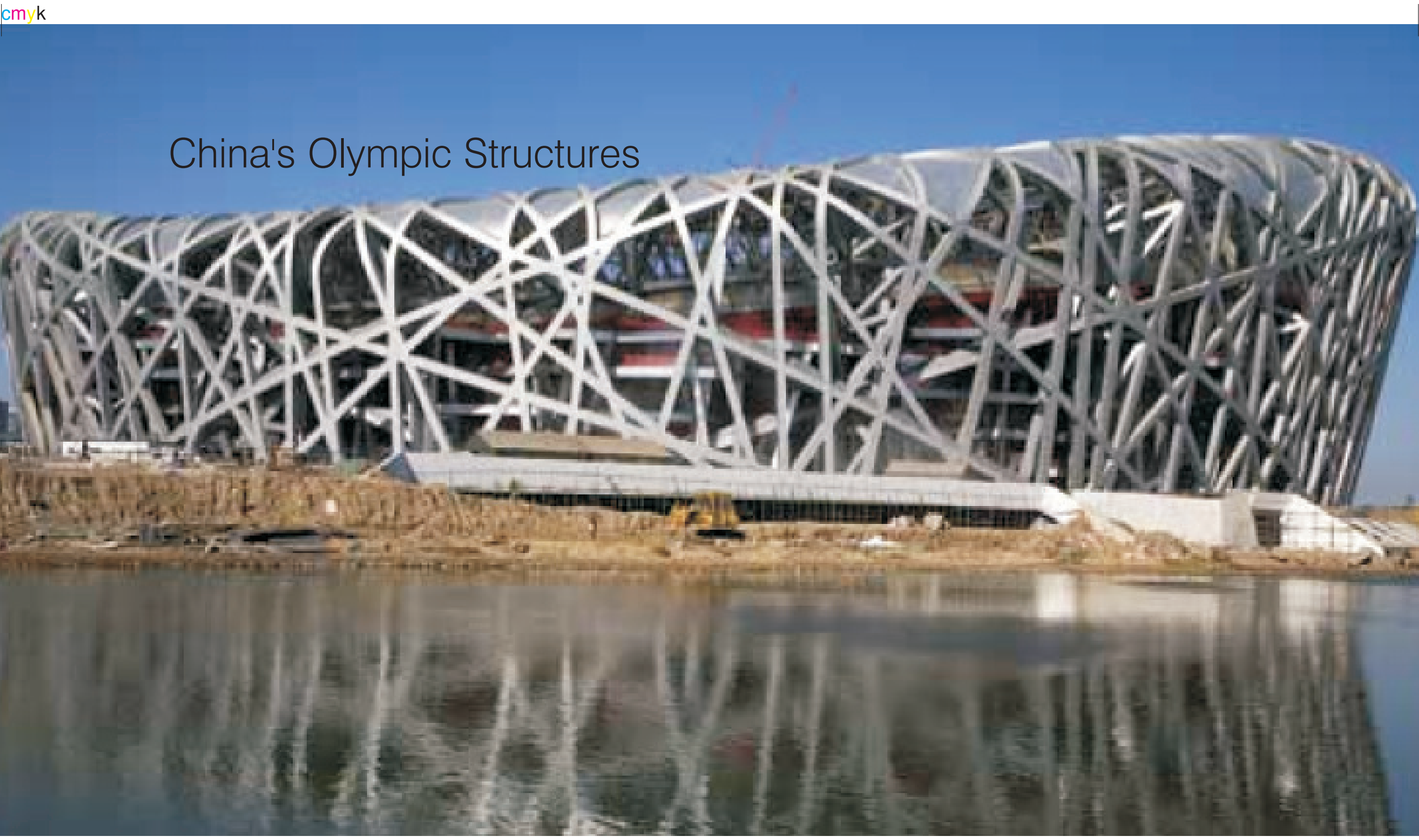

Olympic Structures of China

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Introduction

The Olympic Games is an international multi-sport event subdivided into summer and winter sporting events. According to legend, the ancient Olympic Games were founded by Heracles (the Roman Hercules), a son of Zeus. Yet the first recorded Olympic Games were held in 776 BC Olympia, Greece, and were celebrated until AD 393[1]. The very first modern Olympic Games opened in Athens, Greece during the first week of April 1896. At that time, the Greek government was unable to fund the construction of a stadium. Hence a wealthy Greek architect, Georgios Averoff, donated his wealth to restore the Panathenaic Stadium, originally built in 330 BC, with white marble for the Olympic Games[1]. Since then a number of impressive Olympic stadiums have been built in several parts of the world.

