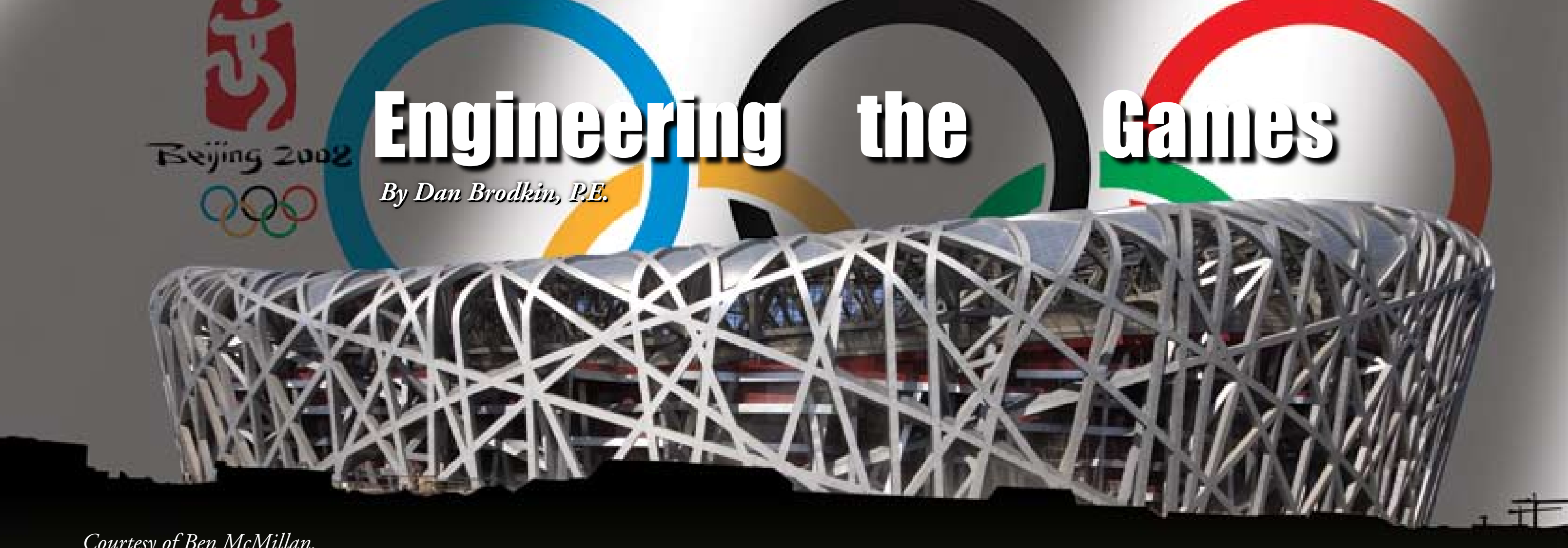


Engineering the Games

By Dan Brodkin, P.E.

Courtesy of Ben McMillan.

China's construction activity continues apace, drawing on the skills of the world's leading design architects and challenging the engineering community. As China finished preparations for the 2008 Olympics in Beijing, four particularly significant new projects took center stage, two of them for the games themselves: the National Stadium and the National Aquatics Center for the Olympics, along with China Central Television Headquarters and Terminal 3 at Beijing Capital International Airport. Arup has provided structural engineering for each of these projects, along with other multidisciplinary engineering and consulting services.

The National Stadium

As the centerpiece of the 2008 games, the stadium provides seating for 90,000 spectators within 2.7 million square feet of space. In addition to hosting track and field events, it hosted the opening and closing ceremonies of the games. Overall dimensions are 920 x 1,090 feet in plan, with a height of up to 225 feet (68.6 meters).

The project was designed, in a sense, from the inside out. The seating bowl geometry was set first, with a focus on optimizing the sight lines and drawing the seats as close as possible to the field of play. The overall form of the outer structure was then configured to create a smooth, curved wall and roof around the seating. The base of this outer shell lies along an ellipse. Interior walls are vertical, forming an elliptical cylinder, while the saddle form of the roof is cut from a toroid. The outer walls trace a warped surface between the edge of the roof and the elliptical base.

