

# Carrying the Torch



Over the centuries, the Olympic torch has come to symbolize much more than an athletic event. As the torch travels around the globe to the site of the next Olympic Games, it seems to embody the ideals and aspirations of an entire generation. Perhaps for this reason, the highest of expectations are placed on Olympic stadia, which are asked not only to host the games but somehow to embody their spirit. Carrying the torch this year is an iconic structure that boldly rises to those expectations: Beijing's new National Stadium. By Jeff L. Brown



The stadium's porous facade gives spectators plenty of room to stop and enjoy the view; it also provides natural light and ventilation.

On Friday, August 8, when the torch is lit and the games of the XXIX Olympiad begin, the eyes of the world will be on Beijing's Olympic Green, a vast urban park on the north side of the city. Millions will watch the opening ceremony on television, but those fortunate enough to attend the games in person will enjoy the best views of all inside China's spectacular new National Stadium, where the Olympic torch will burn for the duration of the competition.

Even before entering the arena, athletes and onlookers from around the world will no doubt pause for a moment to enjoy the sight. Measuring 330 by 220 m and rising to a height of 69 m, the recently completed building is a major addition to China's capital city. The saddle-shaped structure—designed by a team comprising Herzog & de Meuron Architekten AG, of Basel, Switzerland, Arup, of London, and the China Architecture Design & Research Group, or CAG, of Beijing—occupies an area of 21 ha and contains 258,000 m<sup>2</sup> of floor space. Its seating bowl accommodates 91,000 fans.

Given its enormous size, the stadium could have been a faceless monolith, but fortunately it is quite the opposite. Its

steel exterior, a dynamic arrangement of crisscrossing lines, evokes a sense of movement and excitement. Yet its gentle curves and lack of rectilinear forms also suggest tranquility and harmony with nature. In short, the building has a complex, magnetic personality, as thousands of visitors have already discovered. Long before it opened, in fact, the site had already become a local tourist attraction.

When Herzog & de Meuron first approached Arup about entering the competition to design an Olympic stadium for Beijing, Steve Burrows—a director of ArupSport, Arup's sports architecture company—remembers feeling some hesitation. The two firms had worked together once before, quite successfully, on the Allianz Arena, a soccer stadium in Munich, Germany, that hosted a semifinals game during the 2006 World Cup. Still, "competitions are expensive, and we were pretty busy at the time," recalls Burrows. The two former partners agreed to enter the competition together, on the condition that they "have some fun in doing it," Burrows says.

In the competition phase, discerning what the client is really looking for is paramount, says J. Parrish, who leads ArupSport. In this case, the criteria laid out in

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the competition guidelines made one thing quite clear. "They wanted a landmark building, without a shadow of a doubt. They wanted one that would be the best in the world," says Parrish. "It was a very clear, very attractive challenge."

If the winning design would have to measure up to the highest international standards of excellence, it would also need to meet another, equally important criterion: harmony with Chinese aesthetics. The participation of CAG, a Chinese design institute, on the team certainly helped. So did a creative collaboration with the Chinese artist Ai Weiwei, who acted as a consultant for Herzog & de Meuron on the winning design. No matter how wonderful the architectural scheme appeared, however, "there was always this big question mark," says Parrish. "Was this going to appeal to the Chinese culture?"

In search of a design concept that would be unmistakably Chinese, the design team drew on a variety of forms for inspiration. Lingbi stones—naturally occurring rock formations prized in centuries past for their symbolic value and inherent beauty—were a particular source of insight. Chinese pottery and other ancient art forms also informed the design.

Despite this rich and varied cultural backdrop, a single image, drawn from nature, has dominated public perception of the project from the very beginning. In fact, the stadium is best known not by its true name but by its unofficial nickname: the Bird's Nest. The building's broad appeal—not only to the client but also to the Chinese public in general—is no longer in doubt.

The competition guidelines made it clear that the client was looking for something truly stunning: a world-class stadium that would seat 100,000 people and accommodate a retractable roof. The design team knew that the retractable roof would dominate the design unless it could somehow be masked from view. Gradually, an architectural scheme began to emerge. Two long, parallel lines along the length of the stadium were necessary in order to support the tracks for the roof. But those lines would be disguised by a wild, seemingly random arrangement of crisscrossing lines. Hidden among those lines, right there on the exterior of the building, would be the load-bearing structure, or exoskeleton, of the entire building.

For Burrows, the concept was bold, even heroic. But there were practical considerations as well. As the complexity of the design became increasingly apparent, Burrows recalls asking, "If we end up winning this competition, how are we going to draw it?" The team concluded that such a project would be impossible without the use of a three-dimensional parametric model. The team selected the software package CATIA, developed by Dassault Systemes, which has been used to design airplanes, automobiles, and a growing number of buildings.

