LONG SPAN STRUCTURES: PART 2

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Sustainable Constructions
under Natural Hazards and Catastrophic Events

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CONTENTS

1.5 Rigid-flexible combined long-span space structures [1]

- Have become the mainstream of application and development of modern space structures

- Include ten different types (in the recent classification)

Types of rigid-flexible structures

- Beam + string
- Suspen-dome
- Composite structures of cable dome and single layer lattice shell
- Tensairity structures
- Prestressed grid
- Cable-stayed grid
- Truss string
- Prestressed segmental steel
- Cable truss structures
- Cable domes

Beam+string structures (BSS)

Combined space structure composed of:

- Bottom chord cables
- Upper chord beams
- Vertical compressive bars

BSS has been proposed in Japan in the years 1990’

- Self balanced structures
- Design state reached by tensioning of bottom chord cables
- Bracing system installed in the roof to provide out-of-plane stability
- Spatial beam string developed out of planar beam string structures

Special design provisions for BSS:

- Principle of multi-stage tensioning and loading applied and principle of multi-stage design should be adopted

- This allows to obtain the relevant state of internal forces in the structures in the structure under service loading

- The non-linear effect of the structure should be taken into account in the analysis

Example: Shanghai Pudong International Airport

- First representative beam string in China
- Longest span = 82,6 m
- Longitudinal spacing between string beam is 9,0 m

Terminal T1 of Pudong Airport

Terminal T2 of Pudong Airport

- Three span continuous beam string structures supported by spatial double-layer Y-shaped columns (simplest tree-type)
- Column spacing 18,0 m
- Plan size = span(48+89+48) x 414 m

Terminal 2 roof:

Suspen-dome structures

Composed of the following structural elements

- Horizontal hoop cables
- Diagonal cables (cable elements)
- Vertical compressive members (bar elements)
- Single-layer lattice shell (beam elements)

- Combine the advantages of both lattice shells and cable-domes
- By reasonable arrangement of pre-stressing cables the horizontal reactions may be reduced and the stiffnes of the structure improved
- Platform shape: round but also ellipse, polygon, rectangle,etc

Example 1:

- Jinan Olympic Gymnasium built in 2009
- Round platform
- Diameter 122 m (longest span suspen-dome in the world)

Jinan Olympic Gymnasium

Example 2:Non-column canopy for Shenzhen North Railway Station

- Built in 2010
- Two-way multi-span continuous cylindrical lattice shell
- Column grid of 28 m x 43 m
- Covering area of 68000 m^2
- First suspended cylindrical lattice shell with rectangular platform in the world

Shenzhen North Railway Station

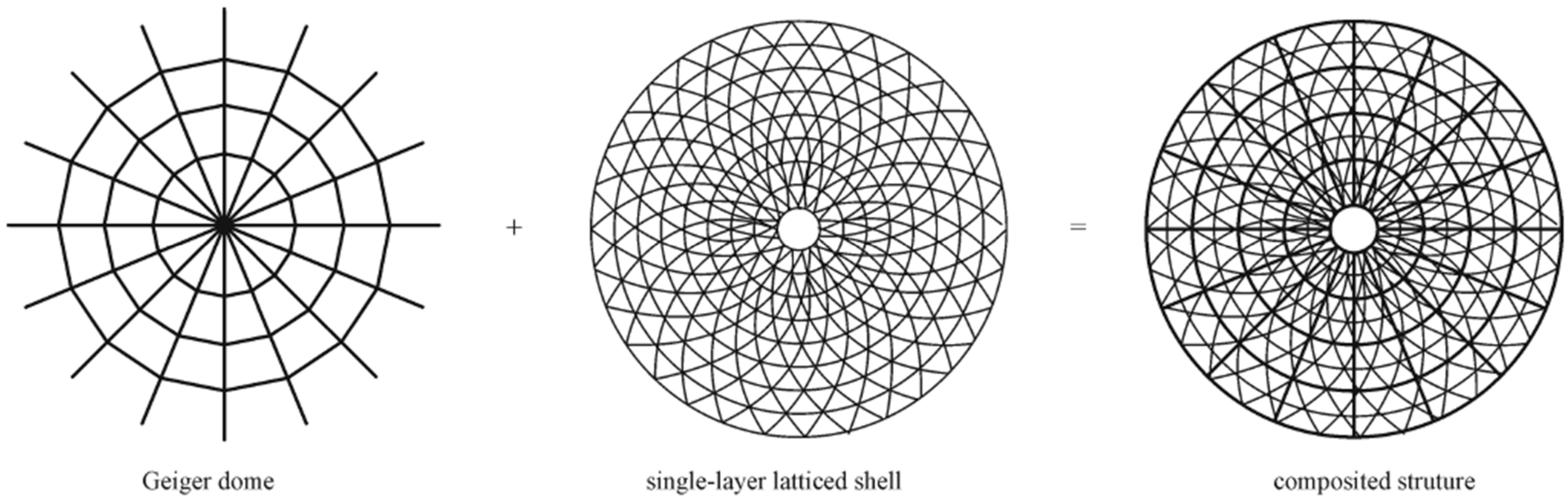
Composite structures of a cable dome and a single layer lattice shell

- New long-span space structures proposed by Chinese scholars

Rigid-flexible combined space structures composed of :

- Bar
- Beam
- Cable elements

Composite structure of cable dome + single layer lattice shell



Cable dome +

Single layer rigid shell=

Composite structure

Advantages:

- The single-layer lattice shell can be installed on the self-balance system without the full scaffolding system

- Rigid roofing material may be employed on the single-layer lattice shell instead of the membrane of the cable domes

- Result: wider application of this kind of structures than cable domes

Model of 5m diameter to be tested in Zhejiang University

Example: Jinan Olympic Gymnasium (initially proposed structure)

Tensairity long span structures

- "Tensairity" = Tension + air + integrity
- New space structure created by replacing the vertical bar in the beam string structure with the air-rib
- Composed of three types of elements:

- Beam
- Cable
- Membrane

- First reported at the IASS France Symposium in 2004
- Still under research as structural system

Example: Garage of Montreux Station in Switzerland

Relevant detail at Montreux Station:

Air-rib

Prestressed grid structures

- Combine the prestressing technology with space structures (including also space trusses and lattice shells)
- Composed of bar and cable elements
- Prestressing cables installed on the bottom chord or below the bottom chord plane of space trusses
- Also, prestressing cables installed at the perimeter of lattice shells
- Applying prestressing technology improve the structural behavior and reduce material consumption by up to 25%

Example 1: Qingyuang Gymnasium

- Built in 1994
- Hexagonal platform
- Length of diagonal up to 93,6 m
- The roof is a combination of six unisymmetrical double-layer twist lattice shells supported on six columns
- Six prestressing cables installed along the perimeter of the lattice shell

Model of Quingyuang Gymnasium

Example 2: Roof of Panziuha Gymnasium

- Octogonal platform
- Plan size 74,8m x 74,8 m
- Double layer spherical lattice
- Eight perymetral trusses are designed between adjacent supports
- Pre-stressing cables at the bottom chords instead of steel bars

Model of Panzihua Gymnasium

Cable-stayed grid structures

- Introduce the concept of cable-stayed bridge into long span space grid structures
- Structures = composed of bars and cable elements
- By installing several stay cables on space trusses or lattice shell the span of the structure is reduced and the stiffness is improved
- Stay cables could be pretensioned to optimize member stresses and reduce material consumption
- Cables should be arranged in multiple directions
- Cables should NOT be relaxed under ANY condition of loading

Example 1: Warehouse of the Port of Singapore Authority (PAS)

- Built in 1993
- Six buildings covered with cable stayed space trusses
- Type A buildings (4 pieces) with plan dimensions of 120m x 96 m and six towers each
- Type B buildings (2 pcs) with plan dimensions of 96 m x 70 m and four towers each

Warehouse of the PSA

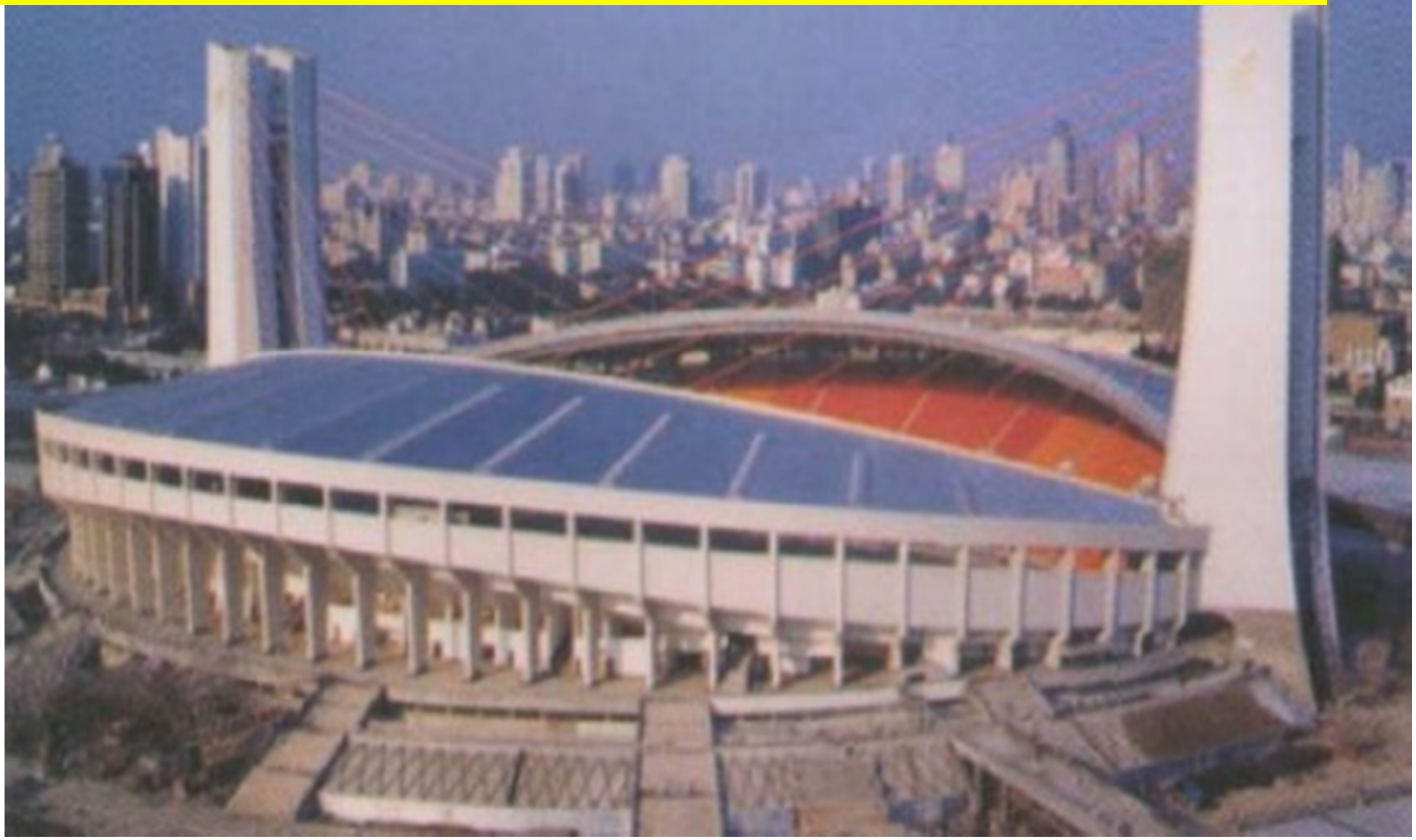
Example 2: Jiuguan Tollhouse of the Taijiu expressway iin Shanxi

- Cable stayed double-layer latticed shell with a single tower
- Plan dimensions 14 m x 65 m

