LONG SPAN STRUCTURES: PART 1

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Sustainable Constructions
under Natural Hazards and Catastrophic Events
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CONTENTS

1.1 General about long span structures [2]

- Definition of long span building [2]: Buildings that create unobstructed, column-free spaces greater than 30 m (100 feet) for a variety of functions / activities

Examples of relevant activities:

- …where visibility is important: i.e. auditoriums and covered stadiums
- …where flexibility is important: i.e. exhibition halls and certain type of manufacturing facilities
- …where large movable objects are housed: i.e. aircraft hangars

Spectacular long span structures in late 20th century [2]:

Upper limits of span for previously mentioned categories:

- Largest covered stadium =210 m span
- Largest exhibition hall = 216 m span
- Largest hangar = 75-80 m span (to fit largest commercial fixed-wing aircraft with a wingspread of 69,4 m)

- OBSERVATION: in such buildings the structural system is a MAJOR CONCERN!

Structural systems: Classification

Classified into two groups [2]:

- Structural systems subject to bending (have both tensile and compressive forces)

- Funicular structures (work either in pure tension or in pure compression): use of cables combined with rigid members

OBSERVATION: Bridges are a common type of long-span structure which has continuously influenced the development of long span buildings!

Bending structures include:

- The plate girder (made of welded steel plates to produce beams deeper than standard rolled shapes: span up to 60m)
- The two-way grid (made either of two-direction plate girders : span up to 90 m)
- The one-way truss (hollowed out beam, made of linear slender members joined together in stable triangular configurations with optimum h/L = 1/5…1/15)
- The two-way truss (made of two-directions trusses)
- The space truss / grid (optimum h/L=1/40)

[h/L = depth-per-span ratio]

Funicular structures include:

- The parabolic arch: in form of truss for greater rigidity, reach spans up to 98 m;
- Tunnel vault-and-dome (act in pure compression; have rise-to-span ratio 1:10…1:2).Steel truss domes = used for several stadiums reaching 204 m span
- Cable stayed roof = derived from bridge building (steel cables radiating downwards from masts that rise above roof level: spans up to 72 m result)
- Bicycle wheel = two layers of radiating tension cables separated by small compression struts, connect a small inner tension ring to the outer compression ring supported by columns
- Warped tension surfaces (act in pure tension). Built of cable networks and synthetic fabrics to form <u>tension surfaces</u>

Material used for long-span structures (1):

- All reinforced concrete (RC) including precast
- All metal (e.g. mild-steel, structural steel, stainless steel or alloyed aluminium)
- All timber
- Laminated timber
- Metal + RC (combined)
- Plastic coated textile material (fabric) – for roofing / cladding
- Fiber reinforced plastic – for roofing / cladding

Material used for long-span structures (2):

- Each of previous materials is applicable up to a certain value of the (long) span
- Steel is the MAJOR material for long-span structures, allowing for the maximum spans to be reached
- The frequent use of steel is due to its advantages: i.e. light weight, high strength-to-weight ratio, ease of fabrication, ease of erection and convenient cost

1.2 History and classification

- Proposed periods of the history of long-span space structures (by the authors of paper [1]):

- Period of ancient long-span space structures (up to 1925)

- Period of premodern long-span space structures (between 1925 and 1975)

- Period of modern long-span space structures (from 1975)

Ancient long span structures (before 1925):

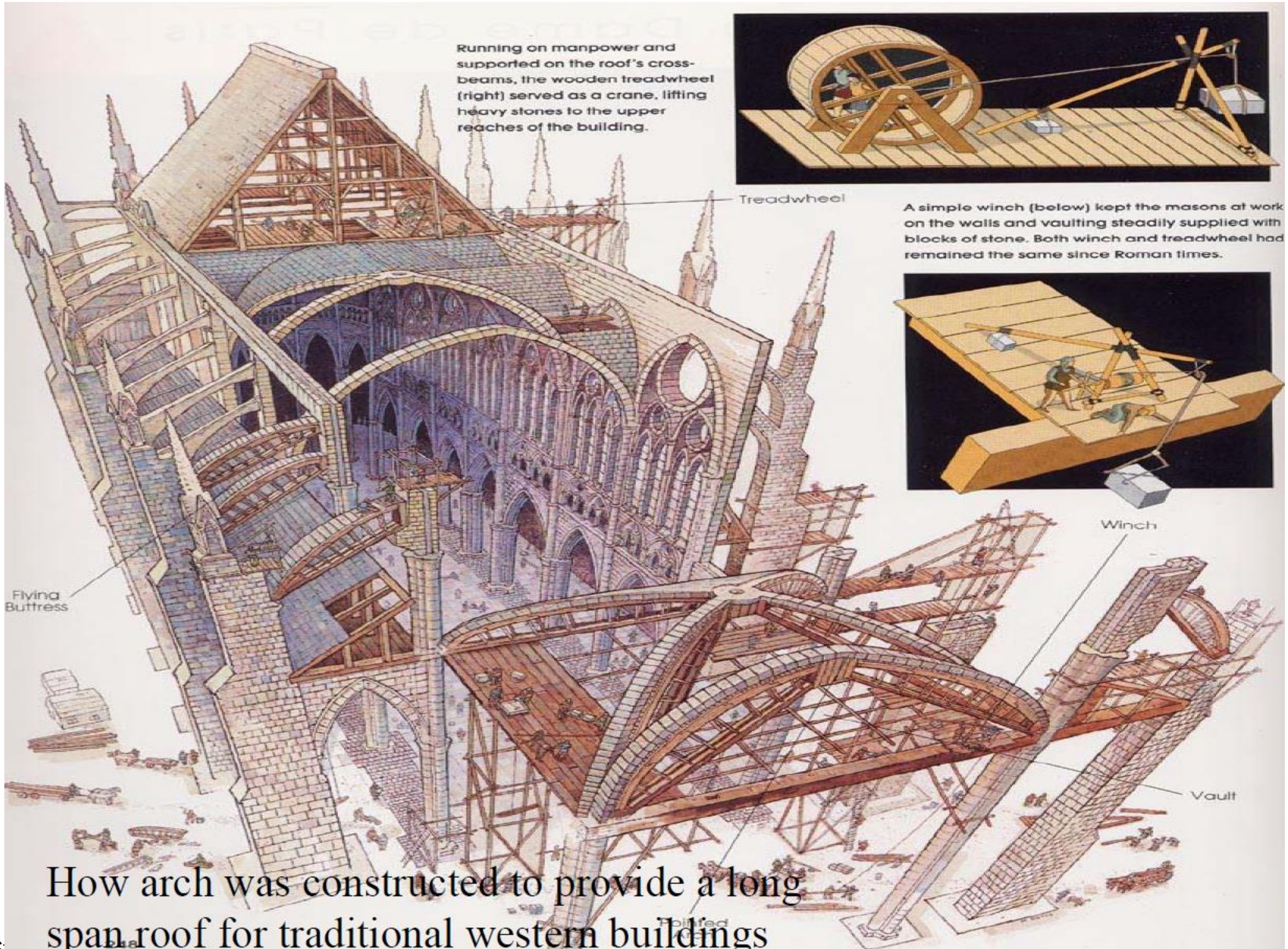
The only materials available in ancient times:

- Timber
- Masonry made of **stone** (vulnerable in tension and bending)
- Masonry of bricks made of **clay** (also vulnerable in tension and bending)

RESULT: Reaching long spans in such constructions = EXTREMELY DIFFICULT!

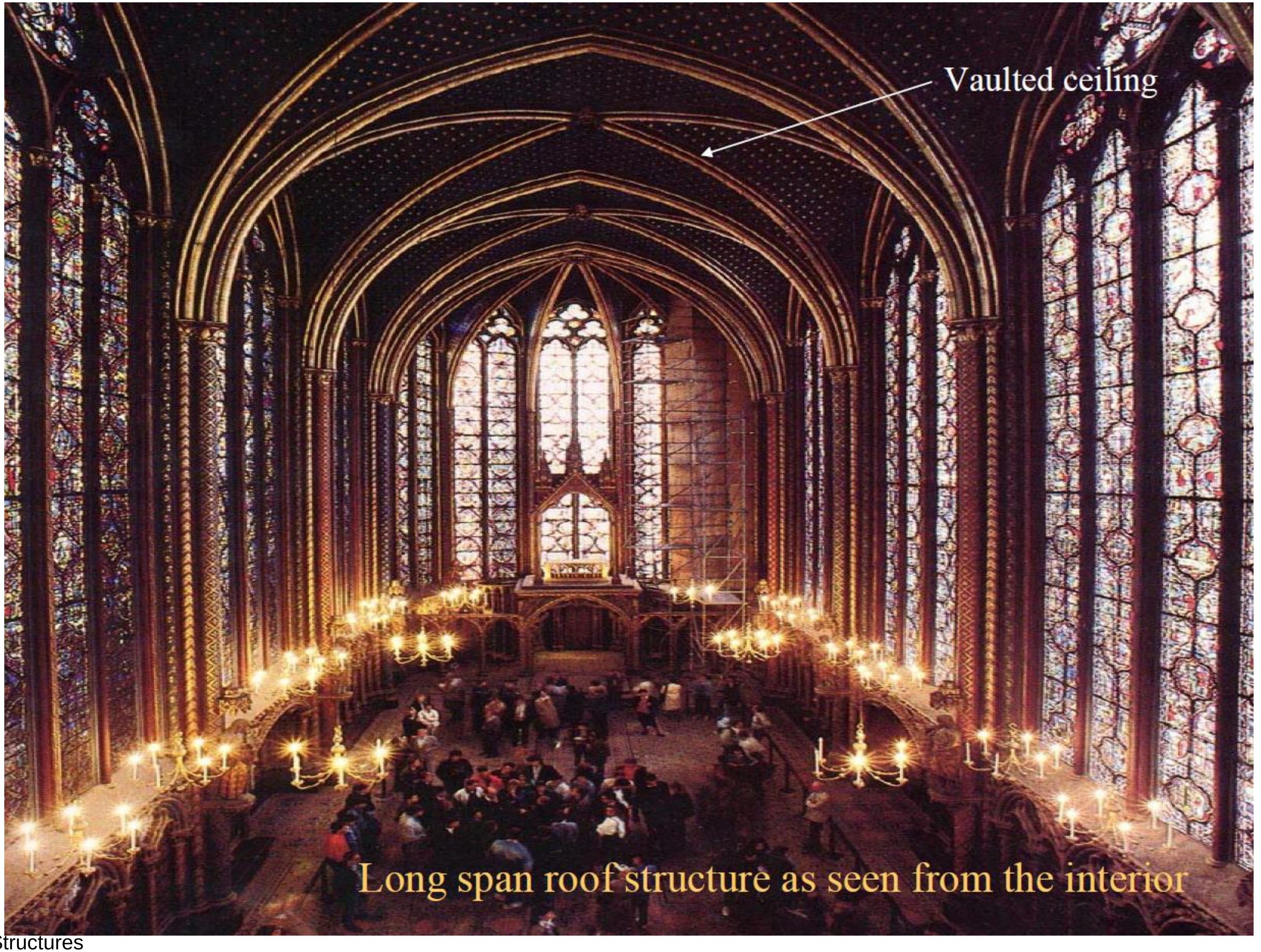
ONLY POSSIBILITY: via the arch-and-vault systems (cathedrals, palaces) working in compression only

Construction of an arch system [3]



How arch was constructed to provide a long span roof for traditional western buildings

Vault system in cathedrals [3]



