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Patrons : 34
Organisation Member : 23
Sponsors : 8
Members : 1345
Junior Members : 33

TOTAL STRENGTH 1443

FIELDS CONSIDERED AS ASPECTS OF STRUCTURAL ENGINEERING

- Structural Designing & Detailing
- Computer Software
- Materials Technology, Ferrocement
- Teaching, Research & Development
- Rehabilitation of Structures
- Construction Technology & Management
- Geo-Tech & Foundation Engineering
- Environmental Engineering
- Non Destructive Testing
- Bridge Engineering

& Other related branches

AIMS & OBJECTIVES

1. To restore the desired status to the Structural Engineer in construction industry and to create awareness about the profession.
2. To define Boundaries of Responsibilities of Structural Engineer, commensurate with remuneration.
3. To get easy registration with Governments, Corporations and similar organizations all over India, for our members.
4. To reformulate Certification policies adopted by various authorities, to remove anomalies.
5. To convince all Govt. & Semi Govt. bodies for directly engaging Structural Engineer for his services.
6. To disseminate information in various fields of Structural Engineering, to all members.

STRUCTURAL ENGINEERING - AN ART OR SCIENCE? PART 2

Dr. Subramanian Narayanan

In part 1 of the paper, elegant structures up to the 17th Century were discussed. Examples of modern elegant structures and a few important developments that took place after the 17th century and up to about 1960 were described in Part 2 of the paper. In part 3 of the paper, let us consider examples of aesthetic structures in the past 55 to 60 years.

The Science of Structural Engineering

The period beyond 1950-60 is characterized by refinements and extensions of structural analysis, design and construction methods. For example, there was a growing interest in shell and three-dimensional structures, and analysis of structures including non-linear and dynamic effects. The 'modern age' began after about 1960s resulting in integration of analysis, design and drafting. This modern age is typified by the use of modern computers and powerful numerical methods. During this period, theory of structures was integrated into the structural process of conceptual design, analysis, detailed design, detailing, and construction. In his Foreword to the book 'The History of the Theory of structures', Prof. Ramm of the University of Stuttgart remarks: "In the world of data processing and information technology, theory of structures has undergone rapid progress in conjunction with numerous paradigm changes. It is no longer the calculation process and method issues, but rather includes principles, modeling, realism, quality assurance and many other aspects. It now includes dynamics alongside statics; in terms of the role they play, thin-walled structures like plates and shells are almost equal to trusses and frames, and taking account of true material behaviour is obligatory these days. During its history so far, theory of structures was always the trademark of structural engineering; it was never the discipline of “number crunchers”, even if this was and still is occasionally proclaimed as such upon launching relevant computing programs. Theory of structures continues to play an important mediating role between mechanics on the one side and the conceptual and detailed design subjects on the other side in teaching, research and practice. Statics and dynamics have in the meantime advanced to what is known internationally as computational structural mechanics, a modern application - related structural mechanics".

In addition, due to the phenomenal advancements in computer hardware and software, the computer power, which was in the realm of big research organizations only, is now available in the desk of the design engineer. Several standardized computer software packages such as STAAD Pro, ADINA, ANSYS, SAP2000, SAFE, etc. have been developed and are being used increasingly by design engineers (In addition to these proprietary software some excellent open source software such as OpenSees and Frame3DD are also available). Because of these developments, the design engineer is relieved of the complex task of analyzing the structure for several load cases. The Graphical User Interface (GUI) provided in many standard software packages also simplifies pre-processing of input data and post-processing of results.

Through the use of BIM and Civil 3D software we can now create constructability studies to review our designs before they enter the construction phase. Factors such as smart location, storm water management, steep slope protection, constructability, etc., can be considered in our designs in the initial stage itself, so as to create accurate models that can result in sustainable designs and reduce the overall impact on our urban surroundings. These facilities make the architect/ design engineer to concentrate on the project at hand and develop novel solutions, which are safe, stable, economical, aesthetically pleasing, and environmental friendly.

There was spectacular progress in the material science also and a number of materials were introduced during this period, which include aluminum, special cements, high strength/high performance concrete, different additives to concrete which will increase their durability and performance, ferro-cement, high strength strength steel, stainless steel, laminated timber, plastics, structural glass, and high-performance fiber-reinforced cementitious composites (HPFRCC), and fiber-reinforced polymer (FRP) composites. Progress has also been made on repairs and rehabilitation, and some of these techniques, such as FRP composites have been used for both structural retrofit in the form of thin sheets and new construction in the form of bars and tendons. Recently the concept of using FRP composites for structurally integrated stay-in-place formwork has been used which maximizes the advantage of both FRP and concrete while simplifying the construction process and reducing construction time (Nelson et al 2014). In addition, several structural systems were developed for resisting lateral loads, especially for high-rise buildings (Subramanian 2013). Hence, now the designer can choose different materials and systems to develop the structure at hand, satisfying the criteria of safety, economics, aesthetics, durability, and sustainability. Precast and prestressed concrete have been used extensively in bridge and other long-span construction (see www.pci.org/ for a number of examples).

In addition to the developments in materials and construction techniques, several developments took place in the design methods. The traditional working stress method does not provide realistic measure of the actual strength or factor of safety underlying a design. Hence it has been replaced by the more rational limit states method, which considers safety at ultimate loads and serviceability at working loads. Recently, performance based design (PBD) methods have also been developed. It was introduced in FEMA 283/349 and refined and extended in FEMA 445. They allow building owners to choose the performance of their buildings. For example, they may consider spending more money to achieve higher performance than provided in normal codes, thereby reducing risk and potential losses.

Achieving Structural Art in Modern Age

During the modern age, several spectacular buildings and bridges have been built by exceptional structural engineers and architects like Pier Luigi Nervi (1891 –1979), Oscar Niemeyer (1907- 2012), Fritz Leonhardt (1909 – 1999), Pierre Lardy (1903-1958), Heinz Isler (1926-2009), Jörg Schlaich (1934-), Felix Candela(1910-1997), Eduardo Torroja (1899-1961), Frank Gehry (1929-), Santiago Calatrava Valls (1951-), and others combining art and science. Let us consider few of these structures in this section of the paper.