These overall surfaces are constructed from a seemingly random pattern of structure, which earned the facility its nickname, the "Bird's Nest." The pattern was actually inspired by "crazed" pottery, a style characterized by a random, crackled pattern in the glaze. The style is thought to have first occurred by accident 1,000 years ago and is still commonly found in markets around the city. In essence, the stadium's design magnifies this symbol of local culture for celebration on a grand scale.

The primary structure is actually derived from a simple geometric principle and structural system. Twenty-four columns rise from the ellipse at the base to support trussed portal frames spanning the stadium, as shown in *Figure 1*. These trusses are arranged to run tangentially along an oval roof opening, creating a complex geometry that, when coupled with secondary tube members, generates the nestlike appearance (*Figures 2* and *3*).

The portal frame system supports gravity loads effectively, pulling structural demand from the roof towards the walls. It also provides positive seismic resistance. The truss members are actually box sections up to 3.9 feet (1.2 meters) on a side, and fabricated from plates.

Although the interior seating bowl is roughly elliptical in plan, an efficient, repetitive, modular structural design was developed that yielded economies in fabrication in particular. The column grids to the east and west of the field were set out in a series of concentric circles with large radii of curvature, while those to the north and south were arranged similarly with smaller radii. The result was a repetitive system with two grid patterns supporting the four main quadrants. Transition zones were limited to corner areas. The structural system was made up of precast concrete step-and-seating units spanning to sloped raker beams.

continued on next page

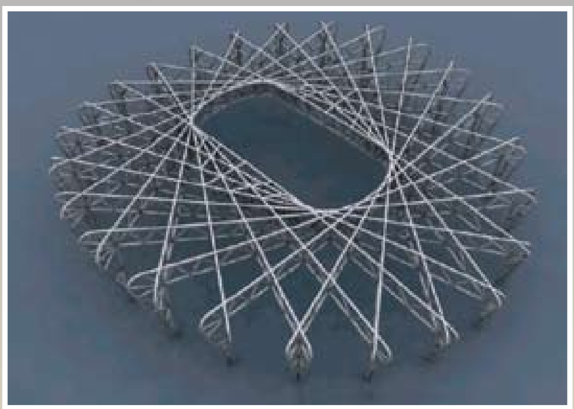


Figure 1: 24 Trussed Portal Frames Span the Stadium.

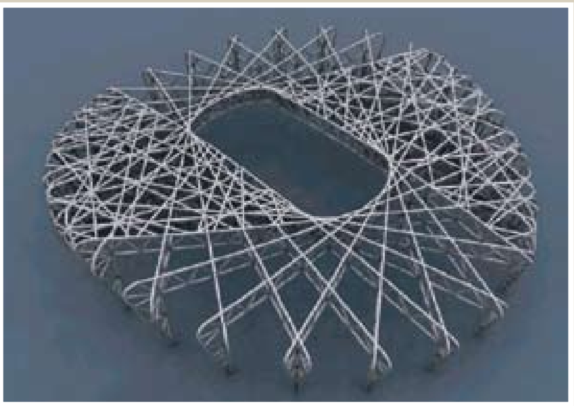


Figure 2: Secondary Tubes Coupled with the Frames Create the Random Pattern.

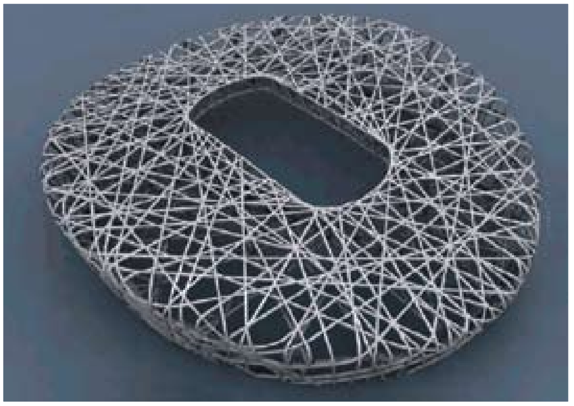


Figure 3: Secondary Tubes Coupled with the Frames Create the Random Pattern.