The Olympic Games (also called Olympics) provide a venue for the world to meet and celebrate peace and beauty. Today, the Olympic Games are the world's largest pageant of athletic skill and competitive spirit. They also display nationalism, commerce and politics. During Olympics people from all over the world come to a central location to compete in different sports. Each country has a team and the team consists of the best players that country has selected. The Olympic Games is subdivided into summer and winter sporting events (Olympic winter games, were established in 1924). The summer and winter games are held once in every four years. Until 1992, both were held in the same year. Thereafter, they have been separated by a two year gap[1,2]. The Winter Olympics is less known because it has fewer events.

While the sports persons eagerly awaited for Olympic Games for breaking sports records, for architects and civil engineers it was an opportunity to show their skills, by constructing novel and breath-taking structures. Several Olympic venues stand out as unique structures. For example, the roof of the Olympic stadium at Munich for the 1972 Games, which is made from plexi-glass panels suspended in a web, formed by steel cables that are hung from huge 'tent poles,' is considered revolutionary for its time(It attracts a number of visitors even now). The 2008 Summer Olympics, officially known as the Games of the XXIX Olympiad, an international multi-sport event, was held in Beijing, People's Republic of China from August 8 (8 is considered as a lucky number in China) to August 24, 2008. Though China is well known for the huge Great Wall in the past, it will be remembered for its memorable Olympics and also some of the structures, built in connection with it, for many years to come.

Sports Venues

China had to build or renovate 31 competing stadiums and gymnasiums and 43 training venues for the 2008 Olympics. In addition to this challenge, China faced the challenge of Magnitude 8.0 Sichuan earthquake on 12th May 2008, in which 69,197 are confirmed dead (with 18,340 listed as missing), 374,176 injured, and about 4.8 million people were rendered homeless[3]. The stadiums built/renovated for the 2008 Olympics are listed in Table 1.

Table 1: Stadiums Built/renovated for 2008 Olympics

Venue #	Venue	Sports	Capacity
1	Beijing National Stadium	Athletics, Football	91,000
2	Beijing National Aquatics Centre	Swimming, Diving, Water Polo, and Synchronized Swimming	17,000
3	Beijing National Indoor Stadium	Artistic Gymnastics, Trampolines, Handball	19,000
4	Beijing Shooting Range Hall	Qualifications and finals 10-, 25-, and 50-meter range shooting events	9,000
5	Wukesong Indoor Stadium	Basketball	18,000
6	Laoshan Velodrome	Cycling (track)	6,000
7	Shunyi Olympic Rowing-Canoeing Park	Rowing, Canoe/Kayak (flat-water racing and Slalom Racing)	37,000
8	China Agricultural University Gymnasium	Wrestling	8,000
9	Peking University Gymnasium	Table tennis	8,000
10	Beijing Science and Technology University Gymnasium	Judo and Taekwondo	8,024
11	Beijing University of Technology Gymnasium	Badminton and Rhythmic Gymnastics	7,500

With the Olympic Games as a showcase, Beijing officials early this decade commissioned cutting-edge buildings, drawing leading architects and designers from the world and giving a platform to what is dubbed as "star-chitecture."

We will consider four important structures, two of them built for the games: the National Stadium and the National Aquatics centre, and two built along with them: the China Central Television Headquarters and Terminal 3 at Beijing Capital International Airport.

The Beijing National Stadium

The 91,000-seat Beijing National Stadium, also known as the National Stadium is designed to look like a bird's nest and hence named Bird's nest (Figure 1). It hosted the main track and field competitions for the 2008 Summer Olympics, as well as the opening and closing ceremonies. It is located right next to the Beijing National Aquatics Centre.

Pritzker Prize-winning Swiss architects Herzog & de Meuron collaborated with ArupSport and China Architectural Design & Research Group (which supervised the local construction) to win the worldwide design competition in 2002 for this stadium. Contemporary Chinese artist, Ai Weiwei, is the Artistic Consultant for design. The pattern of steel members was inspired by a traditional 'crazed' pottery![4] The construction started in March 2004, but was halted by the high construction cost in August 2004 and continued again(it was decided not to include a retractive roof, in order to reduce the cost). In January 2008, concerns about construction working conditions arose when it was revealed that at least 10 workers had died during the stadium's construction.