Jiuguan Tollhouse of Taijiu expressway

Example 3: Roof of the main stadium of Gragon Sports Center in Hangzhou

Cable-stayed double-layer lattice shell with two towers (18 stability cables on upper chord plane against wind up-lift)



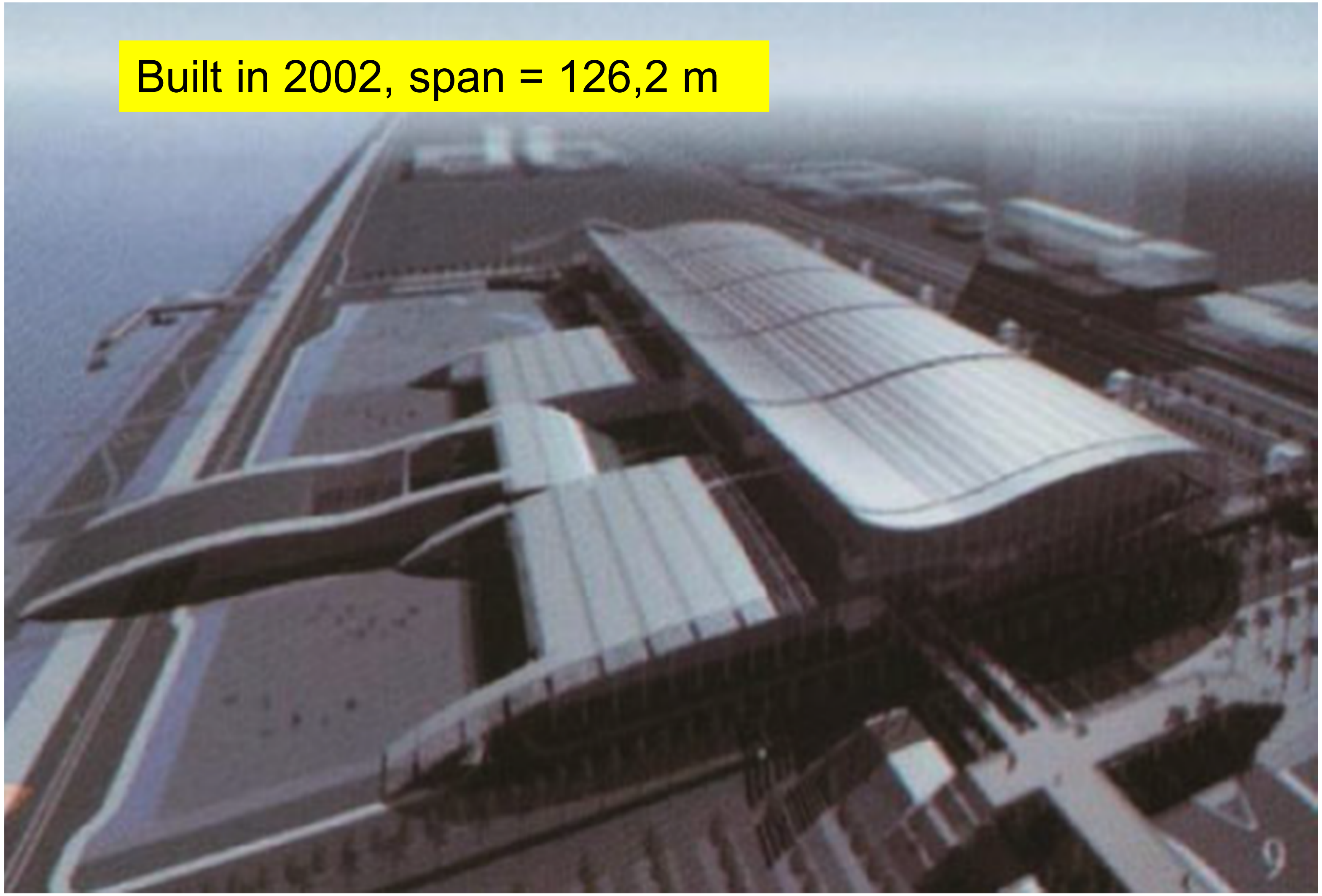
Example 4: Roof for the Sports Center of Zhejiang University

Single layer lattice shell suspended by cable-stayed net

Truss string structures (TSS)

- Result by substituting in beam string structures the simple profile upper chord beams with trusses
- Composed of bar and cable elements
- The truss may be designed as planar or spatial
- A bracing system should be installed to ensure the out-of plane stability!

Example 1: Guangzhou International Convention and Exhibition Center



Example 2: National Gymnasium for the Beijing Olympic Games

Two way orthogonal truss (planar!) string structure built in 2008: longest span in the world in its cathegory

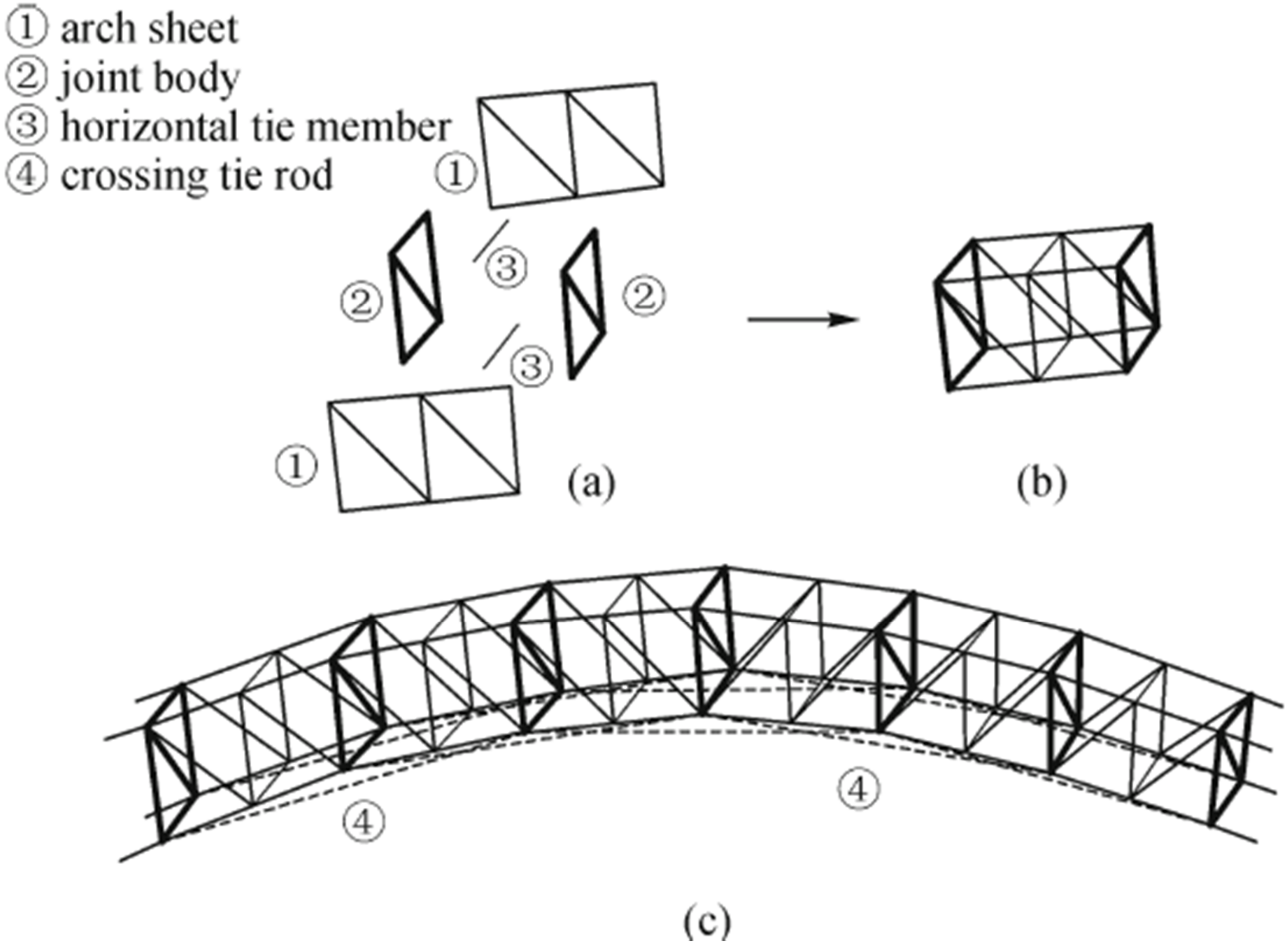
Prestress segmental steel structures

- Developed by Chinese engineers and researchers
- Composed of the following elements:

- Prefabricated arch sheets
- Horizontal tie members
- Joint bodies as diaphragms with crossing tie rods

A panel of lattice arch is composed of two pieces of arch sheet, horizontal tie members at upper and lower chord planes and two pieces of joint bodies

Scheme of prestressed segmental steel structure



Prefabrication & site procedure:

- Arch sheets and joint bodies = usually prefabricated off-site
- Assembled with segments on the ground on site
- Crossing tie rods used to connect bars between nearby panels during installation
- Prestress introduced into the structure via the tie rods
- Long span structures may be assembled from small and light components, without the use of large hoisting facilities
- Consequence: construction easy and fast
- Used to build small hangars in the early stages

Example 1: Roof of the indoor tennis court al Diaoyutai State Guesthouse

- Built in 1994
- Has a prestressed segmental steel structure composed of three pieces of cylindrical lattice shell
- The middle piece is a retractable part, opening the space

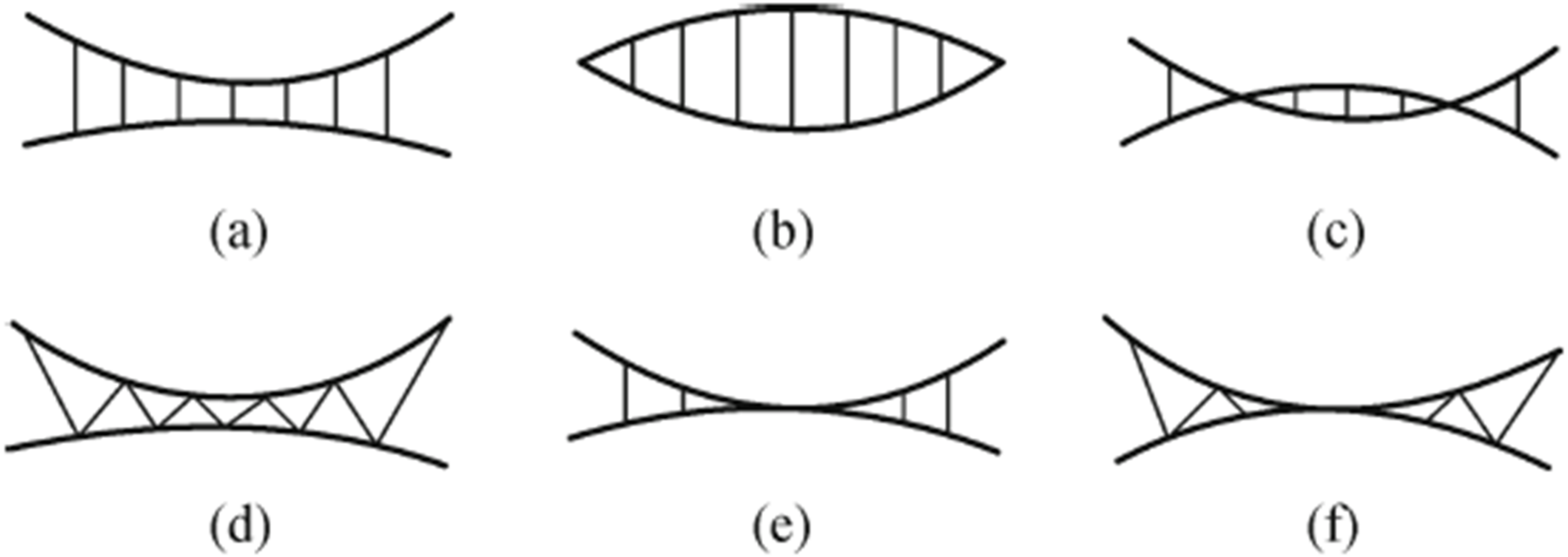
Indoor tennis court of Diaoyutai State Guesthouse