Courtesy of Zhou Ruogu Architecture Photography.

The National Aquatics Center

The National Aquatics Center, nicknamed the "Water Cube," is sited directly across the Olympic Green from the National Stadium. Measuring 580 x 580 feet in plan, and standing just over 100 feet (30.5 meters) tall, it houses five pools and seating for 17,000 spectators. While the circular form of the stadium makes a cultural reference to Heaven, the square form of the Aquatics Center provides contrast by embodying the Chinese symbol for Earth.

The Aquatics Center design was put to an international design competition, with technical considerations among primary drivers. The winning design was selected, in part, because it addressed a broad range of engineering and design issues beyond structural considerations alone.

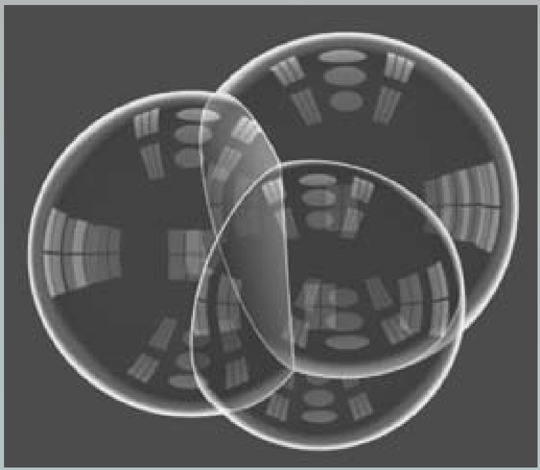
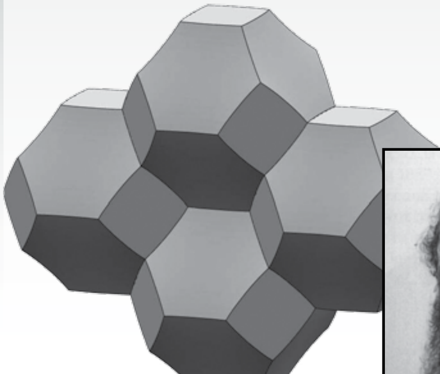
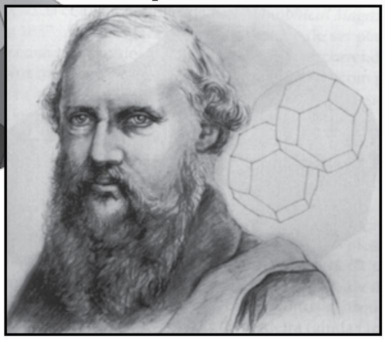


Figure 4: Deriving Form From Soap Bubbles. Courtesy of John M. Sullivan, Berlin Institute of Technology.

Acoustics was one of the first considerations. Aquatic facilities typically employ hard, water-resistant surfaces that are, as a result, acoustically reflective. When occupied by a large enthusiastic crowd, these spaces often become unacceptably loud. The search for a solution led the team to the idea of enclosing the building with ETFE (ethyl tetra fluoro ethylene) pillows. These are essentially two layers of durable and recyclable plastic inflated by air. The pillows are acoustically "transparent," allowing internal noise to pass directly outside without reverberating in the space. They insulate better than glass and their transparency creates greenhouse-like conditions that are ideal for a swim facility where heating demands exceed cooling demands. In fact, a ventilated cavity was created by using a double layer of pillows inside and outside the primary structure. Finally, architectural and structural considerations led directly to the idea of a long-span steel structure. The inner layer of ETFE pillows offers an effective vapor barrier, protecting the steel from the humid and corrosive environment inside while maintaining direct views of the system. Also, weighing roughly one percent of an equivalent glass panel, the pillows also reduced the dead load, a primary consideration for the economy of a long span structure.