The stadium is elliptical in shape, and the Bird's Nest's open roof curves

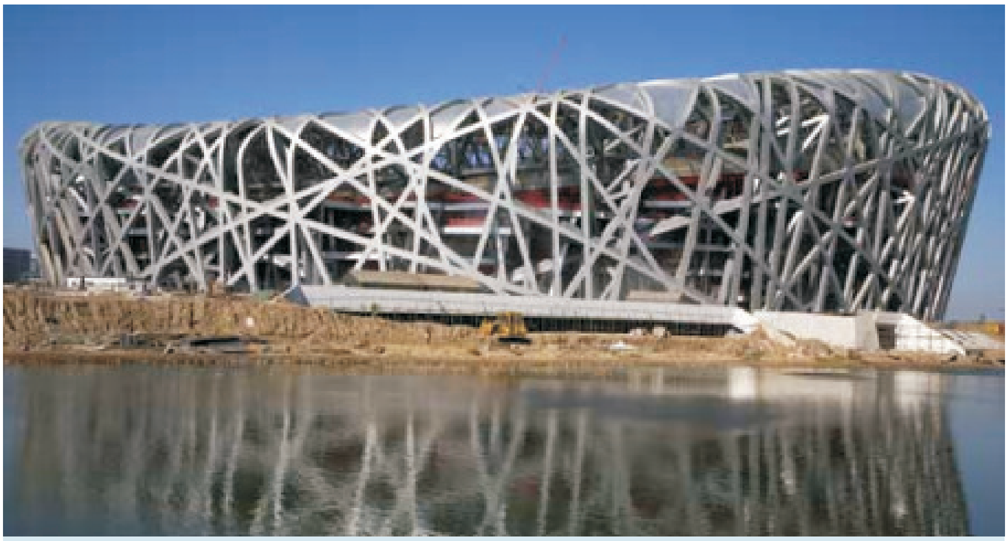


Figure1: The Beijing National Stadium (Bird's Nest), underconstruction (note the outermost layer of ETFE cladding at top) (source: Ref.4)

like a saddle. The stadium consists of a concrete bowl with seven tiers, around which the nest-like façade of steel segments is connected (see Figure 1). Some of these segments are also concourses people will use to gain access to the tiers and to ascend into the stadium. Designed to seat 80,000, the stadium in Olympic mode will have additional seating for 11,000. It has replaced the original intended venue of the Guangdong Olympic Stadium. The stadium is 330 m long by 220 m wide, and is 69.2 m tall. The central opening above the field is of size 190m x 124m. The 258,000 m^2 (gross floor area) stadium is built with 36 km of unwrapped steel. As constructed the roof structure consists of 42,000 tonnes of steel, while the stadium as a whole contains 110,000 tonnes of steel. The stadium has been built at a cost of about $423 million. This stadium boasts a state of the art Solar PV system produced by Suntech Power.

Though the outward appearance of the stadium received greater attention, inside received relatively less attraction. Chaotic as it appears, the stadium is really quite elementary in its structural design, consisting of primary, secondary, and tertiary steel members. The 24 columns that form the primary system are arranged at regular intervals around the perimeter of the building, forming an ellipse and carrying the bulk of the loads (see Figure 2a, which is a model built by M/s. Arup to explain the concept of this stadium). These main columns define the plane of the facade, which is not strictly vertical but rather leans outward at and approximate angle of 13 degrees as it raises, lending the building its distinctive saddle shape[4,5]. These mega columns rise to the full height of the stadium to join 12 m deep horizontal trusses that span the roof (see Figure 2a). The mega column has three main booms–one vertical and two inclined, they are tied together by diagonal elements forming a three dimensional truss system. The roof truss is composed of top and bottom booms with diagonal struts. Depth of the bottom chords reduces towards the center of the stadium from 1.2m to 0.8m The main elements for the columns and trusses are 1.2 by 1.2m box sections, fabricated with thickness varying from 15mm to 60mm.

The 10m deep roof trusses follow a diagonal path criss-crossing each other and leaving an opening above the athletic field in the centre, as shown in Figure 2 (During a design review, the originally planned retractable roof was eliminated, increasing the opening in the roof and reducing the amount of required steel by 30%). Thus the columns and trusses form a series of interlocking portal frames, efficiently distributing loads to the foundation. A series of struts transfer axial

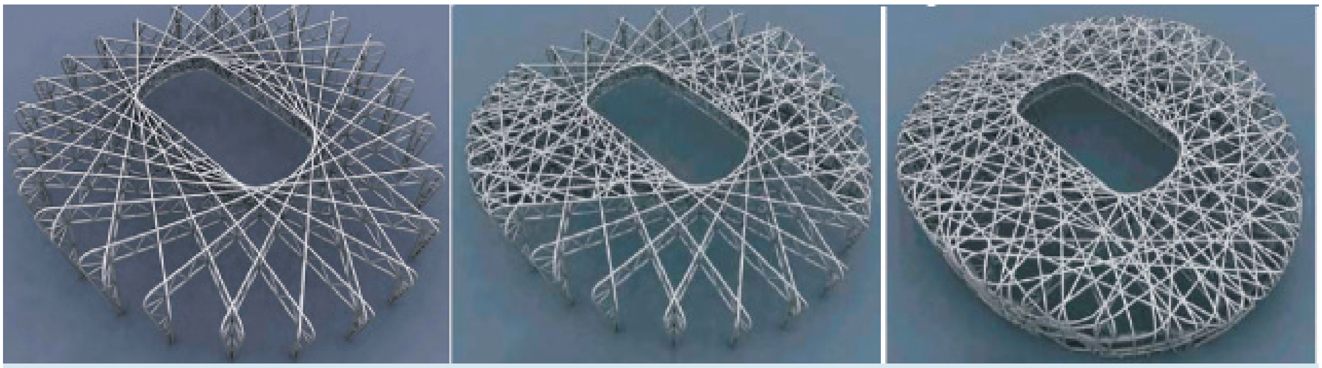


Figure 2: A model of Bird's nest stadium by M/s Arup showing the primary load carrying elements and the secondary and tertiary members (Source: Brodkin, 2008)

