LONG SPAN STRUCTURES: PART 1

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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 tension surfaces
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]

Exterior view of the Crystal Palace, built in 1851 for the first World Fair.
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 to the apex. The pin supports at the arches’ tops allowed the building to flex if its metal expanded. The strikingly innovative building was completed in 1887.

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

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]:

The development of long span structures
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
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:

- **Premodern space structures** (thin shells, space trusses, lattice shells, ordinary cable structures) were also **modernized** to fit nowadays requirements.

New space structures have been developed on premodern basis by:

- **Combination** of different structural forms and materials
- Application of **prestressing technology**
- **Innovation** 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 obsolete: i.e. unable to cover new existing space structures! (new types 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]:

![Diagram of structural elements and space structures]
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)
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
Tie systems to stabilize the cantilevered roof

Open lattice roof

Tie systems
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]
Roof detail at Stuttgart Terminal Building [3]
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:

Cutting surface
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
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
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-fluoroethylene).

- 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 Shanghai 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 m²
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
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]
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]

Arch span 240 m x 55 m rise
Roof: 8000 m² PTFE coated glass fiber fabric

Membrane on rigid steel structure
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