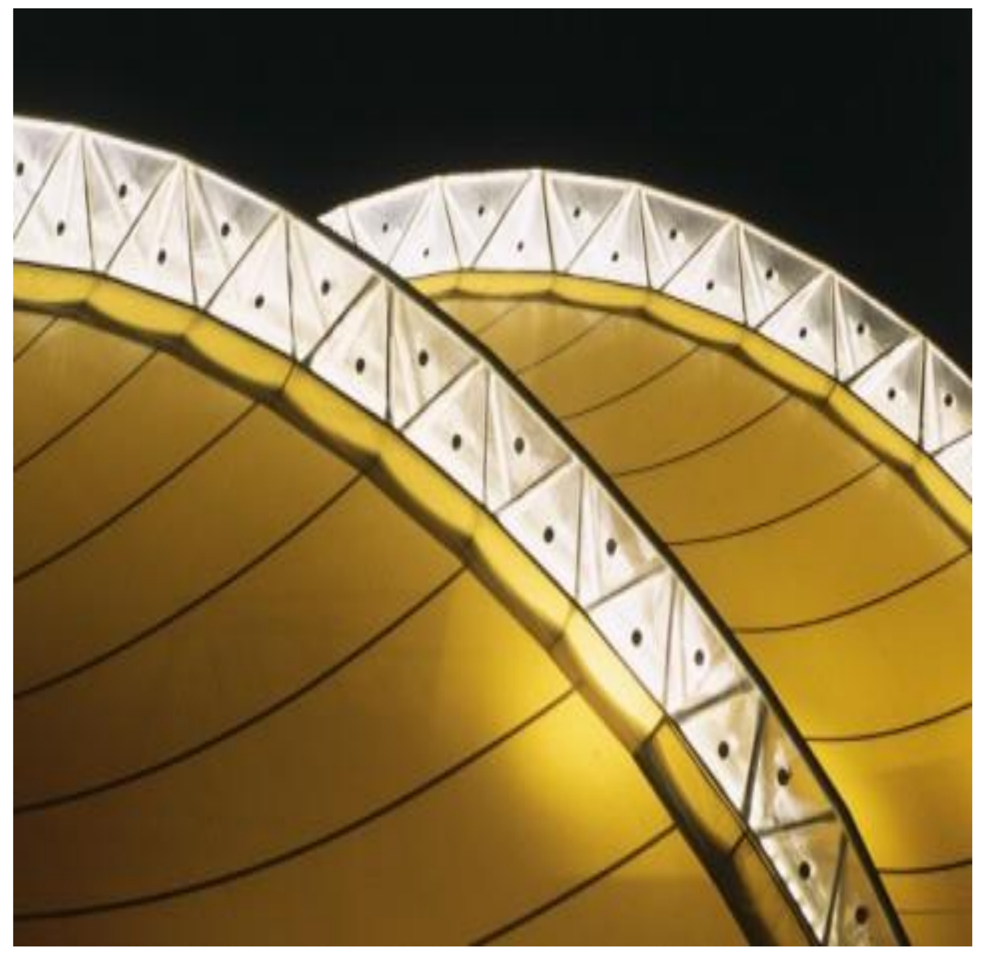


Figure 96) Roof View

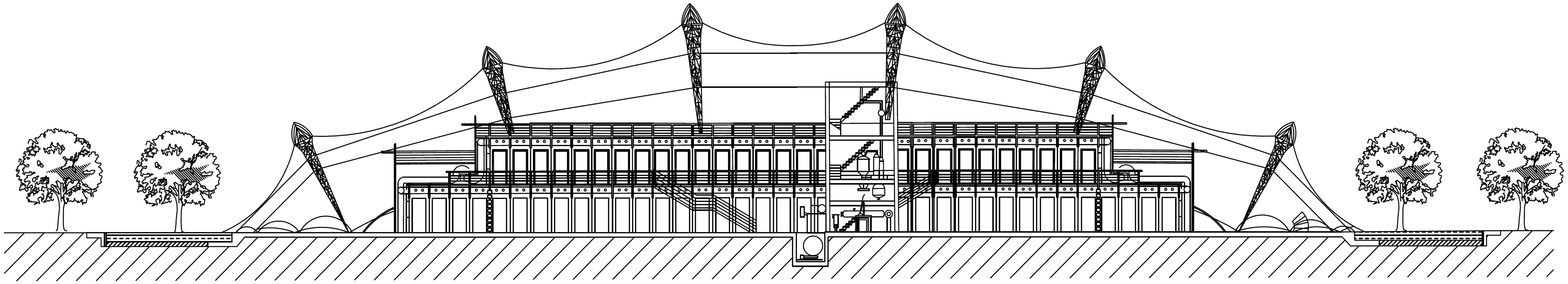


Figure 244) Longitudinal Section

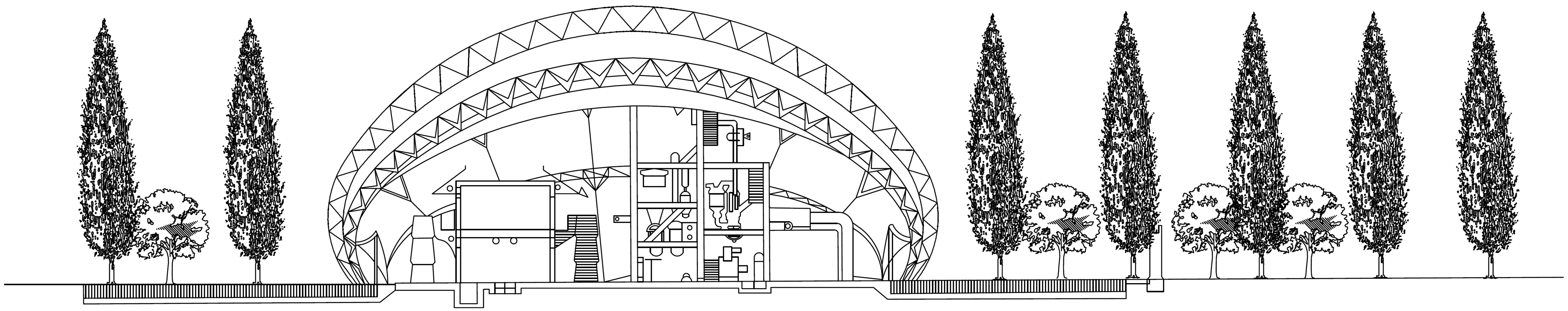


Figure 245) Cross Section

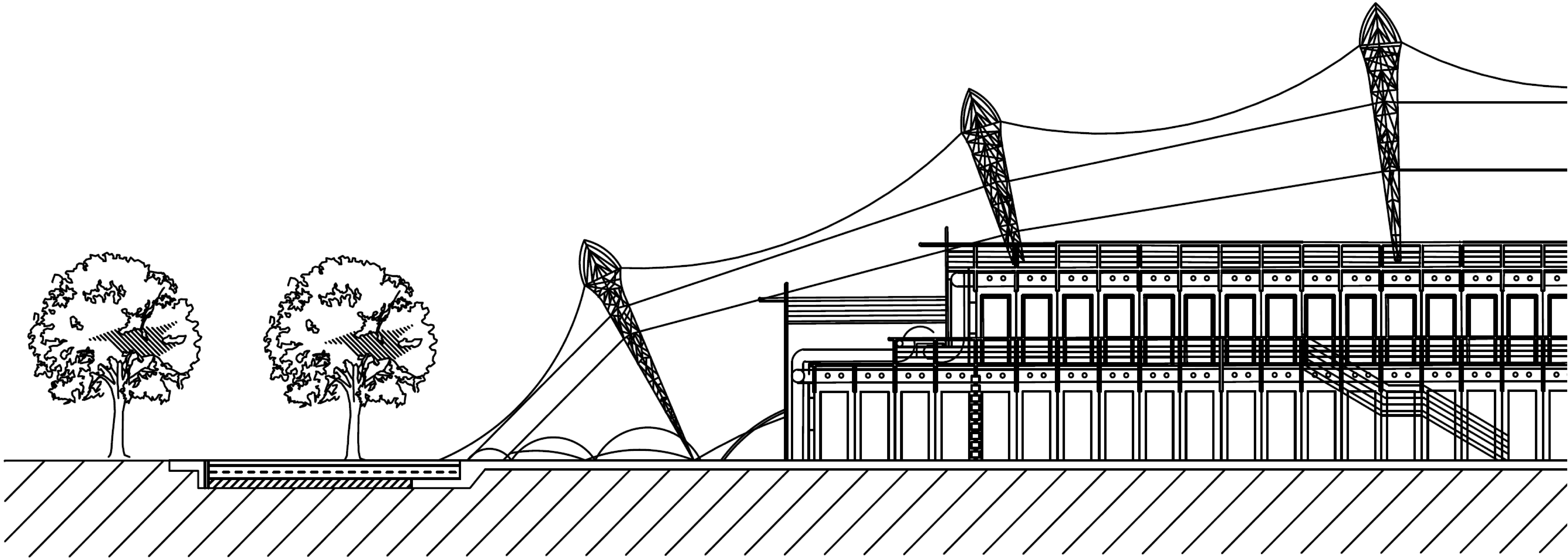
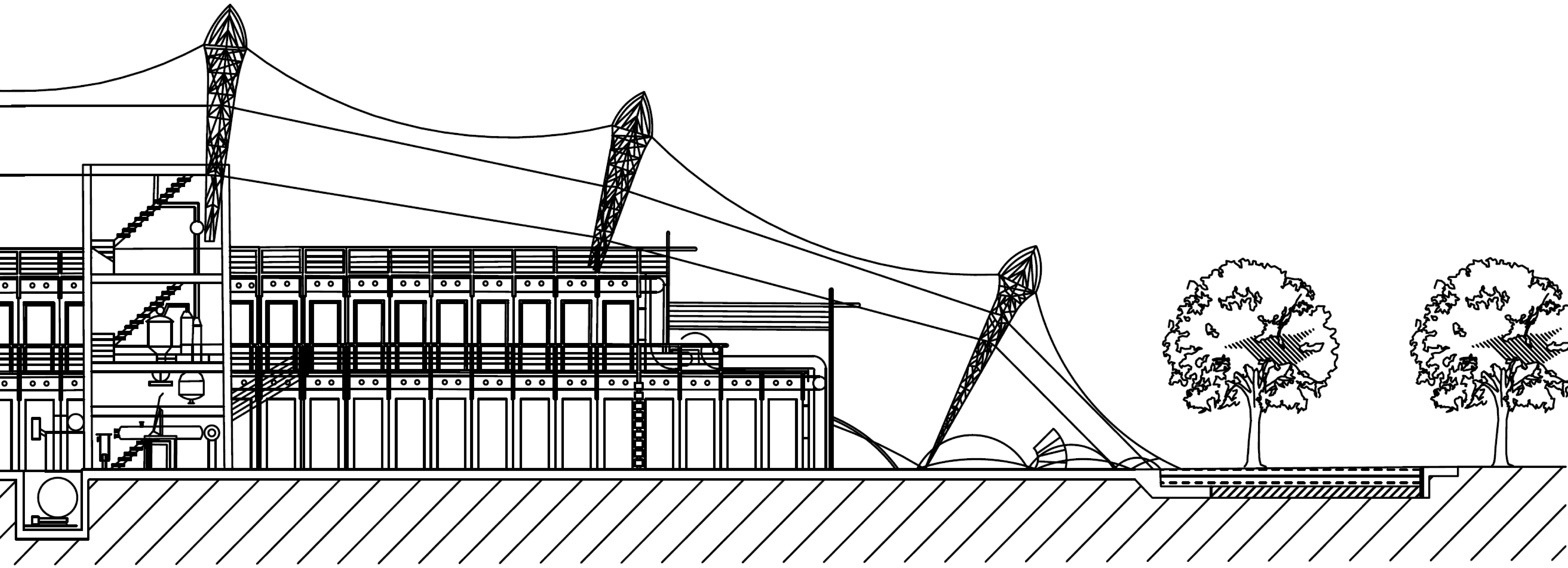


Figure 246) Longitudinal Section



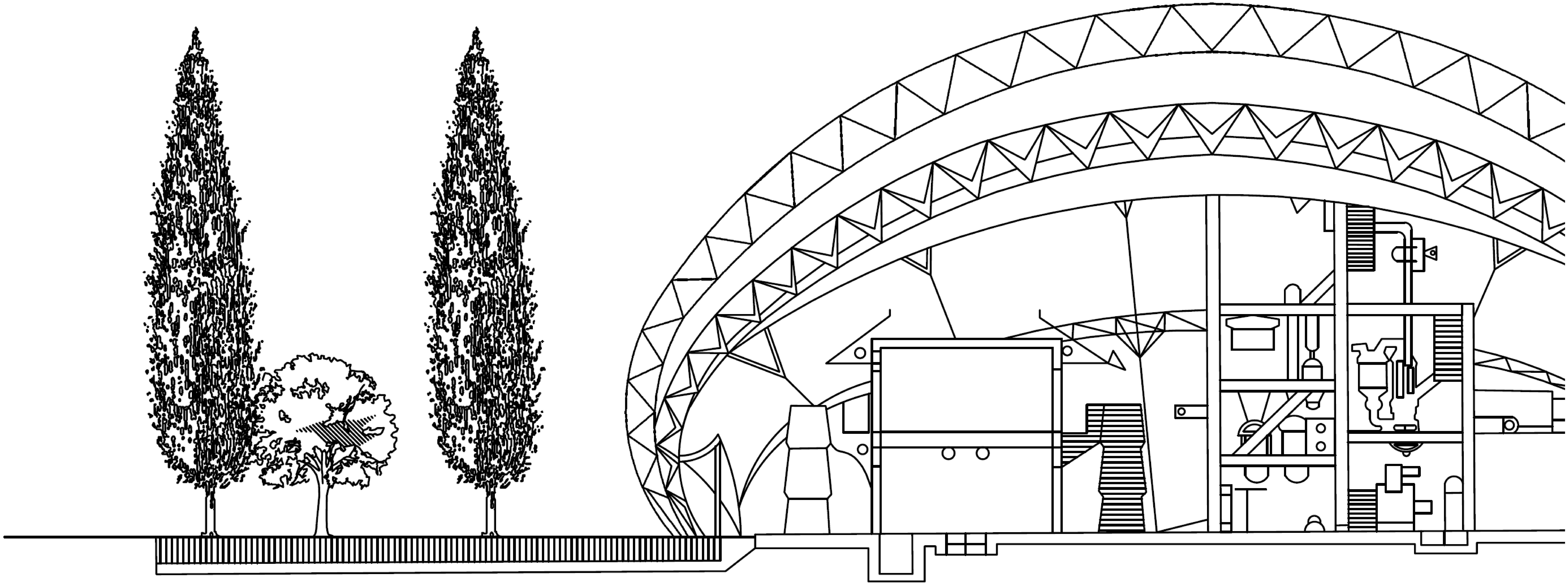


Figure 247) Cross Section

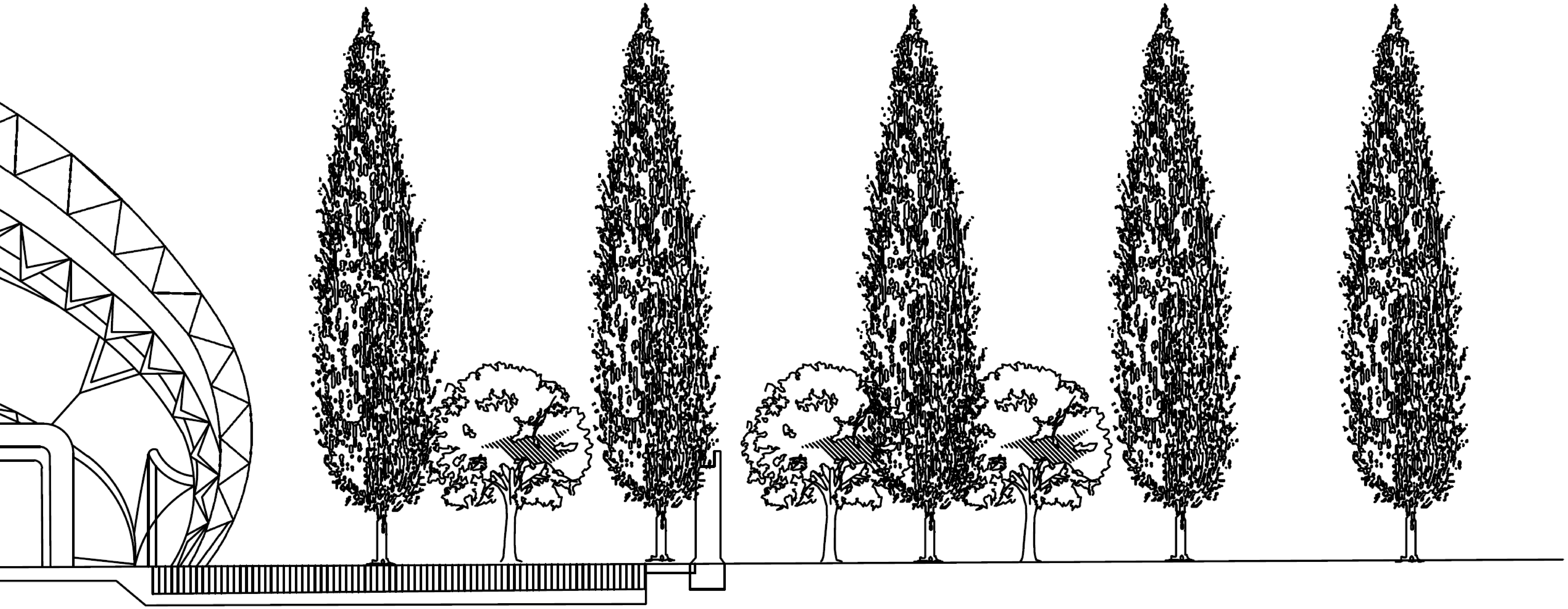


Figure 248) Model

Substructure, Foundations

The continuous reinforced concrete ground slab wits foundation pads and strips under the walls of the lab buildings and under the arches were designed for a live load of 20 kN/m2.The arch feet are supported on the water level plain on reinforced concrete foundations, which are separated structurally and visually from the ground slab.