The Palazzo del Lavoro (Palace of Labour) designed and built by Nervi and his son Antonio for the Turin exhibition of 1961 was the result of a competition held in 1959. The building as shown in Fig. 18(a) had 7432 m^2 of exhibition space, and had to be capable of conversion to a technical school at the end of the exhibition. The project revolved around the subdivision of the square roof into sixteen independent 'umbrellas', each 40 meters per side, and separated by continuous strip skylights and made from a sunburst pattern of steel beams fixed to a central 19.8 m high column with a variable geometry, as shown in Fig. 18(b). The external walls, entirely clad in glass, wrapped round the perimeter of the building, incorporated large 21.3 m high vertical mullions. The structure was erected in less than eighteen month

Fig. 18 Palazzo del Lavoro, Turin, Italy, Designed by Nervi and built during 1959-61
(a) View of the structure, (b) Close up view of the roof (Source: http://torino.repubblica.it/)

Shell structures

The modern era of thin concrete shells began in 1922, when Franz Dischinger, of the German engineering firm Dyckerhoff and Widmann designed a 16m diameter and 30 mm thick reinforced concrete dome in Jena, Germany. That feat was followed by Eugene Freyssinet's design, in 1923, for his famous hangars at Orly: cylindrical barrel vaults with a parabolic cross-section and corrugated surface, 144 m long and 75 m span. Anton Tedesko, another Dyckerhoff and Widmann engineer, designed the first large thin concrete shell in the U.S. in 1936, which is a 71 m span, 104m long barrel shell for an ice hockey arena in Hershey, PA. In the next three decades, a number of innovative designers, such as

Pier Luigi Nervi, Eduardo Torroja, Vasilii Vlassov, Heinz Isler and Felix Candela, advanced the state-of-the-art by introducing new design theories and construction techniques and experimenting with shells of different forms. During this time that a variety of landmark shells of double curvature, such as hyperbolic and elliptical paraboloids, were constructed.

Innovative thin reinforced concrete shells were built by Eduardo Torroja (1899-1961), whose structures include the Market Hall at Algeciras (1933), the Zarzuela Race Track(1935), and Recoletos Jai-Alai Court (1936)]. Inspired by these shells, Félix Candela (1910-97) built his first experimental catenary funicular shell (Ctesiphon Vault) in 1949 at San Bartolo de Naucalpan, Mexico. Thereafter Candela went on to build a host of innovative and beautiful thin reinforced concrete shells, which include the Fernández factory conoid in 1950, and the "umbrella" at Las Aduanas in 1953, Cosmic Rays Pavilion for the National Autonomous University at Mexico City in 1951, Church of Our Lady of the Miraculous Medal, Narvarte, Mexico City (1955), saddle shaped Chapel Lomas de Cuernavaca (1958), Los Manantiales Restaurant in Xochimilco, Mexico City (1958), Bacardí Rum Factory in Cuautitlán, Mexico(1960),Templo de Santa Mónica in Colonia Del Valle, Mexico City (1963), Roof of metro stations at Candelaria and San Lázaro (1969), and the Oceanographic, Valencia, Spain (2003). Fig.19 shows the L'Oceanogràfic, City of Arts and Sciences, Valencia, Spain and Fig. 20 shows the Our Lady of the Miraculous Medal Church and the Bacardí Rum Factory.

Fig. 19 L'Oceanografic at Valencia, Spain *(2003) by* Félix Candela *(source: en.wikipedia.org)*

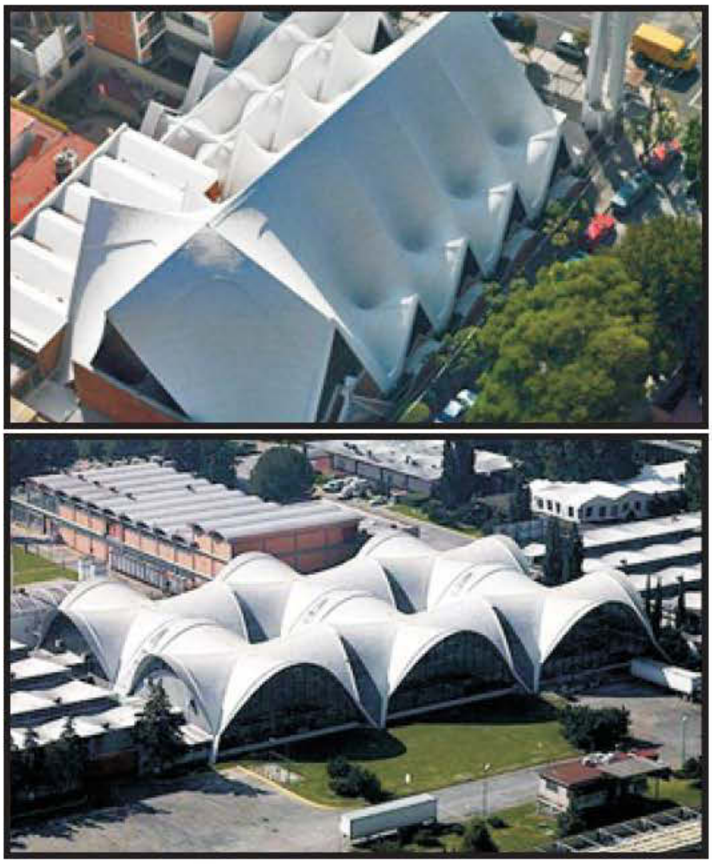

Fig. 20 Candela's Our Lady of the Miraculous Medal Church and Bacardí Rum Factory (source: www.studyblue.com)

The first dome designed by engineer Nervi(1891-1979) at a significant scale that featured interior ribs, is the 40 m half-dome at the Exhibition Hall, Salone Principale (Turin, Italy, 1949). The details of other domes designed by him are given in Table 1. For the 1960 Olympics, Nervi designed and built four masterpieces: the Palazzetto dello Sport (Fig. 21), the Palazzo dello Sport in the EUR, the Flaminio Stadium and the Corso Francia Viaduct. Based on his experiments with statics and construction and with the intention of minimizing the costs of formwork and supports, he developed a system with a number of authentic inventions, such as *ferrocement*, structural prefabrication and a series of original technical solutions. Fig 21 shows the interior of Palazzetto dello Sport, Rome, Italy which is a ribbed concrete shell dome 61m in diameter, constructed with 1620 prefabricated concrete pieces, braced by concrete flying buttresses. Since the structure was prefabricated, the dome was erected in 40 days. The Austrian engineer Ildefonso Sanchez del Rio Pison (1898-1980) developed corrugated shell system and used it for the Oviedo Sports Pavilion (1975) and roof of the Pola de Siero market (1929), both in Spain and in a number of water tanks.