As these ideas developed, it became clear that a unique structural form was needed to take advantage of the pillows, engaging their irregular geometries and supporting an iconic design. A key concept was to "wrap" the building in a system consistent across all four walls and the roof. A width of 11.8 feet (3.6 meters) was nominated for the walls, and a 23.6-foot (7.2-meter) depth for the roof, leaving designers the task of establishing a structure to occupy that volume. Space trusses, though efficient, were quickly ruled out as too ordinary. Arup's explorations led to forms found in nature, such as the intersections of soap bubbles studied by the 19th Century Belgian physicist Joseph Plateau (*Figure 4*). This subsequently led to studies by Lord Kelvin, in which he sought a means to partition space with minimal surface area (*Figure 5*). While interesting, the resulting structural patterns proved uninspiring. Arup's studies eventually took them to a contemporary solution to Lord Kelvin's problem, developed in 1993 by Professor Denis Weaire and Dr. Robert Phelan of Trinity College, Dublin. Using a combination of 12- and 14-sided volumes, they were able to divide space with a lesser area of partitions than Lord Kelvin did 100 years earlier (*Figure 6*). A volume built by this method is termed a Weaire-Phelan foam. The more irregular nature of these surfaces seemed promising, and the team was delighted when a seemingly random pattern emerged at the intersection of the foam and a skewed plane (*Figure 7*). Once it became clear that a geometry that appears random could be derived from a repetitive, mathematically derived geometry, Arup realized that they had hit upon a buildable solution. The general approach to carving the water cube's geometry from the Weaire-Phelan foam is illustrated in *Figure 8* .





Figures 5: Lord Kelvin's Solution to the Most Efficient Partitioning of Space. Courtesy of John M. Sullivan, Berlin Institute of Technology.

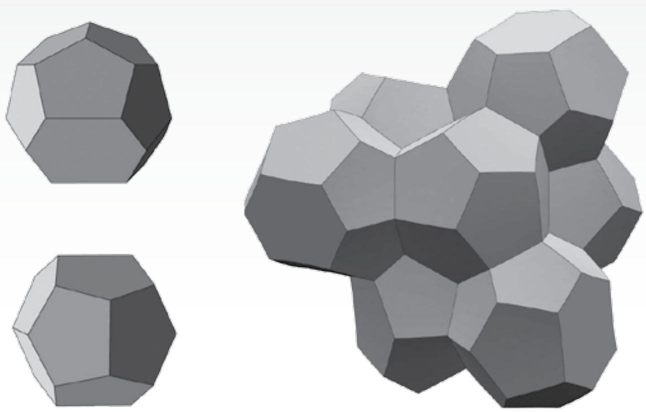


Figure 6: The Weaire-Phelan Foam, a More Efficient Partitioning of Space. Courtesy of John M. Sullivan, Berlin Institute of Technology.