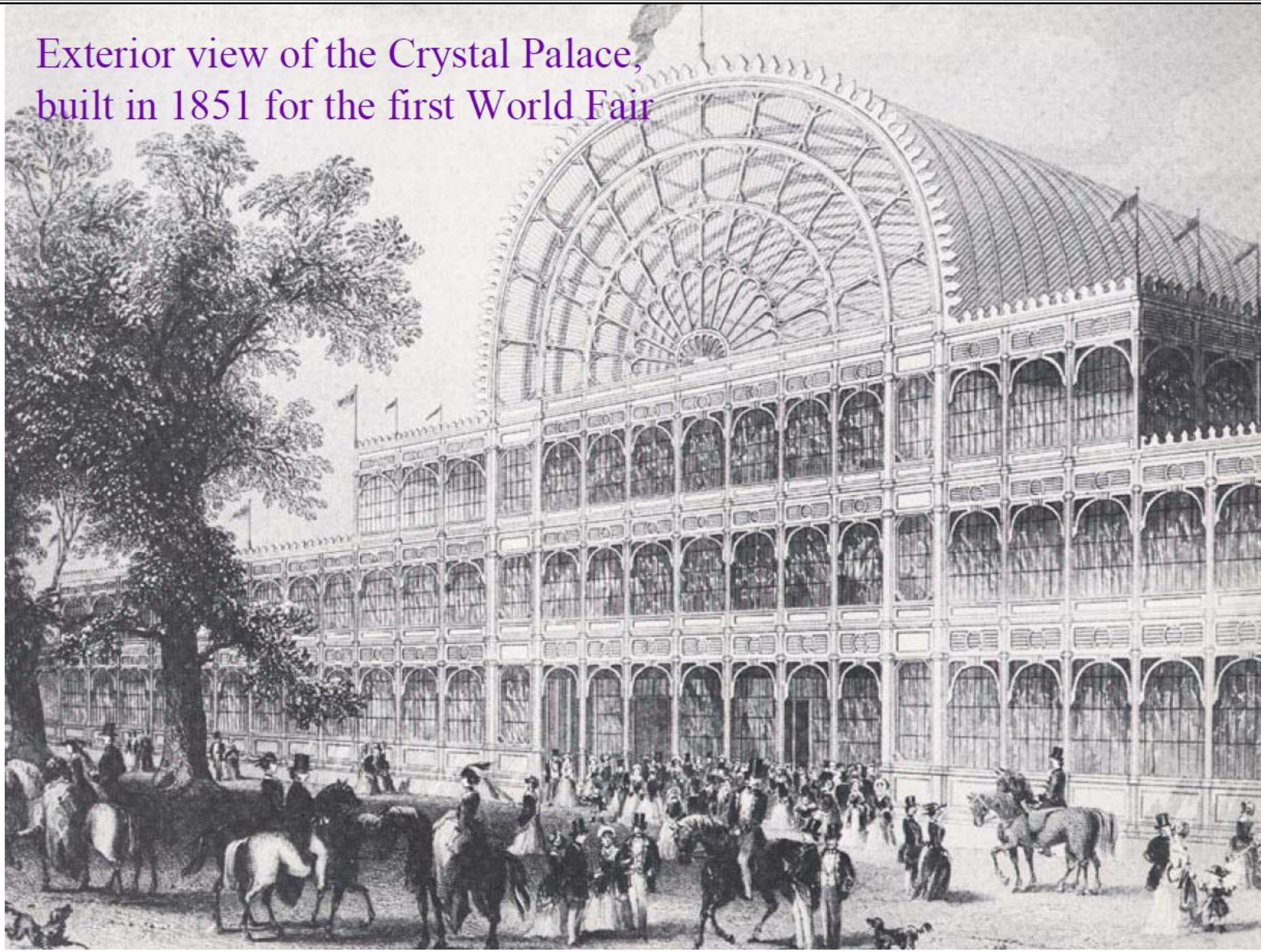
Progress: Industrial revolution (started in England-XVIII.th century)

- Production of steel on industrial scale
- Available price of steel as material used in construction
- Capability of steel to resist in tension and bending under loads

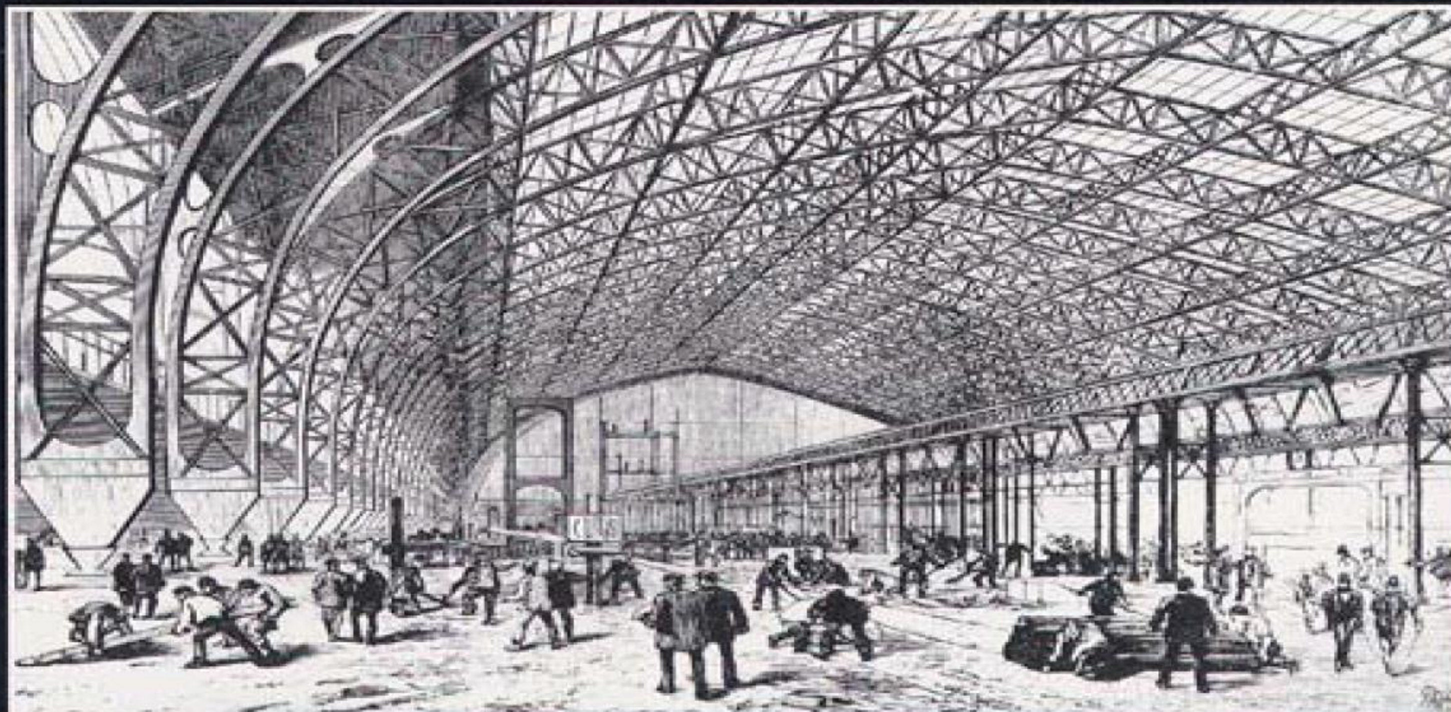
RESULT: Possibility of ever larger span construction:

World fairs organized after 1850 by the new industrialized countries (England, France, Germany) = occasion to expose technological progress in construction

Example: Crystal Palace-London [3]



Example: Gallery of Machine-Paris [3]



Designed to celebrate French industrial prowess, the 1889 Paris Exhibition also marked the centenary of the French Revolution. The Gallery of Machines, on the Champs de Mars opposite the Eiffel Tower, was itself an engineering triumph. Framed in the new harder and stronger material—steel—instead of iron like the Crystal Palace, the Gallery's glass panels were fixed to its exterior, shaping a vast inner, seemingly limitless, space. Twenty pairs of hinged girders formed arches
apex. The pin supports at the arches' to
building to flex if its metal expanded
The strikingly innovative building was d

The Gallery of Machine, constructed in 1889 for the Paris Exhibition

Later ancient space structures **[1], [4]** **(between 1920 and 1975) :**

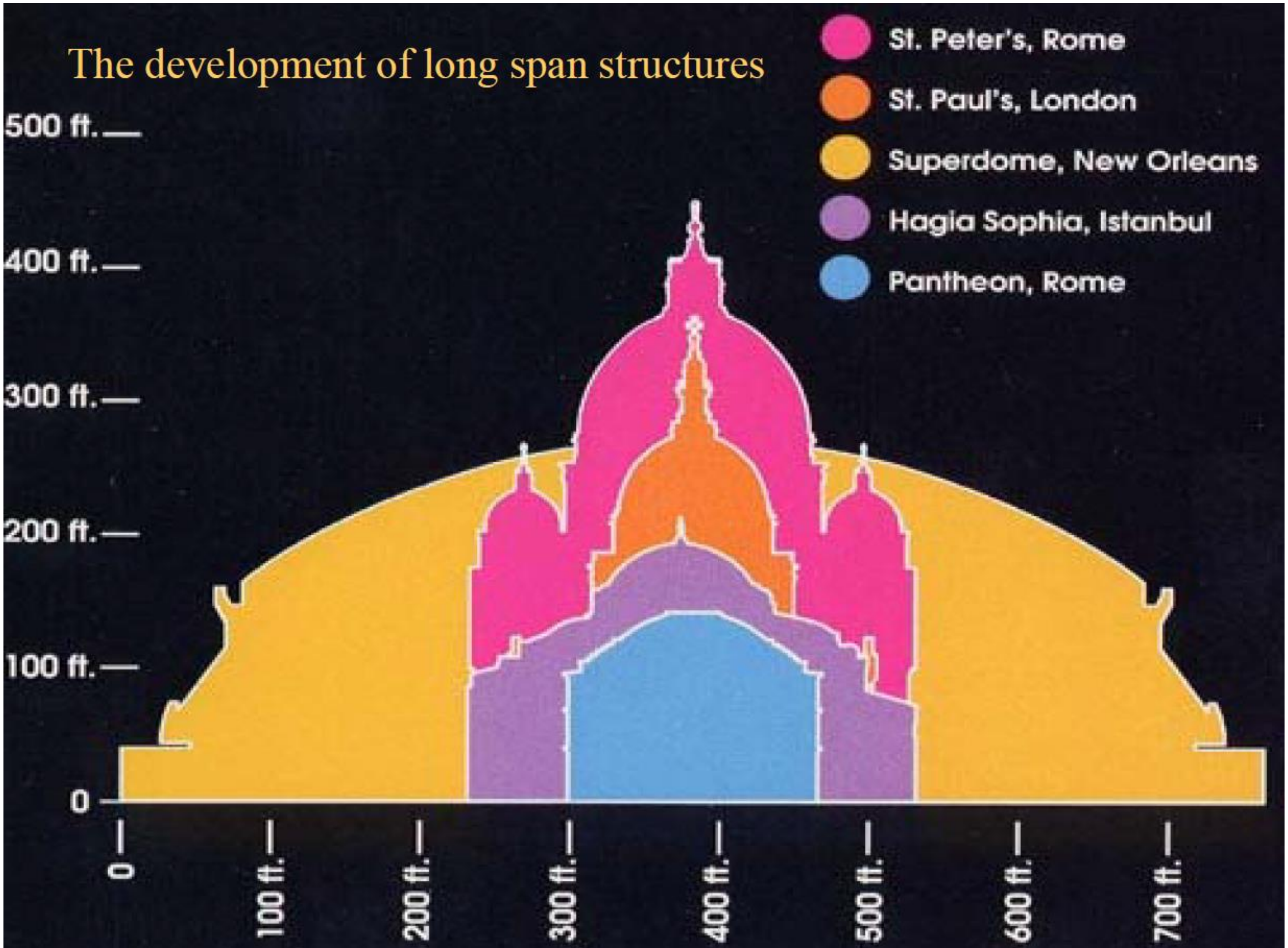
- Examples:
- 1922: Airship hangar US Navy-New Jersey -79 m span
- 1924: the first hemispherical single-layer latticed shell, made of steel (pig iron) was built in Zeiss Planetarium, Germany
- 1925: the first reinforced concrete thin-shell structure with a diameter up to 40 m was built in Jena, Germany
- 1937: Glenn L. Martin Co. Aircraft Assembly Building-Baltimore –Flat truss 91 m span
- 1942: Airship hangar US Navy-New Jersey -100 m span