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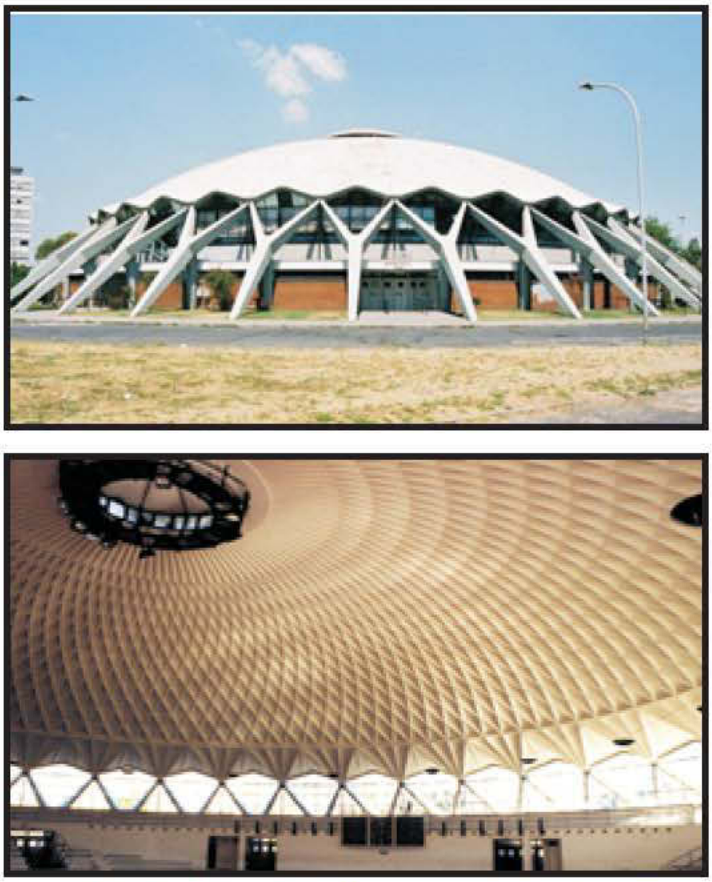


Fig. 21 **Palazzetto dello Sport,** *Small sport complex, Rome, 1956-57 by Nervi (a) Outside view and (b) Internal view (Source: http://structurae.net / and www.arch.mcgill.ca)*

Table 1 Dimensions and design details of Nervi's domes (Segal and Adriaenssens, 2013)

Dome	Year	Approximate shape in plan[1]	Precast elements forming ribs	Buttresses	Rib-to-buttress member(s)
Salone Principale, Turin, Italy	1949	40 m diameter, semi circle	Diamond-shaped	None	-
Salone C Italy	1950	31.1 m by 45.8 m rectangle	Diamond-shaped	Edge beams	Edge beams
Festival Hall, Italy	1952	25.9 by 32 m ellips	Diamond-shaped	None	-
Small Sports Palace, Italy	1957	59 m diameter circle	Diamond-shaped	Y-shaped in plan with simple cross-section (one tier)	Transitional elements
Large Sports Palace, Italy	1960	59 m diameter circle	Corrugated	Complex cross-section (Multiple tiers)[2]	Transitional elements
Norfolk Scope Arena, USA	1970	99.5 m diameter circle	Triangle - shaped	Complex cross-section (one tier)	Edge ring beam

1. Plan dimensions are based on the clear span between supporting members at the dome's base.
2. The most visually prominent tier, the middle tier, has complex cross-sections.

Nicolas Esquillan(1902-1989), under the guidance of Nervi built the double corrugated ribbed thin vault, which spans 218 m over a triangular floor plan for the Centre for New Industries and Technologies (CNIT) in Paris (see Fig. 22). It has World's largest unsupported concrete enclosed space [a similar structure, but with a smaller span, was built in the campus of college of Engineering, Guindy, Chennai during 1973, but it collapsed while removing the formwork, due to several reasons]. It may be interesting to note that the California architect Wallace Neff used a form made out of inflatable balloon and built a number of bubble houses in Florida. In the 1960s, the Italian architect *Dante Bini* used a spherical balloon of plastic fabric, laid the reinforcing bars and pouring concrete on it before it was inflated, then lifted the wet concrete and its reinforcing by pumping air in the balloon. He deflated the balloon after two days, and using a rotary saw cut openings for doors and windows; the pulled out balloon was reused several times. He built 1500 such structures ranging in diameter from 7.5 to 90m in twenty three countries.

Fig. 22 World's largest building with a span of 218 m-CNIT building, Paris (source: http://en.wikipedia.org/)

The Swiss structural engineer Heinz Isler (1926 – 2009) is one of the great reinforced concrete shell builders of the 20th century. He left a legacy of more than 1,000 elegant yet economical forms across Europe, notable among them are the roofs for a complex of sports halls and a swimming pool at the Norwich Sports Village (1987-91), concrete shell roof of the garden center Wyss in Zuchwil, (1962), Concrete dome roof of a building of the former company Kilcher in Recherswil, (1965), Highway service area Deitingen south, triangle concrete cupola roofs, (1968). He introduced revolutionary methods of form-finding shells using three methods of shaping: through using earth mounds, inflated rubber membranes, or hanging cloths, which potentially allowed the design of an infinite spectrum of new forms. The second and third methods generate forms that are in pure tension. His inflated membrane method led him to develop a standard "bubble" shell that was utilized in hundreds of examples up to 58.8 m in span, mainly for commercial and industrial buildings. However, his reputation as a structural artist was earned primarily from the slender shells shaped by inverting the form of a hanging cloth or membrane. The elegance and structural purity of forms such as the two 31.6 m span triangular plan canopies of the filling station roof at Deitingen, near Bern, Switzerland gained the respect and acclaim of architects as well as engineers [see Fig. 23(a)].