loads from the curving members of the truss to the vertical columns. The joints where the beams transmit their loads to the columns are critical and 100 mm thick plates are used in the box sections at these locations.

Though the arrangement of primary structural members is regular, the secondary and tertiary members are laid out randomly (see Figure 2b and c). Although they are structurally less important, they are also made up of the same 1.2 by 1.2 m steel box sections (however the thickness of plates of these sections varied between 10 mm to 100mm depending on the load carrying capacity). The secondary and tertiary members support the roof cladding and play a vital role in the seismic design. Even in a severe earthquake, the primary structure will remain elastic. The secondary and tertiary members, however, are designed to yield-thus minimizing the damage to main load- bearing members. At its edges the roof flows into smooth corners, creating a seamless transition into the façade. Thus, at the corner between façade and roof the box sections are curving and twisting in three dimensions. The interior view of Birds nest stadium showing the interior main columns, truss members, secondary and tertiary steel members and their connections, is seen in Figure 3.

The roof cladding is in two layers. The outermost layer consists of ETFE (ethylene tetrafluoro–ethylene) membrane, with thickness of 0.25mm, and protects the seating bowl from wind, rain and sun's ultraviolet rays. It covers the entire seating bowl of approximately 38,000 m^2. The inner membrane is made up of PTFE (polytetrafluor– oethylene) membrane and acts as the acoustic ceiling of the stadium and covers an area of 53,000 m^2.

The interior seating bowl itself is a conventional structure of reinforced concrete, elliptical in plan. It has six levels of above ground space and two and a half levels below grade. Expansion joints are provided in the bowl which divides it into six segments. Many of the outermost columns of the concrete bowl are also inclined to match with the exterior steel structure. The structural system was made up of pre-cast concrete step-and-seating units spanning to sloped raker beams.

Much thought was given to make the Olympic venues safe for people with physical disabilities, as the Bird's Nest also hosted the 2008 Paralympic Games in September. The concourses are handicapped-accessible, and there is a special elevator for people to reach upper-level areas. The stadium also has special zones for spectators who are disabled.

In 1976, just 91 miles from Beijing, the world's second most destructive earthquake on record, measuring 7.9 on the Richter scale, hit Tangshan City[3]. While China places the official death toll at 240,000, the U.S. Geological Survey reports that some estimates place the death toll closer to 655,000. More than 799,000 people were injured. Hence China wanted to make safety as a top priority for the designers, engineers, and builders of the new Olympic facilities. (During the construction of Olympic structures a magnitude 8.0 earthquake struck Sichuan Province of China, which was felt in Beijing also).

In addition to earthquake protection, fire protection design was also given importance. The fire protection engineering division of Arup, Inc., developed fire protection methods for the National Stadium and the National Aquatics Center[6]. Since China was not having fire safety regulations for sports facilities, at the time of construction of these stadiums, Arup referred to British standards, specifically the Guide to Safety at Sports Grounds, nicknamed the "green guide," and to NFPA standards that apply to stadiums and to fire protection for all-steel structures[6]. After the 1985 [Bradford City football stadium] fire in the U.K., there was some extensive research. They developed the 8-minute rule: if people are in an evacuation situation, they become unstable after 8 minutes, and hence have to be evacuated within 8 minutes.

Figure 3: Interior view of Birds nest stadium showing the interior main columns, truss members, secondary and tertiary steel members and their connections (Source: http://en.wikipedia.org/wiki/Beijing_National_Stadium)

Fighting fire in the Bird's Nest

The height (maximum height 69.2m) meant the normal sprinkler would generally not work in this area, so sprinklers were not provided. Chinese have developed a special fire suppression system called 'water cannon'. The stadium was provided with a detection system which scans the whole area for fire, and automatically shots water to the fire, if detected.

The areas of the facility other than those designated for the public, such as offices and training areas are all built to code as normally required. They include firewalls, smoke control systems, sprinklers, and other typical fire protection solutions.

The open design of the stadium gives spectators a clear view of exit routes, which are the same routes people will use to enter the facility.