Observation:

- Prestressed segmental steel structures (with **maximum span approximately 130 m**) can be used widely in either permanent buildings or temporary buildings, as they can be built or disassembled easily

Cable truss structures

Composed of double layer cable (upper chord + bottom chord) and vertical bars



Function of the elements:

- The concave (bending-down) cables are referred to as load-bearing cables
- The convex (bending-up) cables are referred to as stability cables
- The vertical bars between cables are referred to as compressive web members

When load-bearing cables (or else stability cables) are pre-stressed the structure becomes self-balancing

Cable truss structures with can be used to build long span structures with rectangular, round or toroidal plan forms

Example 1: Roof for Jilin Skating Hall (built in 1986)

Example 2: Foshan Century Lotus stadium

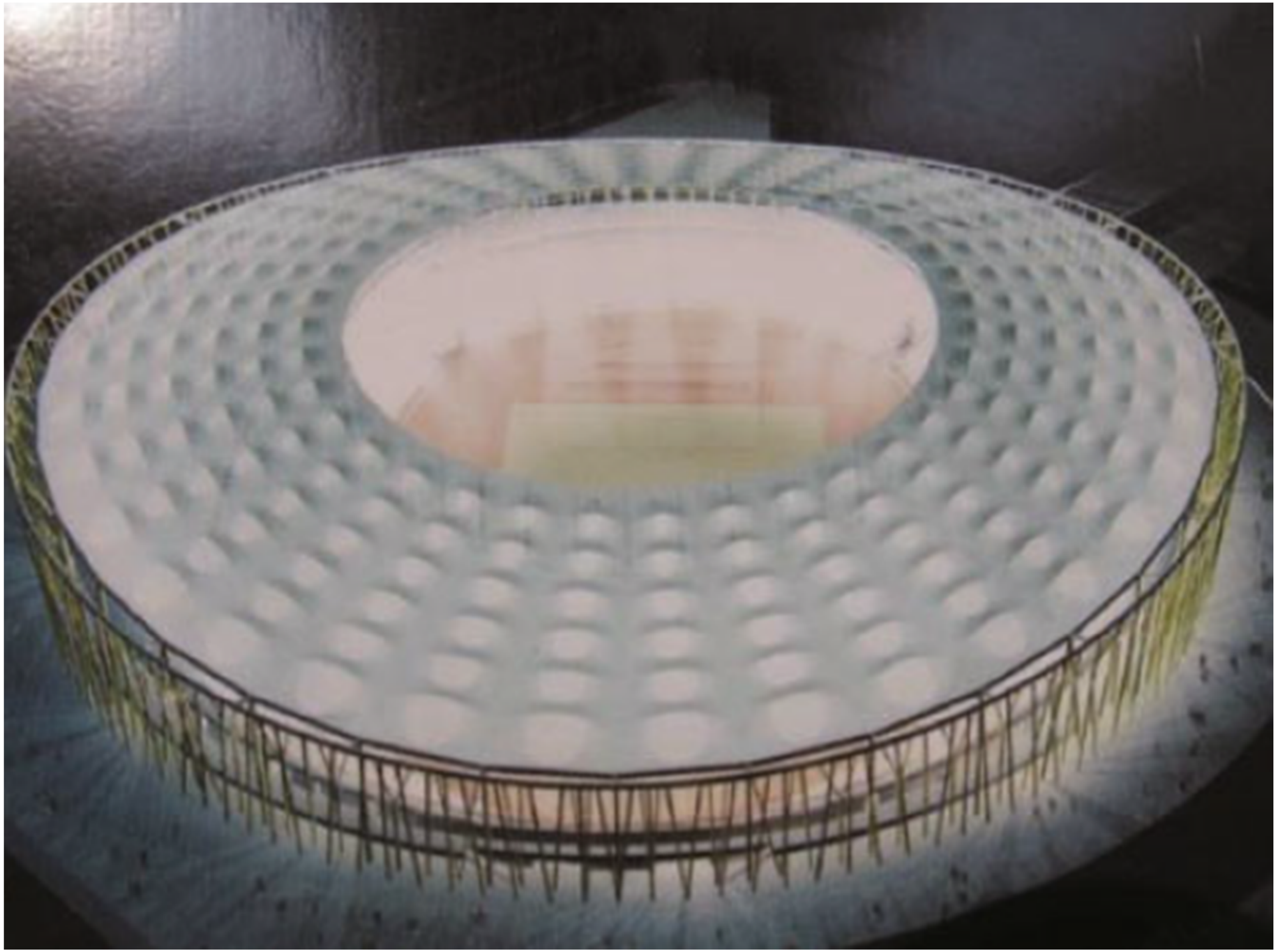
- Outer diameter = 310 m
- Inner diameter = 125 m
- Folded-plate type cable truss structure
- Toroidal plan supported on a toroidal truss

Foshan Century Lotus Stadium

Example 3: Baoan Stadium for Shenzhen Universidade

- Built in 2010
- Cable truss structure with an elliptic plan (230 m x 237 m)
- A box section ringbeam and tubular flying columns are arranged at the outer and inner ring of the roof
- The roofing has membrane material supported on small arch beams

Baoan Stadium of Shenzhen Universidade

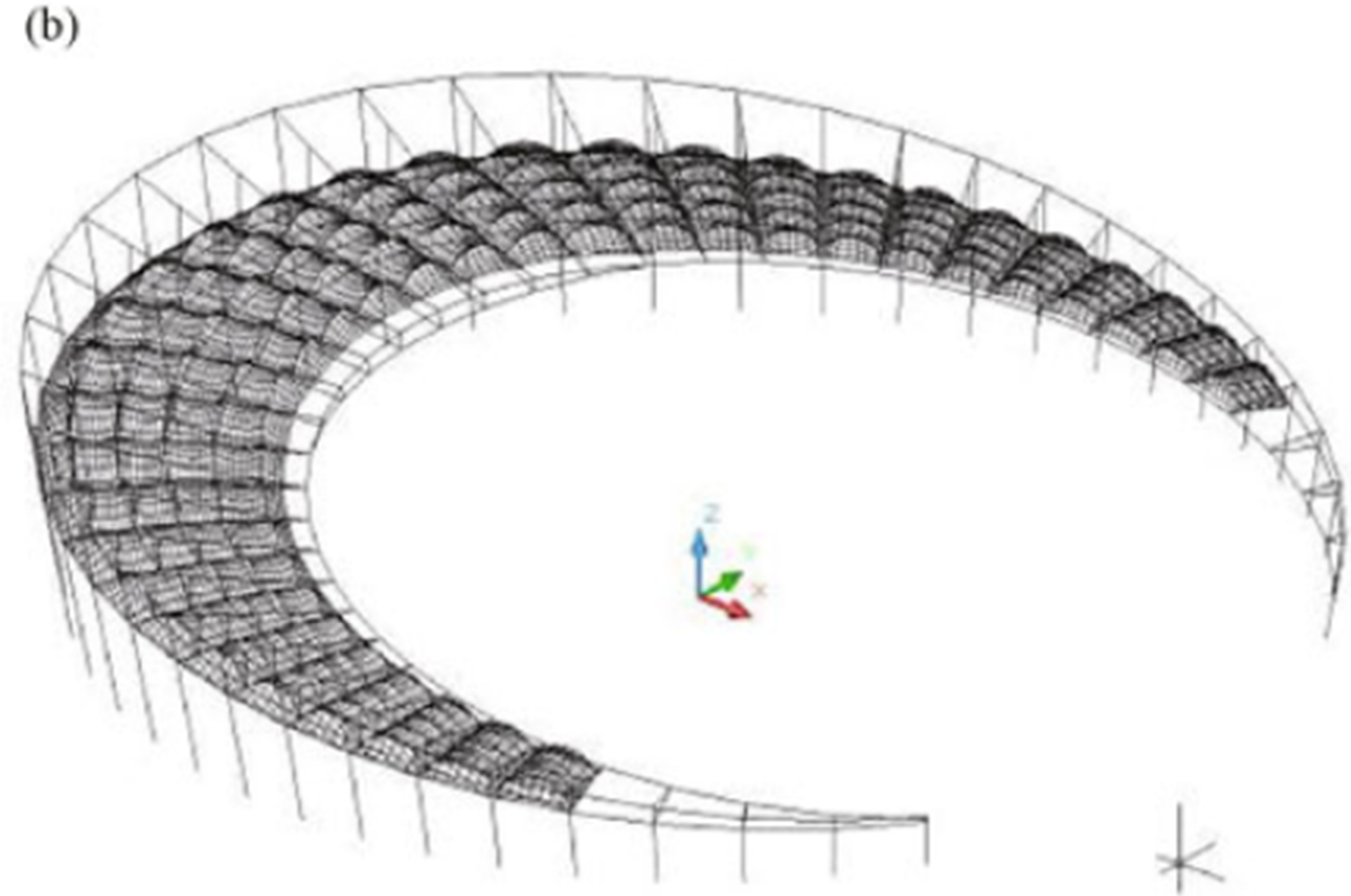


Example 4: Yueqing Stadium in Zhejiang Province

- Cable truss structure with a crescent plan
- Plan dimensions 229 m x 221 m
- Model test finished and installation started in 2011

Yuequing Stadium

Yuequing Stadium- calculation model



Cable domes

- Type of rigid-flexible combined space structure that is more flexible
- Composed mainly of cables + bar + membrane elements
- A cable dome fully realizes Fuller's ideea that "islands of compression reside in a sea of tension"
- A cable dome is a structure with high efficiency and is usually regarded as the climax of modern space structures