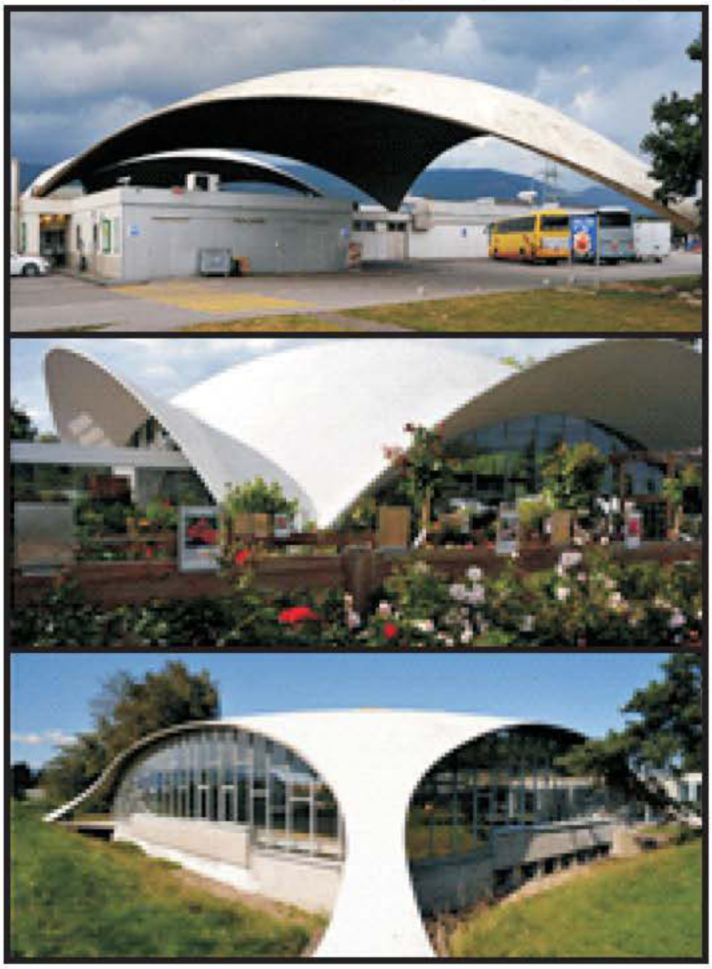


Fig. 23 Aesthetic shells by Heinz Isler (a) filling station roof at Deitingen, near Bern, (b) Concrete shell roof of the garden center Wyss in Zuchwil, and (c) Dome over the building in Recherswil (source: http://en.wikipedia.org/)

The Sydney Opera House

Another remarkable iconic structure is the Sydney Opera House in Sydney, Australia, which was designed by the Anglo-Danish engineer Sir Ove Nyquist Arup (1895–1988) of Ove Arup & Partners [Architect: Danish architect Jørn Utzon (1918-2008)]. It was declared as UNESCO World Heritage monument in 2007 as an architectural work of outstanding universal value from the point of view of both art and science. The massive concrete sculptural arched vaults that form the Sydney Opera House's roof appear like billowing sails filled by the sea winds with the sunlight and cloud shadows playing across their shining white surfaces. Even though the construction of this project was started in 1959 (Utzon won an international competition in 1957), it was completed only in 1973, with huge cost overrun- with a final cost $102 million, as against the estimated cost of $ 7 million in 1957 (Utzon left the project before its completion).

The original geometry of the shells based on a parabola presented several engineering and construction problems. The unprecedented structure required complex, repetitive research and exacting structural analysis. From 1957 to 1963, the design team went through at least twelve alterations of the form of the shells, trying to find an economically acceptable form before a workable solution was completed. In mid-1961, the design team found a solution to the problem: arched vaults all created as sections from a sphere. This solution allows arches of varying length to be cast in a common mould, and a number of arch segments of common length to be placed adjacent to one another, to form a spherical section. The roof is actually made of precast concrete panels that rest on prefabricated concrete ribs. The roofs are covered with about one million Swedish glazed tiles of matte cream white color, forming a faint inverted "V" (chevron) pattern though from a distance the tiles look only white.

The Sydney Opera House was one of the first buildings in the world to make use of computers in its construction process. It can be seen as a precursor to the complexity of architectural constructions that have now become possible by means of computer-aided design (Carter 2005). Design techniques devised by Utzon and Arup for the Sydney Opera House have been extensively developed and are now used for work such as Blobitecture (explained in the future part of the paper). Another significant innovation was Ove Arup & Partners' use of *wind tunnel testing* during the construction of the shells. An adjustable mounting and assembly steel erection arch was invented especially for the project by a French engineer working for the building contractor the Hornibrook Group. An innovative epoxy resin process was developed for bonding the segments together, following extensive research by the Cement and Concrete Association (England) and the University of New South Wales.

The design solution for the glass walls of the Sydney Opera House pushed the boundaries of contemporary technology to the limit and took eight years to complete. Extensive research, experimentation and testing were undertaken to resolve the problems which involved calculation of the load-bearing characteristics of the glass; design of a supporting framework that would load the glass to a degree it could withstand; investigation of structural materials for the mullions; and construction and erection of prototypes under the shells. The Sydney Opera House was the forerunner of many dramatic glass walls that have been constructed since, notably the glass wall at La Villette in Paris by Peter Rice and the engineered glass structures of the eminent German engineers Jörg Schlaich and Werner Sobel (Addis 2005). The walls won Ove Arup & Partners an award for engineering excellence in 1972 from the Association of Consulting Engineers of Australia. The Pritzker Prize formally recognized that the Sydney Opera House was 'one of the great iconic buildings of the twentieth century' and that it was 'an image of great beauty known throughout the world'. More details of this structure may be found at Ref. 25,26 and 27.

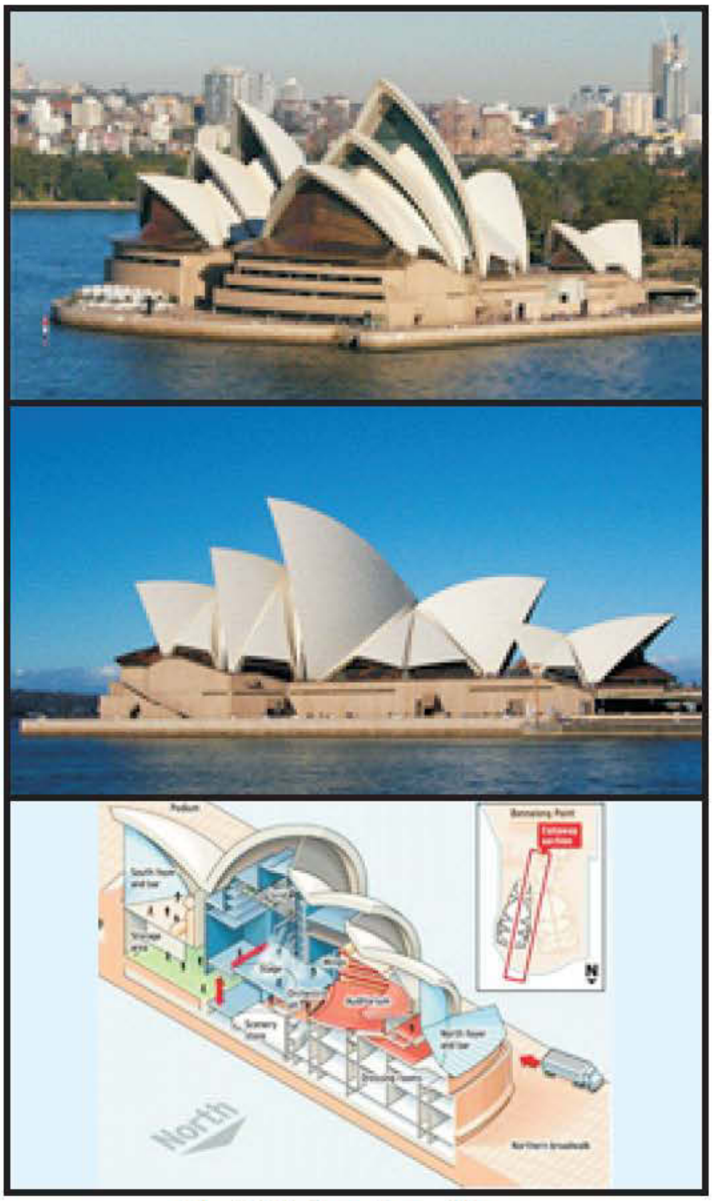


Fig. 24 Sydney Opera House
(Source: http://en.wikipedia.org/wiki/Sydney_Opera_House)