Figure 249) Exterior at night

2. Auditorium Roof CAMP DE MART

Location: Tarragona, Spain
Date: 1993
Architect: Josep Olle, Angel Martinez
Engineer: Studio Tensoforma
Membrane: PVC-Coated Polyester

This roof over an open-air theatre with 3000 seats situated at the edge of the old city center of Tarragona has some special features, which distinguish it from others of its kind. It lies underneath the city walls and below a monumental tower in a natural bowl forming the amphitheater at the foot of a steep embankment. Tower and city wall serve as backdrop for the open-air theatre, whose membrane roof with its fascinating form has become the landmark of this part of town.

The allusion of a manta ray from the sea, of which the roof form is reminiscent, emphasizes the connection of the city with the Mediterranean. The view of the passing access road, the Avenida de Maria Cristina, and onto the tower and the ancient city wall remain unchanged.

The axis of symmetry of the amphitheater and of the structural axis coincide and lead onto the monumental tower. The masts of the structure rise up high and lean toward the tower. In a common frame of reference the tip of the V-shaped main mast becomes the visor point, redirecting the view onto the tower. The structure appears to be tied in with measure and proportion between membrane roof and tower. Seen from inside the natural backdrop is emphasized by the steel tubes acting as a picture frame. At the same time the translucent roof creates a light-filled space without strong shadows, giving a feeling of openness, of being in the open.

Figure 250) Exterior view with V-shaped edge support

Figure 251) Exterior with amphitheater view

The auditorium with its semi-circular plan has the form of an amphitheater with steeply rising seats. The entrance is from above, through a circular access path on the level of the access road in front of the theatre. The stage is hexagonal; on its left and right stage houses are erected in conventional reinforced concrete construction.

Structure The main structure, nearly semi-circular in plan, consists of a roof membrane, strengthened at the edges by steel cables. It is supported by four V-shaped mast trestles around the edge, and by one A-shaped main mast on the axis of symmetry behind the stage. It is anchored at five guy cables between the lower V-masts, fastened to ground anchors as well as by one large guy cable on the axis of symmetry holding the main mast. Despite the flat membrane shape there is just sufficient surface curvature available at each point. To allow large displacement under snow load a system of snow cables was introduced in the middle of the roof.

Membrane:

Membrane I The roof shape can best be described as a modified symmetrical high point membrane. Along the edge there are five high points with different heights, the highest one lies on the axis of symmetry. At five intermediate low points the membrane is tied down. To avoid large heights and long membrane tips the high points were 'modified', i.e. dissolved into two points with a short edge cable lying between them. The high points are either anchored in V-shaped twin columns or connected by two tension ties to the tip of the A-shaped mast with an inter-mediate guy between them proceeding down to the ground.

The membrane consists of a high-strength PVC-coated polyester fabric. The material is classified as 'difficult to ignite' (class 2 to Italian). It is coated with Fluotop®, a strong PVDF-polymer coating thus extending its service life. The coating forms anti-adhesive protection film against smog and other air pollutants and so visually prolongs the life span of the membrane.

Figure 252) Exterior

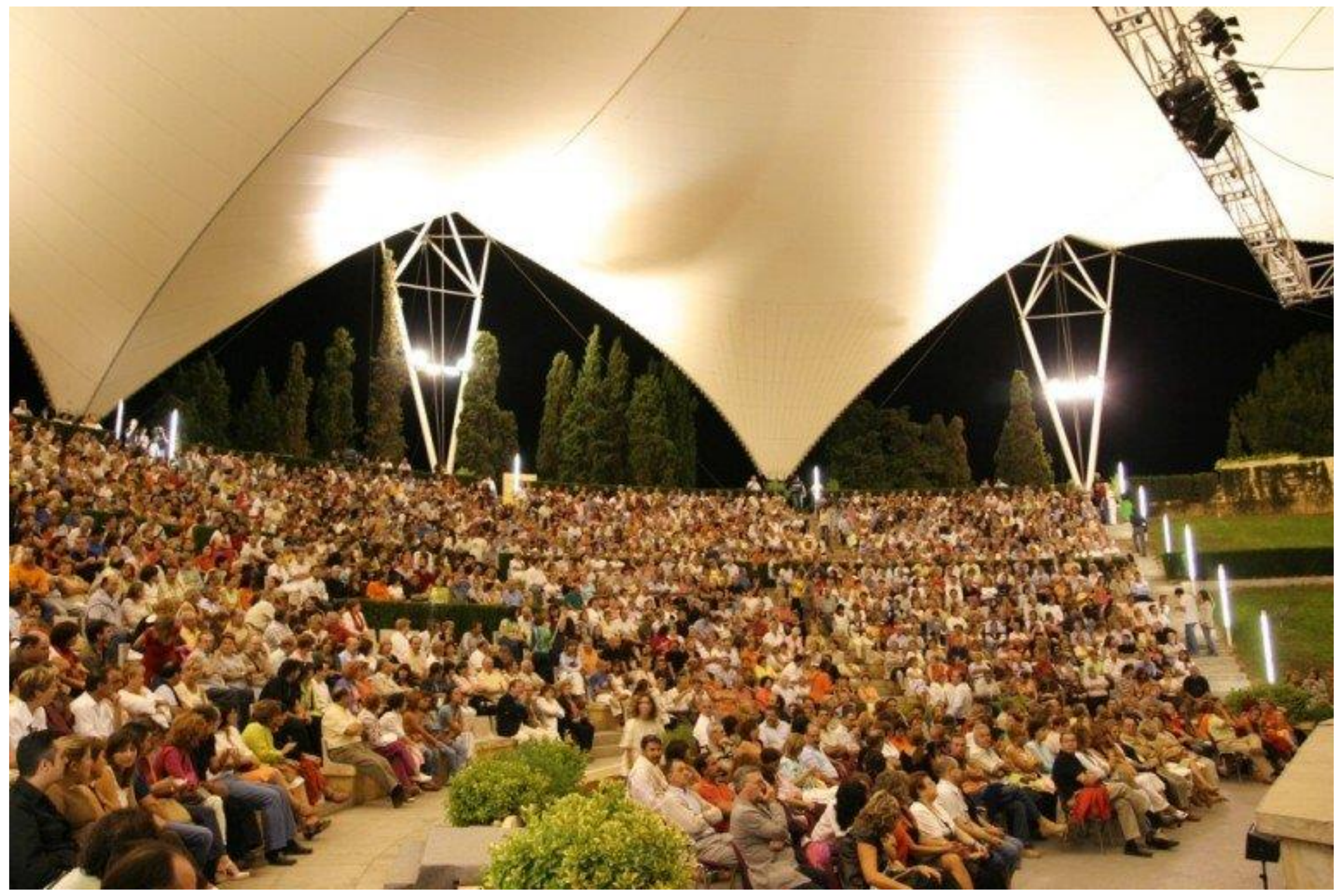


Figure 253) interior view

For the membrane and their textile additions, edge cable pockets, membrane aprons etc. A reduction and safety factor was required between four and five to guarantee a very long service life. (The safety factor applied for coated fabrics on the short-term strength determined in load tests is made up of a real safety factor, allowing for a variation of the manufacturing quality and the applied loads as for conventional building materials, steel, concrete, and one reduction factor, which allows for the decrease of the fabric strength due to long-term loading, ageing and effects from handling, transport and erection. By selecting a higher reduction factor a longer design life of the membrane may be achieved.)

Along the edge the web membrane is held and reinforced by clamping strips. Due to the large membrane forces — the membrane strength corresponds approximately to a type V — and because of the corresponding size of the edge cables (max.0 42 mm) and the associated fit-tings the edge was executed as a clamped edge with a steel boltrope. The clamping section is intermittently fastened to the edge cable by sheet metal straps in short spacing. The boltrope has a threaded fitting at its end and is anchored in a tube sleeve welded to a transverse steel plate onto which the membrane is also connected at the corner by means of sheet metal straps.

Functions

Due to the flat curve and the high loads the supports and guys of the tensile structure suffer relatively high tension or compression forces. A geological survey showed very unhomogeneous soil conditions, so that the foundation design was adjusted according to the particular situation. For tension piles and compression foundations the same pile type was used, namely steel micropiles (injection piles of the type Ropress/Tubfix). According to ground type and load, up to 16-m long injection piles were used, for the compression piles to reach a load-bearing stratum, free of mud inclusions or for the tension piles to activate a sufficiently large earth volume to be used as ballast weight.

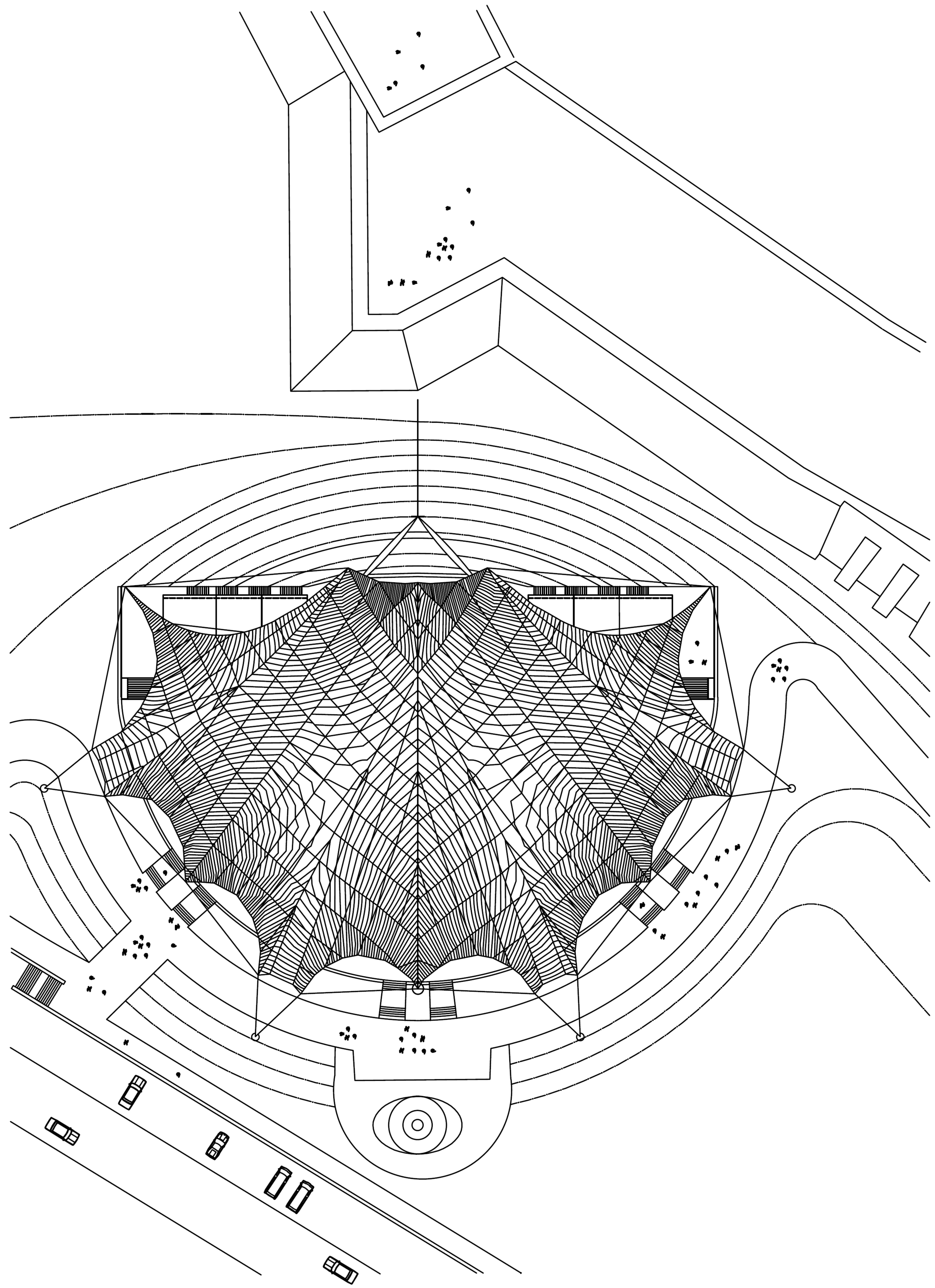


Figure 254) Plan view with contour lines

Assembly

The steel structure was assembled and erected within 16 days, for installation and prestressing of tie membrane a further 25 days were required. The installation proved extremely difficult due to the problematic terrain conditions at the rear edge of the amphitheater, where a mobile crane could only be used with difficulty. Only a mobile crane with a capacity of 15 t could be used, the A-shaped main mast however weighs 20 t and is positioned in an inaccessible location underneath the wall. it had to be divided into parts, assembled on the construction site and pulled up the sloping terrain and into its final position with tirfors. Scaffolding had to be erected on the slope and a chute, on which the mast was dragged with tirfors horizontally to its foundations, without loading the crane with the full mast weight.