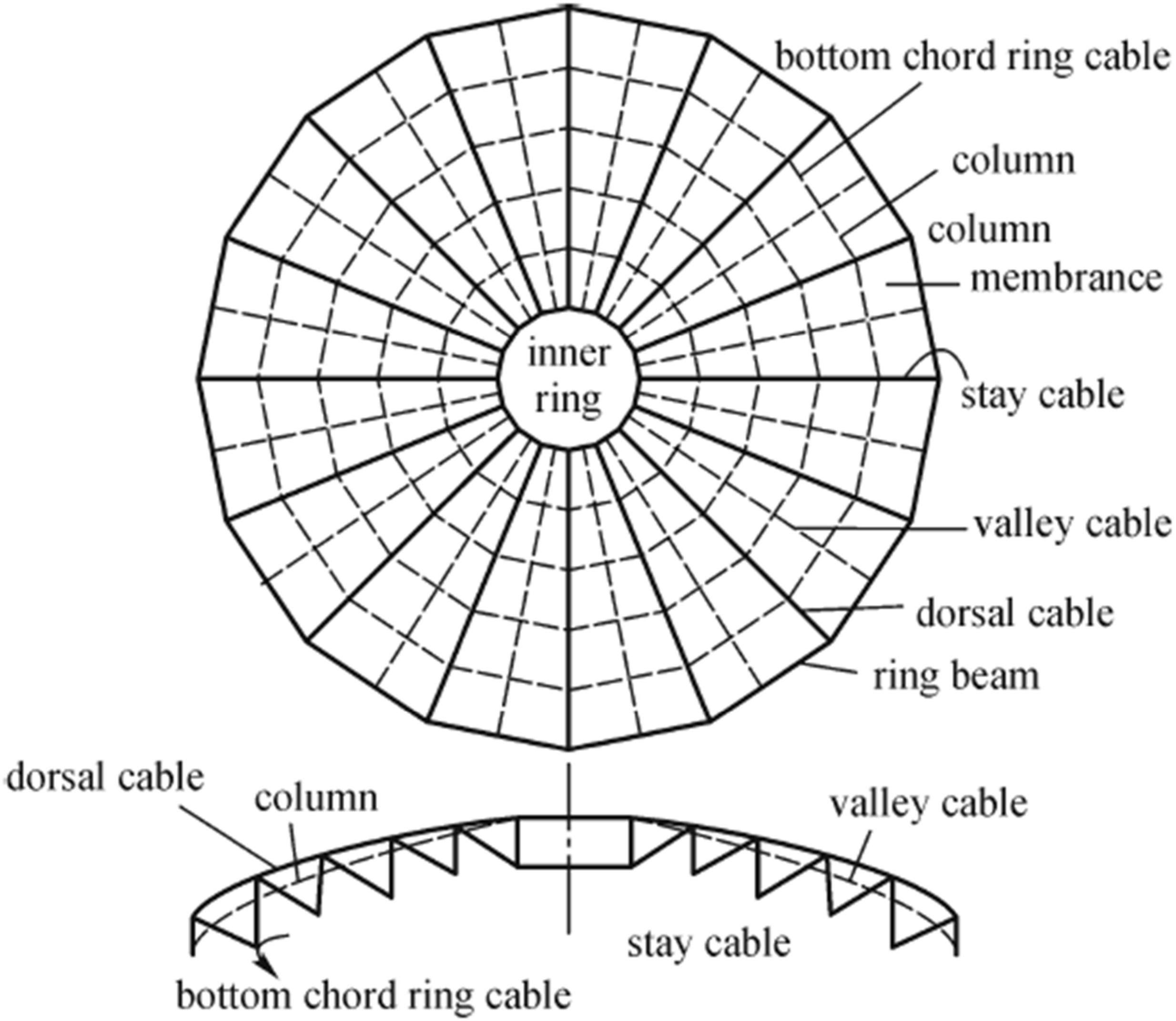
Example 1: Comprehensive Gymnasium of the Seoul Olympic Games

- Designed by the American engineer Geiger in 1986
- First cable dome in the world

The Geiger dome is composed of :

- Ridge cables
- Valley cables
- Stay cables
- Bottom chord ring cables (hoop cables)
- Vertical struts (masts)
- Outer ring beams
- Inner rings
- Membrane roofing

Scheme of Geiger dome



Comprehensive Gymnasium of Seoul Olympic Games

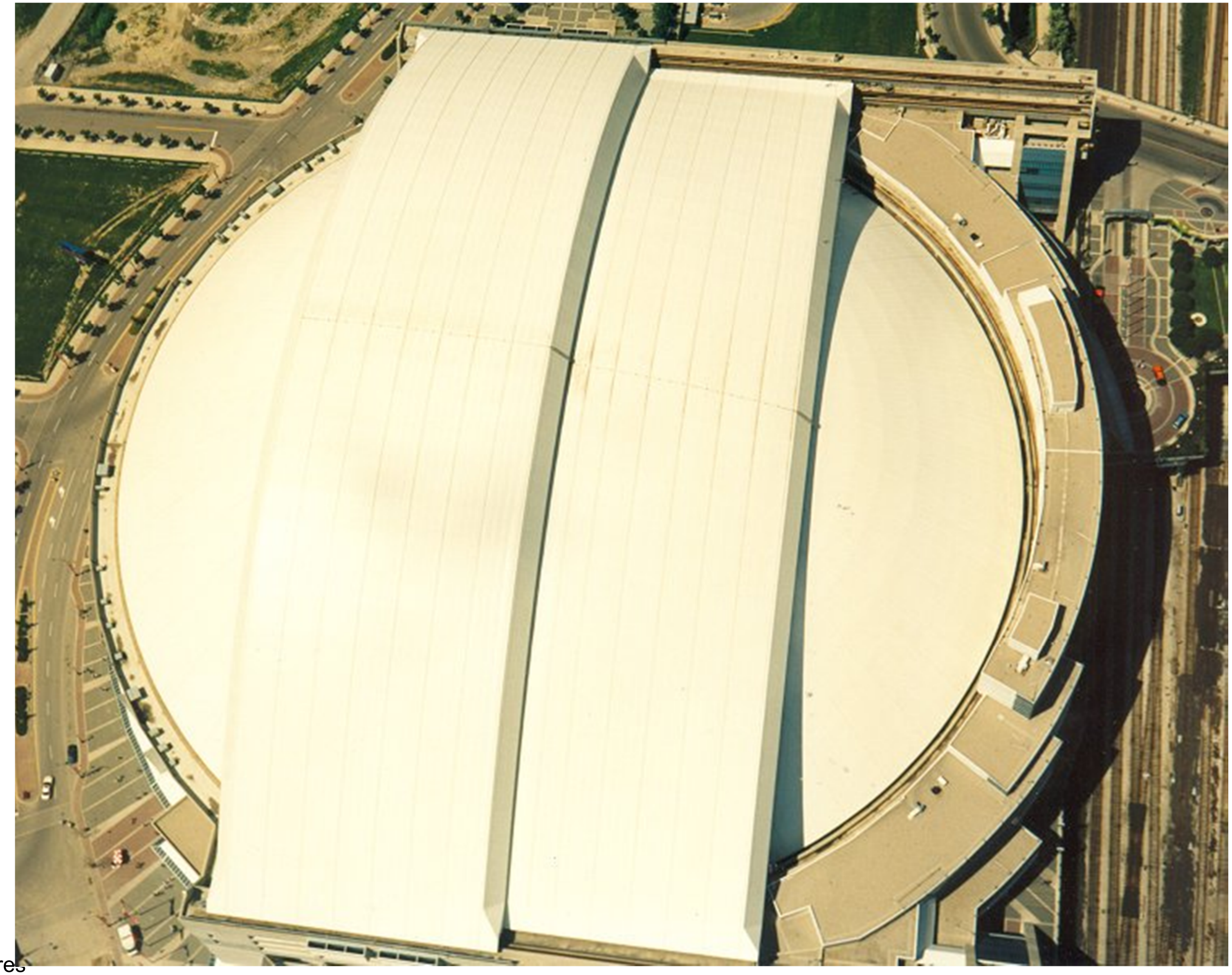
Example 2: Atrium of the factory building of the Jinhua Shengyuan Group

Example 3: Roof of Yijinhuoluo Gymnasium in Ordos

Example 4 (dome progress): Sky Dome, Toronto, Canada (1989) [3]

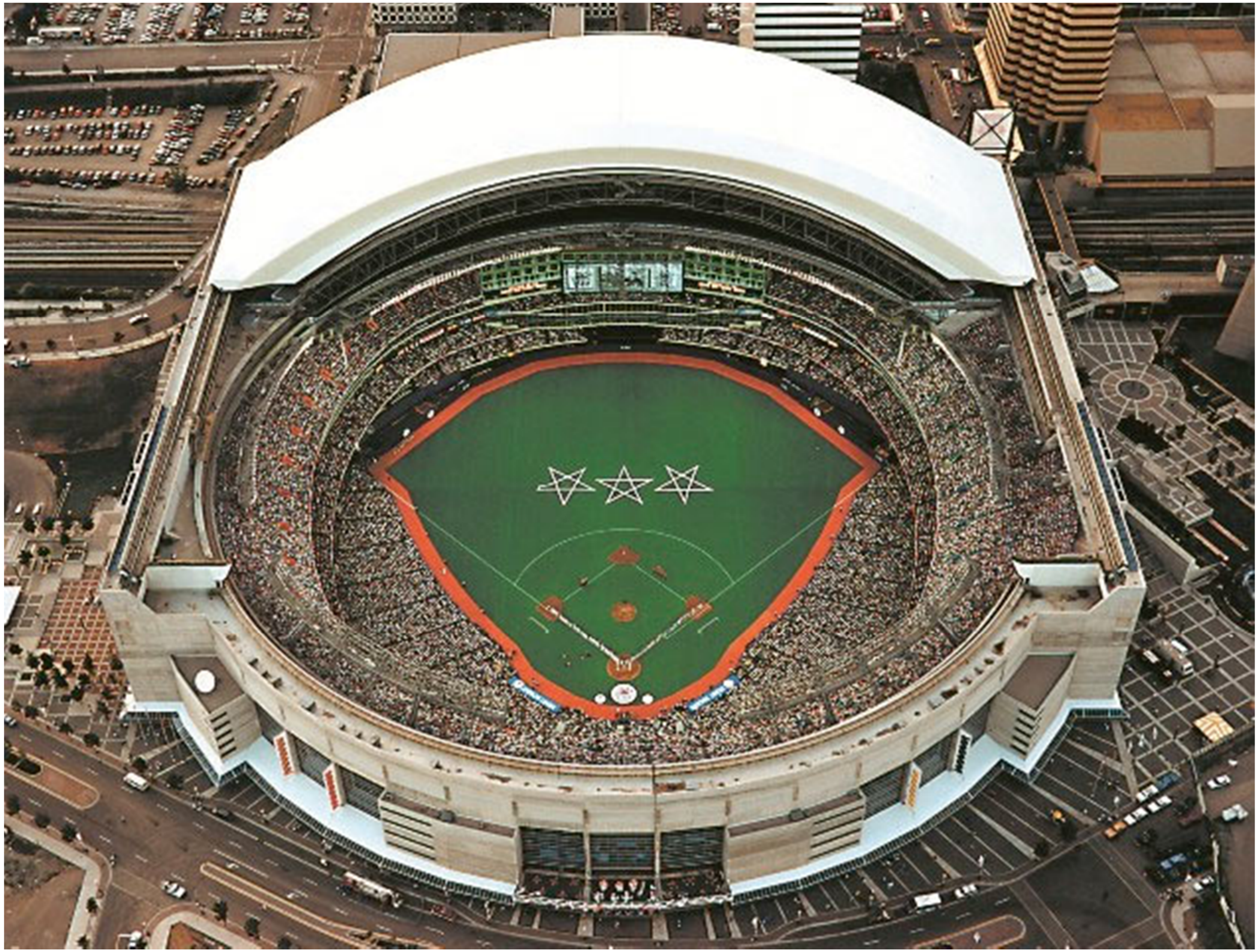
- First and only stadium to have a fully retractable roof (double layer rigid structure)
- The roof consists of four panels: one FIX panel and three MOVEABLE
- The roof operates on a system of steel tracks and is powered by a series of DC motors
- Roof weight = 11000 tons
- Span at widest point = 209 m !
- Maximum height =85 m
- Roofing material = PVC on insulated acoustic steel deck

Sky Dome, Toronto – Overview [3]



Panel one rotates around 180 degrees while panel 2 and 3 telescope straight forward [3]

100% of the field and 91% of seating area exposed with open roof [3]



Audience capacity: up to 54.000

Conclusions:

- Modern long-span space structures are structures with promotional value and application prospects
- At present time, 17 types of modern space structures exist
- More and more new types will be developed in the future

- China has won several “first in the world” awards for long span structures (serving as a relevant example), such as:

- The earliest application of new space structures
- The longest span of space structures
- The largest quantity of space structures
- The largest covering ares of space structures, etc

1.6 CHALLENGES OF LONG-SPAN STRUCTURES DESIGN

Main loads acting onto long-span structures [3]:

- Dead load
- Live load
- Wind load
- Stress created by temperature difference
- Stress created by other form of disruption, including:

- ground movement,

- vibration,

- deformation

- ….or earthquake.