Notre-Dame-du-Haut Chapel at Ronchamp (France 1950–1955), is one of the finest examples of the architecture of Franco-Swiss architect Le Corbusier and one of the most important examples of twentieth-century religious architecture. This Chapel is made mostly of concrete and is comparatively small, enclosed by thick walls. It has an upturned roof supported on columns embedded within the walls, like a sail billowing in the windy currents on the hill top (see Fig. 25). The design of Sydney Opera House and Notre-Dame-du-Haut Chapel are exceptional and define architecture in terms of size, form, shade, sun light and colour.

Fig. 25 La Corbusier's Notre-Dame-du-Haut Chapel at Ronchamp, France
(Source: http://www.organicarchitecture.info/)

Masterpieces of the 20th century that challenged conventional norms of building expression, planning, and architectural typology, in ways comparable to the Sydney Opera House, include the City of Brasilia, Brazil (1957–1960) which was conceived by the Architect Oscar Niemeyer, Frank Gehry's Guggenheim Museum, Spain (1993 –1997), Richard Meier's Getty Centre, Los Angeles, California, USA (1989-1997) and the Centre Georges Pompidou, Paris, France (1971-1977), which was designed by the architectural team of Renzo Piano and Gianfranco Franchini of Italy and Richard Rogers of UK; and Ove Arup & Partners (structural design).

Skeletal Space Frames

The breakthrough invention was made by Dr. Ing. Max Mengeringhausen of Würzburg, Germany in 1948, when he developed the MERO system [see Fig. 26(a)], which later lead to the development of several other patented space frame nodes. A number of breath taking space structures have been built all over the world in the past 60 years. Two notable structures built using the MERO system are the Singapore Arts Center built in 2002 (now called *Esplanade Theatres on the Bay* and nick named as *"the durians", it was* designed by DP Architects (DPA) of Singapore and the London-based Michael Wilford & Partners (MWP) and MERO GmbH & Co. KG. This structure consists of two rounded space frames fitted with triangulated glass elements and sunshades, which balance outward views with solar shading. Geometry played a major role from the design to the fabrication of the Arts Centre. The surfaces of both envelopes are NURBS, which stands for 'Non Uniform Beta Splines', a mathematical description for *free form surfaces*. Stimulation for the development of NURBS came from the ship building, automobile and airplane industries), and the *Eden project* at Cornwall, U.K., built in 2000 (Designed by architect Nicholas Grimshaw and structural engineering firm Anthony Hunt and Associates, these biomes comprise of several intersecting double layer domed structure varying from 38 - 125 m in diameter and made of the standard MERO-TSK nodes. The cladding consists of inflated membrane cushions made of ETFE foil which maximize the ultraviolet from the sunlight needed by the plants. With the total covered surface of about 30,000 m^2, the Garden of Eden is the largest greenhouse in the world). The birds-eye view and interior view of the Singapore Arts Center is shown in Fig. 26(b) and (c) and the Eden project in Fig. 27. More details of structures built with the MERO system may be found in http://www.mero-structures.com.

Fig. 26 MERO system: (a) KK-Ball node system, (b) and (c) Singapore Arts Center built in 2002 (source: http://en.wikipedia.org/)

Fig. 27 Double layer intersecting domes of Eden project at Cornwall, U.K., built in 2000 (source: http://en.wikipedia.org/)

Prof. Mamoru Kawaguchi of Hosei University, Japan has contributed much to the design and construction of space frames. His designs include the Grand Roof for Expo'70 in Osaka with a double-layer space frame, the Fuji Group Pavilion for the Expo 70 with an air-inflated membrane structure, the West Japan Exhibition Center with a cable-stayed roof system, Steel spatial structure for Kobe Municipal Sports Centre, Timber shell-Steel lattice hybrid of Aira Gymnasium, Space frame for the new Parliament House of the Republic of Georgia, Kutaisi (2012) and Xativa Building of Valencia, Spain. Kawaguchi also developed a structural system called the *Pantadome System*, which results in high safety, speed, and economy [Subramanian(2007), www.kawa-struc.com/index_e.html]. Some examples of structures using his Pantadome System are the World Memorial Hall, Kobe, Japan (1984); Space frame of Singapore National indoor Stadium (1989), Sant Jordi Sports Palace for Barcelona Olympics, Spain (1992); Sundome, Fukui, Japan(1995), and Namihaya Dome, Osaka, Japan(1996). Fig. 28 shows the model and actual erection of space structures using the Pantadome system.

Other notable names who contributed to the development of space structures include Dr. Buckminster Fuller (did early work and designed the 76 m diameter, three-quarter sphere, geodesic dome for the US pavilion for Expo '67 in Montreal, Canada), Prof. Z.S. Makowaski (he designed several space frames and also established the Space Structure Research Centre at the University of Surrey, U.K. The Indraprastha Stadium (Indira Gandhi Stadium) in New Delhi, erected for the 1982 IX Asian Games, and two aircraft hangars at London Airport, Heathrow, were designed by him), Prof. Nooshin (He invented *Formex* configuration processing, which is used along with the programming language *Formian* to generate and process complex space frame configurations), Stephane Du Chateau (who developed several space frame systems such as S.D.C., Pyramitec, and Tridimatic systems), architect Kenzo Tange and engineer Yoshikatsu Tsuboi (1907-1990) (they together designed several novel space structures in Japan), Prof. J.F. Abel (He is extensive computer studies on concrete shells, membrane roofs, and domes and co-authored one of the earliest published textbooks on the finite element method with C.S. Desai)