Modern space structures [1], [2] (after 1970):

Examples:

- 1970: Shanghai Exhibition Hall- China (28 m x 36 m) air supported membrane
- 1975: at the Pontiac Gymnasium (span >100m), the first representative air-supported membrane structure was built in the US
- 1986: Comprehensive Gymnasium of Seoul Olympic Games = first cable-dome in the world designed by the American engineer Geiger
- 1988: Tokyo Dome = air supported membrane structure (ellipse 180 m x 150 m)

Comparison ancient-modern in terms of span [3]:



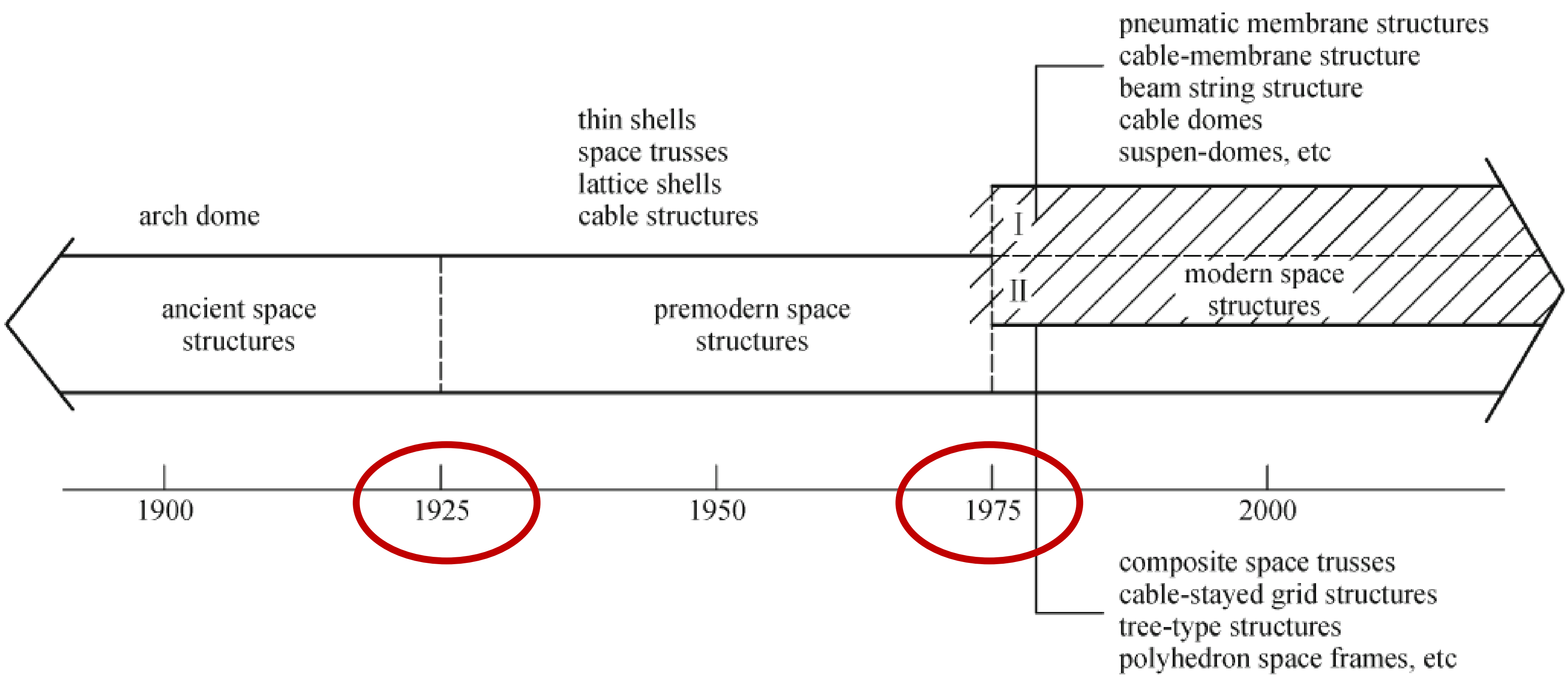
Example: Louisiana Superdome, USA [3]

Longest span dome: 680 ft = 210 m clear span; 252 ft =77,1 m height

Interior of the superdome (approx. 70.000 audience)

CLASSIFICATION OF LONG-SPAN SPACE STRUCTURES

Age partition of space structures [1]



As visible on the figure: premodern space structures are STILL in use!

Definition of modern long-span space structures [1]:

Modern long-span space structures are light and efficient structures, developed starting in the 1970's and 1980's on the basis of:

- new technologies
- and light-weight high-strength materials such as
  - high strength steel,
  - membrane
  - …and steel cables

Extension! Renewing premodern space structures in recent times:

- **<u>Premodern space structures</u>** (thin shells, space trusses, lattice shells, odinary cable structures) were also **<u>modernized</u>** to <u>fit nowadays requirements</u>

New space structures have been developed on premodern basis by:

- <u>Combination</u> of different structural forms and materials
- Application of prestressing technology
- <u>Innovation</u> of structural concepts and configurations

Basic elements of space structures: (also used in FEM analysis):

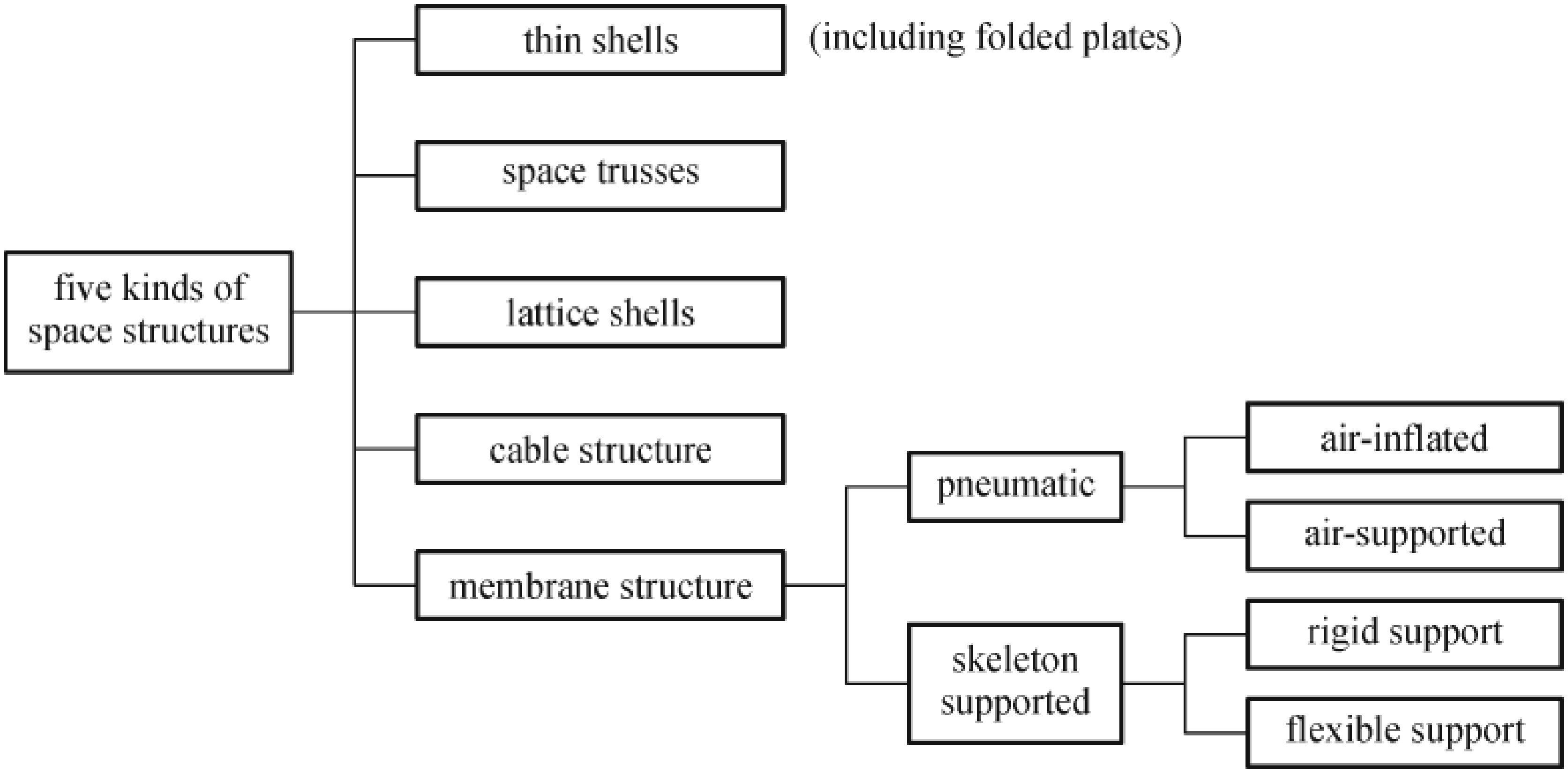
- Rigid elements (plate / shell, beam, bar)

- Flexible elements (cable and membrane)

Resulting categories of modern long-span space structures:

- Modern rigid space structures
- Modern flexible space structures
- Modern rigid-flexible combined space structures

Traditional classification for long-span space structures [1]:

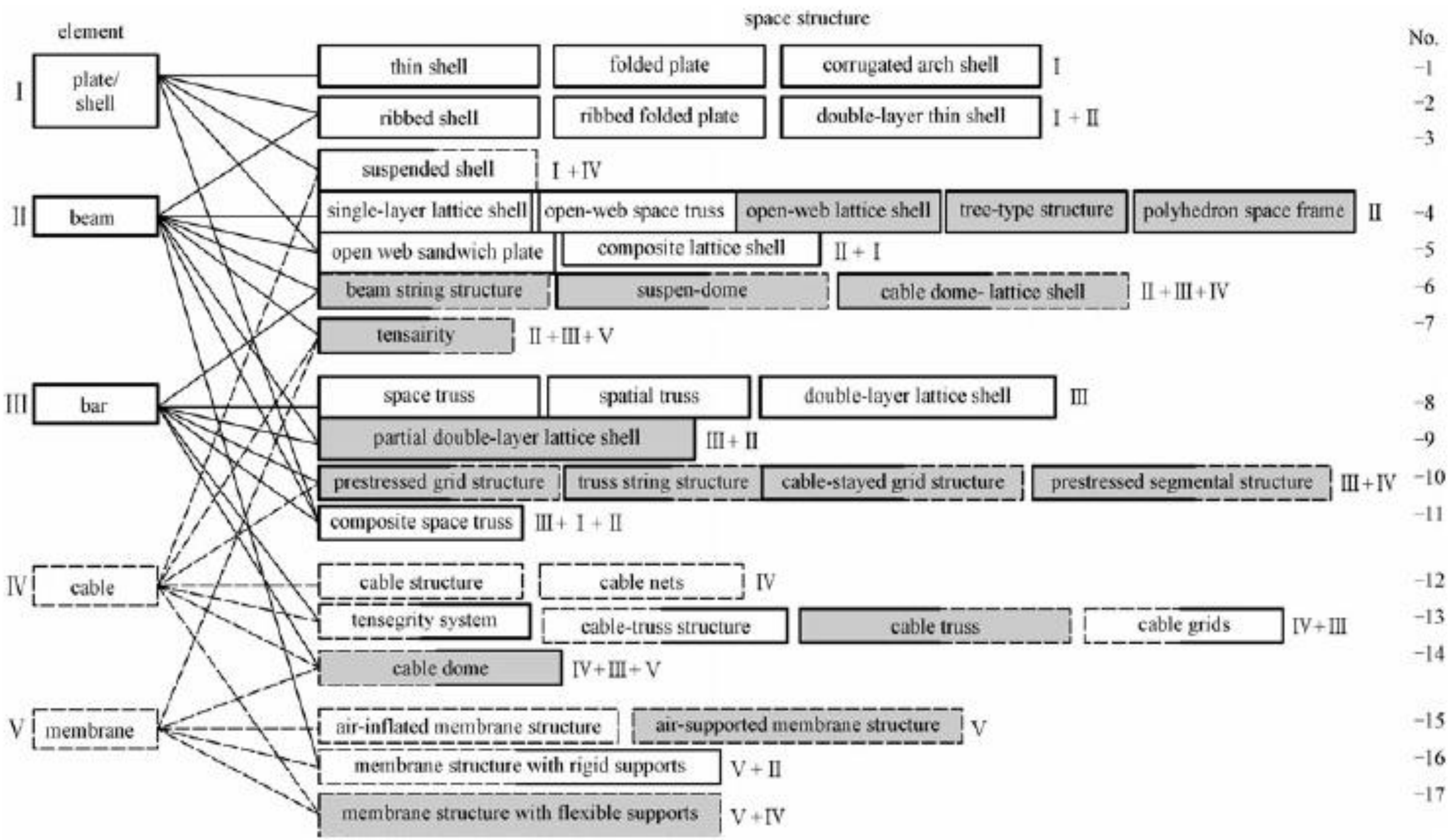


Already <u>obsolete</u>: i.e. unable to cover new existing space structures ! (<u>new types</u> of space structures are constantly emerging)

New method of classification proposed in [1]:

- Built on the basic structural elements composing the structure (i.e. plate/shell, beam, bar, cable, membrane) versus structural rigidity of the structures (rigid=solid wireframes, flexible= dotted wireframes, rigid-flexible = combined dotted and solid wireframes)
- Practical method
- Related to the calculation method and computer analysis of the space structure
- Allowing for new structural types to be included anytime in the future

New classification proposed by the authors of paper [1]:



1.3 Rigid space structures [1]:

Include:

- Open-web latticed shell
- Tree-type structures
- Polyhedron space frame
- Partial double-layer lattice shell
- Composite space-truss structure

1.3.1) Open-web latticed shell structures

- Usually composed of beam elements (no diagonals)
- Some systems however use diagonals (see examples)
- The latticed shell with a curved surface evolved from the planar open-web truss
- Most latticed shells are two-way orthogonal or diagonal
- Joints in upper and bottom chord are usually connected with five members

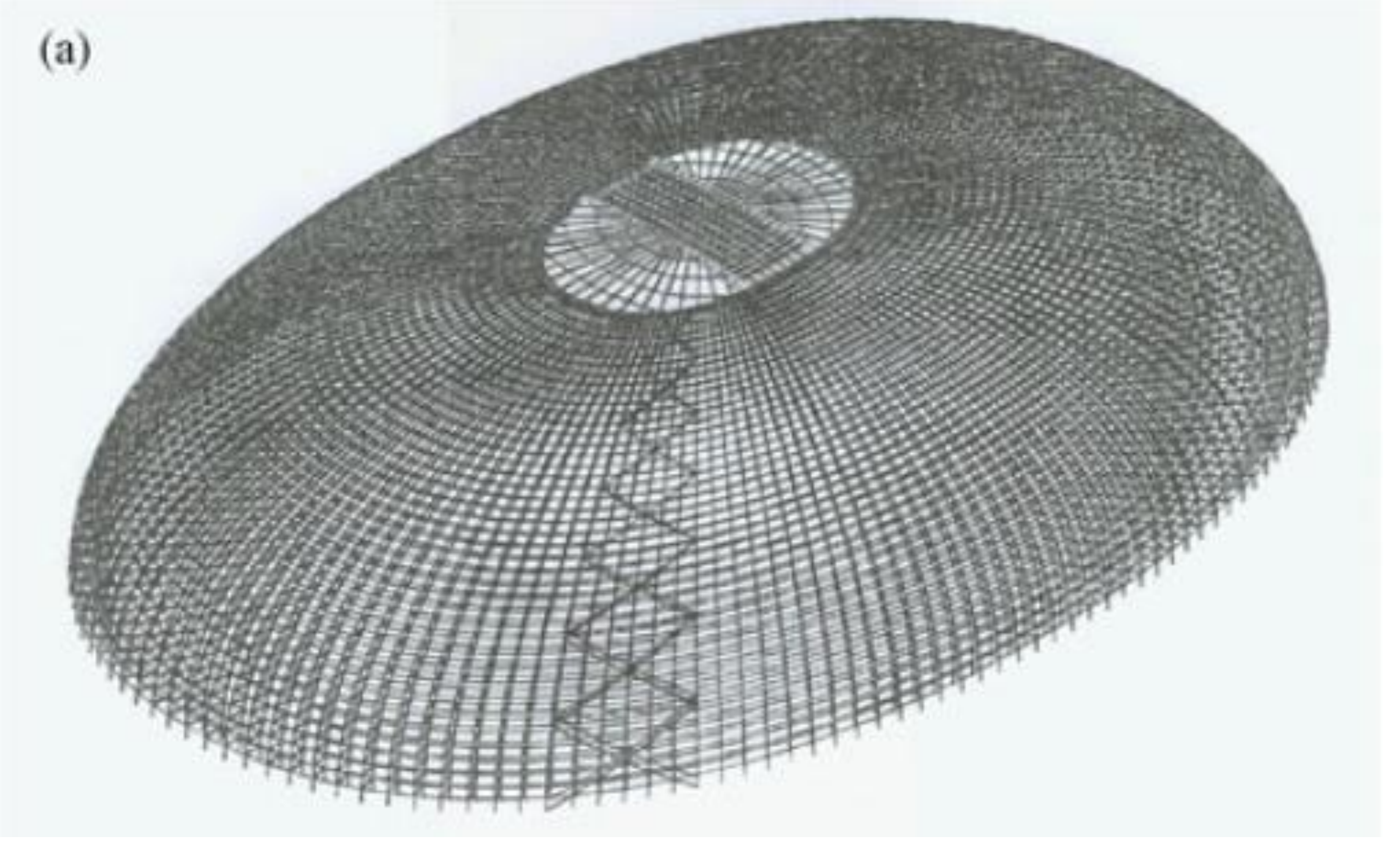
Advantages of open-web latticed shells:

- Improve the structural behavior
- Reduce material consumption
- Provide enough space for a mechanical floor

Example 1: the Roof of the National Grand Theater in Beijing:

- Ellipsoidal shell
- Overall plan size of 146m x 212 m
- Height of 46 m
- Longest span open-web latticed-shell in the world
- Roof composed of 144 radial open-web arches + circumferential steel tubes
- Four groups of large cross-bracings improve the torsion resistance and stability of the structure

Computer model



Structure under construction

Example 2: Charles-de-Gaulle /Roissy International Airport, France (1998) [3]

Usual trusses employed (NOT open-web)

Example 3: Hamburg Airport, Germany (completed in 2005)

Hamburg Airport, Germany

Roof span = 62 m (diagonals present)
The form and construction of the roof is based on an aircraft wing.

Hamburg Airport

Example 4: Guangzhou Olympus Stadium

Open lattice roof

Tie systems to stabilize the cantilevered roof

Erection phase: Truss and tie system

Placing the roof truss in position

Example 5: Porto Airport (2006)



Arch structure, 80 m span

Lattice frame + arch structure applied to reach this span

1.3.2) Tree-type structures

- New type of pillar-support structures composed of multi-level branches
- Main member and branch members are all beam elements
- Joints are rigid (resist moment also)
- Branch members connect with the roof structure so that the span of the roof and the internal forces can be reduced

Example 1: Lobby of Shenzhen Cultural Centre

- Three level tree-type structure
- Elements: trunks, branches and secondary branches