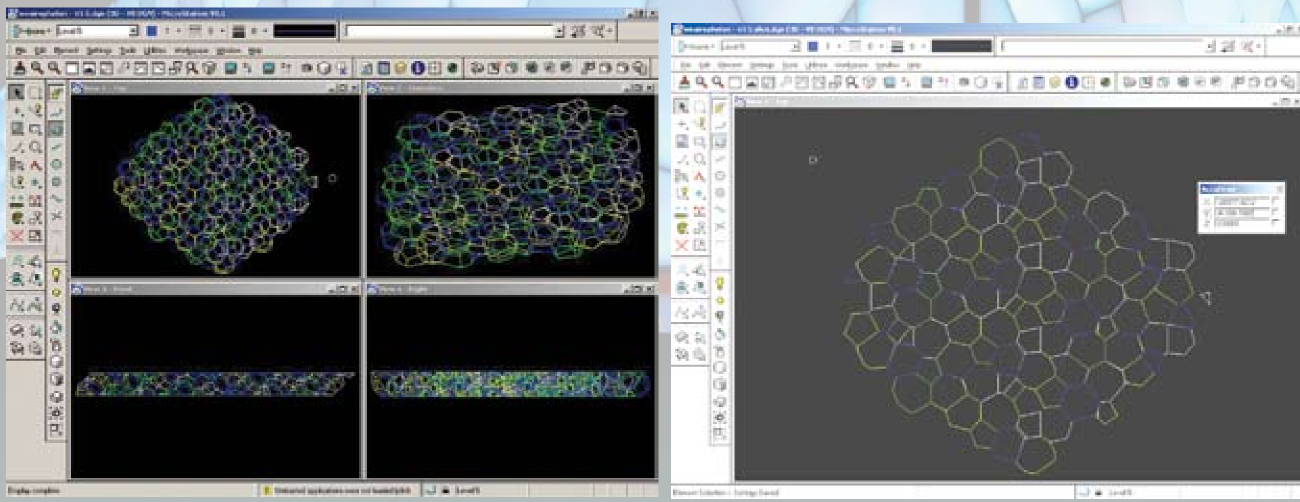


Figure 7: A Skewed Plane Cutting the Regular Foam Produces a Random Geometry.

The building's form is well suited to resist seismic action, an important consideration in one of the world's most active seismic zones. The structural system essentially follows the contours of the exterior walls and roof to create a closed box system. In this configuration, the entire roof serves as a diaphragm to deliver seismic loads to the perimeter wall frames. Within each surface, the arrangement of structural members results in moment frame behavior, which reduces loads by virtue of ductility. Though not as strong as a similar-sized space truss, the length and perimeter location of the frames makes the structure particularly strong. In fact, computer analysis has demonstrated that the entire structure would maintain its shape if it were rotated through 90 degrees and cantilevered from its base.

continued on page 37

Completed exterior of the Aquatics Center. Courtesy of Marcel Lam.