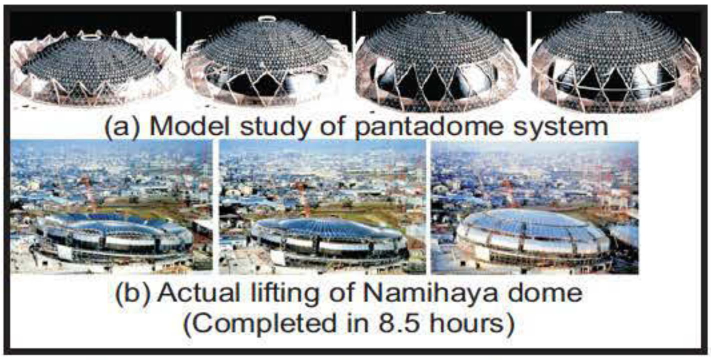


Fig. 28 Pantadome system for erecting domes Kawaguchi (Source: Kawaguchi)

Tensile structures

Tensile structures are one of the oldest structural forms used by humans (Scientists recently found tent ruins in Russia dating to about 40,000 B.C.) All early tents consisted of hide, leather or other fabric material, wooden supports, and ropes. The fabric only resists tension and has almost no compression or bending stiffness. Only in the 1950s, architects and engineers began to take a renewed interest in using tension as the primary method of transferring loads in structures, which will result in elegant and economic structures. Frei Otto and Horst Berger of Germany were notable for this advancement of tensile structures. Otto was a pioneer in tensile architecture and discovered natural forms such as soap bubbles/crystals and created shapes that used minimum amount of materials very efficiently [Otto (1973)]. He then went on to make the connection that these forms could be used as possible shapes of perfect tension and therefore could be utilized in tensile architecture. Due to the low dead weight of tensile or membrane structures, upward and downward wind loads affect their behaviour and it is necessary to pretension the membrane for stability. Berger discovered the mathematical relationship describing the soap bubble form. Since this discovery, tension fabric structures are being constructed all over the world [Berger (1996), Subramanian (2007), Ishii (1995)].

As mentioned earlier, tensile structures are those formed mostly of components acting in tension,rather than in compression. Most tensile structures are supported by some form of compression or bending elements, such as masts (e.g. *Millennium Dome*, now called as the O_2 Arena, London, England designed by Buro Happold and Richard Rogers Partnership), compression rings or beams. They include tents, suspension-bridges, and suspended roofs (where weight can determine the form of the structure and its very stability); prestressed membranes and cable-roofs (where form and stability derive from forces in tension created by stressing); and pneumatic structures (which depend on air to support surfaces in tension). A tensile membrane structure is most often used as a roof, as they can economically and attractively span large distances. Since the 1960s, tensile structures have been promoted by designers and engineers such as Ove Arup, Buro Happold, Walter Bird of Birdair, Inc., Frei Otto, Mahmoud Bodo Rasch, Eero Saarinen, Horst Berger, Matthew Nowicki, Jörg Schlaich, the duo of Nicholas Goldsmith & Todd Dalland at FTL Design & Engineering Studio and David Geiger.

Examples of aesthetic tensile structures include suspension system for the roof of paper-making factory at Mantua by Nervi (1963), tensioned structures using cables by Nowicki [Dorton Arena, NC (1953)], Saarinen's structures [Dulles International Airport Terminal, Chantilly, VA (1963), David S. Ingalls Hockey Rink, Yale University, New Haven, CT (1959)], the National Gymnasia, Tokyo (1964) by Tange, and Denver International Airport, Denver. However, using tent as his precedent, Frei Otto developed numerous designs including the German Pavilion, Expo 67, Montréal, Canada, and the Olympic stadium at Munich, Germany (1972), employing flexible, wire-rope, cable-nets (to which covering membranes were fixed) suspended from masts and framed by cables around the edges which transferred the stresses to anchor-points. The beautiful Olympic stadium at Munich, for which Jörg Schlaich and Fritz Leonhardt were the structural designers, is shown in Fig. 29 and the fabric roof of Denver international airport, Denver is shown in Fig. 30. Skidmore, Owings & Merrill LLP (SOM) used steel pylons to support radial cables carrying conical tent-like fibreglass roofs at the Háj Terminal, International Airport, Jeddah, Saudi Arabia (1982). [Designed in part by Berger/ Geiger during 1978, Háj Terminal is the largest tensile structure in the world. Note that the membrane prestress used for the Haj modules was 123 N/cm. However, later structures, such as the roof of Canada Harbour Place in Vancouver, B.C., which was built in 1984, were designed with a membrane prestress of 61 N/cm only, i.e., half of that of the Haj Terminal]. Several tensile structures have also been executed by Form TL Ingenieure für Tragwerk und Leichtbau GmbH, Germany (www.form-tl.de/en/projects.html)

Fig. 29 Olympic stadium Munich (1972)-
Designed by Frei Otto, Jörg Schlaich and Fritz Leonhardt
(source: http://en.wikipedia.org/)

Fig. 30 Fabric roof of Denver International Airport, Denver (1995), designed by Severud Associates and Horst Berger (Photo by Author)

Tensegritic structures are a special class of tensile structures and have isolated compression members inside a net of continuous tension members, in such a way that the compressed members (usually bars or struts) do not touch each other and the prestressed tensioned members (usually cables or tendons) define the system spatially[Pugh (1976)]. These are more economical than any other structural system. Richard Buckminster Fuller, David Georges Emmerich and Kenneth D. Snelson are usually credited for inventing them during the 1960s. René Motro of the University of Montpelier, France did considerable work on *tensegrity* after 1973. The Georgia Dome in Atlanta, which is a lightweight tensegrity structure was designed by Matthys Levy of Weidlinger Associates and completed in 1992 at a cost of $214 million (see Fig. 31). The 256 m diameter Georgia Dome became the largest cable-supported fabric roof in the world and is an example of tensegritic structure. Stretching more than 36,697 m^2, the Teflon-coated Fiberglas fabric roof is quite an engineering marvel. Short, vertical posts carry the weight of the Georgia Dome roof. The posts are held in place by pre-stretched cables, attached to the top and bottom of each post with steel pins and welded connections. The cables pull on the posts with equal force in all directions to form strong, taut triangles. The cable roof is secured to a reinforced concrete ring along the perimeter of the dome. The 2,750-foot concrete ring rests on slide-bearing Teflon pads that allow the roof to flex slightly during high winds. Several interesting "pleated" tensile membrane tensegritic and other domes were designed by David H. Geiger (1935- 1989) [the 1988 Summer Olympic Gymnastics Venue, Seoul, Korea, first translucent insulated fabric roof at Lindsay Park Sports Centre, Calgary, Alberta, Canada, air-supported fabric roof to cover a stadium at the Silverdome in Pontiac, Michigan, BC Place, Vancouver, Canada (1983), Tokyo Dome, Tokyo (1988)] and Prof. Kazuo Ishii in Japan (Akita Sky Dome(1990), the Retractable Komatsu Dome(1997) and the Akita O-Dome).