Design and construction of long-span roof structures [5]:

- Requires a blend of skills from the structural engineer not normally required in normal building types
- Some forces, normally ignored in many building types, come into play and can have a dramatic effect on the structure, i.e.:
  - Material shrinkage
  - Supports settlement
  - Temperature effects
  - Sequence of erection
- Design considerations may appear belonging unique to this building type

Final Report of the American Institute of Architects (1981) [5]

- Issued after the collapse of five major long-span roof facilities in the USA over a period of two years (late 1970')
- Entitled " Towards Safer Long-space Buildings"
- Message: "Designers and Builders Beware!"
- Recommending some specific actions for the design-construction team;
- More applicable today than ever before as projects get more complex, construction budgets get tighter and schedules ever faster

Recommendation 1 [5]

About proper communication: Establish:

- the key project players
- …their roles and responsibilities
- …the proper lines of communication

EARLY in the project!

Every major design decision should be documented in writing and clearly communicated to all team members

Poor communication among the designers and builders is the biggest source of project disputes, cost overruns and delayed schedules

Recommendation 2 [5]

- Engage the fabricator / erector team as early as possible in the project
- Decisions that need to be made early (together with them):

- Grade of steel
- Connections type
- Bolt size and grade
- Welding procedures and method
- Paint type
- Construction tolerances

Recommendation 3 [5]

- Use high strength steel to save on self weight of structure
- The use of grade 65 (steel between S275 and S355 in Europe) will normally save weight and cost
- The cost premium (0 to 5%) is considerably less than the benefit from the ratio of yield strength (grade 65 / grade 50=1,3)
- Key issue: maintain compression unbraced lengths that permit the higher allowable compression stress advantage to be realized

Recommendation 4 [5]

- Utilize a wind tunnel and snow study whenever possible
- Code specified wind and snow loads can be very crude estimates of actual environmental loads with today's free form roof shapes often utilized in architectural design
- The potential gain in accuracy of these loads will often be more than offset (compensated) by the cost of the study

Recommendation 5 [5]

- Utilize roof framing systems and materials that MINIMIZE the self weight of the structure

- The designer should focus on maintaining as light a structure as possible, because the self weight of the structure is usually THE HEAVIEST design load!!!

Light weight structure types:

- Besides the use of high strength steel, framing systems that use tied arch or king and queen post truss systems usually yield the lightest structures

- Mast and cable suspended structures, possibly with the use of fabric roof membrane (where the architectural design allows) can be particularly economical

- Tied-down cables and masted roof systems should be considered where good rock foundation conditions exist

Recommendation 6 [5]

- Avoid the use of expansion joints in the roof structure
- Expansion joints are very difficult to accommodate in long-span roof design and should be avoided
- According to existing experience, temperature forces in long-span structures rarely seem to control the design of most members
- However, a temperature change analysis should always be performed in a long-span structure, particularly to detect excessive forces in the structure from unwanted support restrains

Recommendation 7 [5]

- Consider additional design dead load for possible future re-roofing of the structure
- It is impractical, disruptive and even dangerous to remove old roof membrane and metal decking in the future (because of unbraced length of the roof members and possible instability from unwary demolition construction workers)
- Additional layers preferable!

Recommendation 8 [5]

- Consider temperature, erection and foundation settlement loads in the design and construction
- Temperature loads rarely control the design of the members but they can have a dramatic effect on erection fit-up, particularly when field welding is involved
- Welding long-span steel is very problematic because of thermal shortening in the temperature variable climate of erection
- Some of the most critical member stresses can occur during erection because of lifting stresses and of un-braced lengths that can exist different from those assumed in the final as-built structure

Recommendation 9 [5]

- Don't be overly concerned with roof deflection and camber in long-span roofs

- The exact position of the final roof structure in space is rarely critical, as long as

- adequate roof slope exists to drain the roof,

- …and architectural form,

- …and sightlines are not compromised

Recommendation 10 [5]

- Pay close attention to diaphragm stresses, diaphragm bracing of structural members and diaphragm attachment
- Diaphragms can be critical to the structural integrity of the roof, because of bracing provided to roof members and the need to transfer external wind and seismic forces to the vertical lateral load resisting system, often at great distances
- The designer must decide whether to allow a metal deck roof diaphragm to brace a long heavily loaded compression chord of a roof truss, or to install special horizontal bracing members for this purpose
- The decision is particularly critical during the vulnerable erection phase of the project

Recommendation 11 [5]

- Use bolted field connections whenever possible
- "Shop weld- field bolt" is a good motto for long-span roof construction
- Difficulty of welding high in the air in windy conditions and variable temperatures =makes field welding difficult to implement and to inspect
- Consider only two bolt sizes on the project: one for highly loaded members and one for routine purlin and brace connection (say M30 and M20)
- Sometimes slip critical bolts in oversize holes is preferred, even though this would imply a larger number of bolts than for bearing type connections

Recommendation 12 [5]

- Consider pre-assembly of long-span trusses in the shop, in whole or in part, depending on available shop space, to reduce fit-up problems in the field

- Fit-up problems can result in costly retrofit and delays

Recommendation 13 [5]

- The structural engineer should design all major long-span roof connections and NOT delegate this responsibility to the fabricator
- This practice will reduce design and shop drawing review time and will ensure that the connection design meets the intent of the long-span structure design
- Long span roof design can often contain as many as 150 or more load combinations. To communicate accurately this information to the fabricator can be a real challenge.
- If the fabricator is on board early, connections designs can be tailored to the shop practices of the fabricator for an economical design

Recommendation 14 [5]

- Group member sizes and make members as REPETITIVE as possible (EVEN at the cost of some extra weight in the structure) to simplify mill ordering of steel and to reduce detailing and fabrication costs
- The structure should be framed to reduce the number of pieces to be fabricated and erected
- Remember that "least weight is not necessarily least cost"
- The price of in-place structural steel in today's marketplace is much more about man hours fabrication and erection per ton of steel than in Euro per square meter of steel
- Labor costs are more dominant than the material cost of steel

Recommendation 15 [5]

- Analyze the structure you design and design the structure you build

- Many past problems with long-span steel have arised from a discrepancy of the structural model from the actual as-built conditions

- Often eccentricity of member forces has not been properly considered and has compromised the structural behavior

Recommendation 16 [5]

- Require a detailed written erection procedure
- The written procedure should be reviewed and approved by the general contractor, fabricator, erector and engineer of record
- This document is important to ensure that all parties are in agreement on the method, sequence and timing of the critical erection process
- A thorough study and documentation of the erection procedure will force all parties to plan the erection procedure early, and help flush out problems befor they occur in the field

Recommendation 17 [5]

- The structural engineer should be actively involved in field observation of the construction process
- It is preferable to have an engineer who is part of the structural design team on site, full-time, observing the construction and making sure that the work is proceeding according to the intent of the construction documents
- All successful projects are a result of close collaboration and teamwork among the owner, designer and builder.

1.7 Some particular aspects regarding membranes

Global analysis of membrane structures: [6]

- Solution using a specialized software
- The supporting structure is an inseparable component of the model
- Separating membrane and substructure leads to imprecision

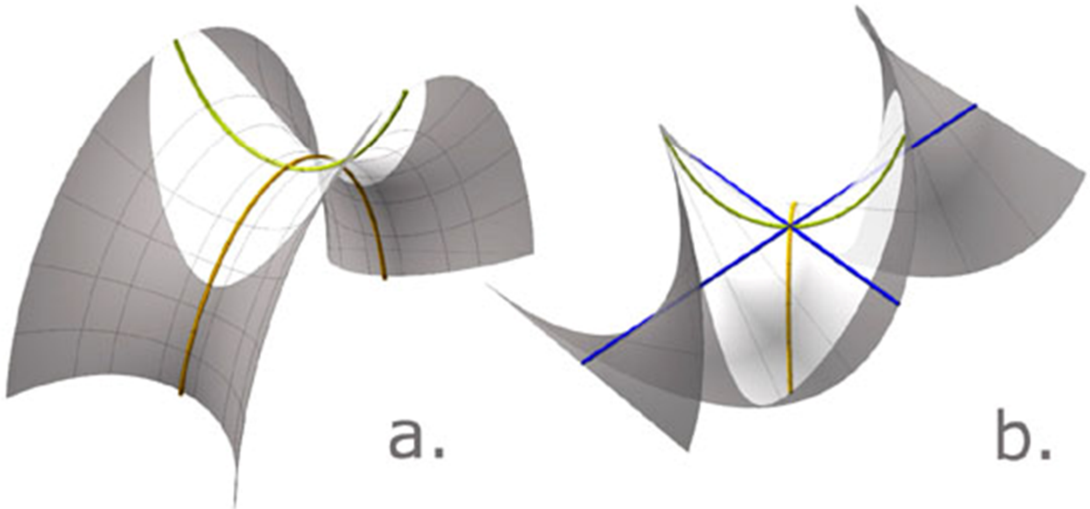
Membrane pre-stress and applicable shapes [6]

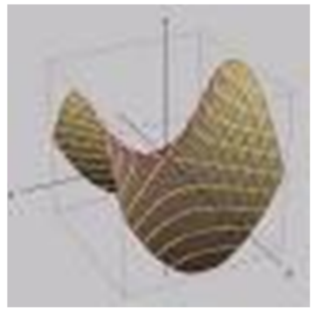
Prestress = fundamental requirement for appropriate function of the membrane

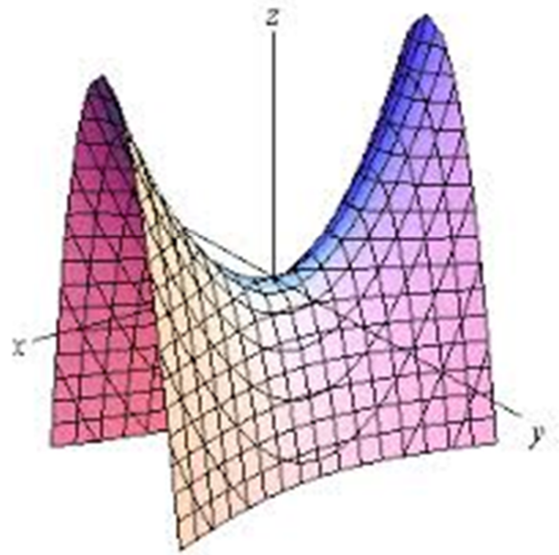
Shapes: Anti-clastic curved shapes are applicable only

Sinclastic surfaces = NOT applicable in case of membrane structures

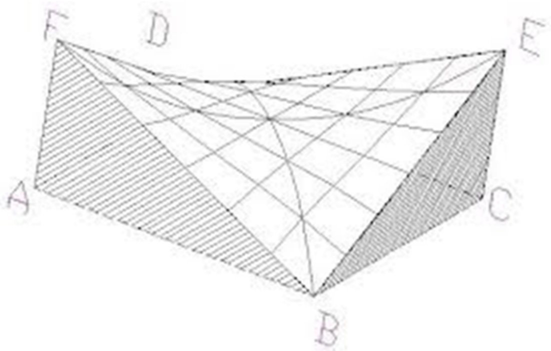
Anticlastic= saddle type surfaces with opposite curvatures