Once the competition had been won, it was time for the design process to begin in earnest. The early phases of schematic design generally took place in Europe as team members met in Herzog & de Meuron's Basel headquarters as well as in Britain in Arup's offices in London and Manchester. Over time, the work gradually shifted from one continent to the other. Teams from Europe began working in Beijing, transferring more and more responsibility for the project to CAG. As required by Chinese law, the local design institute produced the final construction documents. "It was an integrated design team," says Parrish.

To a large extent, team members attribute the success of the project to the highly integrated design process. From the project's inception, the architects and engineers had a close working relationship. This unified approach directly influenced the stadium design. "In many ways, the architecture and the structure are the same thing," says Michael Kwok, Arup's project director, who worked in the firm's Beijing office. "It is almost like sculpture."

Early on, the team realized that the stadium's location in a seismically active region would have a major influence on the overall design scheme. Although it would seem unwise from a seismic design perspective to incorporate a large retractable element in such a long-span roof, the design worked because the roof was to be so flexible that it would be capable of absorbing a huge amount of energy, Burrows explains. However, an earthquake would cause the relatively stiff, short-span concrete seating bowl and the relatively flexible, long-span steel roof to behave quite differently, he notes. For this reason, the team completely separated the roof structure from the concrete bowl.

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The team chose steel for the roof not only for its load-carrying capacity but also because it would make it possible to design a structure that could be fabricated and erected by China's unique construction industry. The design is well suited to China's strong steel fabrication and erection capabilities, observes Kwok. In fact, every detail of the steel roof design, down to the sizes of the individual plates, was designed with constructability in China in mind.

To the casual observer, the structure of the steel exoskeleton appears chaotic—in fact, it is deliberately designed to look that way—but the reality is just the opposite. "The structural system is actually quite simple," says Kwok. "It has a very logical pattern of support with very clear load paths." The structural system is hierarchical, consisting of primary, secondary, and tertiary members, he explains. The key to understanding the structural system is to begin with the primary, load-bearing members.

The real workhorses of the system are the 24 columns that are arranged at regular intervals along the perimeter of the building, forming an ellipse. The steel trusses that make up these main columns define the plane of the facade, which is not strictly vertical but rather leans outward at a slight angle (approximately 13 degrees) as it rises, lending the building its distinctive saddle shape. These columns rise to the full height of the stadium to join the 12 m deep horizontal trusses that span the roof. The main elements of the columns and trusses take the form of steel box sections measuring 1.2 by 1.2 m.

Instead of extending straight across the roof from one side to the other, the roof trusses follow a diagonal path, crisscrossing each other to leave an opening above the athletic field in the center of the arena. In essence, then, the columns and trusses form a series of interlocking portal frames that efficiently distribute loads to the foundations. "In principle, it is first-year college structural engineering," says Burrows—although he goes on to admit that "it is a bit more complex than that to put together."

As one would expect in a portal frame structure, the greatest forces are concentrated at the "shoulders" or joints where the beams transmit their loads to the columns, says

Kwok. Accordingly, the steel plates at these locations are approximately 100 mm thick. A series of struts transfer axial loads from the curving members of the truss to the vertical columns.

While the arrangement of the primary structural members is quite regular, the secondary and tertiary members are deliberately laid out in a seemingly haphazard way to create an illusion of randomness. Although structurally less important, the steel boxes that make up the secondary and tertiary members have the same 1.2 by 1.2 m dimensions as the primary members, making it nearly impossible for passersby to spot the difference.

What the casual observer cannot see is that the structurally less significant members are designed to use much less steel. In fact, the plate thicknesses range from 100 mm to as little as 10 mm, depending on the load requirements, says Kwok. In this way, the illusion of uniformity among the primary, secondary, and tertiary members is maintained while the amount of steel is minimized.

Although they do not carry the bulk of the load, these secondary and tertiary members do fulfill several important functions. For instance, they play a vital role in the seismic design. Even in a severe earthquake, the primary structure will remain elastic, says Kwok. The secondary and tertiary members, however, are designed to yield. In this way, the building is designed to respond to seismic forces in a way that minimizes damage to the main load-bearing structure. To test the design, the team subjected a computer model of the stadium to simulated ground motion.

Another function of the secondary and tertiary members is to support the roof cladding, which comprises two layers. The outermost layer, a lightweight ethylene tetrafluoroethylene (ETFE) membrane, protects the seating bowl from the wind, rain, and the sun's ultraviolet rays. This outer membrane, with a total area of approximately 38,000 m<sup>2</sup>, covers the entire seating bowl. It does not extend over all the concourses, however, because the designers wanted to provide natural ventilation during the hot Beijing summers.

An inner membrane of polytetrafluoroethylene (PTFE) forms the "acoustic ceiling" of the stadium, reducing

noise pollution and ensuring an even distribution of sound throughout the arena. This inner membrane covers an area of 53,000 m<sup>2</sup>.

Although the exterior appearance of the building understandably receives most of the attention, the stadium was in a sense designed "inside out," says Parrish. After all, the stadium's primary function was to house the Olympic Games, so it had to accommodate a track and other facilities that met precise geometric requirements.