The Swiss structural engineer Heinz Isler (1926 – 2009) is one of the great reinforced concrete shell builders of the 20th century. He left a legacy of more than 1,000 elegant yet economical forms across Europe, notable among them are the roofs for a complex of sports halls and a swimming pool at the Norwich Sports Village (1987-91), concrete shell roof of the garden center Wyss in Zuchwil, (1962), Concrete dome roof of a building of the former company Kilcher in Recherswil, (1965), Highway service area Deitingen south, triangle concrete cupola roofs, (1968). He introduced revolutionary methods of form-finding shells using three methods of shaping: through using earth mounds, inflated rubber membranes, or hanging cloths, which potentially allowed the design of an infinite spectrum of new forms. The second and third methods generate forms that are in pure tension. His inflated membrane method led him to develop a standard "bubble" shell that was utilized in hundreds of examples up to 58.8 m in span, mainly for commercial and industrial buildings. However, his reputation as a structural artist was earned primarily from the slender shells shaped by inverting the form of a hanging cloth or membrane. The elegance and structural purity of forms such as the two 31.6 m span triangular plan canopies of the filling station roof at Deitingen, near Bern, Switzerland gained the respect and acclaim of architects as well as engineers [see Fig. 23(a)].

Fig. 31 The 256 m diameter Georgia Dome in Atlanta designed by Matthys Levy, 1992
(a) External view, (b) Internal view
(source: http://www.stadiumsofprofootball.com/)

Tall Buildings/ Structures

Tall buildings such as Chrysler Building of 1930 and Empire State Building of 1931 were accomplished not through notable technological evolution, but through excessive use of structural materials. Due to the absence of advanced structural analysis techniques, they were quite over-designed. Structural systems for tall buildings have undergone dramatic changes since the demise of the conventional rigid frames in the 1960s as the predominant type of structural system for steel or concrete tall buildings. Based on extensive investigations, the Bangladeshi-American structural engineer and architect Fazlur Rahman Khan developed several innovative structural systems and classified tall building frames as per Fig. 32. His idea of *tube structural system* for tall buildings, including *framed tube*, *trussed tube* and *bundled tube*, in which all the exterior wall perimeter structure of a building is utilized to simulate a thin-walled tube, revolutionized tall building design.

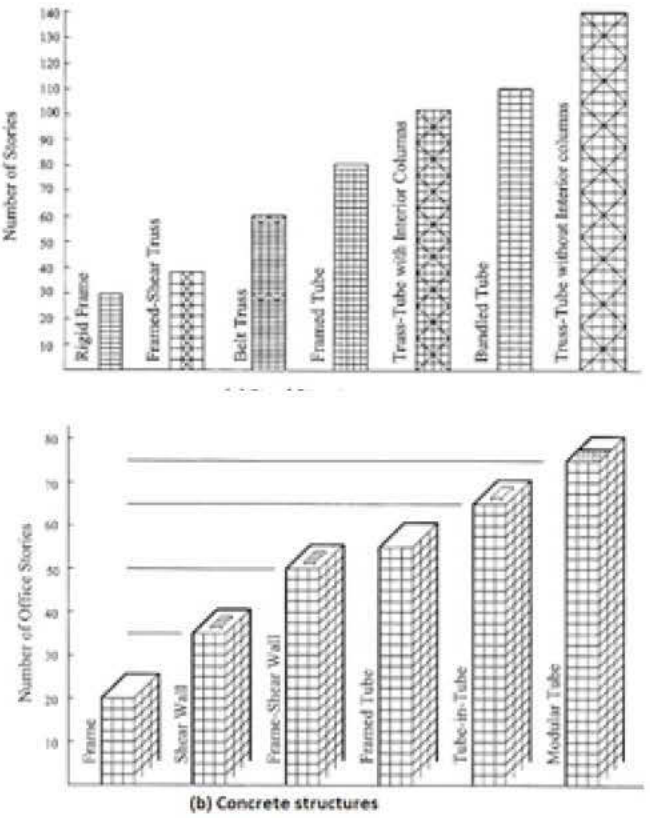


Fig. 32 Classification of tall building structural systems by Fazlur Khan (source: Ali and Moon, 2007)

Khan, employed by Skidmore, Owings and Merrill (SOM), also designed several skyscrapers including the Sears Tower (now *Willis Tower and* was the tallest building in the world for twenty four years), the 100-story John Hancock Center, One Magnificent Mile, and Onterie Center (see Fig 33). Some of the new developments since the 1960s include tubes, megaframes, core-and-outrigger systems, artificially damped structures, and mixed steel-concrete systems (Ali and Moon, 2007).

Fig. 33 Elegant skyscrapers designed by Khan using innovative structural systems (a) John Hancock Center, (b) the Onterie Center (photo: Author)

The structural evolution toward lighter skyscrapers caused serious structural motion problems –primarily due to wind-induced motion. Thus, the serviceability of the structure potentially became a governing factor in tall building design when high strength material was used. Generally, in tall buildings, the lateral vibration in the across-wind direction induced by vortex shedding is more critical than that in the windward direction. The motion problems of tall buildings were solved by the invention of damping systems. These damping systems can be divided into two categories, passive systems and active systems, as shown in Fig. 34 (Ali and Moon, 2007). Example of such damping systems include the viscous dampers, installed as an integral part of the bracing members, of the 55-story Torre Mayor in Mexico City, the visco-elastic dampers installed in the destroyed World Trade Center Towers in New York, sliding type TMDs installed in the John Hancock Building in Boston and the Citicorp Building in New York, and the pendulum-type TMD installed in the Taipei 101 tower, which is also used as a decorative element in the building interior.

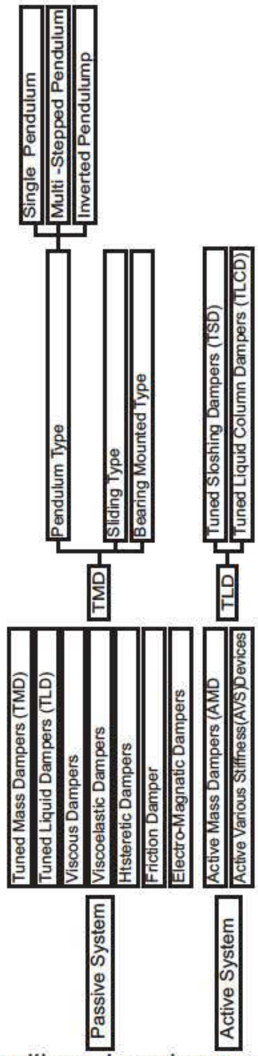


Fig. 34 Various auxiliary damping systems employed in buildings (source: Ali and Moon, 2007)

Fig. 1.1 Coarse Rubber Aggregate

In addition to these dampers, the buildings as a whole could be shielded from external ground vibration due to the invention and use of base isolation techniques (Naeim and Kelly, 1999). The base isolation systems are usually realized by elastomeric and sliding bearings, and if necessary may be combined with supplemental dampers. Numerous base-isolated buildings exit in countries such as USA, Japan, New Zealand and Italy. Examples of such buildings include: Pasadena City Hall, San Francisco City Hall, Salt Lake City, County Building, LA City Hall, and Bhuj hospital building in India.