Anticlastic surfaces



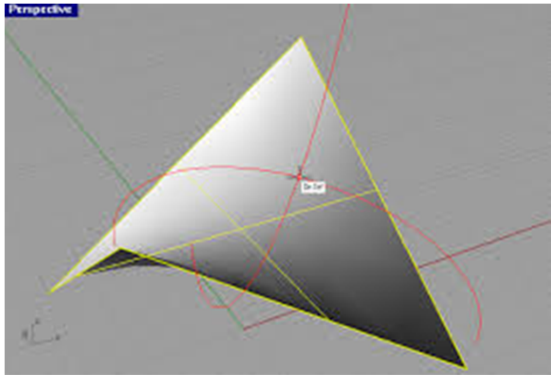
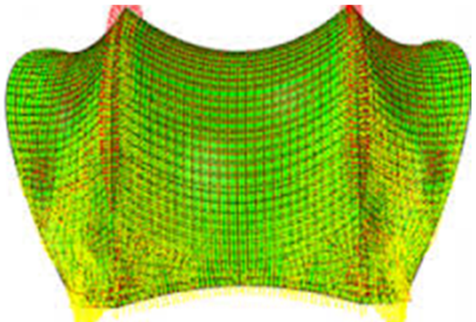
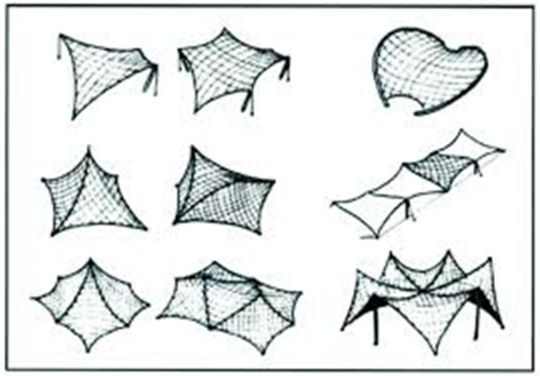
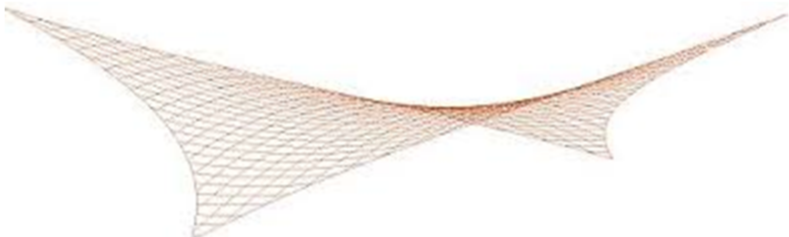


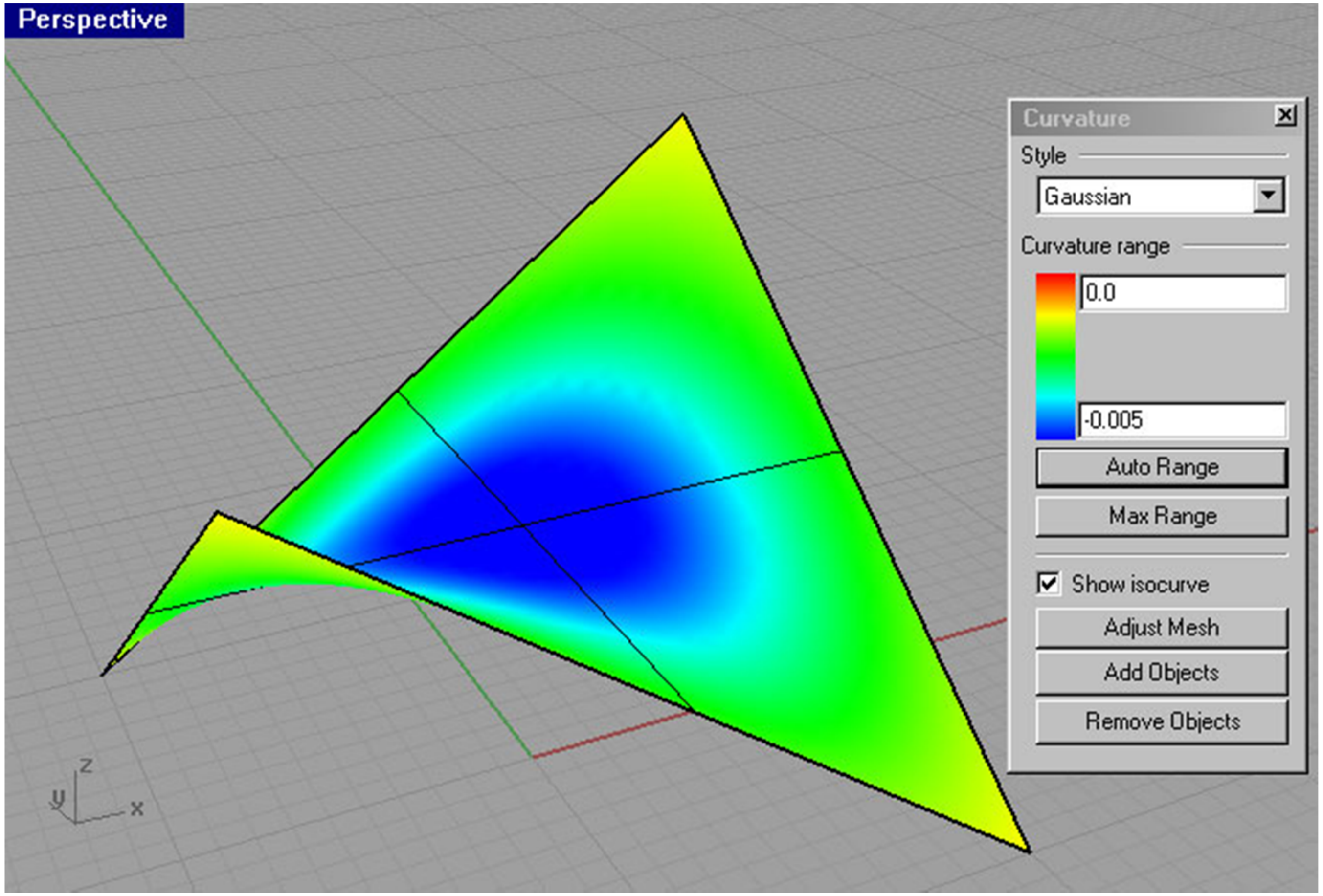
figure 2: a cone



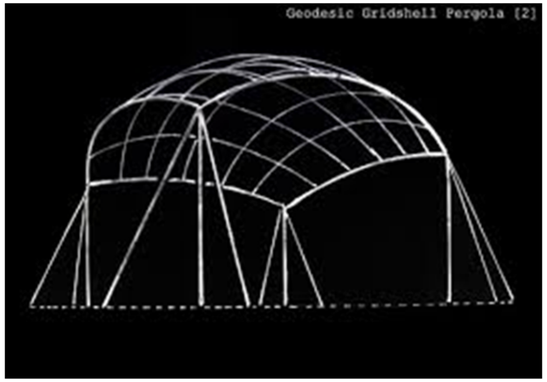


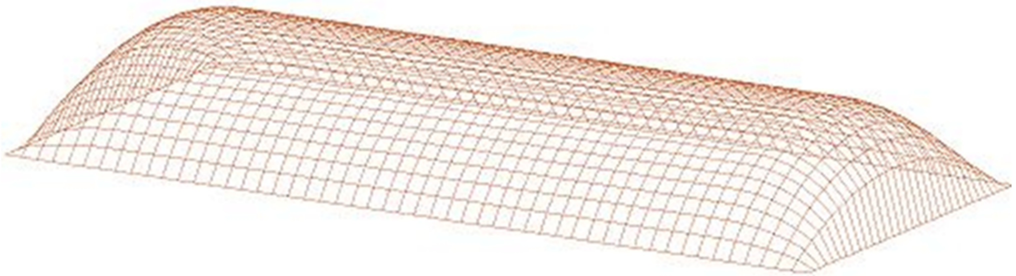


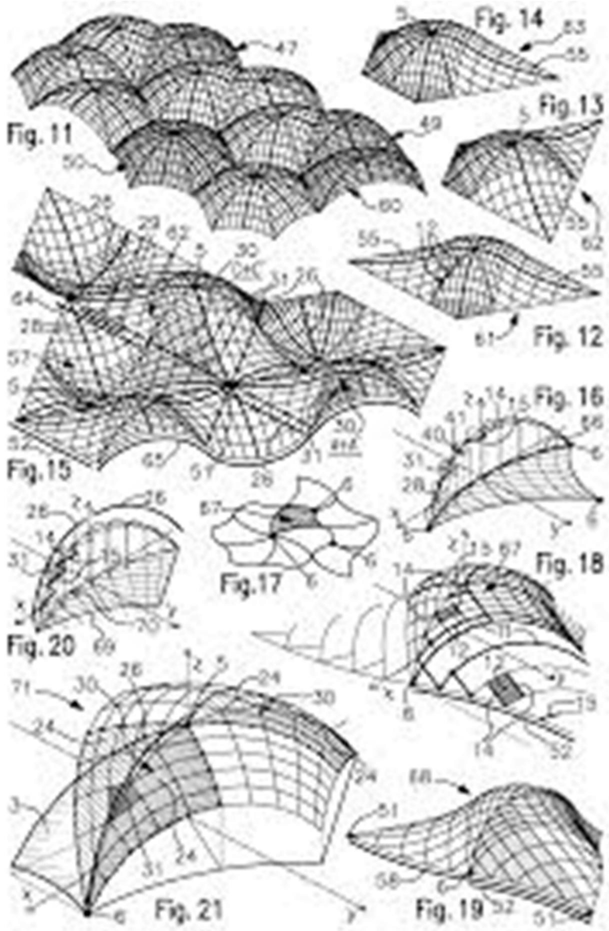
Anticlastic surface:



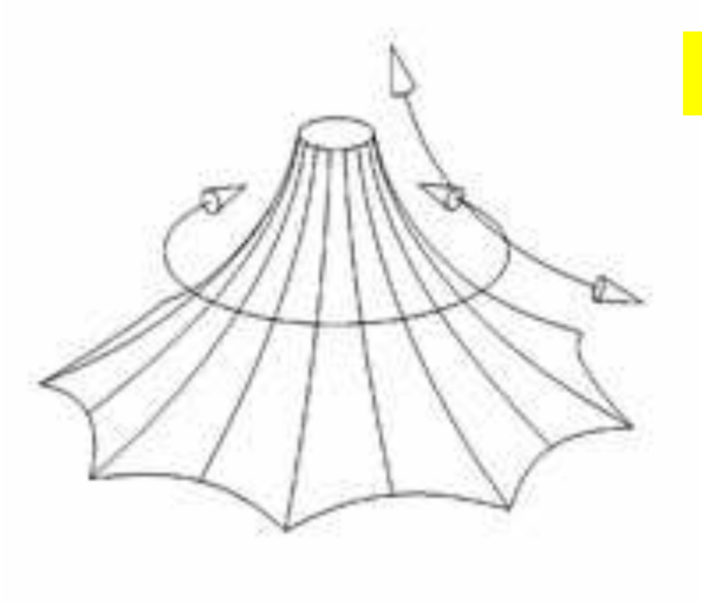
Synclastic shapes = with constant curvature (NOT appropriate)





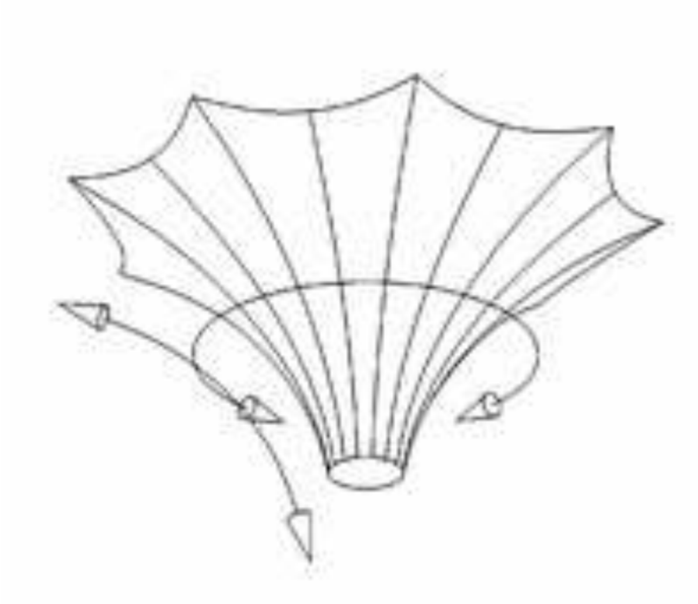


Example 1: Conic membrane, positive orientation [6]