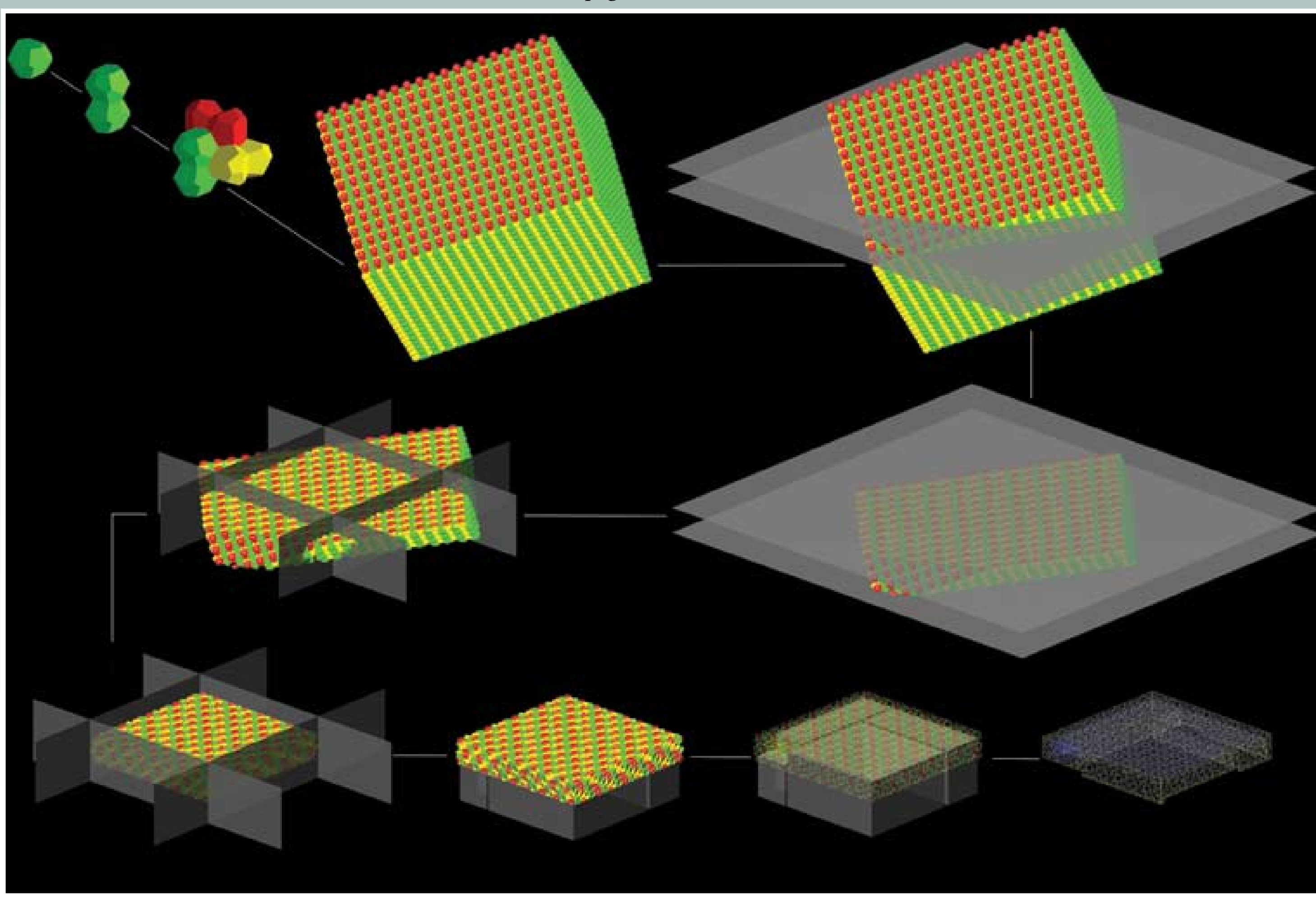


Figure 8: Cutting the Weaire-Phelan Foam to Build the Water Cube.

China Central Television Headquarters

The new headquarters of China Central Television (CCTV), now nearing completion, is a signature piece of architecture in Beijing's new Central Business District. The project's underlying goal was to enable CCTV to expand their operating capacity from 13 television channels to over 200 channels, and centralize the entire television production process in one location. Seeking an iconic design for their headquarters, CCTV selected their design team through an international competition.

The project features two towers leaning 10 degrees from vertical, reaching up to 770 feet (234.7 meters) in height and bent at the top and bottom to form a continuous, angular loop. The loop, which includes the 9- to 14-story bridge structure and a similar structure at the base, is meant to reference the interconnected activities of the television production process. Once complete, it will offer nearly 6 million square feet of new office space for program production, broadcasting, and support.

Courtesy of Frank P. Palmer.

Extensive consideration was given to whether the cores, which house the shafts, elevators, and stairs, should be sloped or vertical. While a sloped core would allow constant floor plates at each level, they would complicate procurement of elevators. Ultimately, a vertical core was selected. With that established, it was decided that the interior columns should be vertical at each floor also. The geometry of the towers is such that many of the interior column lines extend the full height of the building; however, since the towers shift in plan 115 feet (35.1 meters) from base to top, many of the interior columns had to be transferred. A double-story height transfer plate occurs at approximately the mid-height of the building. Equipment rooms are housed at these levels to use the space most effectively.

The structure acts as an integral whole by virtue of its perimeter bracing system. Sloped perimeter columns, horizontal floor beams, and diagonal bracing work together to resist the effect of leaning under gravity loads while also serving as braced frames to resist seismic loads. Fully 55 percent of the building's structural steel is allocated to this system. Grounded in Arup's analysis work, the design team call abortively opted to express the perimeter bracing in the façade, highlighting areas of greater demand with tighter diagonal patterns.

Consistent with its unusual form, the structure is non-compliant with Chinese code design. As such, a performance-based design was carried out, working from first principles to confirm the system. For seismic design, three levels of earthquake were studied:

- No structural damage under a level 1 earthquake, with a 50-year return period and accelerations of 7 percent of gravity.
- Reparable structural damage under a level 2 earthquake, with a 475-year return period and accelerations of 20 percent of gravity.
- Severe structural damage, but no collapse, under a level 3 earthquake with a return period of 2500 years and accelerations of 40 percent of gravity.

Eleven structural analysis packages were used in various parts of this study to carry out modal response spectrum analyses, static pushover analyses, and non-linear dynamic time history analyses to establish capacity of the design.

As leaning towers that rely on a connecting "bridge" at the top, structural behavior during construction was of great concern and was addressed by staged analysis methods during design. In particular, before the bridge linked the towers, each had to act as a pure cantilever, creating large forces in the lower portions of the perimeter structure. Once the link was complete, those construction loads were "locked" into the lower structure. All additional service loads could then follow the new, more efficient, load paths.