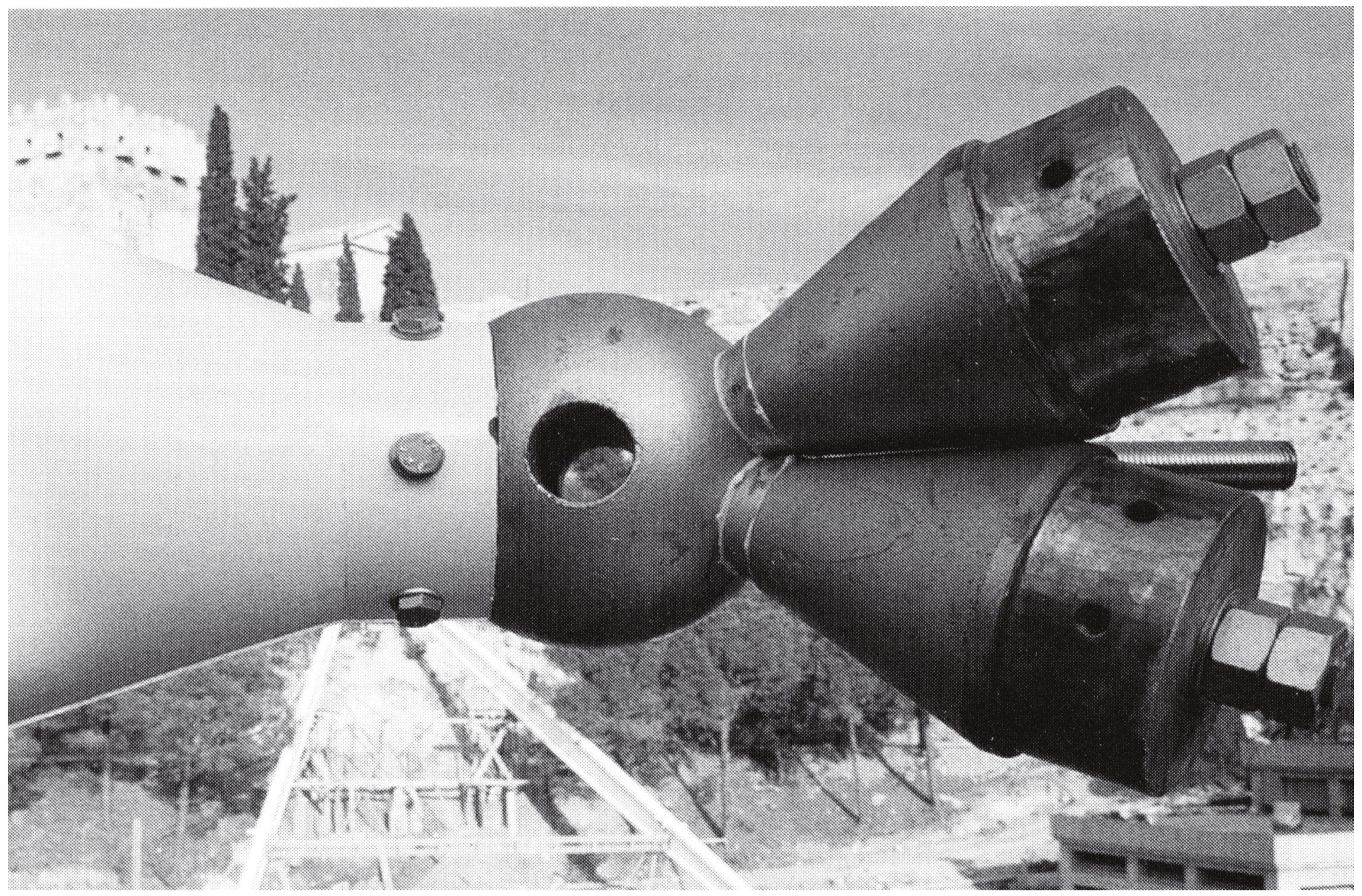


Figure 255) Edge mast during assembly: Steel tube compression member, spherical node and turned cones to attach the compression struts of the space frame. In the main mast using a scaffold substructure on the slope can be seen

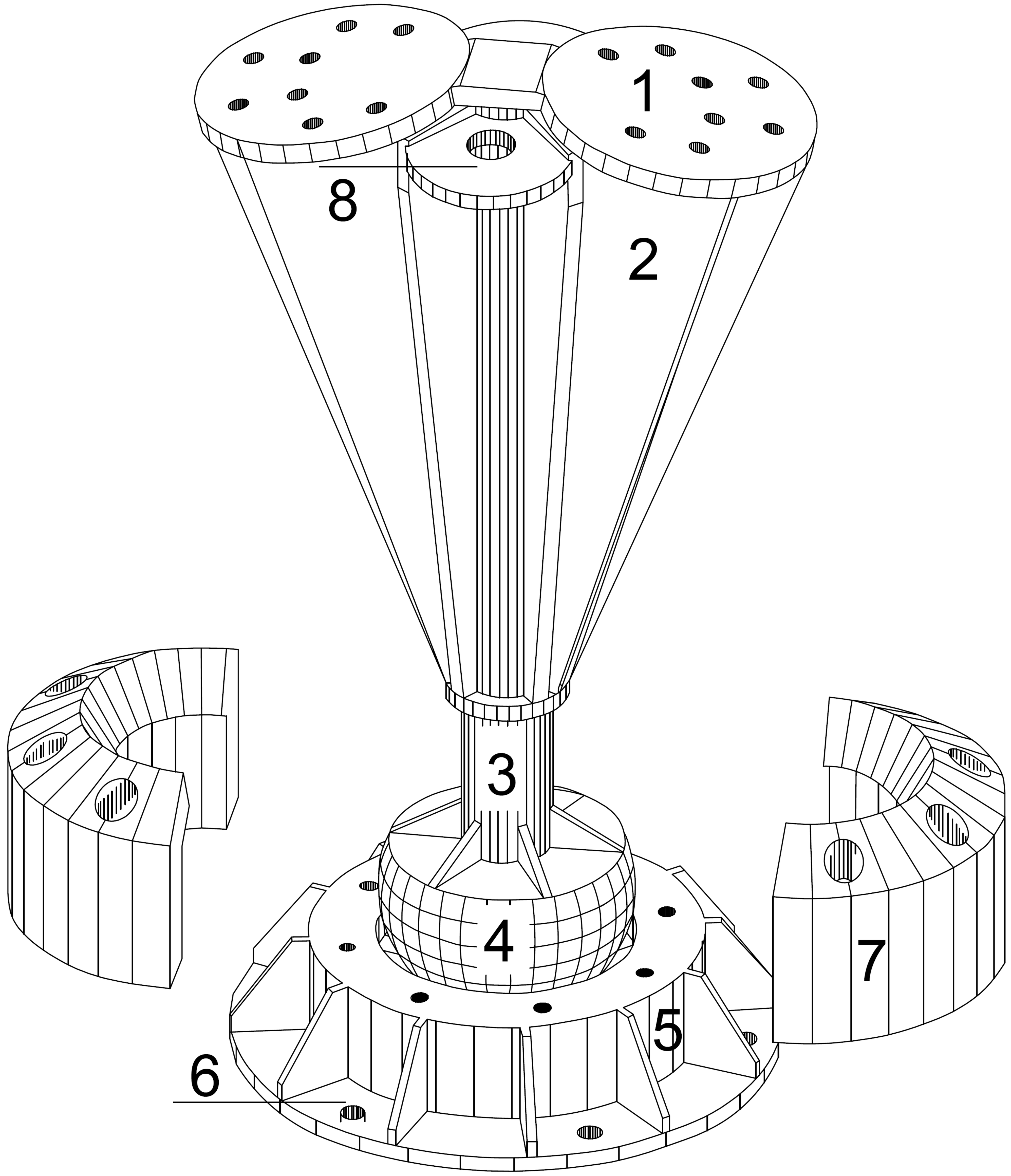


Figure 256) Isometric: Mast base detail at V-edge mast:
1 tube flange connection of the mast tubes, 2 welded transition piece, 3 round steel, 4 steel spherical bearing, 5 bearing bottom, 6 bore for anchor bolts, 7 covering, 8 cable anchorage

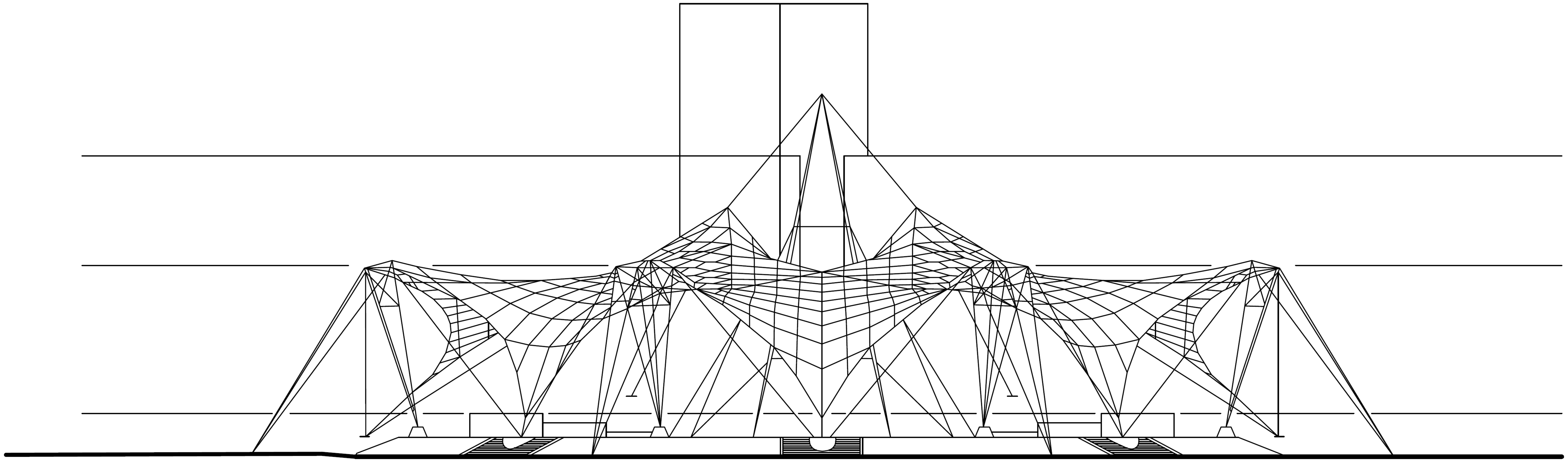


Figure 257) Longitudinal Section

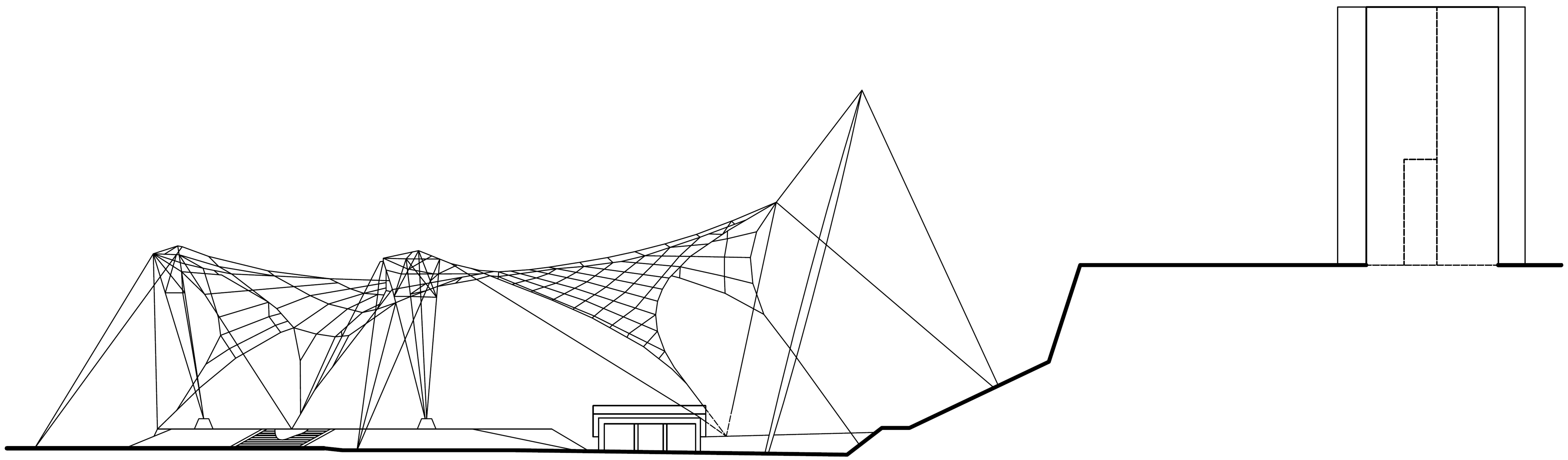


Figure 258) Cross Section

3. Recreational Clinic

Location: Masserberg, Germany
Date: 1994
Architect: Laurens Schneider Zimmerhackl
Engineer: Ingenieuplanung Leichtbau
Ingenieuurburo Stendtke
Membrane: PVC-Coated Polyester-Double Layer

Shortly after German reunification the architect was asked to develop a concept for a recreational center in Masserberg in Thuringia with a recreational clinic and a medical treatment area. The basic idea of the design is the conservation of two typical GDR 'bed houses' (sleeping accommodation) and their connection by a new building which was to be two floors higher. On the east side, in front of the bed houses and the new building lies the leisure complex covered by a membrane roof. The wedge-shaped "pieces of glass" of the new, fully glazed building push into the membrane roof and join the adjacent buildings. The leisure complex with a plan area of approx. 3200 m² extends over the entire length of the new reception building and contains leisure functions and therapy and catering areas. The theatre and the physiotherapy building are partly covered by the membrane roof; their flat roofs serve as terraces. According to the architectural concept this area should differ in style and character from the purely functional bed houses and the fully glazed entrance building and become a symbolic expression of what recreation and leisure mean. So the idea was born to cover this area with a large membrane structure, with a vertical glass façade as a space- enclosing element

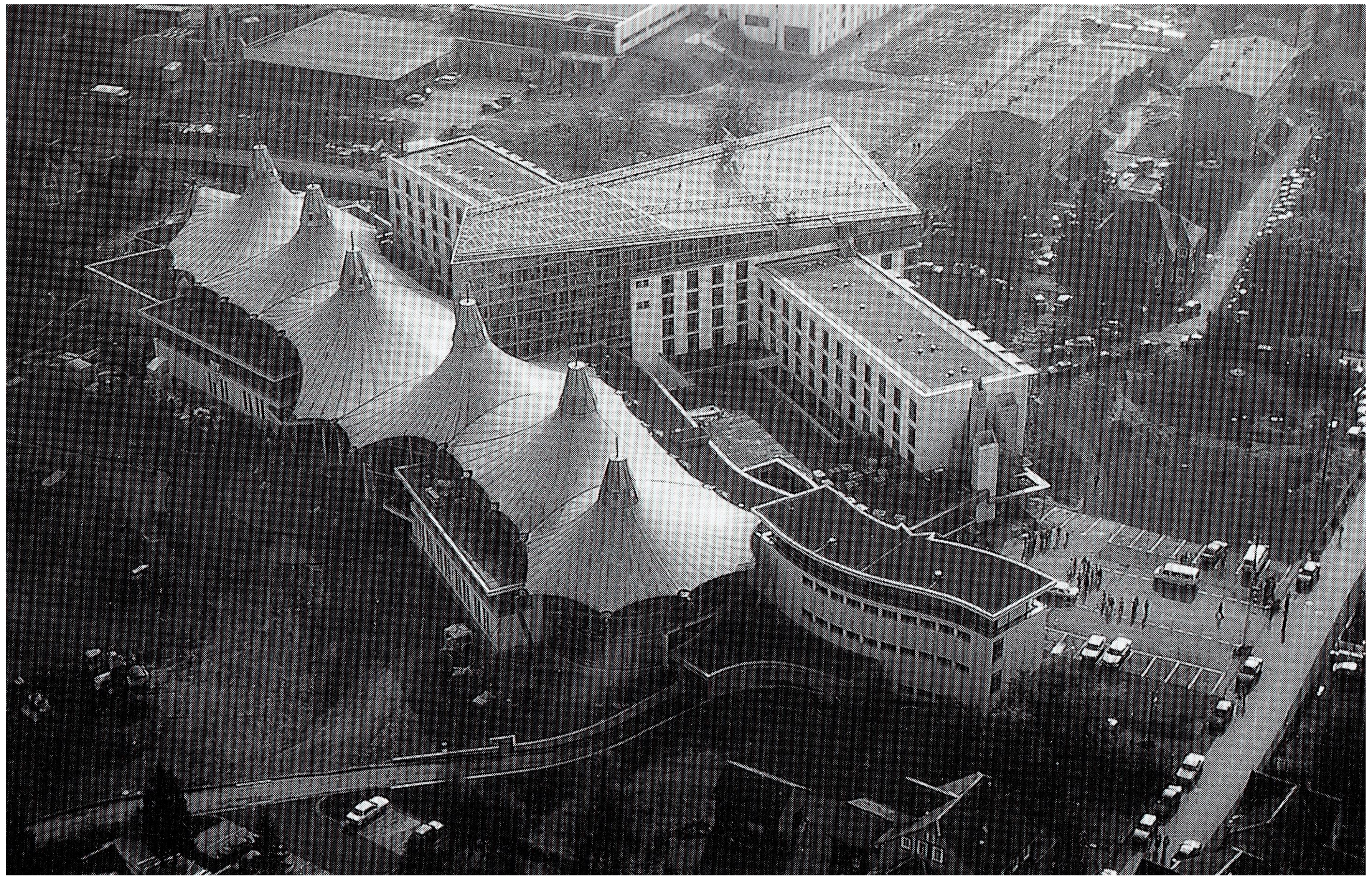


Figure 259) Exterior View

Structure

Masserberg is located at approx. 800 m above sea level in an exposed position wits high wind speeds and snow loads. The design snow load of 2.65 kN/m2 is rather severe, thus six internal masts were needed instead of the originally planned four. The membrane is a self-supporting tensile structure, a high point membrane with inside masts, edge cables and guyed edge masts. In tie bays between the high points it is tied down by groove cables. The inside masts are joined through security cables with the edge guys to secure the masts in case of catastrophic failure of the roof membrane.