The Beijing Fire Department developed a fire response plan ensures that firefighters will be on the scene of any fire in five minutes. To make this possible, the city built 26 temporary fire stations next to the Olympic stadiums and gymnasiums. Last summer, Beijing emergency response teams, including firefighters and fire brigades, trained in disaster drills, simulated responses to fires, earthquakes, and even a nuclear attack, reports the official Beijing 2008 website[6].

The National Aquatics Centre

The Beijing National Aquatics Centre, nicknamed the Water Cube, was built directly across the Olympic Green from the National Stadium. The Water Cube was one of the most dramatic and exciting venues constructed for the Beijing Olympics. It measures 177 m x 177 m in plan and has a height of 30.5m. It houses five swimming pools and seating for 17,000 spectators. It also has a total land surface of 65,000 m^2 and will cover a total of 7.8 acres.

In July 2003, the consortium of Ove Arup, Australian architecture firm PTW, the CSCEC (China State Construction and Engineering Corporation) and the CSCEC Shenzhen Design Institute (CSCEC+DESIGN) won the international design competition for the National Aquatics Centre. The winning design addressed broad range of engineering and design issues, including the acoustics design.

The acoustical solution was arrived by enclosing the steel building with ETFE (ethyl tetra fluoro ethylene) pillows (see Figure 4). These are provided by two

(a) view from outside (b) View from inside

Figure 4: The National Aquatics Centre, Beijing (Source: http://en.wikipedia.org/wiki/Beijing_National_Aquatics_Center)

layers of durable and recyclable plastics (having a thickness of about 0.2 mm), inflated by air. It is the largest ETFE clad structure in the world with over 100,000 m^2 of ETFE pillows. These pillows allow internal noise to pass directly outside without reverberating in the space. The ETFE cladding also allows better light and heat penetration than traditional glass, and resulted in 30% decrease in energy costs. The inner layer of ETFE pillows offered an effective vapour barrier, protecting the steel super structure from the corrosive environment inside. Also the weight of these pillows was only about one per cent of an equivalent glass panel, reducing the dead load of the long span steel super structure. An air inflating system will keep constant pressure (from 200 to 750Pa) in the air cushions so that they can resist loadings.

A thickness of 3.6 m was selected for the walls and 7.2m depth for the roof and the designers were left with the task of establishing a structure that will occupy that volume. M/s. Arup studied the work of Lord Kelvin, who developed solutions to the most effective partitioning of space with minimal surface area, based on intersecting soap bubbles. (Lord Kelvin proposed the foam of bitruncated cubic honeycomb, which is called the Kelvin structure. This is the convex uniform honeycomb formed by the truncated octahedron, which is a 14-sided space-filling polyhedron (a tetrakaidecahedron), with 6 square sides and 8 hexagonal sides)[7]. These studies lead them to the research undertaken by Weaire and Phelan in 1993 (professors of physics of Trinity college, Dublin). They used a combination of 12 and 14 sided volumes (an irregular pentagonal dodecahedron and a tetrakaidecahedron with 2 hexagons and 12 pentagons), again with slightly curved faces, to partition the space (see Figure 5). The surface area of Weaire - Phelan foam is 0.3% less than the Kelvin structure.

The outer wall of the Water Cube is based on the Weaire-Phelan foam. The pattern is formed by taking a slice through the foam, and it was chosen in preference to the Kelvin foam because the more complex Weaire-Phelan structure results in more irregular, organic patterns than slices through the regular Kelvin foam.

The structural system is space frame assembled on-site from 22,000 steel tubes welded to 12,000 nodes, which holds the cells in place and provides a column-free structure with spans of 120 m in either direction (see Figure 6). Square or rectangular hollow sections are used for all chord members on the both surfaces of the roof and walls, either connected directly or by semi-spherical nodes. Circular hollow sections are used for the web members inside and connected by spherical nodes. The three-dimensional frame is non-directional—meaning it has no up or down, left or right—making it perfect for a high-seismic zone such as Beijing[7]. The computer