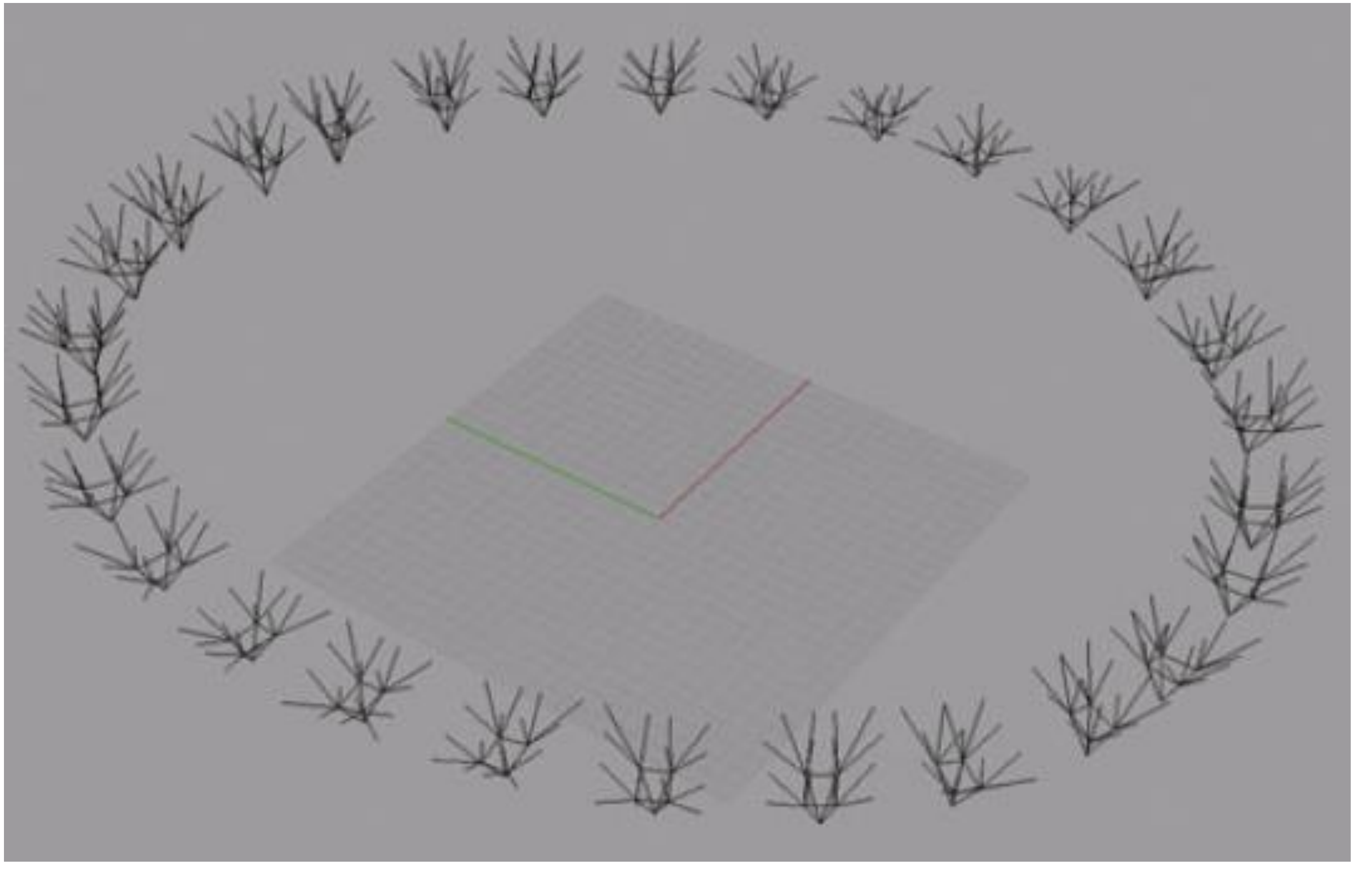
Lobby of Shenzhen Cultural Center

Example 2: Canopy roof of the Hangzhou Olympic Stadium

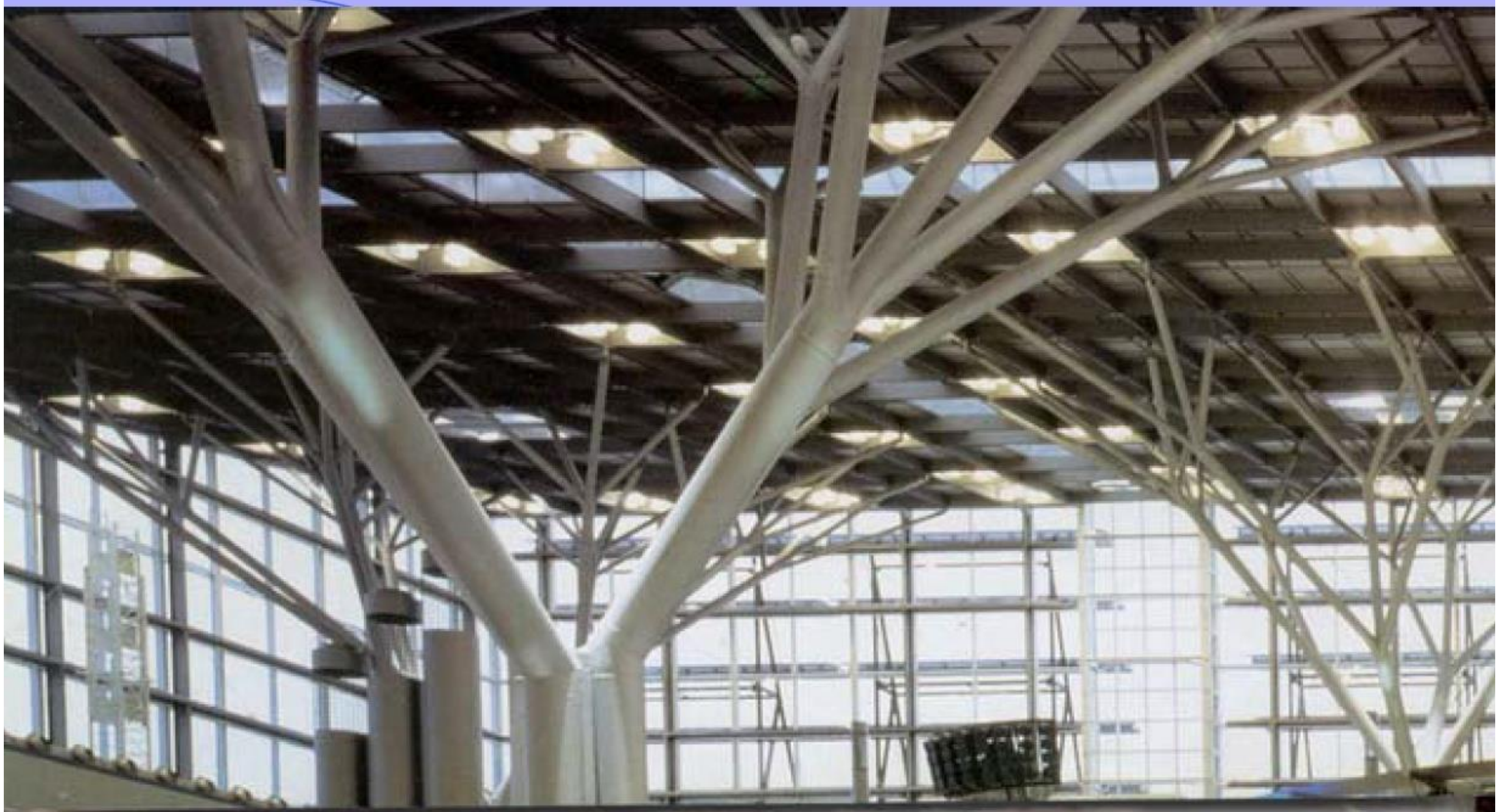
- Only structural scheme presented

- Supporting structure with two-level branches

Canopy roof of Hangzhou Olympic stadium: structural scheme

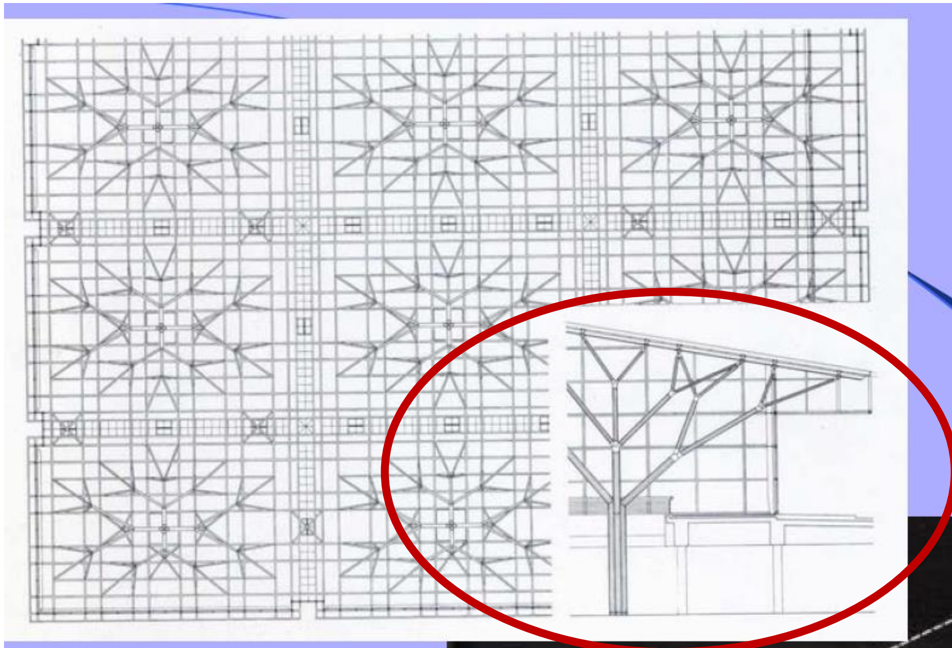


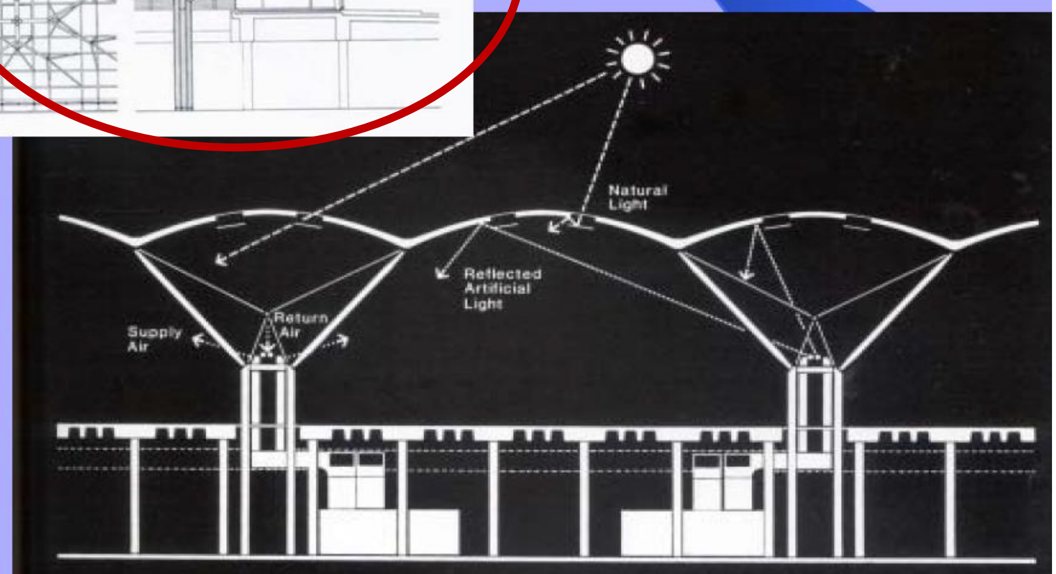
Example 3: Airport terminal in Stuttgart, Germany [3]



Airport Terminal at Stuttgart, Germany

Roof detail at Stuttgart Terminal Building [3]





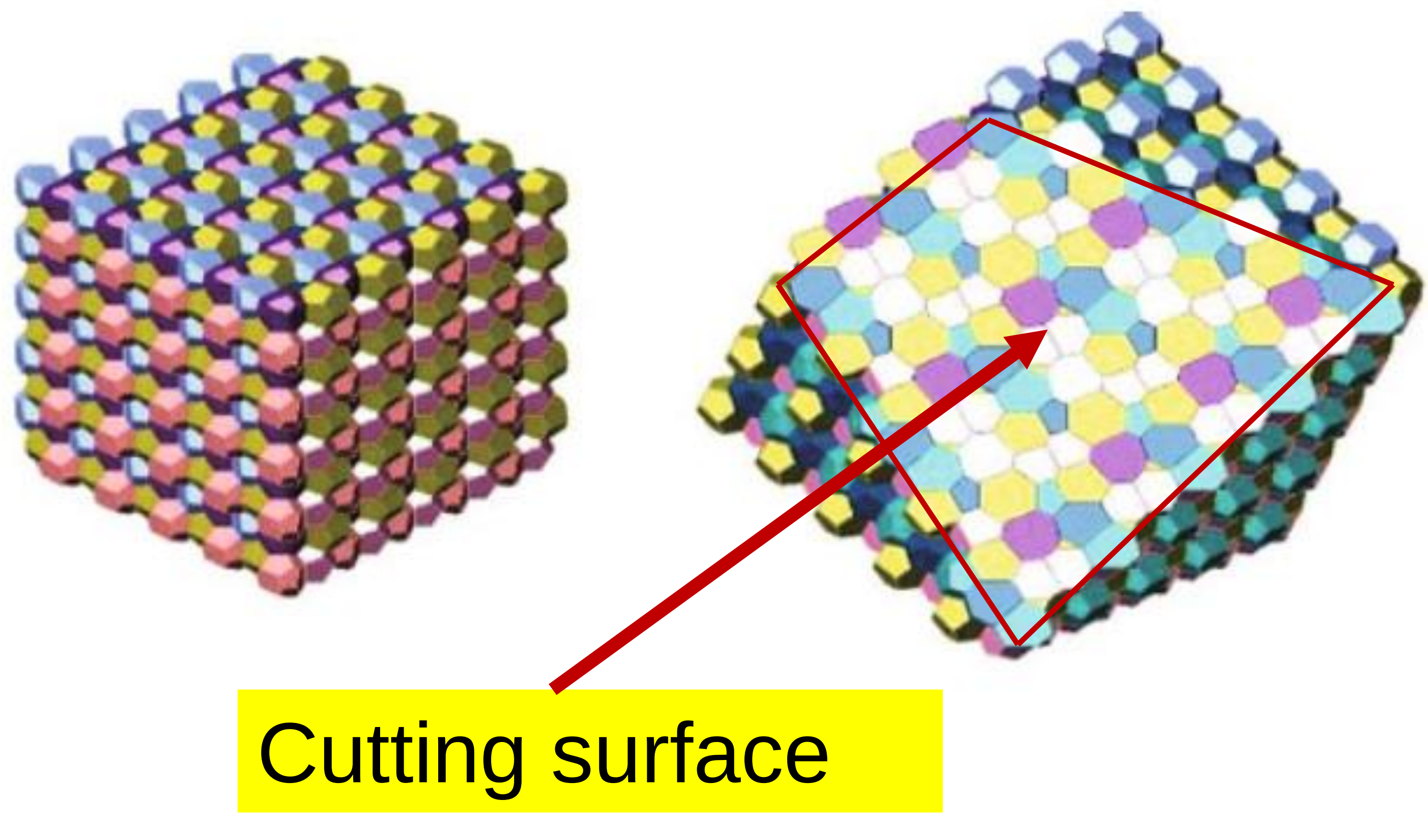
Roof plan/detail of the Stuttgart Terminal Building