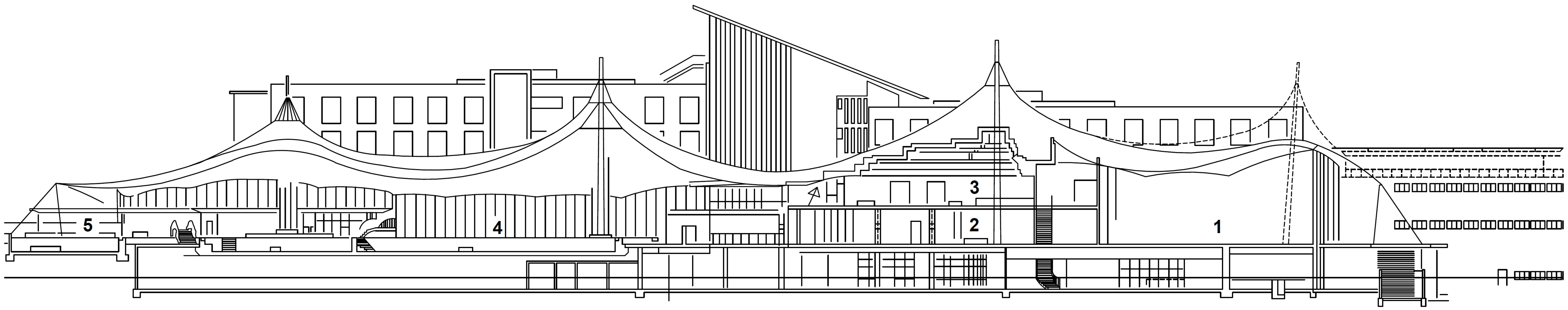


Figure 260) Longitudinal Section: (alternative design with four masts): 1 physiotherapy, gymnastics, 2 restaurant, 4 leisure pool, 5 outdoor pools

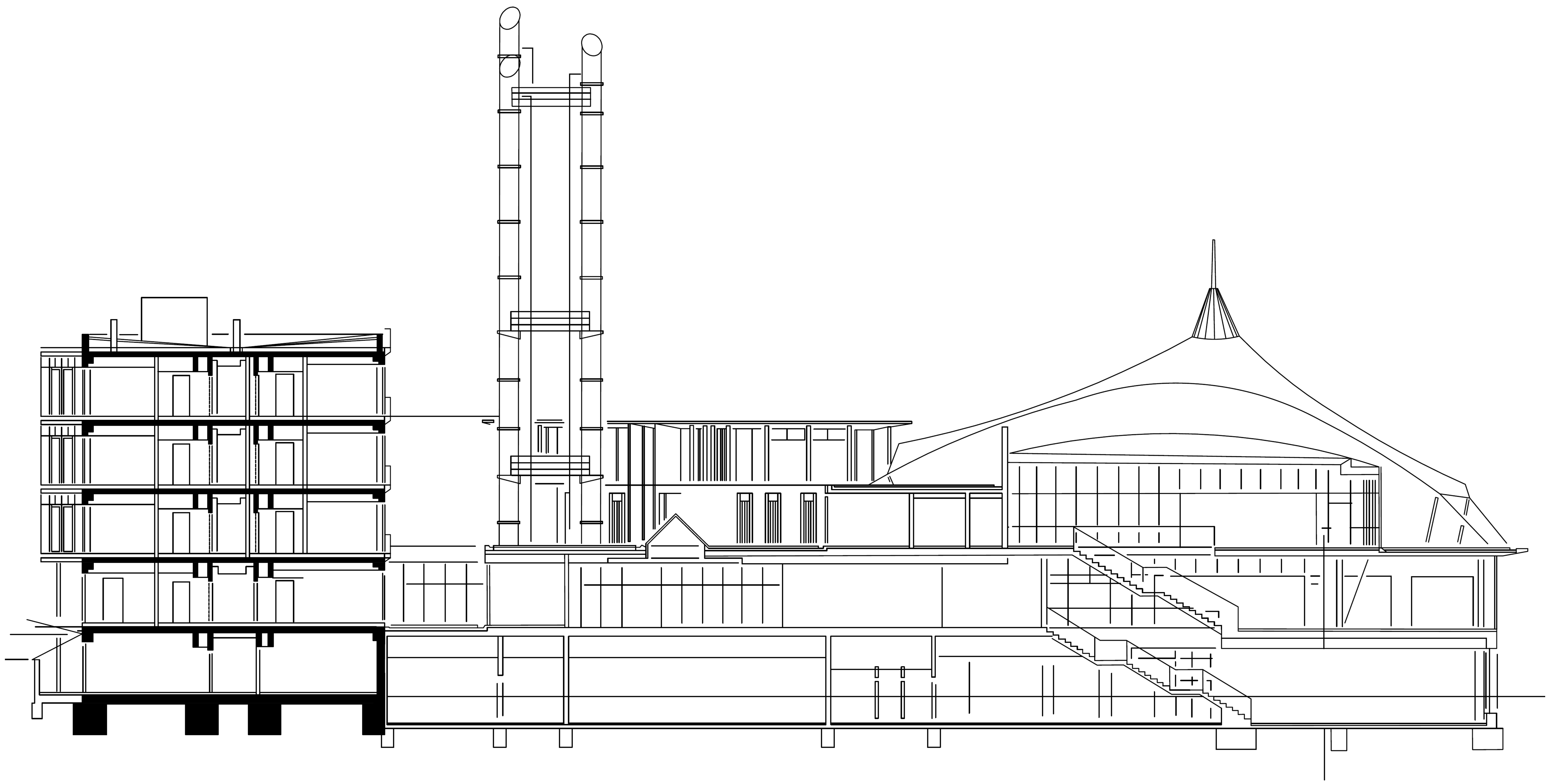


Figure 261) Cross Section

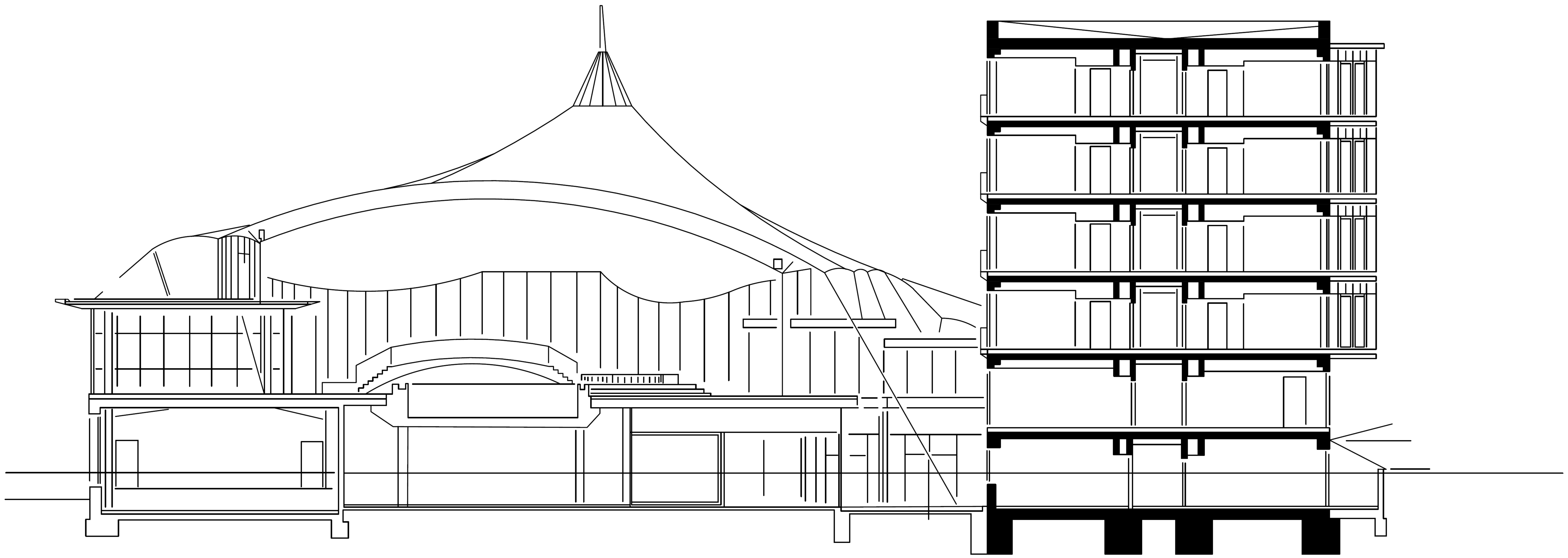


Figure 262) Cross Section

Double layer membrane with thermal insulation

The roof has a double-layer membrane; the outer membrane extends over the entire area (3300 m²), the internal membrane covers the leisure pool (1270 m²) and the sports area (395 m²). It follows the outline of the outer membrane. The internal membrane supports an insulation layer; the air space in between is ventilated. A minimum distance of 50 cm between the membranes had to be maintained under load, to allow the air circulation of min.5000 m³/h. The built-up of the double layer membrane is :

- Outer membrane = waterproofing layer
- Aerated cavity
- PE-cover sheet
- 16 cm mineral wool as double layer insulation, laid with staggered joints
- Inner membrane