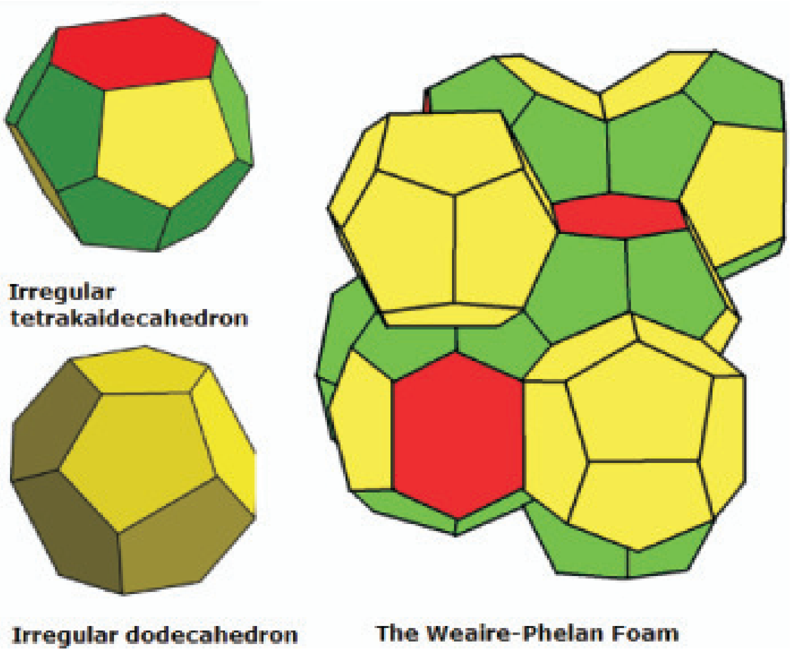


Figure 5: The Weaire-Phelan Foam results in a more efficient partitioning of Space (source: http://en.wikipedia.org/wiki/Weaire-Phelan_structure)

models revealed the extraordinary seismic resistance of this structure[4].

ETFE melts at about 270°C. Hence M/s. Arup performed its fire engineering analysis and proved that the use of this material is within acceptable risks[8]. The building is fully sprinkler-protected and has smoke control systems[8]. The building uses solar energy to heat the pools and the interior area, and all backwash water is filtered and returned to the swimming pools.

Figure 6: Steel superstructure of the National Aquatics Centre (source: http://www.arupinbeijing.com/arup_projects/national_aquatics_center/)

Beijing Capital International Airport

Beijing Capital International Airport is the main international airport that serves the capital city of Beijing, People's Republic of China. The IATA Airport Code is PEK, reflecting Beijing's former Romanization Peking. The airport is located 20 km to the northeast of Beijing city center.

It was designed by a consortium of NACO (Netherlands Airport Consultants B.V), UK Architect Foster and Partners and Arup. They built an integrated, cohesive terminal building without having to accommodate any existing buildings on site. However, while the site gave the team free rein to design a modern facility shaped by the needs of the airline industry, the timescale of the project was an important factor. It was built in just over four years at a cost of US$3.8bn.

This is the single largest airport expansion project the world has ever seen, as well as the fastest ever built. It has a roof area of over 80 acres and measures 800m across at its widest point. Terminal 3 and the Ground Transportation Centre (GTC) together enclose a floor area of approximately 1.3 million square metres. It is the first building to break the one million square metre mark. These structures will have a larger surface area than all of Heathrow's five terminals put together.

Terminal 3 will accommodate 43 million passengers a year (53 million by 2015) and provides 66 aerobridges, bringing the total number of gates at the airport to 120. The terminal has been designed to maximize natural daylight. Terminal 3's curved roof contains thousands of skylights. Their orientation to the southeast is intended to maximize the heat gain from the early morning sun, helping to reduce the amount of energy expended by the structure for heating. The roof design has an uneven 'scaled' surface to minimize energy loss in the winter and maximize cooling in summer.

Terminal 3's dragon-like form and its

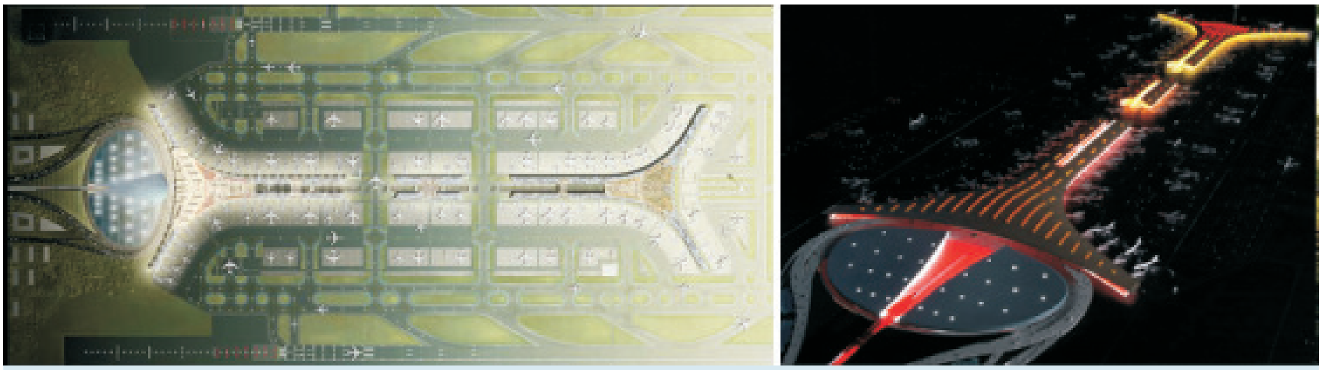
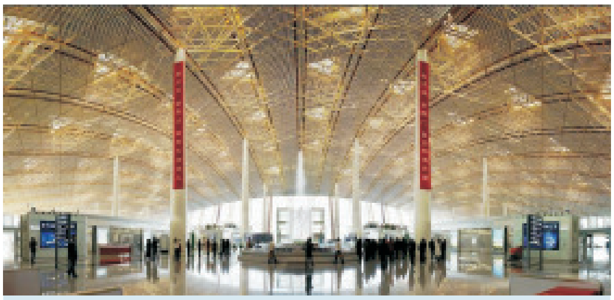