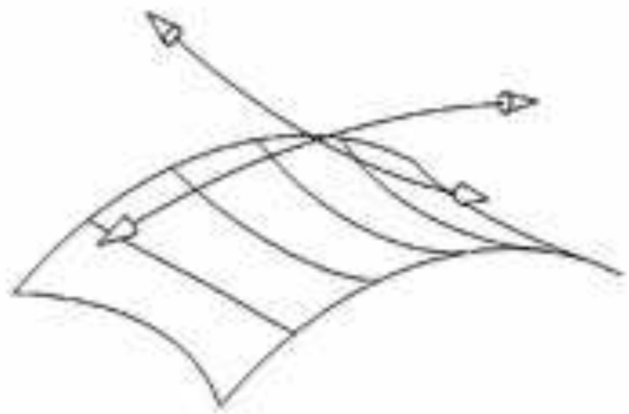
Mechanically pre-stressed

Example 2: Conic membranes, negative orientation

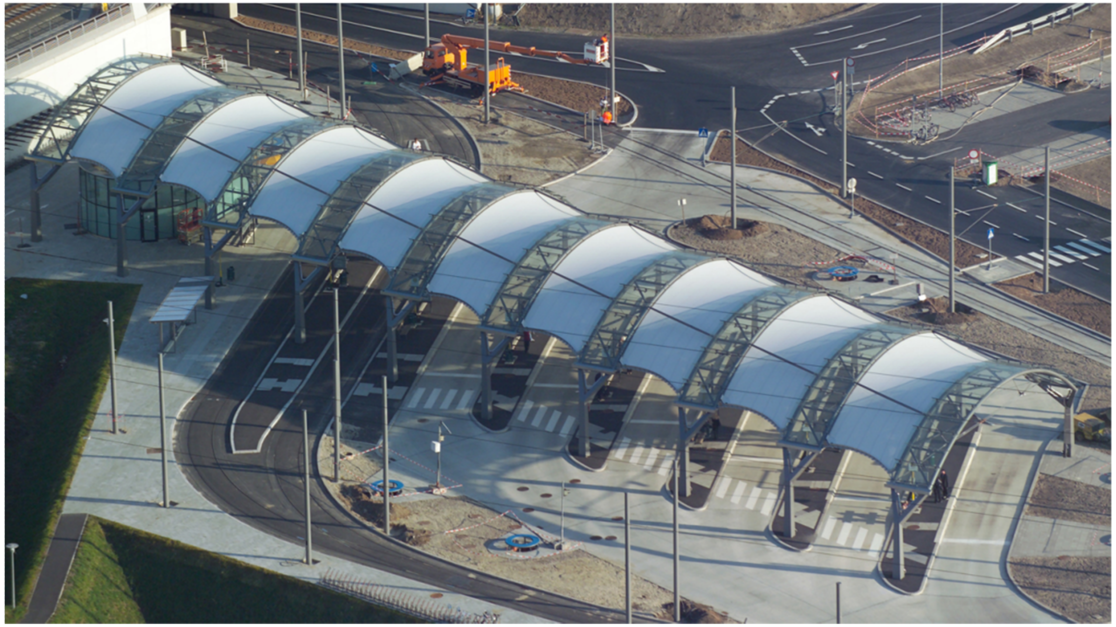


Mechanically pre-stressed

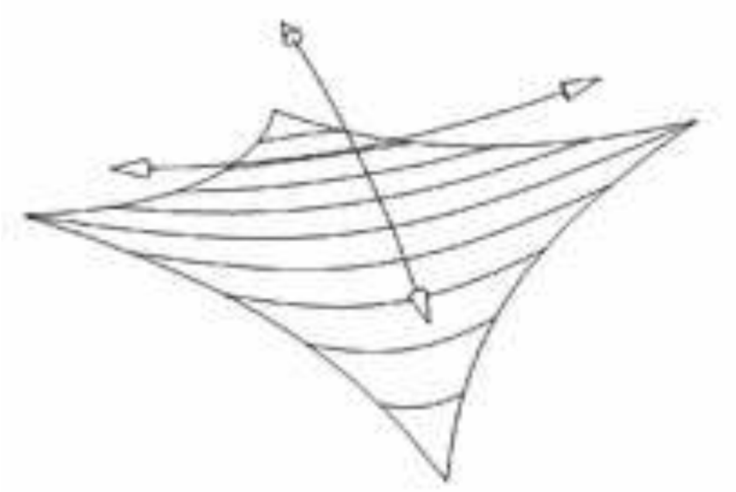
Example 3: Saddle shape (anti-clastic) on arches [6]



Mechanically pre-stressed

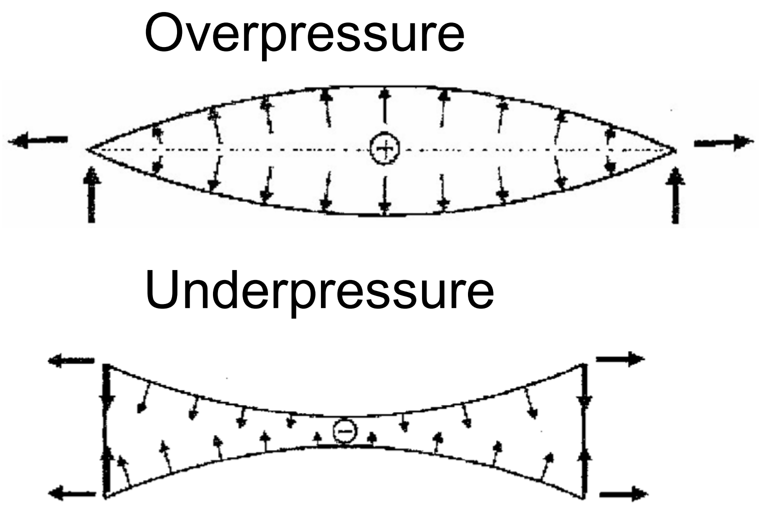


Example 4: Basic 4-points fixed membrane: hyperbolic paraboloid [6]:



Example 5: Cushions [6]

Pneumatically pre-stressed

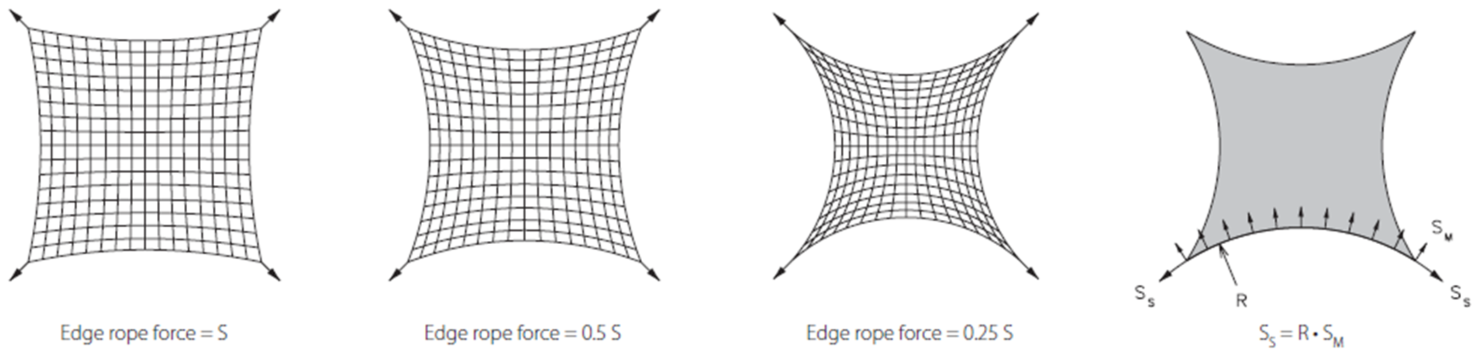


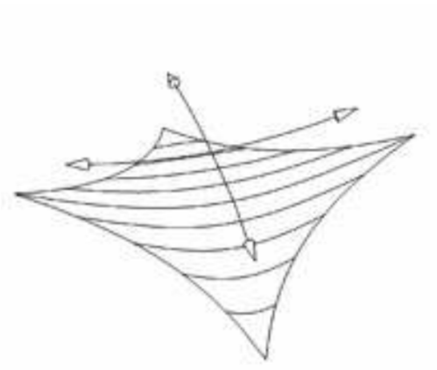
Membrane materials [6]:

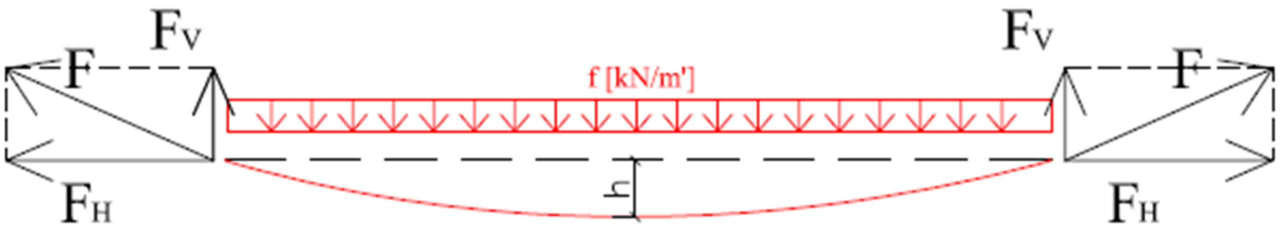
1) Textile ortothropic material with properties measured by bi-axial tensile test [Strength up to 170 kN/m; Young Modulus =approx 900-1000 MPa]
2) ETFE foil [Thickness =0,2 mm; Strength = 65 kN/m; 2-5 foil placed into aluminium frame; span more than 3,5 m needs supporting cable net]
3) Stainless steel cable net [Strength > 1000 MPa, depending on cable materials]

Design rules of the membrane and substructure [6]:

- **Shape of the membrane** corresponds to the state of stress (influence of the prestress and future load on geometry).