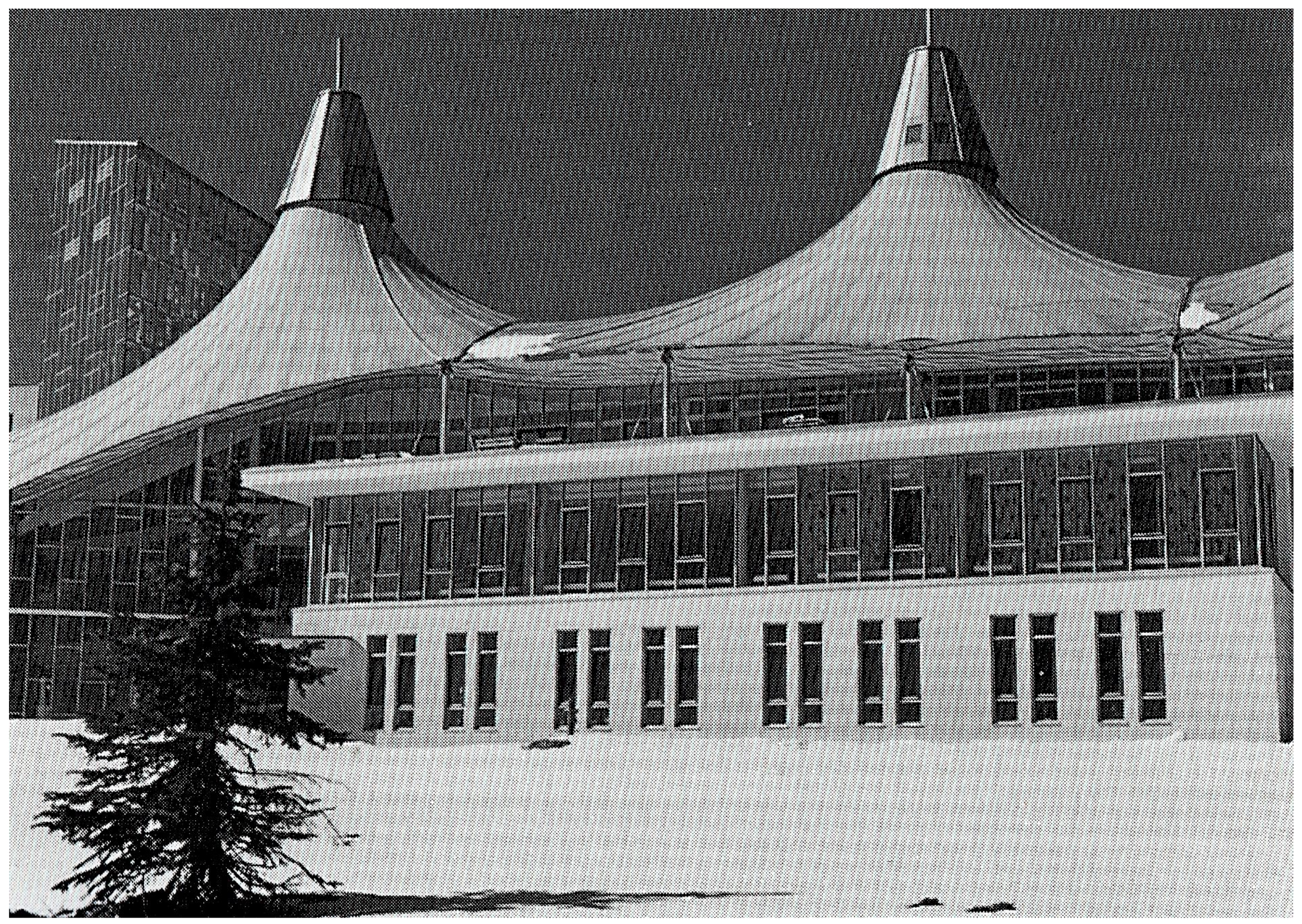


Figure 263) East View

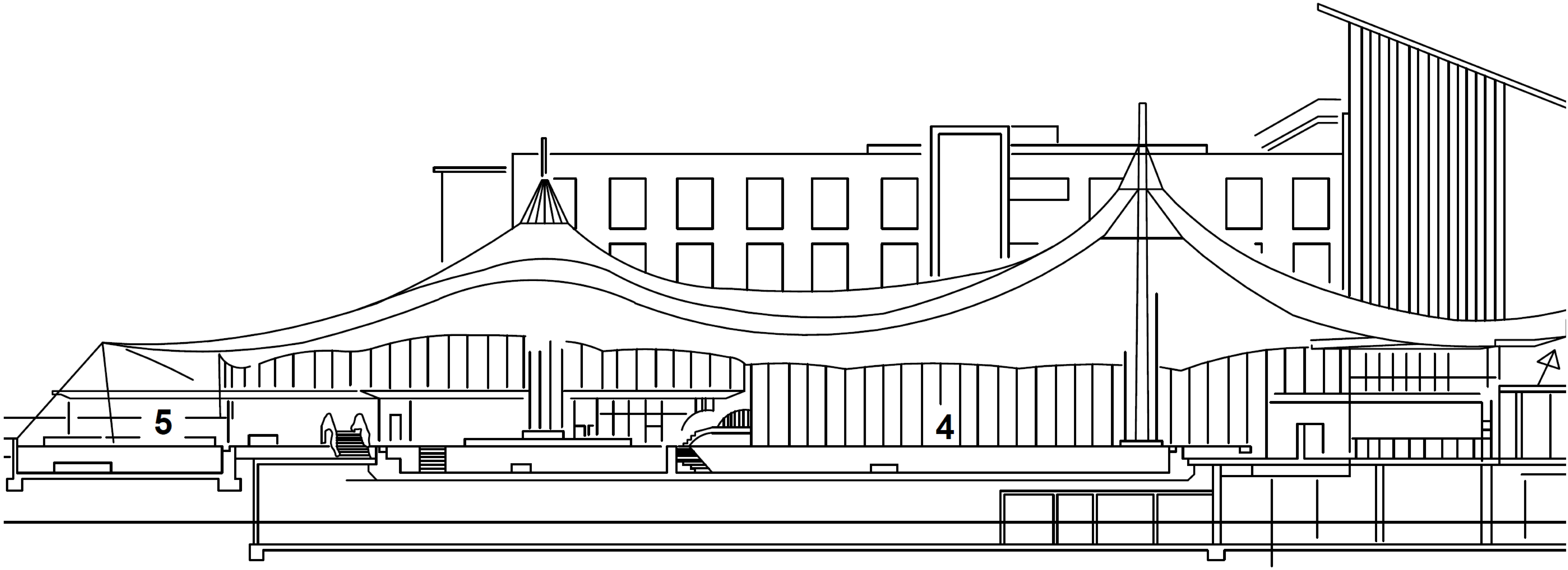
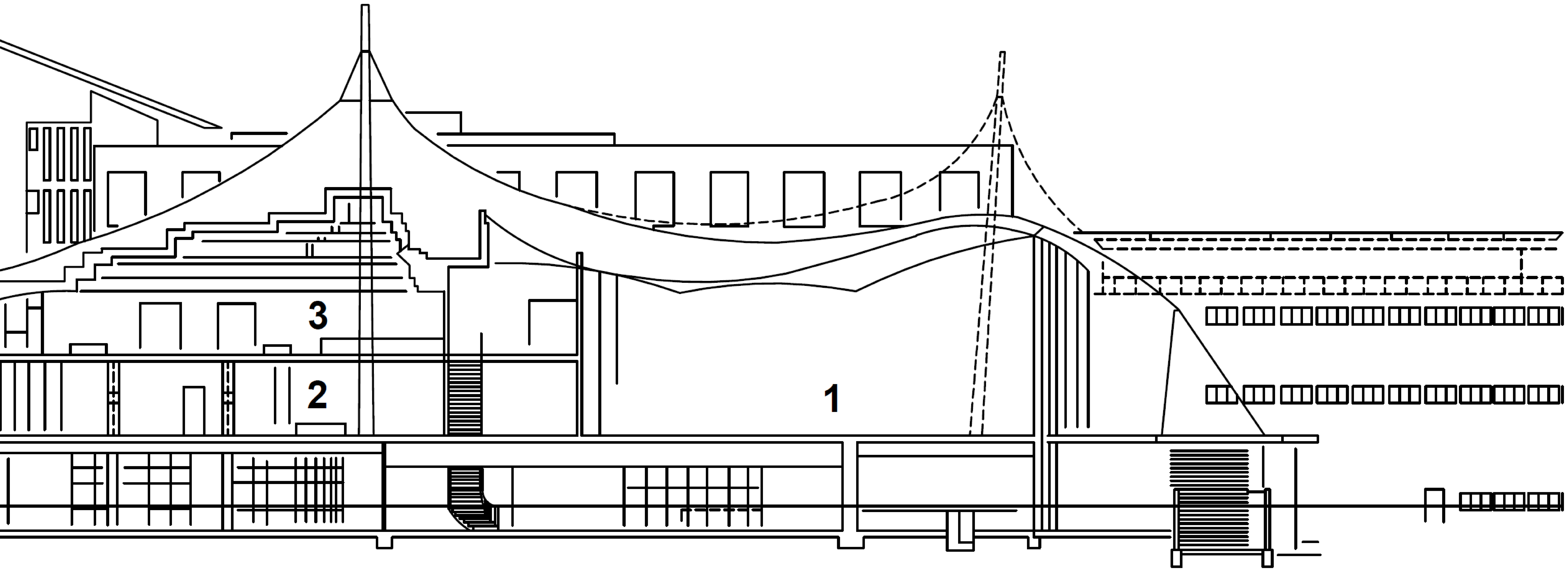


Figure 264) Longitudinal Section


3
2
1

Inner Membrane

The outer membrane consists of 15 panels, joined during the erection stage with clamp strips. The membrane material of the outer skin is a new PVC-coated polyester fabric (Diolen Superfest) specially developed by Verseidag for high-strength applications in wide-span air halls with 60 000 to 120 000 m² floor area. It has a tensile strength of 20 kN/50 mm and 19 kN/50 mm (warp/weft). For comparison: The standard membrane material for wide-span membrane structures, type II (to German specification), has a strength of 3.9 kN/50 mm and 3.5 kN/50 mm, the rarely used type V has 9 kN/50 mm and 8 kN/50 mm. The internal membrane is a PVC-coated polyester fabric (Diolen) type III; together with facade and building walls it forms a largely airtight space enclosure. It is connected to the smaller internal high point ring by a clamping strip. At the edge the inner membrane follows the facade, it is connected there stressed over a steel pipe, forming the upper edge of the facade structure.

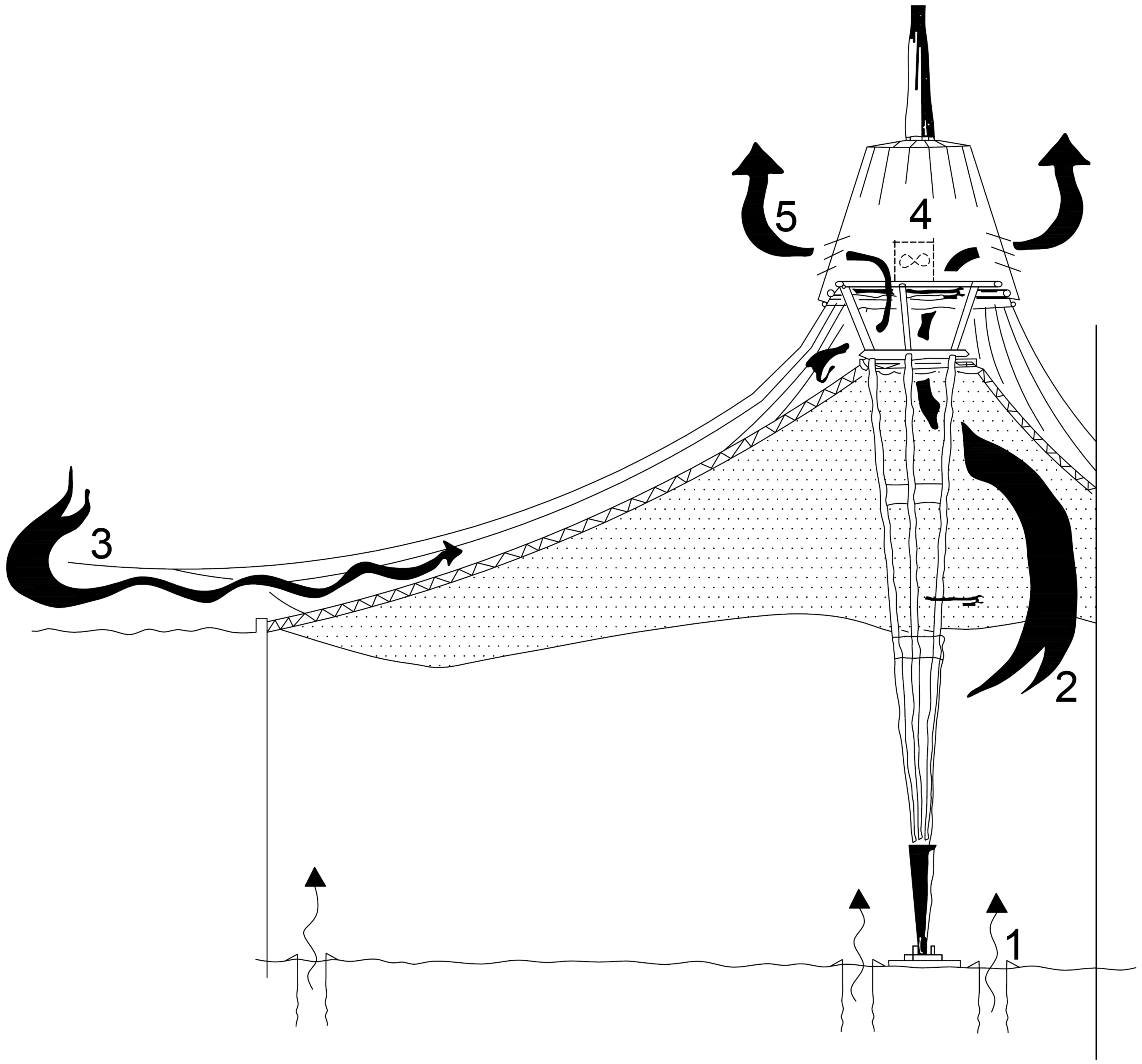


Figure 265) Detail Section: Ventilation of the membrane roof (design variation with lattice mast): 1 supply air, 2 exhaust air from interior, 3 ventilation of membrane space and thermal insulation, 4 fans, 5 exhaust air

Membrane Apron

To keep birds and other small animals from entering into the membrane cavity, it had to be closed by a membrane apron along the edge of the inner membrane. This apron must follow the displacements and movements of the different load cases and at the same time allow air circulation under the roof. The displacement under changing loads relative to the prestressed state amounts to calculated 1.5 m; for safety the maximum distance between inner and outer membrane at the edge was determined at 2.0 m. In the interior the clear space is smaller, being determined by the required minimum ventilation

Figure 266) Model (alternative design with four masts)

cross section and by the minimum clearance for installing the thermal insulation (0.7 m). The upper part of the membrane apron consists of a porous grid fabric, its length corresponds with the minimum distance required to accommodate the movements. The additional length is taken up in a concertina arrangement of fabric in the bottom part, so its length may be extended up to the maximum value of 2.0 m. The concertina folds are held in place by diagonally tensioned elastics.

Assembly

The assembly took place in late fall and early winter. To allow erection of the membrane the substructure shell had to be completed in the area of the membrane roof, as well as the facade construction with the cladding largely in place. Access for a mobile crane was only possible from one side, from the east. Edge and inner masts were erected first, the inner masts were placed over the previously positioned high point rings. To facilitate erection and prestressing of the membrane the edge masts were inclined towards the inside. Scaffolding was erected for the assembly of the 15 membrane panels which for transport reasons are approximately equal in size. The membrane was lifted into place in one day. It was prestressed by moving the edge supports out using tirfors and by jacking the upper mast rings up. For erection of tie inner membrane it had to be laid out roughly at the level of the facade's upper edge requiring scaffolding in some areas. The inner membrane was prestressed by jacking up the high point rings and from the edge masts.

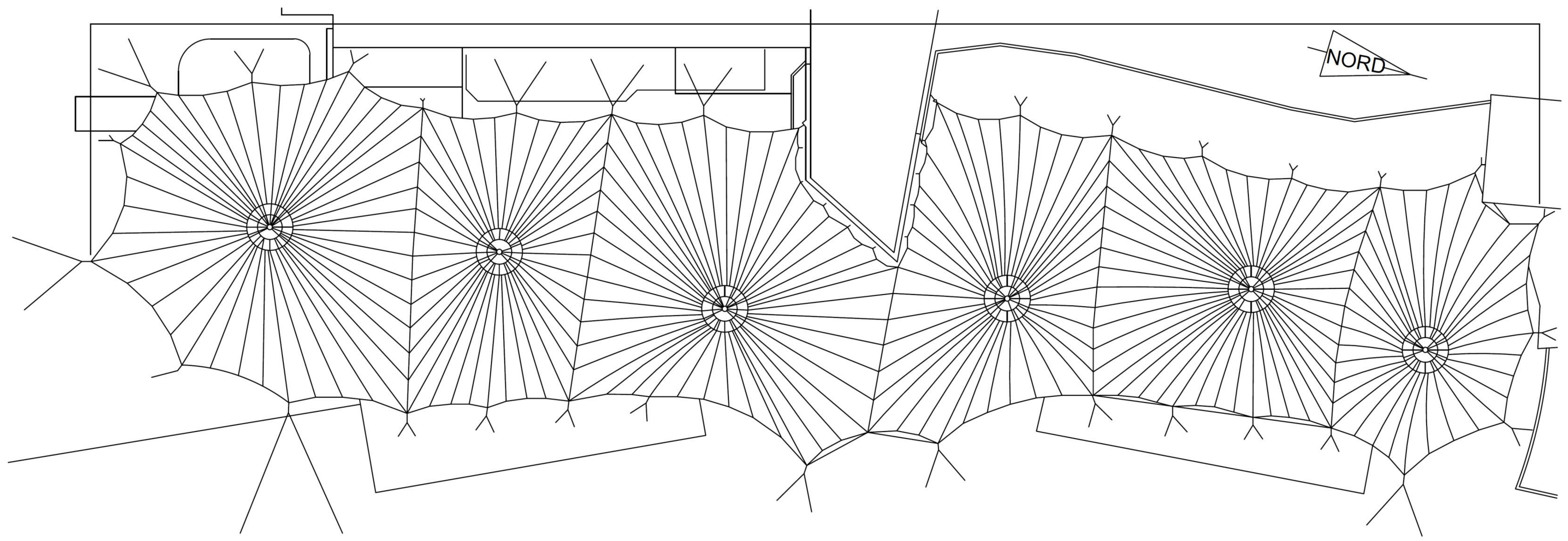


Figure 267) Roof Plan (final design with 6 masts)