Figure 7: overall view of Terminal 3 at Beijing capital International Airport during day and night



(a) Terminal 3-Arrival level

(b) Another section of airport

(C) Dragon like form
Figure 8: Internal and external views of Terminal 3 at Beijing Capital International Airport (source: Ref.9)

gold roof resonates with the Forbidden City, while the striking interior palette of red through orange to yellow evokes traditional Chinese colours (see Figure 7 and 8). Comprising three connected, light-filled volumes–T3A, B and C–the simple, symmetrical plan fans out at either end to accommodate the arrivals and departure halls for T3A (processing terminal and domestic gates) and T3B (international gates). The satellite T3C (domestic gates) occupies the centre of the plan. This arrangement is an efficient means of maximizing the perimeter, so increasing the capacity for aircraft stands, while maintaining a highly compact and sustainable footprint[9].

Despite its size, a modular construction strategy was adopted to support the fast schedule of construction. The base level of the building is made of reinforced concrete with column grids at 12m spacing (typical of airport design which induces a sense of openness and flexibility to reconfigure the space in future). Above the departure level, the column grids are at approximately 36 m centers and covered by a doubly curved steel roof (see Figure 8a).

The roof is a steel space frame with triangular roof lights and coloured metal decking. It curves, rising at the midpoint to create a dramatic central cathedral-like space, and tapering towards the edges of the building to provide more intimate areas as passengers travel towards the gates and the aircraft piers[9]. A total of 76,924 members and 18,262 connection nodes, with little true repetition were fabricated and erected[4]. The weight of this roof was roughly 43 kg/m^2. The trusses that support the glazing echo the changing colour system in the roof–shifting from red to orange to yellow. The high transparency of the curtain walling is made possible by extra large mullions, which are generously spaced to allow larger spans of suspended glazing[9].

Lateral seismic loads are resisted by cantilevered columns in bending. Computations showed that this system offered good ductility and long vibration periods, thus reducing the earthquake loads. The avoidance of diagonal braces resulted in the optimal arrangement of building services and baggage handling systems.

The terminal building is one of the world's most sustainable, incorporating a range of passive environmental design concepts, such as the south-east orientated skylights, and an integrated environment-control system that minimizes energy consumption.

CCTV Headquarters Building

London has Big Ben, Paris has the Eiffel Tower, San Francisco has the Golden Gate Bridge and now Beijing has an iconic structure that's likely to identify the city forever. It's an audacious monolith that looks like two drunken highrise towers leaning over and holding each other up at the shoulders (See Figure 9). CCTV selected this design through an international competition. The design team consisted of the Dutch architectes Rem Koolhaas and Ole Scheeren of OMA (Office for Metropolitan Architecture) and ECADI (East China Architecture & Design Institute), Shanghai, while Ove Arup & Partners (Arup) provided the complex engineering design. The building is 234.7 m tall and has 51 floors. The building has been called an "angular marvel" and a "dazzling reinvention of the skyscraper." Because of its radical shape, it has acquired nicknames such as "Big Shorts", and "twisted doughnut". The architects have built huge glass panels in the floor of the cantilevered cross section of the building, so that visitors can get the woozy sensation of walking above nothing but air. In 2007, the skyscraper was listed as one of the "Top 10 Architectural Wonders of the Year" by Time Magazine.

The building includes broadcasting studios, program production facilities, digital cinemas and is the second largest office building in the world, after the Pentagon outside Washington. The total development is 540,000m^2, consisting of two main buildings: the CCTV building (381,000 m^2) and the Television Cultural Centre (TVCC). The total construction cost has been estimated at $750million.

The new CCTV building is not a traditional skyscraper, but in the form of a three-dimensional continuous cranked

Figure 9: View of CCTV Tower under construction (Source: http://en.wikipedia.org/wiki/Image:CCTV_Beijing_April_2008.jpg)

loop formed by a 9-storey podium at the bottom, joining two high leaning towers (40m x 60m, and 42m x 52 m size, leaning about 6° from vertical), which are again linked at the top via a 13-storey cantilevered " 70m overhang " structure at 36 storeys above the ground (see Figure 9). The building was built in two sections that were joined to complete the loop on December 26, 2007. In order not to lock in structural differentials this connection was completed at the last minute.