1.3.3) Polyhedron space frame structures

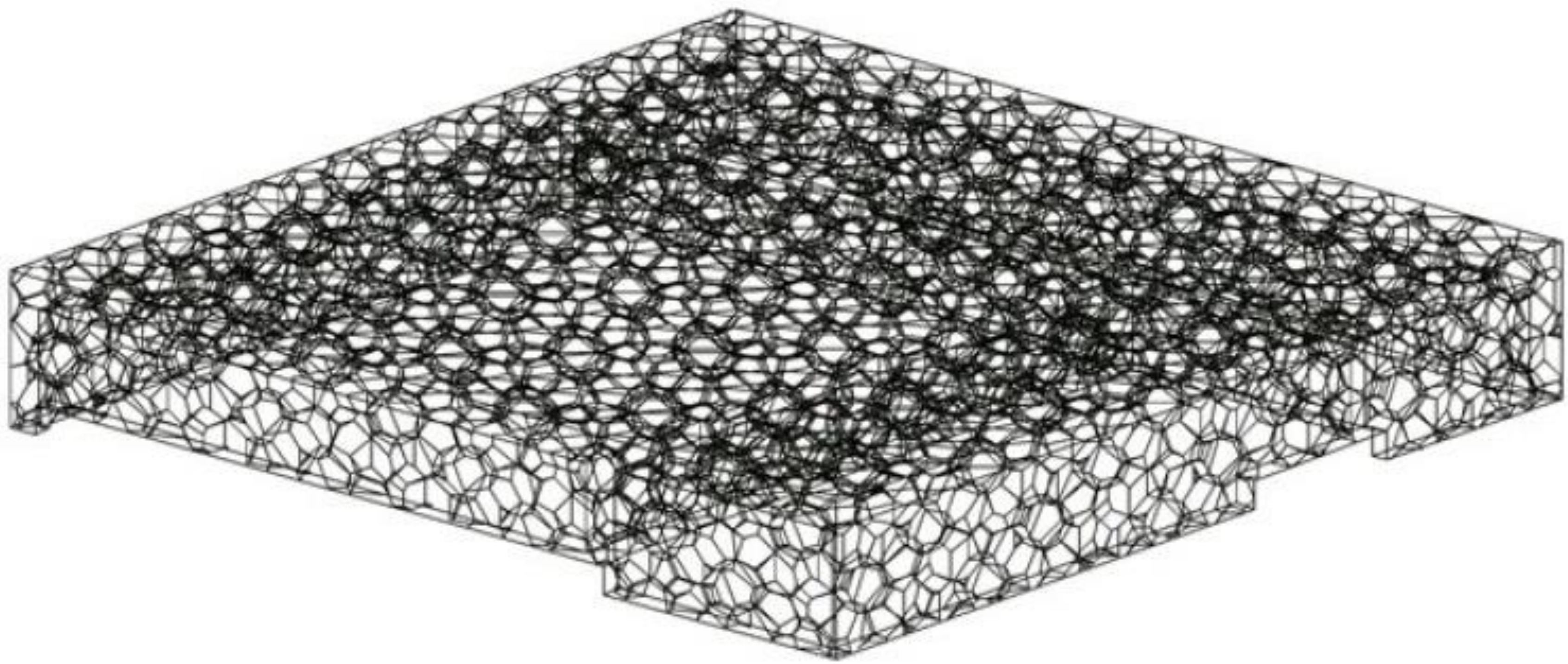
- Completely new structural system!
- A fundamental cell composition consists of two 12-sided polyhedron cells and six 14-sided polyhedron cells
- The intersecting lines of the polyhedron over the cutting surfaces are the chord members of the roof and wall structures
- The remaining boundary lines are the interior web members

Fundamental polyhedron cell:

Polyhedron assembly:



Polyhedron space frame structure



Members and joints:

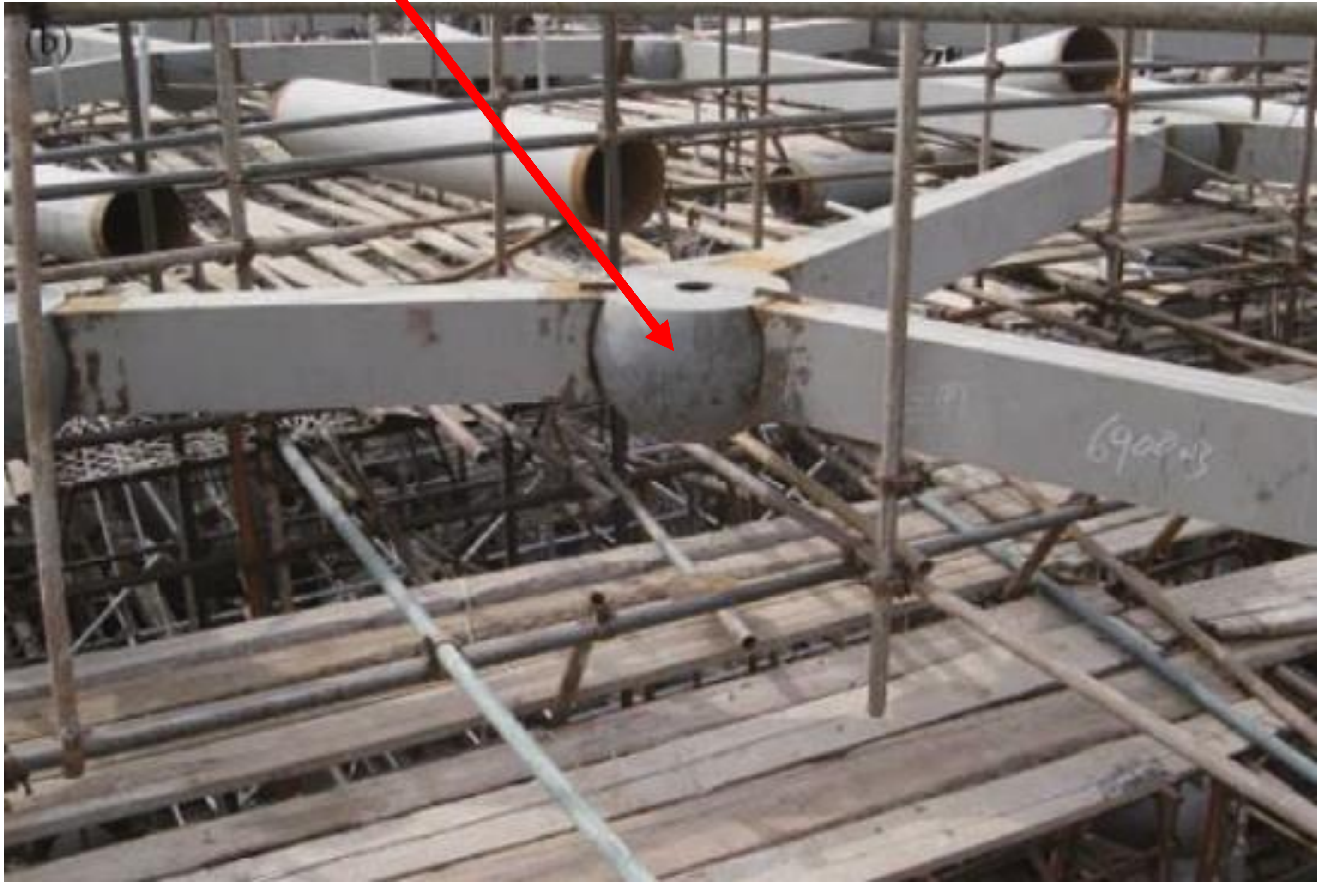
- Each member = three-dimensional beam element to insure that the member can transfer forces and moments from all orientations
- Only four members are connected at each interior joint
- Thus the polyhedron space frame is suited to fill plate or three dimensional structures with the LEAST members and LEAST nodal joints

Example of polyhedron space frame structure:

- National Aquatic Center “Water Cube” for the Beijing 2008 Olympic Games
- First polyhedron space frame structure in the world
- Plane dimensions 177 m x 177 m
- Height 30 m
- Surface members of rectangular steel tubes to accommodate the ETFE cladding cushions with drum-type hollow joints
- Interior members of circular steel tubes with normal hollow spherical joints

Joint on the surface

Drum-type joint



Water Cube
(IABSE 2010 Structure Award)

1.3.4) Partial double-layer lattice shells

- Composed of single-layer lattice shell + double-layer lattice shell + linking structure with bar and beam elements

- The parts of the structures that mainly resist bending forces are designed as double-layer lattice shells

- The parts of the structure that mainly resist membrane forces are designed as single layer lattice shells

Structural configurations:

1) For a structure that needs to set up a skylight or an air vent, a double layer lattice shell with a point-type (local) single-layer shell can be designed

2) Spatial trusses may be set-up to **strengthen** a single layer lattice shell and to form a **partial** double-layer lattice shell with partitions

Example 1:

- Tashan Amusement Center in Yantai City
- Built in 1992
- Example of partial double-layer lattice shell with point skylights

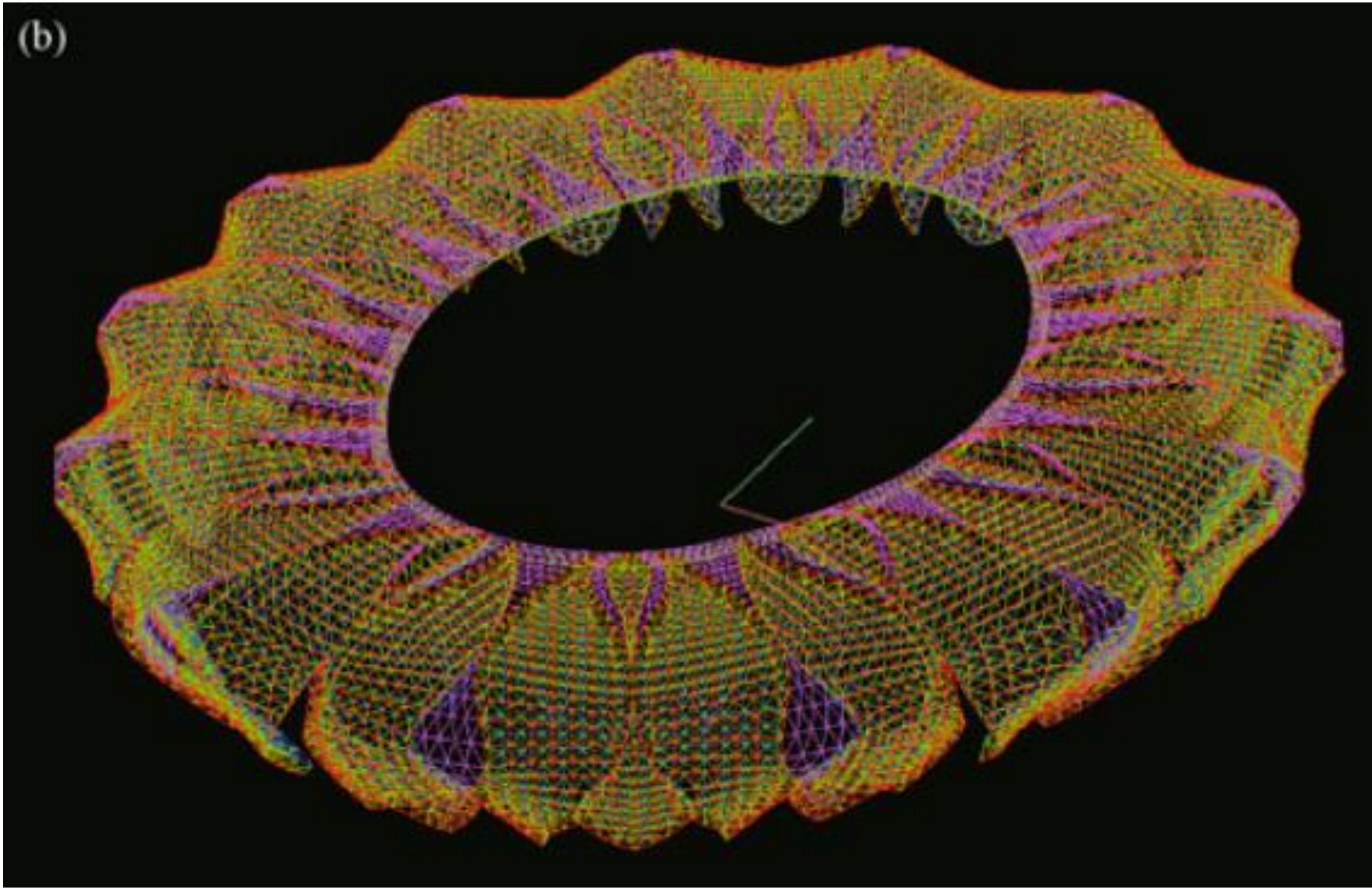
Tashan Amusement Center

Example 2:

- Canopy roof of Hangzhou Olympic Stadium
- Looks like a flower with many petals
- The petals are designed as double-layer lattice shells
- The parts among the petals are designed as single-layer lattice shells

Hangzhou Olympic Stadium

Olympic stadium calculation model



1.3.5) Composite space truss structures

- The top chord of a normal steel space truss is replaced with a reinforced concrete slab
- Composite structure made of bar, beam and plate elements
- Suitable for both roofs and floors
- Combines load bearing (deck) and covering (roof) into one function
- Approximately 60 composite space trusses have been constructed in China so far, as both roof and floors of multi-story buildings

Example 1: Canteen roof of Jiahe Coal Mine in Xuzhou (1980)

Example 2:

- Xinxiang Department Store (four floors)
- Largest composite space truss for a multistory building
- Layout 35 m x 35 m
- First application of the composite space truss in floor structures

Xinxiang Department Store

1.4 Modern Flexible Space Structures [1]

Include:

- Pneumatic membrane structures including:

  - air-inflated membrane structures

  - air-supported membrane structures (discussed in the presentation)

- Membrane structures with rigid or flexible steel supports

1.4.2) Air-supported membrane structures

- The pressure inside the air-supported membrane structure is relatively low (only 1,003 standard atmospheres) so that people can live inside the structures
- Membrane material = fabric substrate + coating (mainly PVC and PTFE= poly-tetra-fluoro-ethylene)
- Membrane material suitable for use as air cushions is a type of polymeric material (that does NOT include a fabric substrate) such as ETFE (=ethylene tetra-fluor-ethylene)
- Basic requirements for membrane materials: strength, light transmission, self cleaning capacity and fire resistance

Example: Resonant Sand Gorge of Inner Mongolia

- Air supported membrane used as sand sculptures exhibition hall
- Ellipse 95 m x 105 m
- Year of construction: 2010

Sand Sculptures Exhibition Hall

1.4.3) Skeleton supported membrane structures:

Types of skeleton-supported membrane structures:

- Membrane structures with rigid supports
- Membrane structures with flexible supports (supporting members are mainly steel cables)

1.4.3) Membrane structures with flexible supports

- Membrane structures with flexible supports are flexible space structures composed of **cable** and **membrane elements**
- They are also referred to as **tensile membrane structures**
- An **interaction** appears between the membrane and the supporting cables
- This effect must be accounted for in the design and analysis of tensile membrane structures (special software!)

Observation:

- In practical design, membrane structures with **flexible support** are usually adopted **combined** with membrane structures with **rigid support**

Example 1: Canopy roof for Weihai Stadium

- Composed of 24 umbrella-like tensile membrane elements
- Overall size of 209 m x 236 m
- Inner ring of 143 m x 205 m

Weihai Stadium

Example 2: Roofing system for Expo Axis Sanghai 2010

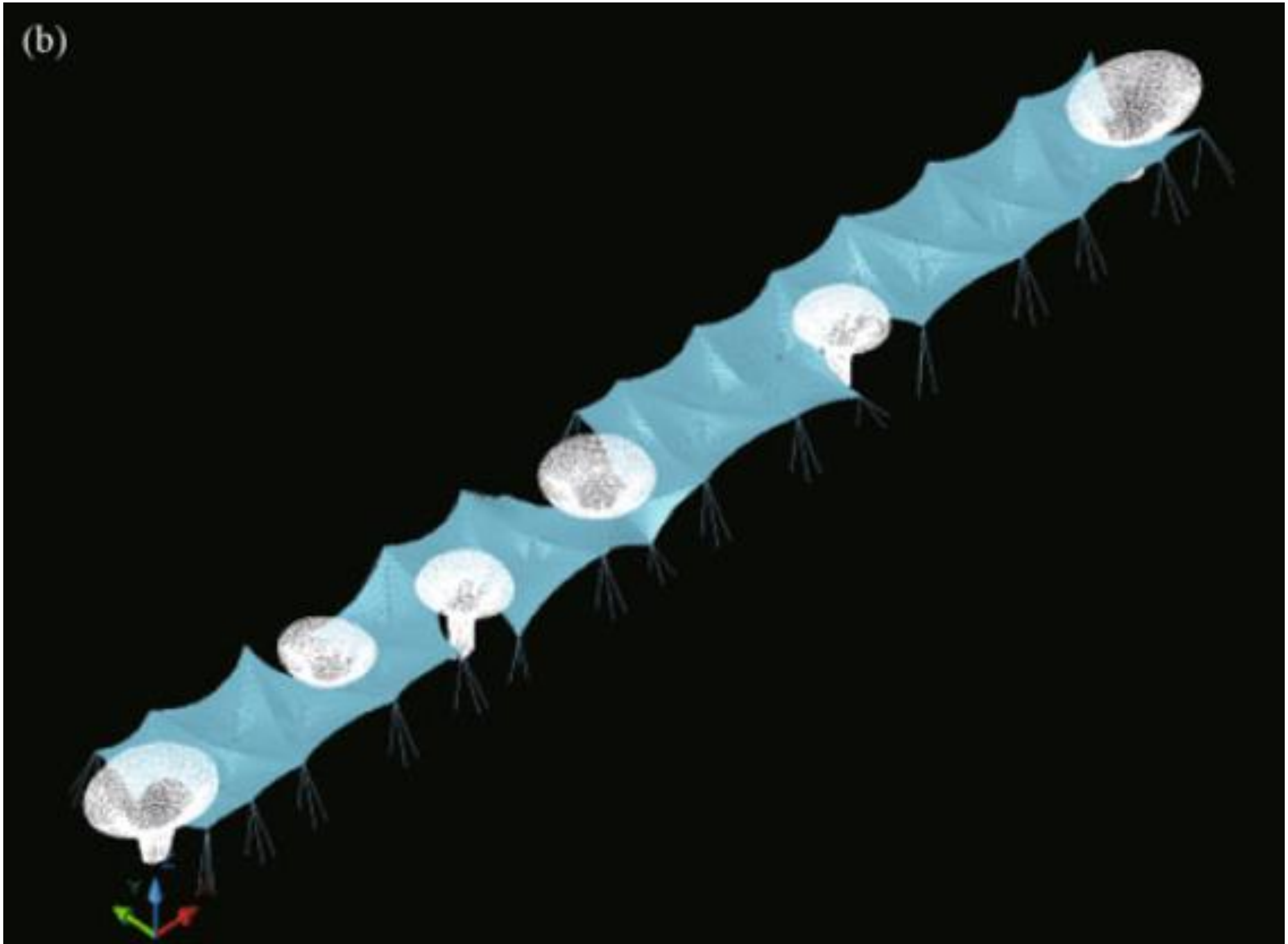
- Composed of six steel structures named “Sun Valley” and multi-span continuous cable membrane structures
- This is the largest tensile membrane structure in the world to date
- Total length of 840 m
- Largest span of 97 m
- Total covering area of 64000 m^2

Expo Axis Sanghai 2010

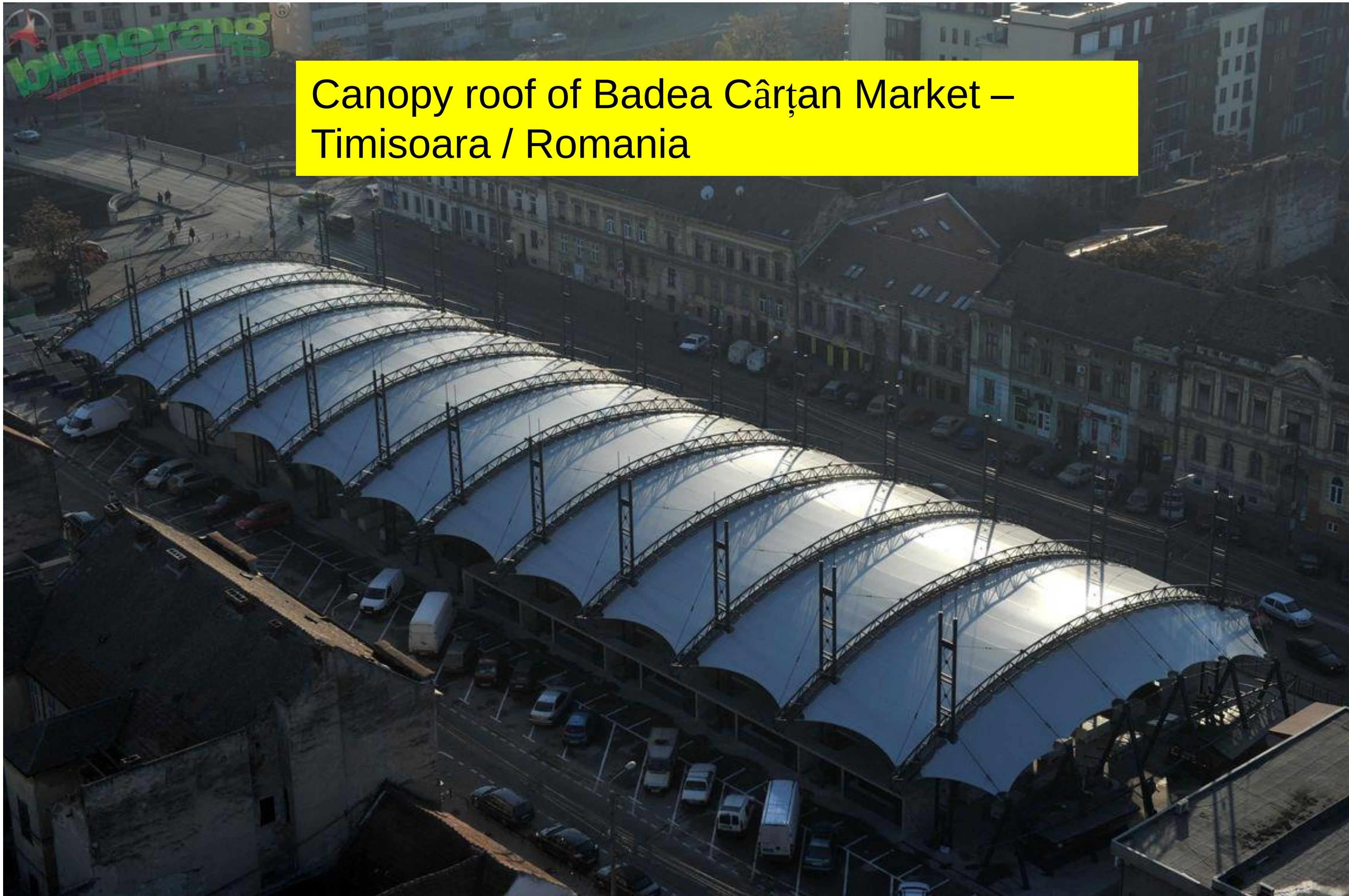
Supporting system for the membrane consists of:

- Ridge
- Valley
- Edge
- Suspension
- Wind suction
- Back stay cables
- 19 inner masts
- 31 outer masts
- 18 supporting points on the sun valleys

Calculation Model



Example 3: Membrane structures with rigid support



Canopy roof of Badea Cârțan Market – Timisoara / Romania

Badea Cartan Market – Timisoara
Owner of the ECCS 2003 Award

Example 4: Beijing 2008 Olympus Centre –The Nest (membrane+rigid)

- The 3D steel roof spans a 330m-long by 220m-wide space.
- The geometry of the roof was worked out from a base ellipse of which the major axis measures 313 m and the minor axis measures 266 m, with a height of 69.2 m.
- The National Stadium's main structure is an enormous saddle-shaped elliptic steel structure weighting 42,000t.
- The 91,000-seat stadium was designed to incorporate elements of Chinese art and culture.
- The stadium design included also demountable seats of 11,000.