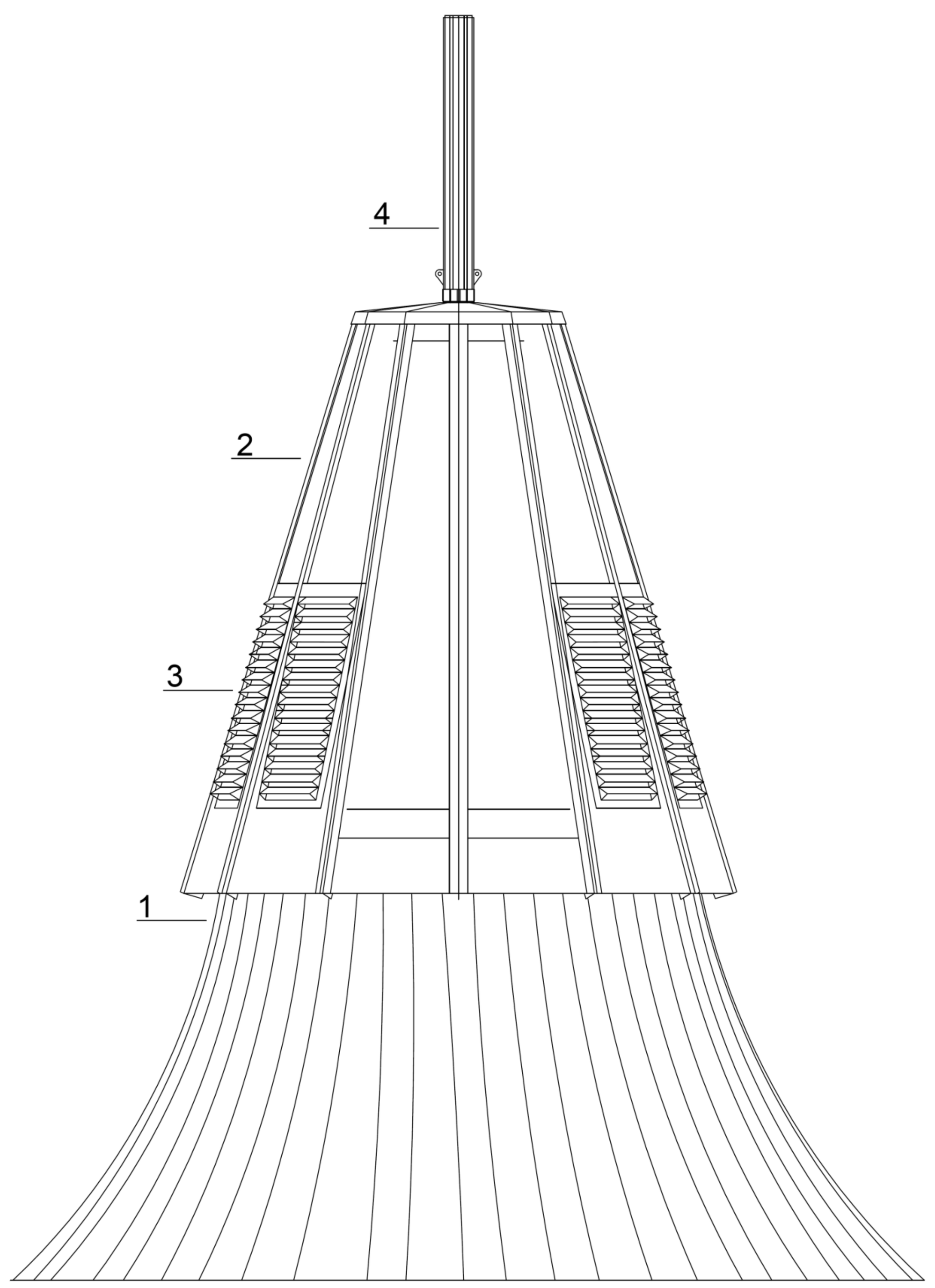


Figure 268) Sheet metal high point cover (tin hat), 1 outer membrane, 2 folded sheet metal elements joined by a welt, 3 ventilation grill, 4 steel tube mast tip

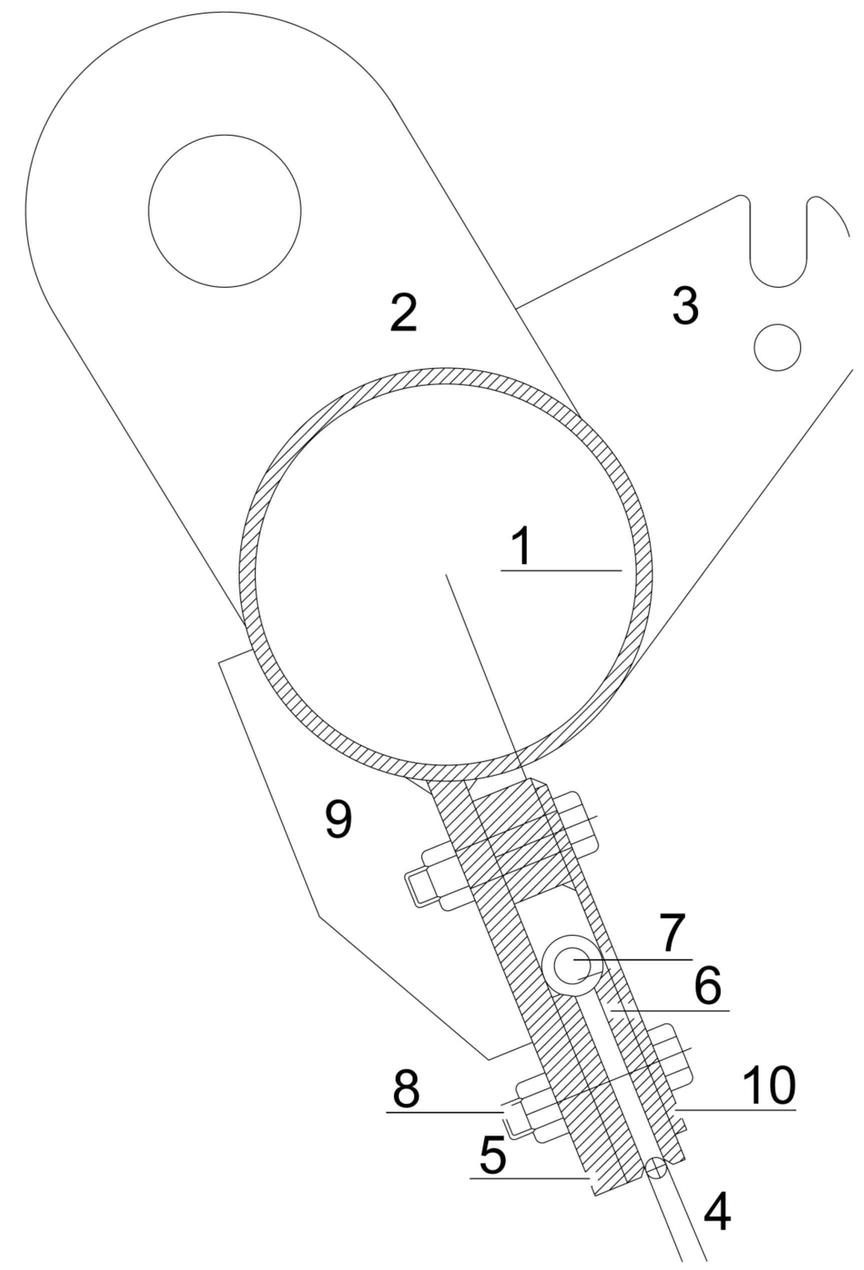


Figure 269) Membrane connection at the outer high point ring, 1 outer ring (steel tube), 2 connection plate for hanger cables, 3 connection plate for sheet metal covering, 4 outer membrane (PVC-coated polyester), 5 steel plate ring, 6 clamping strip, 7 boltrope, 8 fixing screws, 9 stiffener, 10 outer connection plate

4. Mobile Theatre for Buddy Holly Musical

Location: Hamburg, Germany
Date: 1994
Architect: Urban Project GmbH,Klaus Latuske
Engineer: Ingeneurplanung Leichtbau GmbH
Membrane: PVC-Coated Polyester–Double Layer

The 'Neue Metropol Theater' in Hamburg commissioned the construction of a mobile theatre which was to be used for the first time for a musical on the life-story of Buddy Holly, the Texan rock star who died in 1959 in a plane crash. The mobile theatre, with a textile roof structure covering a floor area of 500 m², was constructed in 1994 within the space of six months. The roof construction itself was designed and planned within only eight weeks. The theatre is located in the free port area opposite the St. Pauli pier. The membrane roof had to cover an auditorium with 1400 seats, with a main and two side stages as well as a two-storey lobby in the front part of the long, rectangular building. The lobby was closed with a cable-stabilized glass facade, curved in plan, which offers a splendid view over the city and harbour.

The 1400 velvet-upholstered chairs are arranged under a dark blue ceiling; by skillfully arranging the 11 lower and 15 upper rows and the six boxes, no seat is further than 25 m away from the stage. Each row of seating is raised 12 cm above the one in front and thus offers a good view of the three stages. The double-layer skin enveloping the building consists of an outer and an inner membrane, which serve simultaneously as weather protection, soundproofing and thermal insulation. The outer membrane is translucent, while the inner one is opaque, so that theatre performances are possible during the day. Although the structure is described as a mobile arched hall, it is conceived as a permanent building. After two years of service it is scheduled to be disassembled at the end of 1996 and set u.9 again in a different location.

Figure 270) Exterior View

Heating, Ventilation, Air-conditioning

The spaces between the inner membrane and the upper edge of the facade as well as the internal membrane space along the roof edge are closed by a double layer sealing apron. A 40 to 80-cm thick airspace between inner and outer membrane provides thermal and acoustic separation. A specially developed ventilation system allows effective and energy-saving air conditioning. Warm inner air is drawn into the membrane improved by adding fresh air and returned again into the auditorium. This method of circulating the air allows a multiple use of the already warmed inside air and thus leads to considerable energy savings. Separately controllable exhaust fans in the apex of the hall complete the ventilation system.

Structure

The primary structure consists of five welded pin-supported steel truss arches (at 15 m c/c.),in the shape of a three-centre arch, with a span of 55 m and an effective depth of 1.5 m, which are stabilized in longitudinal direction through prestressed steel cables. The middle arches are vertical, the outer ones are slightly tipped to the outside which gives the building its distinct appearance. Each arch consists of five sections for ease of transport. At each end of the building six tripods are placed, where both the stabilizing cables and the edge cables of the roof membrane are attached. The building envelope consists of a double layer roof membrane of PVC-coated polyester fabric. The outside membrane is supported along the arches with a garland cable and intermittently connected to the arch bottom chord. The inner membrane is suspended in garlands under the arch. At the edge along the facade, both membranes are anchored via edge cables in arches and tripods and are prestressed from there.

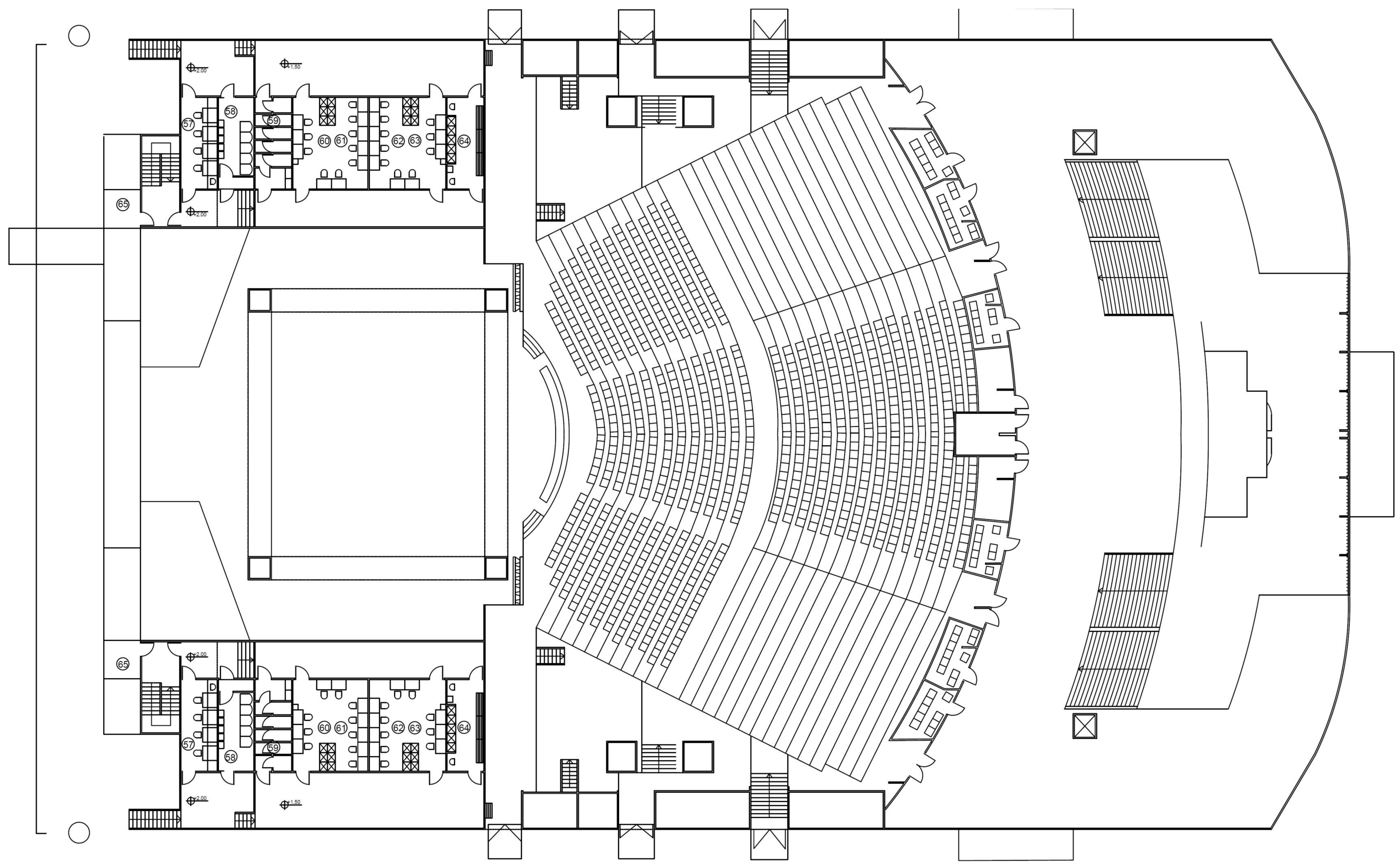


Figure 271) Plan – First Floor

Arches and Tripods

The two-pin arches are braced in longitudinal direction by four prestressed cables, which join the arches; they are anchored at the building ends at the above-mentioned tripods. The self-supporting roof membrane spans between the arches. The three-chord tubular truss of mild steel St37 consists of five short, transportable sections, joined by high-strength friction grip bolts in a circular pipe flange: top chord tube Ø 244.5 x 8 mm, bottom cord Ø 323.9 x 16 mm, diagonals Ø 101.6 x 4.5 and Ø 114.3 x 7.1 mm, and the transverse struts in the middle arch Ø 48.3 x 5 mm.

A tripod consists of a compression member inclined at 15° to tie vertical and of two diverging tension members with a steel bar tie fixed above to carry the forces from the stabilizing cables. Arches and tripods are protected by a zinc dust undercoat and by a double top and fixings are galvanized.

Membrane Roof

The roof consists of four saddle-shaped membrane parts spanning between the e arches and of two free-form end membranes as transition from the arch form to the polygonal edge formed by edge cables. For the existing brief this form has some distinct advantages: A rectangular plan can be covered without difficulty. Through the arch construction a large building height and associations win circus tents are avoided and the loads are still transferred into the ground in an efficient way. Due to the subdivision of the roof membrane into panels and their point wise connection at the arches the membrane installation is also relatively simple. To connect them with the arches the outer membrane panels are equipped with a continuous steel edge ca ale (Ø 16 mm). Rounded corner plates are connected with forked turnbuckles via gusset dates welded to the arch bottom chord tube. With a continuous membrane apron clamped to the cord tube the membrane is closed and sealed to the outside.