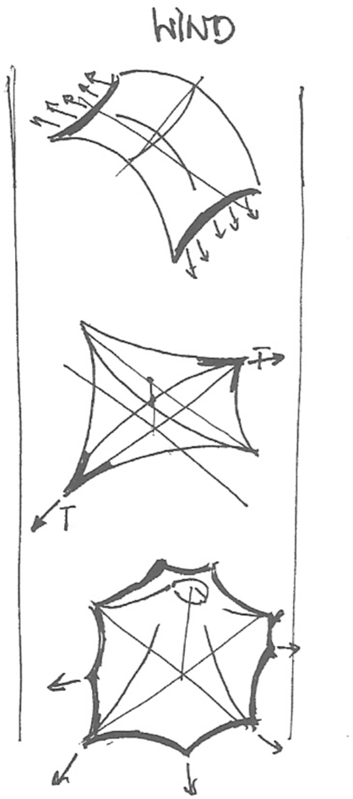


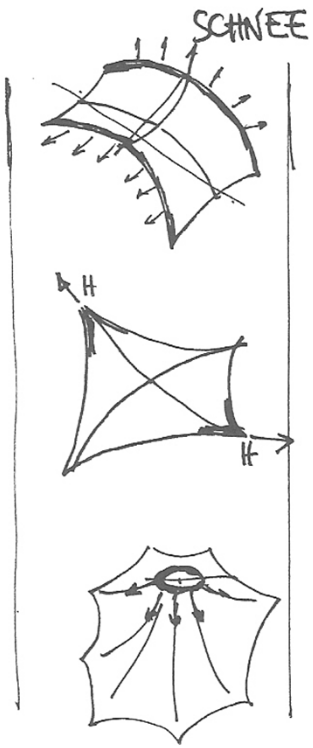


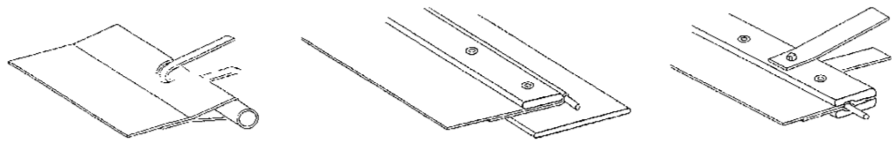
Software for forming – www.formfinder.at

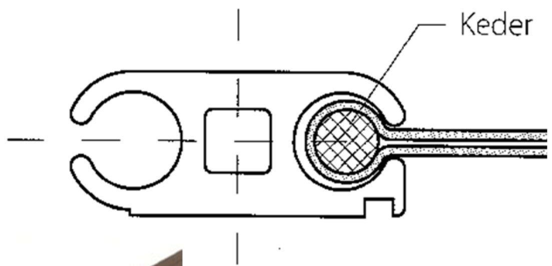
Design rules of the membrane and substructure [6]:

- Fixing (attachments) and steel substructure have to carry the tension forces from the membrane subjected to prestress and external surface load.









Rectification of the installed membrane using tensioning devices [6]:

- Possibility of rectification during construction and life-time.

Condition for the supporting steel structure [6]:

- The structure has to exhibit spatial stability to be able to carry out all possible loads to the base ground.

Design rules of the membrane and substructure [6]:

- The interaction between membrane and steelwork has to be taken into account (either by unified analysis of steel structure and membrane or considering geometry and rigidity of the supporting framework in separate membrane analysis).

Unified analysis

Separate analysis

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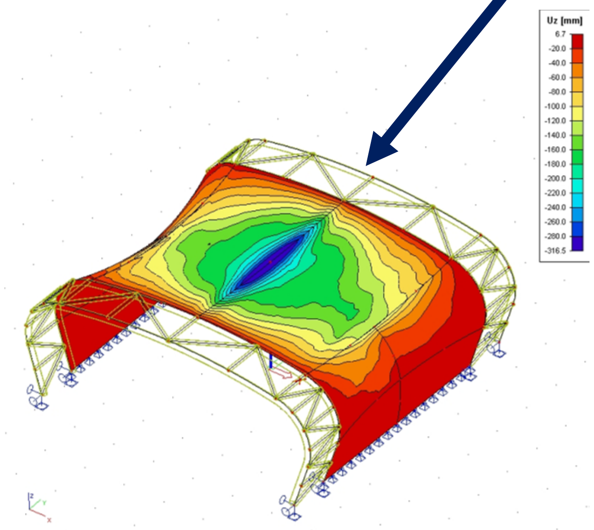

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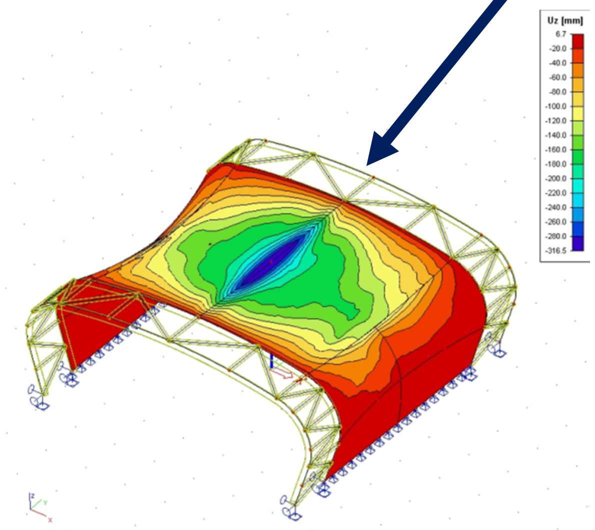

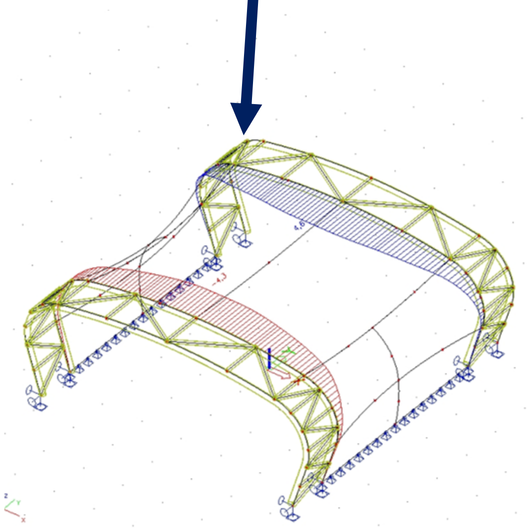

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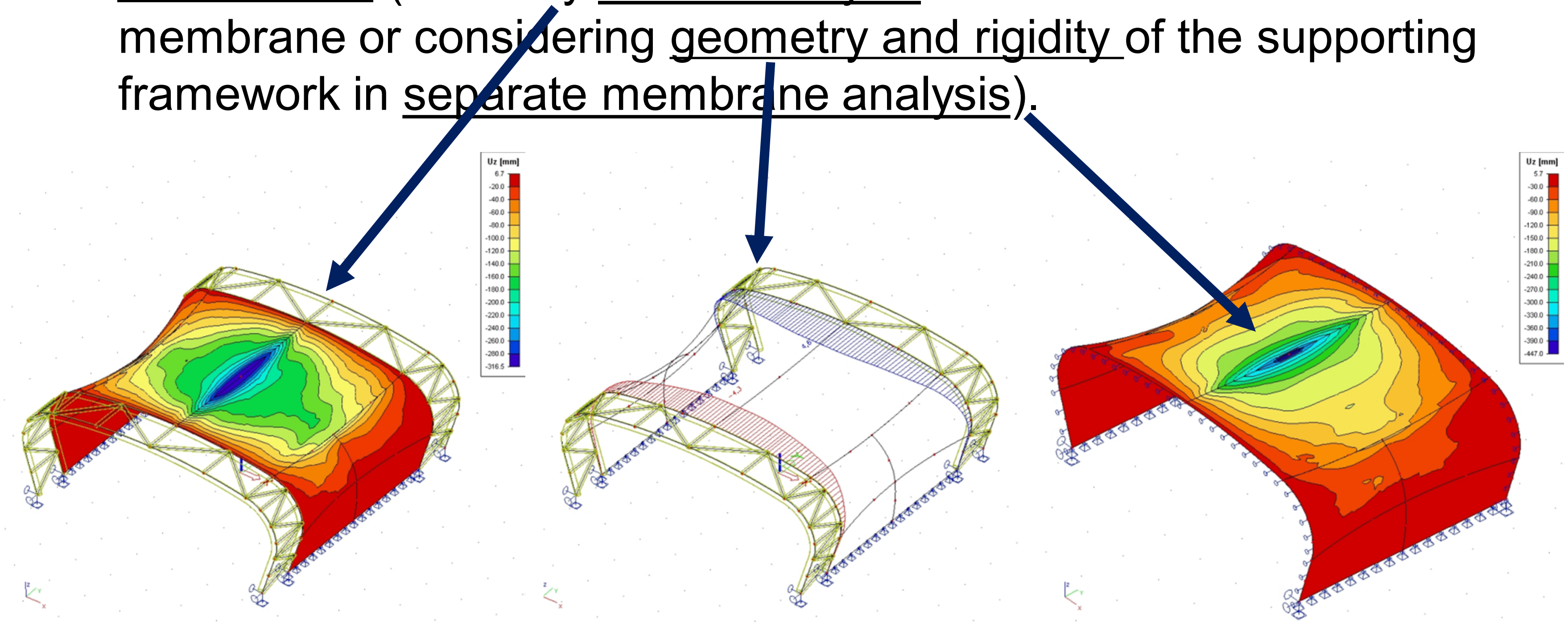


Unified analysis

Separate analysis

Prestress [6]:

- fundamental parameter of all membranes
- activates the stiffness of the membrane and its ability to carry the load
- required level of prestress can be reached in practice by:

1.) Stretching of the membrane in 2 direction with opposite curvature.

2.) Stretching of the membrane towards stiff points or continous structure

- adequate prestress level requires:

1.) Properly designed details (allow rectification).

2.) Well designed construction procedure (prestress in one direction affects the other one).

Prestress level is ussually 0,7 – 2,0 kN/m, exceptionally 5,0 kN/m^2

Individual for each structure according to the geometry and external load

Prestress [6]:

Processes of applying edge loading:

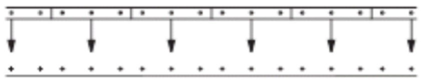
[redacted]

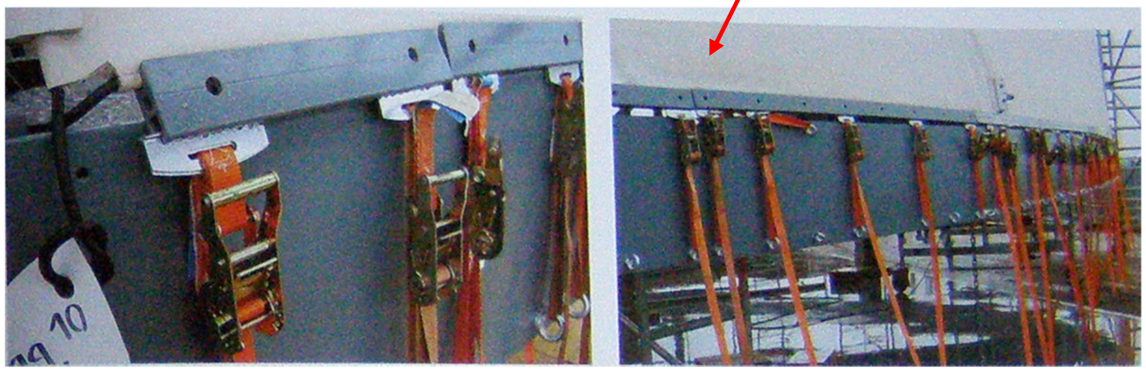
linear

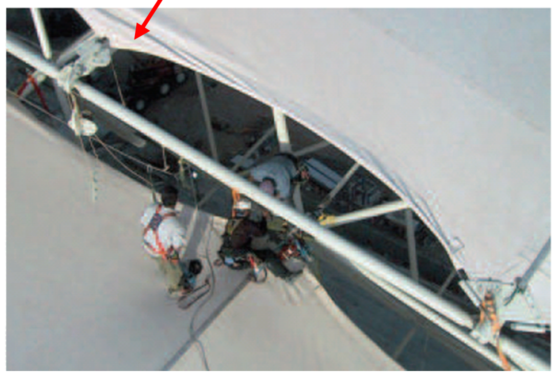
at points

Tensioning the flexible element by

direct pulling







Example of membrane- Exhibition hall [6]:

References (2):

5) Lawrence G. Griffis –The Nature of Long-Span –Structure Magazine, November 2004 [www.structuremag.org/OldArchives/2004/november/LongSpan.pdf]

6)M. Netusil – Membrane Structures: Design, Calculation, Evaluation, Performance…-SUSCOS lecture

7)Prof. Schierle – Anticlastic membranes and cable nets [www-classes.usc.edu/architecture/structures/Arch513/lecture/07-membranes.pdf]

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