The interior columns are vertical and many of them extend the full height of the building. However, since the tower shift in plan 35.1m from base to top, many of the interior columns were transferred at mid-height of the building (where a single floor—also a building services floor—is heavily braced to transfer the loads across)[4,12]. For the cantilever, the transfer structure is over two floors, onto which the seven storeys of office space are built[12]. Internal columns are concrete-encased structural steel, where the concrete adds three-hour fire protection and an additional 30% strength. Arup has made the structure with a high degree of redundancy. The authorities specified that even when the corner columns are removed at the bottom, the cantilever wouldn't collapse progressively. Arup's analysis proved that the loads could be redistributed even if a three-column failure took place in this area[12].

Diagrid Exoskeleton

A diagrid system 'exoskeleton' adopted on the external perimeter faces of the building, makes the structure act as an integral tubular unit. Sloped perimeter columns, horizontal floor beams, and diagonal bracing work together to resist gravity and any other lateral forces. The positioning of the columns and diagonal tubes reflects the distribution of forces in the surface skin of the building. Note the tighter diagonal pattern highlighting areas of greater demand (see Figure 10).

The columns of the diagrid have the same exposed width but the depth varies according to the load, while the diagonals are all 1m × 60cm plate girders, with only the steel thicknesses varying. A butterfly plate links perimeter columns, braces and beams. The detailing of the diagrid enabled the vertical and horizontal elements to remain comparatively unstressed in an earthquake[12].

Seismic Requirements

The seismic design was outside of prescriptive Chinese codes of practice so, given he national prominence of the CCTV building, Arup proposed a performance-based design approach with three objectives: no structural damage when subjected to a level one earthquake (with an average return period of 50 years and a peak ground acceleration of 0.07g.); repairable structural damage when subjected to a level two earthquake (475 years and 0.2g); and severe structural damage permitted but collapse prevented when subjected to a level three earthquake (2,500 years and 0.4g). The detailing of how the floor plate meets the elevated structure was critical. The detailing is to ensure the brace yields first, and in places that are ductile; in other words not across the weld, where it might form a brittle failure mechanism. This was tested on full-scale mock-up, and shown to perform under extreme earthquake conditions[12].

Arup used advanced non-linear dynamic time-history analysis to determine the effect of seismic shock on

Figure 11: The external skin of the CCTV building has a diagrid exoskeleton which makes the tower act as an integral tubular unit (Source: Ref.11)

the building's 40,000 structural elements. Eleven structural analysis packages were used in this study[4]. A 1:20 shake-table model (which is now standing at the site's car park) was also made, and was shaken under various levels of earthquake[12]. Beijing Geotechnical Institute has also collaborated on the earthquake resistance part of the design as well as surveying the site for ground water levels.

The main towers stand on piled raft foundations. The piles are typically 1.2m in diameter and about 52m long. Due to the magnitude and distribution of the forces, the concrete raft is up to 7.5m thick and extends beyond the towers' footprints to distribute the forces more favourably into the ground. The centre of the raft is close to the centre of load at the bottom of each tower, and no permanent tension is allowed in the piles; limited tension in some piles is only permitted in major seismic events.

Connecting the Top Loop

As the structure neared completion, the loading changes considerably. Before the cantilevers are joined together, the towers have to act as pure cantilevers, thus having large forces at the lower portion of the perimeter structure. After the link is connected, the highest stresses are in the overhang structure as the towers are propped together. Between the two stages, three construction options were considered: jacking (lifting whole sections up); corner column (supporting the corner with scaffolding); and cantilever (simply building out bit by bit). The latter option was selected, and shown in Figure 11[12].

It is a challenge to tie the transfer level together while both sides were moving around at such a height. Soft connections, where the beam is hinged, were made in 12 locations. One morning several construction workers welded these together simultaneously. Before this was done, the extreme corner columns of the towers were omitted to throw more of the load back into the building and prevent overstressing of the corner member[12].

Despite the above challenges, the construction of these towers proceeded at an average of one storey per week with more than 10,000 construction workers working at site.

Summary

A number of exiting structures were built in connection with the Summer Olympics in Beijing, China, which define the current state-of-the-art structural design and construction. Details of four of the iconic structures, designed and detailed by Ove Arup & Partners, are given. Greater attention was given to earthquake resistance, fire resistance and safety. It is also gratifying to note that sustainability issues were also considered by the architects to reduce the energy needs of these structures. However it is ironic that several poor people living at the location of these venues before their construction were forcefully evacuated without much compensation and that China had to shut down polluting factories, halt construction projects, and curtailed traffic during and before the Olympic Games in order to reduce the air pollution around these venues.

Figure 11: Cantilevering the top bridge structure (source: Ref. 12)

Acknowldgment

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