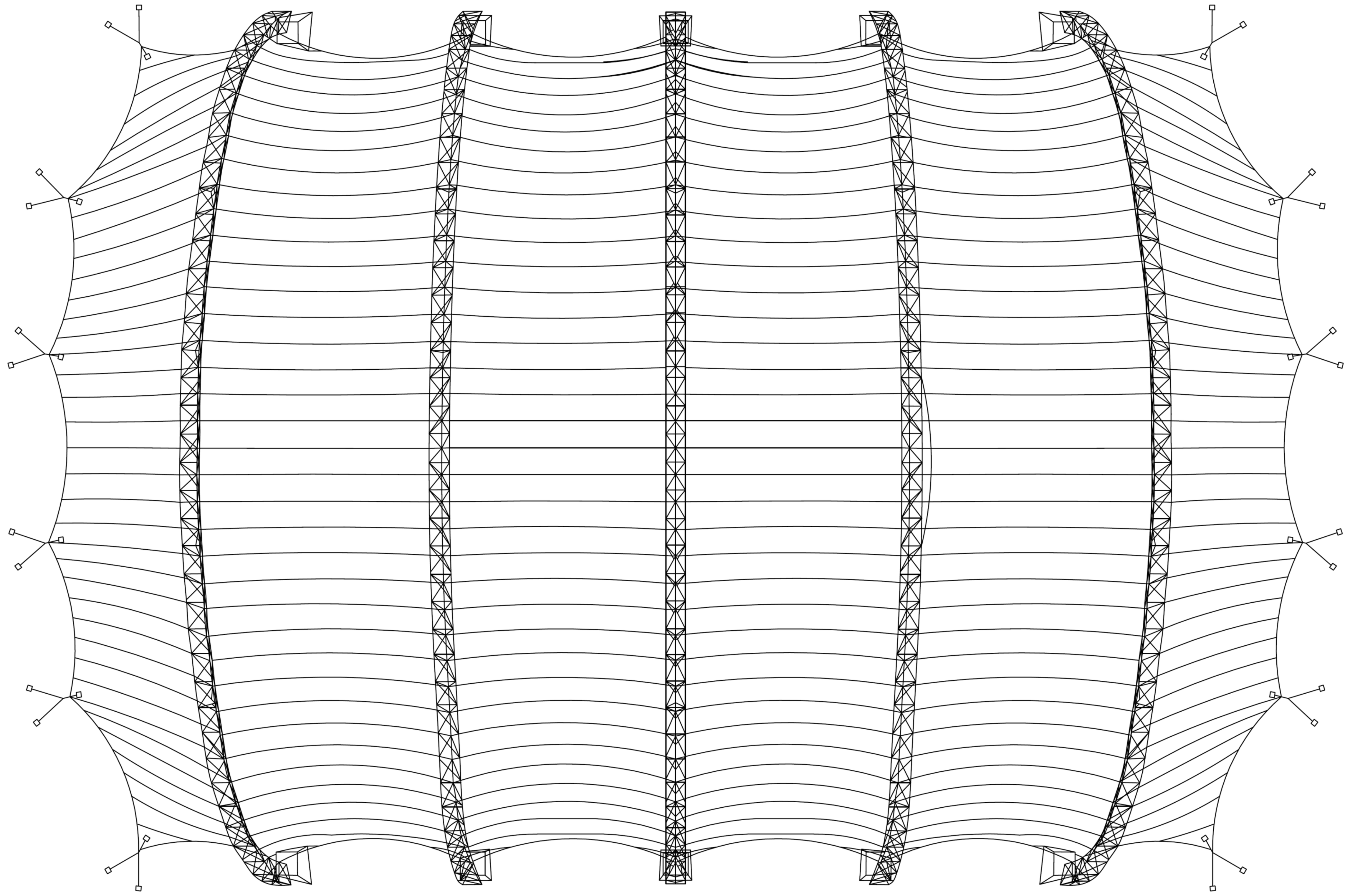


Figure 272) Roof Plan

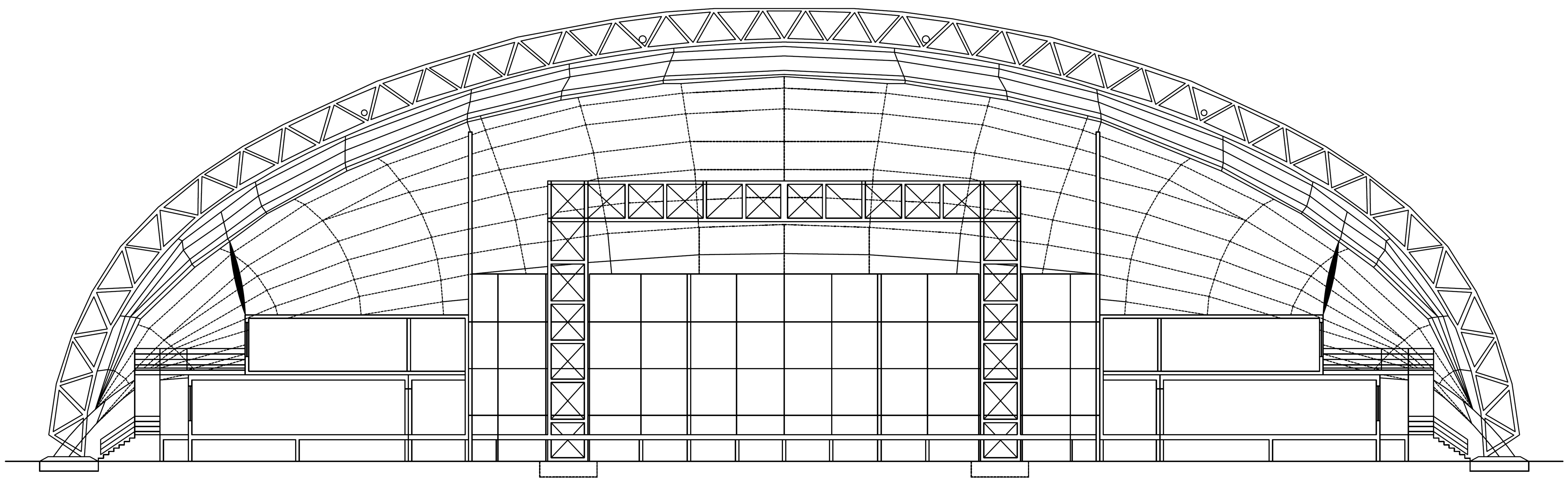


Figure 273) Cross Section

The inner membranes of two adjacent bays are connected underneath the arch along the parting line by two angle sections and edge boltropes. They are connected with the bottom cord tube by an almost vertical membrane strip lying in the arch plane, with edge cable (Ø 12 mm), corner plates and forked turnbuckles. At the tripods the outer and inner membranes are connected to a complex, welded, multi-layer mast head structure: The corner plates of the inner membrane are connected via an adjustable eye bar which runs in a welded-on tube sleeve with connection plates welded onto the edge mast (compression strut). The corner plates of the outer membrane are joined via a bolted connection to two plates, welded onto the tripod head. The stabilization cables (spiral strand Ø 28 mm) are fixed by means of a bent steel plate welded onto the tripod head. This carries the tension forces via two round bar sections, lying above the tripod guys, into the system point of the guy structure (tension strut. This way additional bending moments in the tension guy are largely avoided.

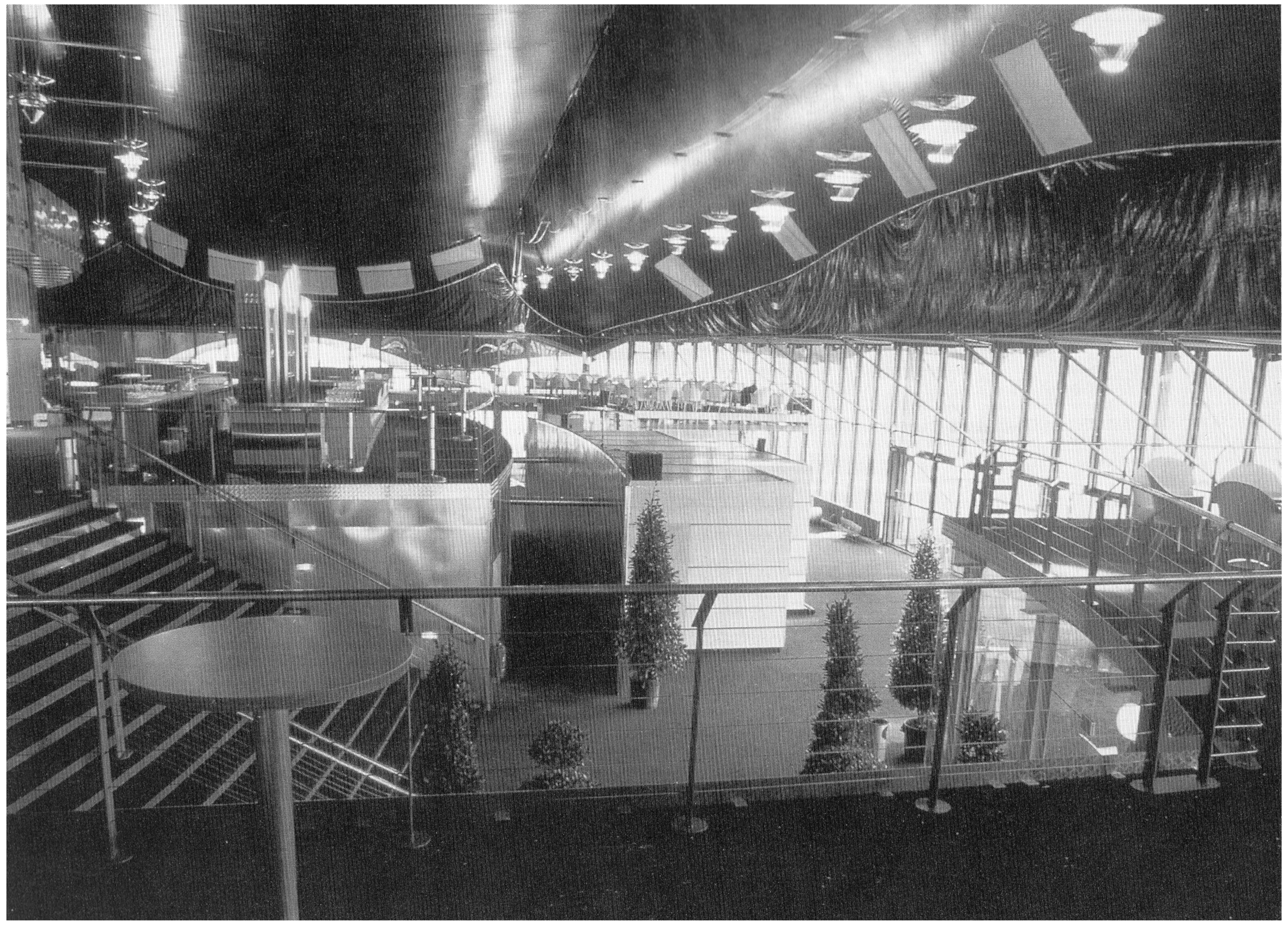


Figure 274) Interior

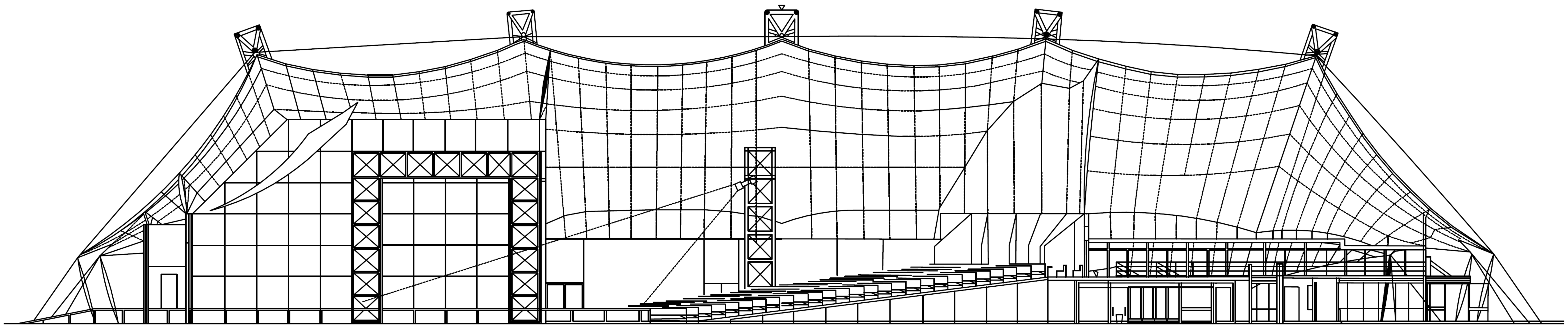


Figure 275) Longitudinal Section

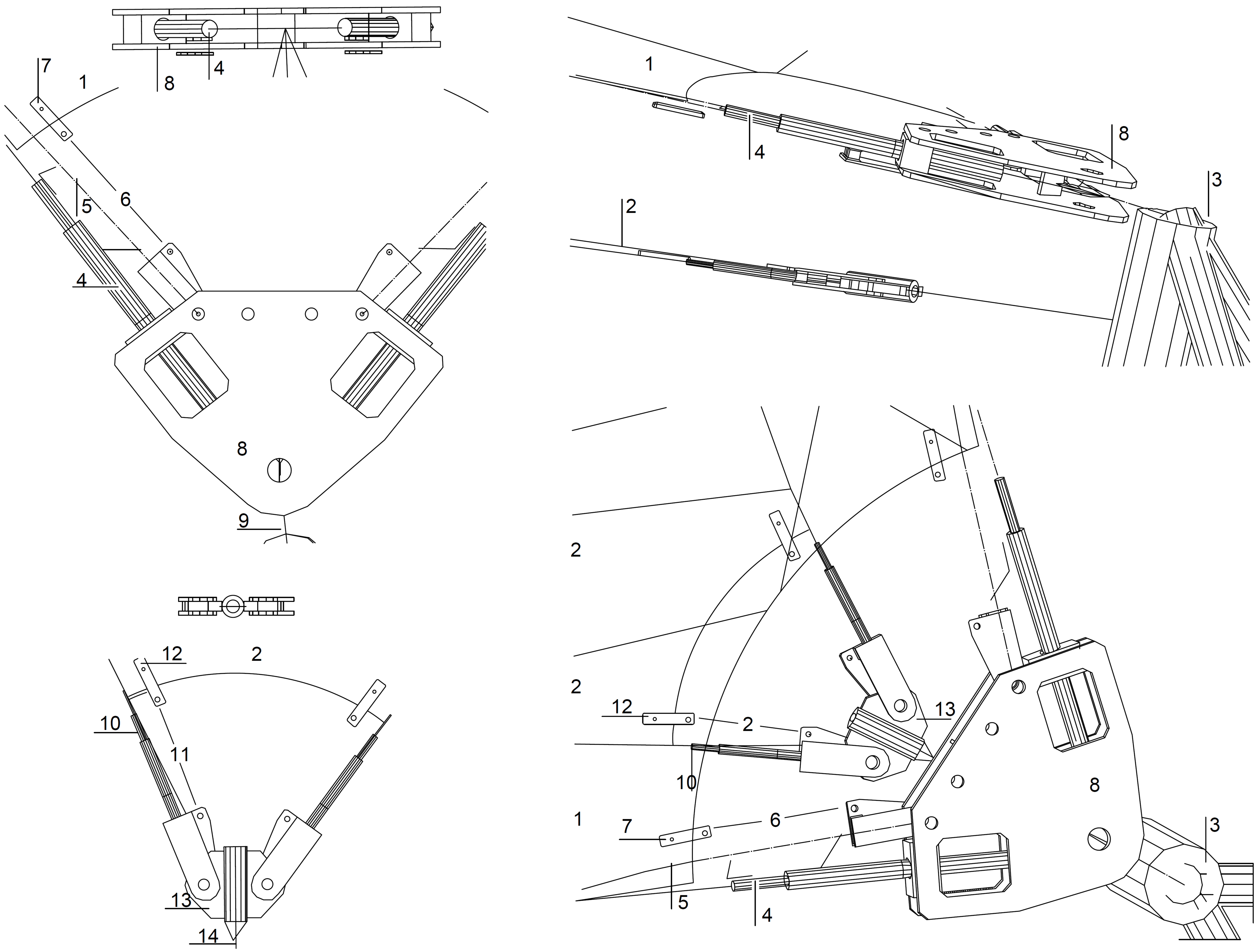
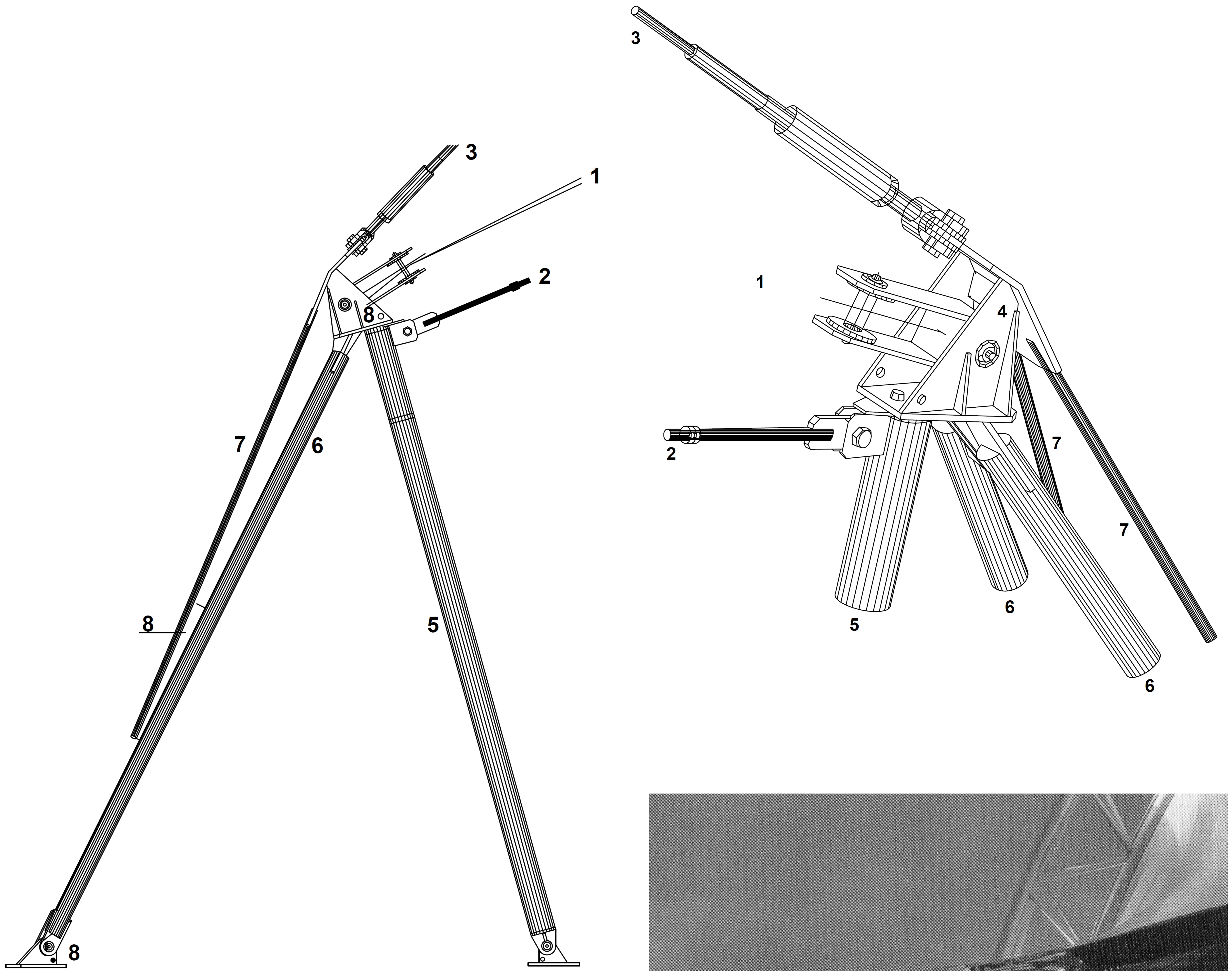