Building movements were another reason that construction considerations became central to the design process. In particular, construction phasing had to be carefully coordinated with structural analysis so that movements prior to linking the towers could be anticipated and so that, ultimately, the final building could be properly level.

Despite the challenges, construction of the towers proceeded at an average of approximately one story per week.

The structure is supported on a piled raft foundation. Piles are typically 4 feet (1.2 meters) in diameter and 170 feet (51.8 meters) long. The raft is up to 25 feet (7.6 meter) thick. By continuing beyond the tower footprint, it provides a toe and allows for a design that does not require piles in permanent tension to resist gravity loads.

In the final condition, the perimeter braced tube structure is quite stiff. Horizontal deflections are no more than 3.5 inches (8.9 cm) under the 50-year return period wind load, and vertical deflections and vertical deflections are no more than 4 inches (10.2 cm) under the 50-year return period earthquake.

continued on next page

Courtesy of Palmer Art-Net Ltd.

Terminal 3 at Beijing Capital International Airport

Olympic Games attendees who traveled by air passed through Beijing Airport's new Terminal 3, which opened earlier this year. The facility promises to represent the next step in operational efficiency and set new standards for passenger experience. A dedicated high speed train will provide a 15-minute direct trip from downtown, while an Automatic People Mover will facilitate travel within the airport itself. Nearly 300 check-in desks will greet departing passengers with reduced wait times while the baggage handling system, controlled by intelligent IT and automation systems, will offer both high speed and efficiency. The building design also offers passengers direct travel routes, quick transfer times, and few level changes.

Spread over more than 9 million square feet of space and with a capacity approaching 43 million passengers per year, the terminal's scale is enormous. At times during construction, more than 100 tower cranes were simulataneously active on site. Despite its size, a modular construction strategy supported a fast schedule of construction. The project opened in February, just four years from the start of design.

The base building is structured as a reinforced concrete frame. At nearly 40 feet (12 meters), column grids are fairly large and provide both a sense of openness and flexibility to reconfigure the space in the future, a particularly important characteristic of airport design. Above the departures level, the column grid expands to roughly 120 feet (36 meters) and is spanned by a steel roof structure.

Courtesy of Zhou Ruogu Architecture Photography.

The roof features a double-curved surface. While the form's esthetic is a signature of the project, the curvature is too modest to engage membrane action and, as such, it must span as a bending structure. The curvature did, however, pose challenges to fabrication and erection. Given these considerations, a space truss was adopted for the roof's structural system. Invented by Graham Bell in 1904, the space truss offers one of the most efficient solutions for lightweight systems in bending. Despite its slender profile, the roof in fact includes approximately nine pounds of structural steel per square foot. Using space trusses, the curved surfaces were created simply by customizing member lengths and connection node geometries, rather than by bending or faceting and splicing heavy steel sections. A remaining challenge was the small amount of repetition in the roof geometry. Computational design and fabrication techniques were heavily relied upon to support this geometric variability. In all, 18,262 connection nodes and 76,924 members, with little true repetition, were fabricated and assembled.

Lateral seismic loads are resisted by cantilevered columns in bending. This system offers good ductility and long vibration periods, both of which contribute to lower equivalent seismic loads. By avoiding the need for diagonal braces, the design facilitates more optimal arrangements for other systems, including building services and baggage handling systems, while facilitating future changes to the use of the terminal.

Any one of these four projects on its own would represent an instant new architectural and technological landmark for its host city. That all four have been built in just one city, virtually at the same time, is without precedent. This is another testament to China's remarkable growth, its aspirations, and its emergence on the world stage that the 2008 Olympics helped to herald. Arup, having worked in China for nearly three decades, is deeply honored and exceedingly proud to have worked on all of them with four separate teams of world class professionals.▪

*Daniel Brodkin P.E. is a structural engineer and principal in Arup's New York office. His professional experience includes project management, structural design and site supervision for large-scale projects. Daniel may be reached at **daniel.brodkin@arup.com**.*