Khan also designed several notable structures that are not skyscrapers: Hajj terminal in Jeddah (1981), which is a tent-like tensile structure and Baxter company's headquarters in Deerfield, which has a cable stayed roof system. Khan and *Mark Fintel* developed the concept of *shock absorbing soft-story* for protecting structures from abnormal loading, particularly during strong earthquakes. According to Khan, elegance can be achieved simply by the expression of the structure. The John Hancock Center, shown in Fig. 33(a) with exposed X-braces, and the Onterie Center shown in Fig. 33(b) are examples of this philosophy.

Recently, a system called diagrid, using which structural effectiveness and lattice-like aesthetics can be achieved, has been developed for skyscrapers. Note that in diagrid structures almost all the conventional vertical columns are eliminated. Examples of structures employing diagrid system are the 30 St. Mary Axe in London – also known as the Swiss Re Building or *the Gherkin* [see Fig. 35(a)] and the Hearst Headquarters in New York[see Fig. 35(b)], both by Sir Norman Foster, and Guangzhou Twin Towers in Guangzhou by Wilkinson Eyre. The Gherkin's tapered top and bulging center maximize ventilation; the building uses half the energy of similar towers of the same size. Another ultra-tall building designed by Skidmore, Owings and Merrill is the Lotte Super Tower in Korea, which employs a diagrid multi-planar façade. The 555-m tall, 123-story tower, when completed in 2014, will be the tallest building in Asia and the world's second tallest after the Burj Dubai. The O-14 Building in Dubai by RUR Architecture employs reinforced concrete diagrids as their primary lateral load-resisting system [Fig. 35(c)].

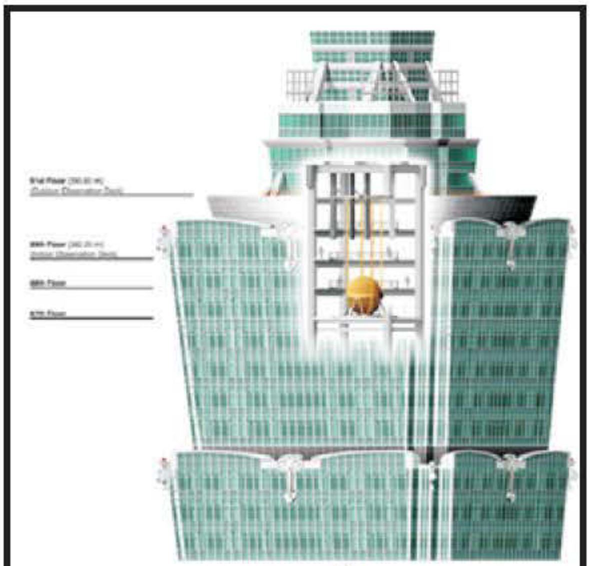
Fig. 35 Buildings with diagrid system:
(a) *the Gherkin* at London (b) Hearst Headquarters at New York (c) The O-14 Building in Dubai
[Source: (a) & (b) http://en.wikipedia.org/,
(c) Reiser et al (2010)]

Other types of lateral load-resisting systems include space trusses (the 1990 Bank of China Tower by I. M. Pei in Hong Kong), super frames (the 56-story tall Parque Central Complex Towers of in Caracas built in 1979) and exoskeleton (Hotel de las Artes in Barcelona, Spain).

Two other tall buildings which are visually appealing are shown in Fig. 36. Fig 36(a) shows the Petronas twin Towers (1998), which were designed by Thornton Tomasetti, New York (Architect: Argentine American architect César Pelli). They stand as a cultural and architectural icon in Kuala Lumpur, Malaysia and are a reflection and homage to the dominant Islamic culture of Malaysia.

Taipei World Financial Center (2004), located in Xinyi District, Taipei, Taiwan, is shown in Fig. 36(b). The design of this building is inspired by traditional Chinese architecture, with a shape resembling a pagoda. The sectioned tower is also inspired by the bamboo plant, which is a model of strength, resilience, and elegance. Taipei 101 was designed by Thornton Tomasetti and constructed by KTRT Joint Venture (Architect: C.Y. Lee & partners). This impressive skyscraper contains a circular 660-tonne tuned mass damper to counter seismic and wind-induced movement [see Fig. 36(c)]. It is constructed from 41 steel plates, is suspended from eight steel cables, rests on eight viscous dampers and can move five feet laterally in any direction. It is the largest and heaviest of its type in the world. The building was awarded LEED Platinum certification, the highest award in the LEED rating system and thus became the tallest and largest green building in the world in 2011.

(a) (b)



(c)

Fig.36 Visually attractive skyscrapers:
(a) Petronas Twin Towers, Malaysia (1998),
(b) Taipei World Financial Center, Taiwan (2004),
(c) Location of world's largest tuned mass damper in Taipei 101 (Source: http://en.wikipedia.org/)

Impressive structures designed by Ove Arup & Partners

In addition to the impressive structures mentioned earlier, Ove Arup & Partners also designed a number of notable structures, which include: Kansai International Airport, Japan (This airport built in 1994 was not affected by Kobe Earthquake in 1995 due to the use of sliding joints; In 1998, this airport survived a typhoon with wind speeds of up to 200 km/h), Millennium Bridge in London(2000), Øresund Bridge linking Sweden and Denmark(2000), London Eye, London(2000), The Gherkin (2004), Allianz Arena, Munich, Germany (2005), Melbourne Cricket Stadium (2005), Beijing National 'Bird's Nest' Stadium (2008), National Aquatics Centre (Water Cube), Beijing (2008), CCTV tower in Beijing(2008), London Heathrow Terminal 5(2008), Kurilpa Bridge Brisbane, Australia (world's largest hybrid tensegrity bridge, 2009), Stonecutters Bridge, Hong Kong(2009), Canton Tower, Guangdong, China (2010), Marina Bay Sands – Singapore (2010), Aquatics Centre, London (2011), and The Shard (87 story skyscraper in London built in 2013).

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