Figure 276) Membrane anchorage at the tripod: 1 outer membrane, 2 inner membrane, 3 tripod, 4 edge cable, 5 garland cable, 6 fork turnbuckle for tangential membrane forces, 7 hinged plate for the transfer of tangential membrane forces, 8 corner plate, 9 connection to tripod, 10 edge cable of inner membrane, 11 fork turnbuckle for tangential forces, 12 hinged plate for tangential membrane forces, 13 connecting element, 14 threaded tie as connection to tripod.

Figure 277) Guy tripod with connection of double layer membrane and of the stabilizing cable: 1 outer membrane, 2 threaded tension tie for inner membrane, 3 stabilizing cable with fork fitting, 4 head element, 5 compression strut, 6 tension strut, 7 round bar tie



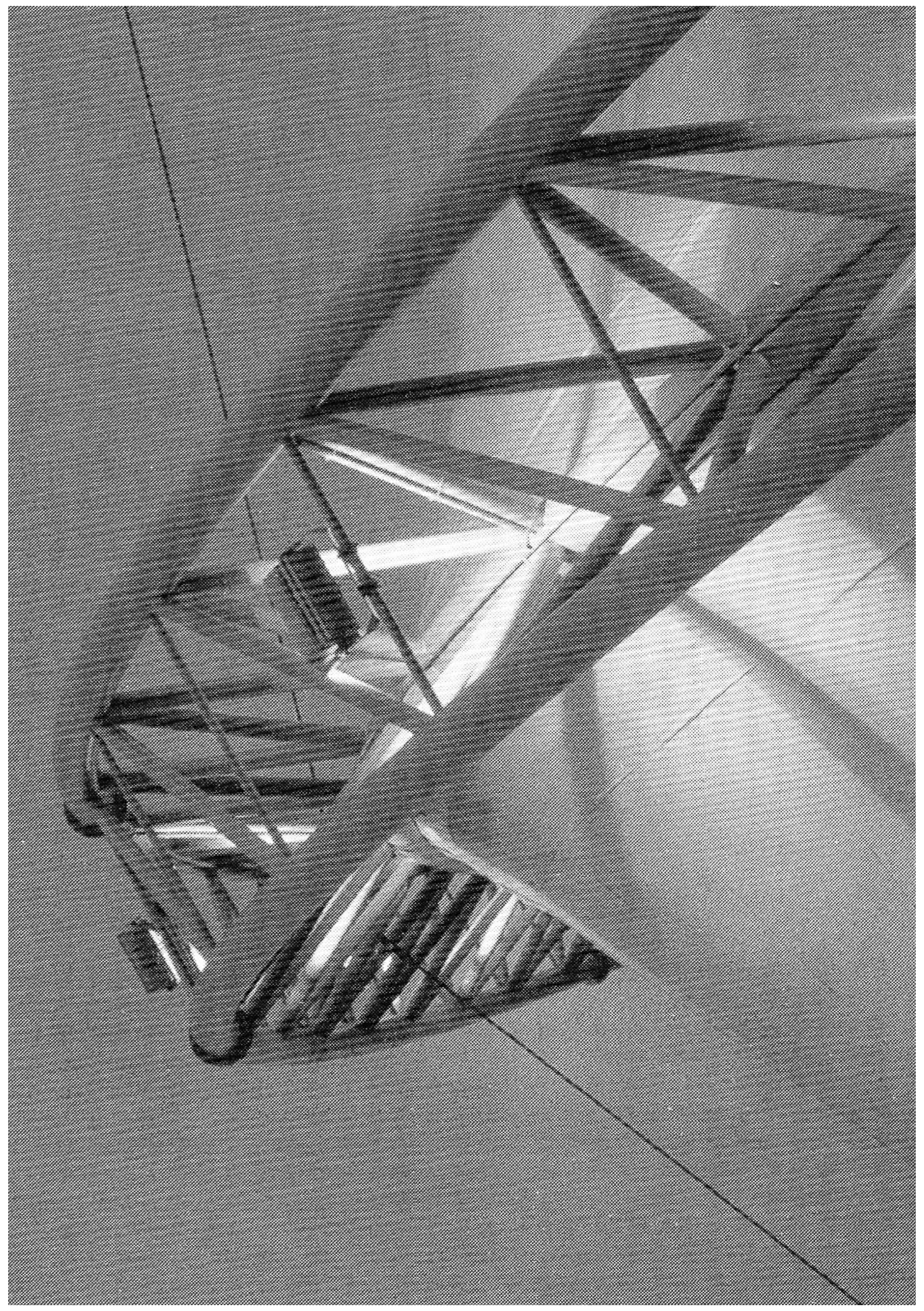


Figure 278) Membrane connection at arch

Figure 279) Membrane connection at tripod

5. Rothenbaum Tennis Stadium

Location: Hamburg, Germany
Date: 1997
Architect: Architekten Schweger & Partner
Engineer: Sobek & Rieger
Membrane: PVC-Coated Polyester – Single Layer

The roof of the Rothenbaum Center Court covers spectators' stands and playing arena in a free span of 102 meters. The roof structure, which is based on the spoked wheel, comprises a permanently covered outer area as well as a convertible inner area of approximately 63 m diameter, which represents an opening roof area of 3000 square meters. The inner roof can be opened or closed within a few minutes without interfering with the match in progress.

The membrane is made of PVC and the roof structure has 2 concentric areas, the one outside measuring 5,300 m^2, and the one inside 3,200 m^2.

Rothenbaum Tennis Arena (8,500 m^2) hosted the annual Masters Series tournament in Hamburg (German International Open), and since 2008, is the venue for the Masters ATP (Association of Tennis Professionals), part of the ATP World Tour 500. Also, the arenas host many concerts and exhibitions during all seasons.

In this condition every sliding carriage must be moved at a different speed, because all the radial cables have different lengths. The movement of the inner roof is completely automatic and carefully controlled by contactless sensors. The prestressing of membrane textile is done by 18 hydraulic jacks located at the outer edge of the inner roof. High accuracy is required for their operations, because membrane is easily damaged or collapsed by the force of hydraulic jacks.

The primary structure has been stiffened by connecting the upper and lower radial cables of both the inner and outer roofs, using hanger cables, so that they work together as a load bearing structure. This mechanism has made the large scale of the retractable membrane roof possible. At 3000m2, this was the largest convertible textile roof at that time.

Figure 280) Exterior View, Open roof

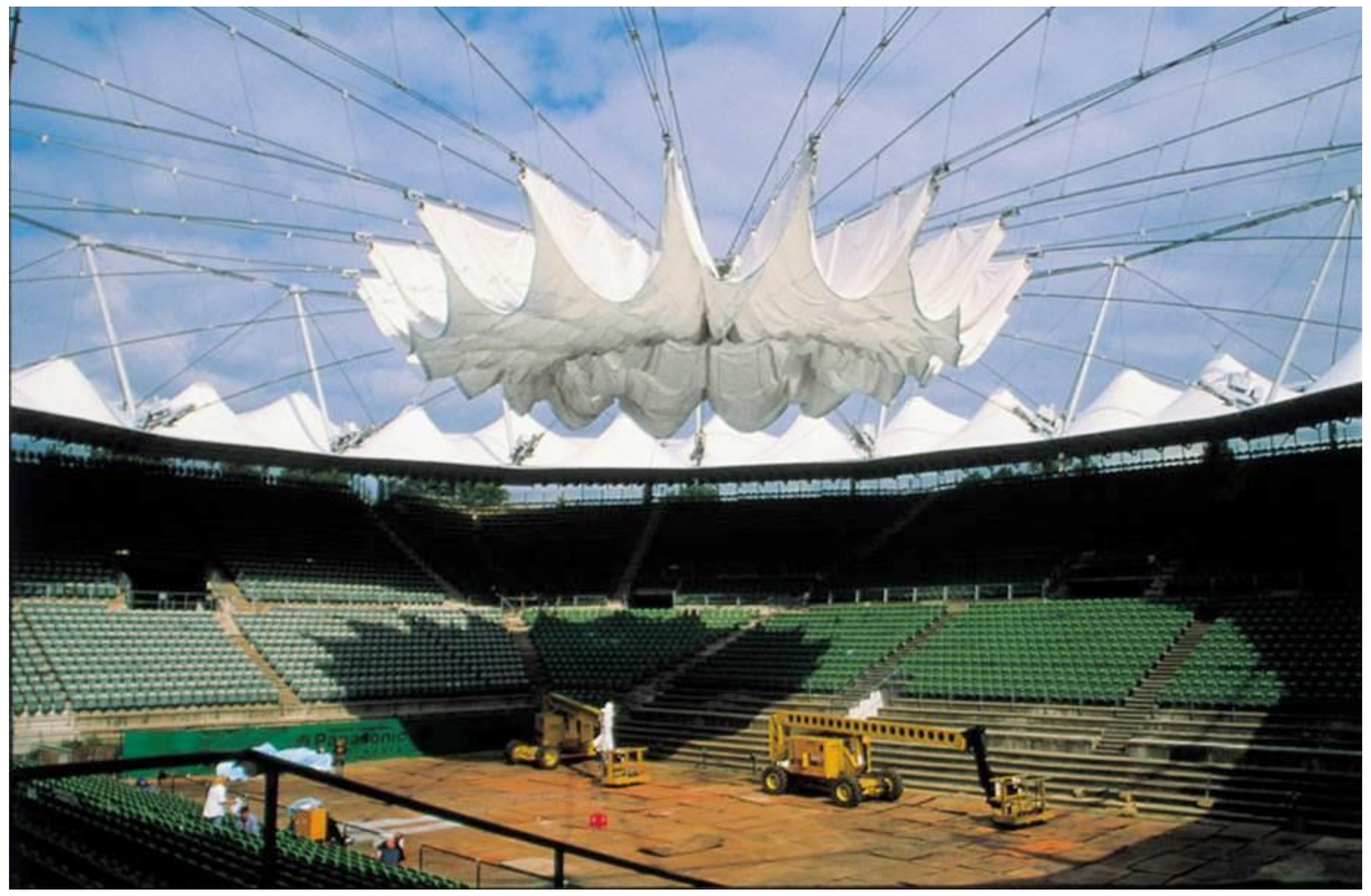


Figure 281) Retractable PVC roof

This roof over an open-air theatre with 3000 seats situated at the edge of the old city center of Tarragona has some special features, which distinguish it from others of its kind. It lies underneath the city walls and below a monumental tower in a natural bowl forming the amphitheater at the foot of a steep embankment. Tower and city wall serve as backdrop for the open-air theatre, whose membrane roof with its fascinating form has become the landmark of this part of town.

For spectators area the roof was built statically, and for the central events area was implemented a retractable roof, automatic, with a single layer of PVC. This allows 10% light penetration and retraction process is easy (approx. 5 min).

Figure 283) Interior View, Closed roof

Figure 282) Open roof, Spoked Wheel

Figure 284) Exterior View, Closed roof

Conclusion

ETFE cladding is the perfect material for greenhouses because of low dead weight, excellent ultra violet light transmission, and thermal properties. The main design concern for botanical gardens is a large, column-free volume and excessive sunlight. Therefore, ETFE is an optimal building skin solution for efficient greenhouse structures that are easy to maintain. The material has been similarly successful in zoological buildings, temporary exhibitions, theaters, and stadiums. The applicability of a lightweight, sustainable, easy to maintain, interesting ETFE roof or façade is not limited to large structures. ETFE is suitable for courtyards, atria, and skylights in more traditional office, residential, and institutional buildings. Incorporating ETFE into traditional structure cladding has the potential to decrease environmental costs of construction by minimizing support structure and costs of operation by reducing cleaning and insulation expenses.

Foil cushions made from ETFE have been used successfully as thermally insulating building envelopes for almost 30 years. They enable large transparent or translucent areas to be created with an extremely low degree of shading from frames and supporting structures.

The flexibility of the ETFE cushions and the possibility of variable welded seams enable the cushions to be made to measure for almost any shape. Long rows of cushions that are slightly sloped longitudinally or transversely with a width of up to approximately 4 m, in conjunction with an adequate supporting structure are recommended. This design concept has been extensively applied for over 30 years and allows for economically beneficial building envelopes. Buildings that can be filled with natural light and that are a tribute to architectural expressiveness.

Future

The future of ETFE is very bright, it has been successfully in use for over twenty years and is benefiting greatly from the popularity of several high profile projects. ETFE offers all of the advantages of glass except clear visibility and offer distinct advantages in terms of support structure, sensitivity to building deformations, geometric flexibility and constructability. The increasing utilization of ETFE cladding systems will lead to industry standards and eventually design guidelines that will concrete ETFE's future in the construction industry.

The technology is not static. Specialty design fabricators continue to push new advancements and architects develop innovative concepts for system integration that drives building performance, sustainability and aesthetics. LED integration within ETFE systems is similar to any other cladding system in that the lighting systems are secondary to the cladding system itself lighting the skin for graphic or informative display. What is unique about ETFE is that several foil types are very good with absorbing or transmitting the light that is projected onto it with minimal projections and without hot spots.

In the future, LED will be fully integrated within the skin itself. This type of system - digital skins transmitting digital images from one side of the skin while presenting themselves as transparent skins from the other side - is in the prototype phase.

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