Structure of The Nest

- The "nest" structure, however random it might look, follows the rules of geometry and contains 36km of unwrapped steel.

- The shape of the roof was inspired by yin yang, the Chinese philosophy of balance and harmony.

Bird Nest structure [3]

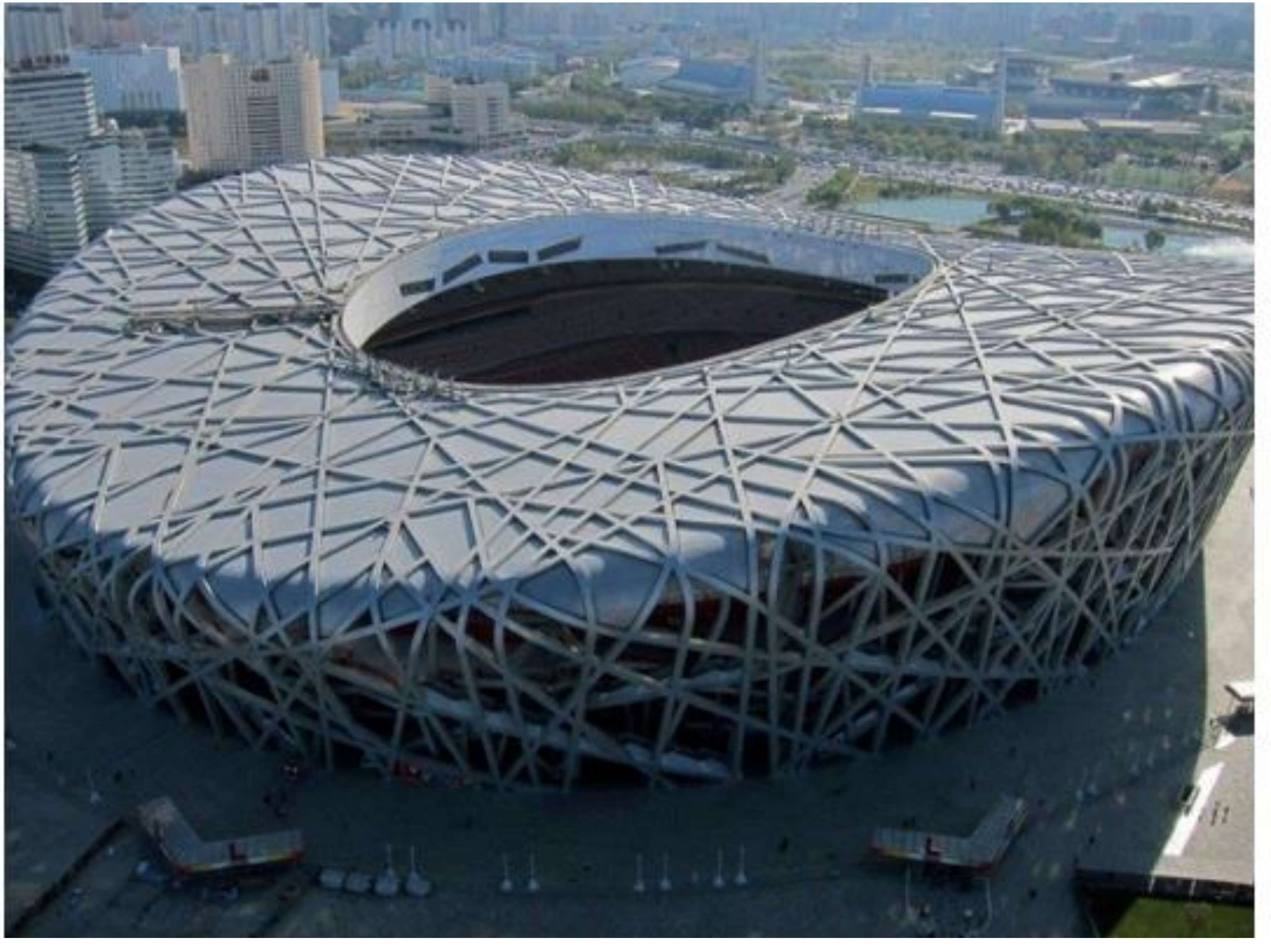
Figure 2: A model of Bird's nest stadium by M/s Arup showing the primary load carrying elements and the secondary and tertiary members (Source: Brodkin, 2008)

Steel structure of Bird Nest

Cladding and roofing of Bird Nest

- The roof is covered with a double-layer membrane structure (on rigid steel support), with a transparent ETFE (ethylene tetra-fluoro-ethylene) membrane fixed on the upper part of the roofing structure and a translucent PTFE (poly-tetra-fluoro-ethylene) membrane fixed on its lower part.
- A PTFE acoustic ceiling is also attached to the side walls of the inner ring.
- The spaces in the structure of the stadium are filled with inflated ETFE cushions. On the façade, the inflated cushions are mounted on the inside of the structure where necessary, to provide wind protection.

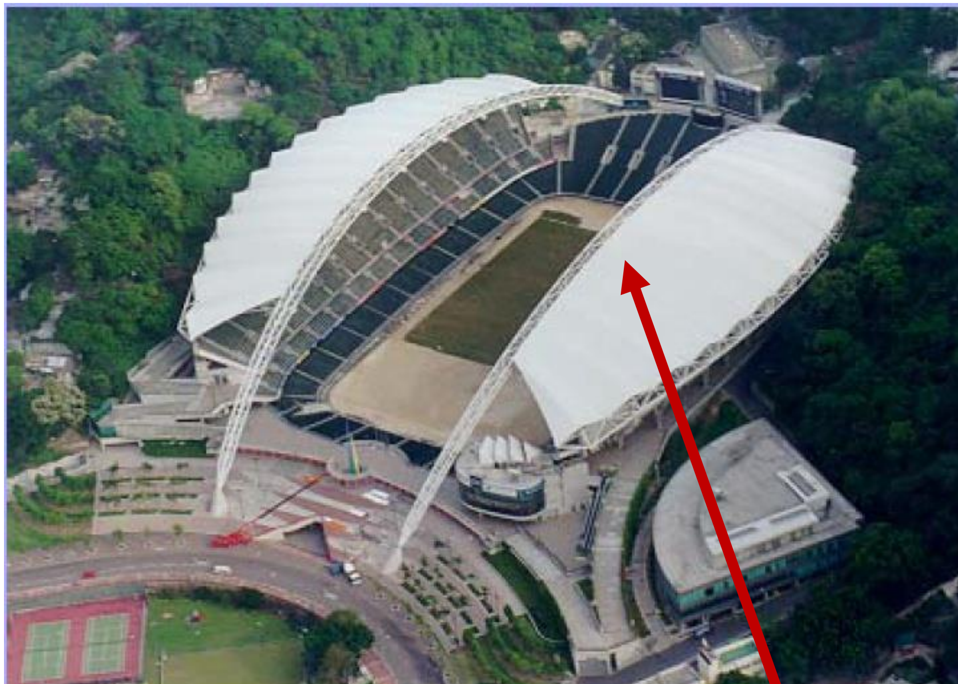
Cladding and roofing of Bird Nest

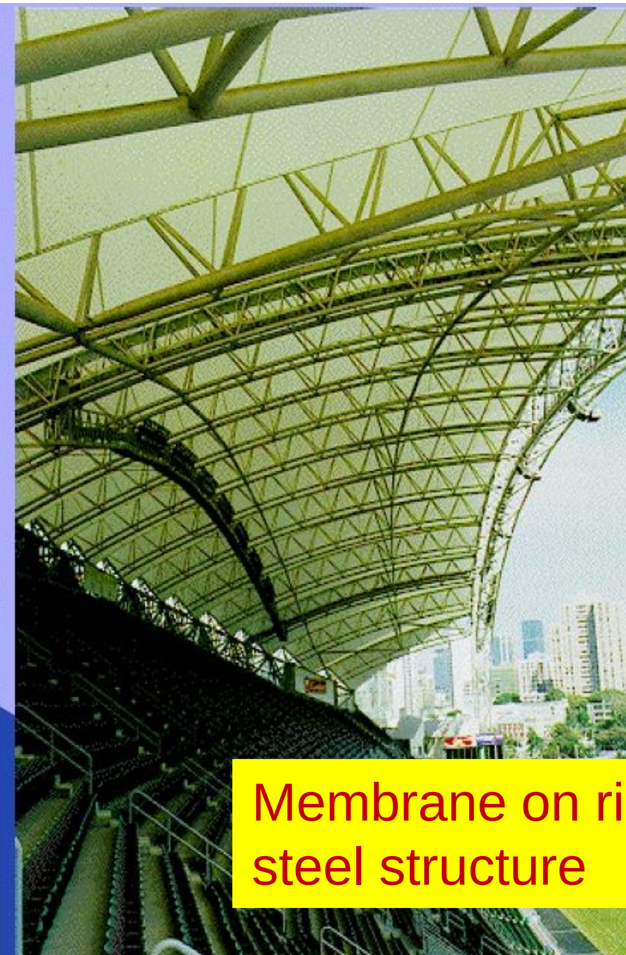


Inside of Bird Nest Stadium

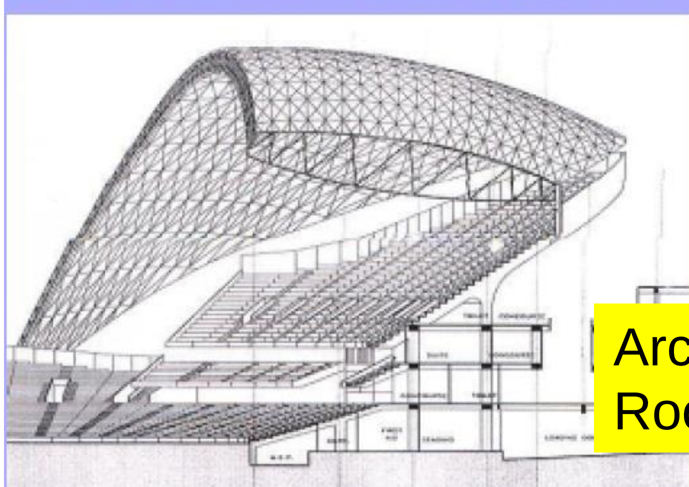
The Bird Nest and The Water Cube

Example 5: Hong Kong Stadium [3]





Membrane on rigid steel structure



Arch span 240 m x 55 m rise
Roof: 8000 m^2 PTFE coated glass fiber fabric

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http://steel.fsv.cvut.cz/suscos

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