Beyond meeting those requirements, the stadium is also designed to give every spectator an enjoyable experience. At a minimum, this means giving every spectator a view of the events unfolding on the field. However, the quality of the experience is about more than just sight lines. "The atmosphere you create is all important," says Parrish.

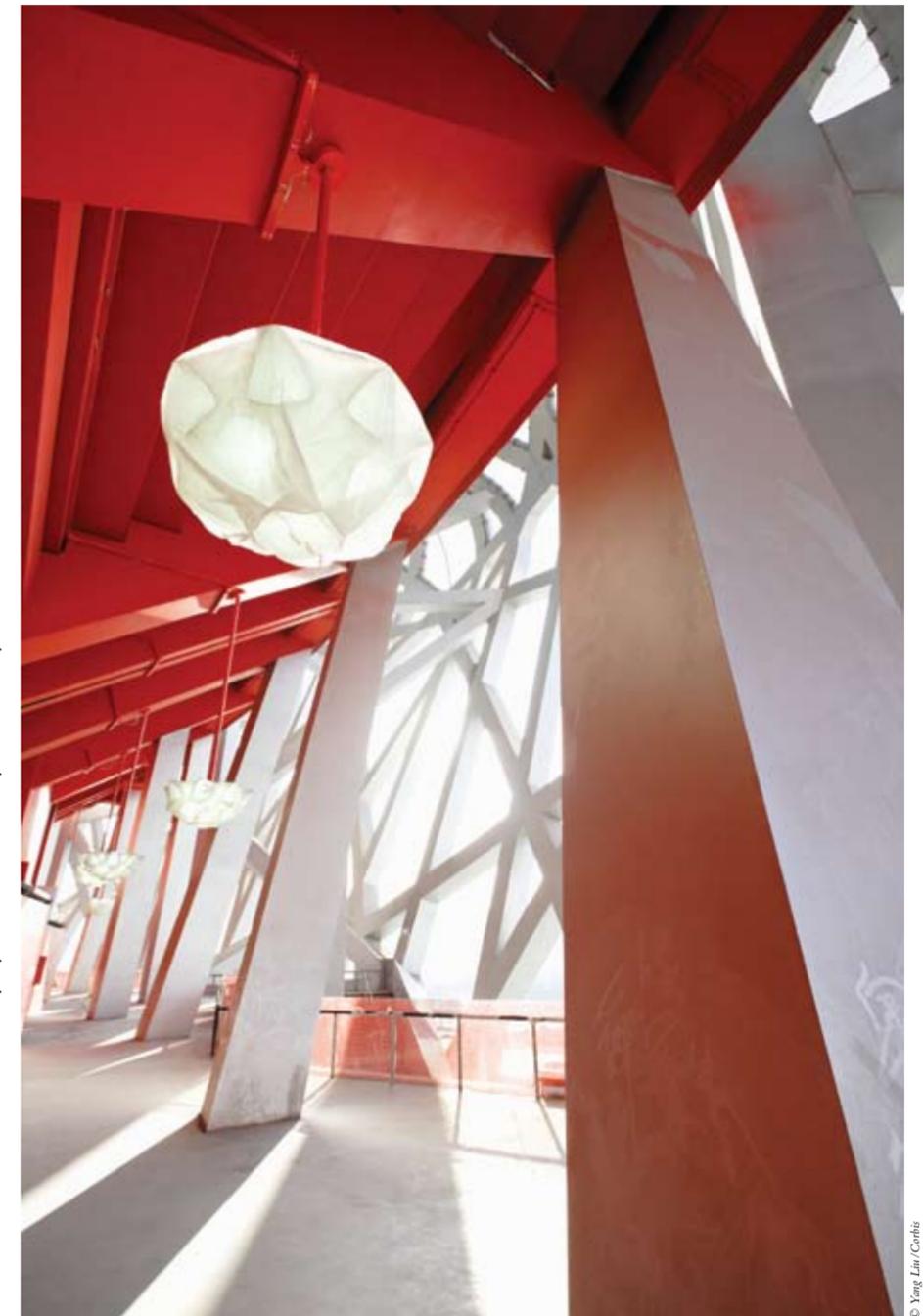
With this principle in mind, the team used a parametric design tool developed by Parrish to optimize the size and shape of the seating bowl. The goal was to give 100,000 spectators the best possible view of the field while aiming for the "feel" of a smaller, more intimate arena. The bowl went through 32 iterations before it assumed its final form. (At the client's request, the number of seats was later reduced to 91,000, that is, 80,000 permanent seats and 11,000 temporary seats for the Olympics.)

The bowl itself is a relatively conventional structure of reinforced concrete. It provides six levels of aboveground space and two and a half levels below grade. Expansion joints divide the bowl into six segments, creating room for expansion and contraction in response to temperature changes as well as to seismic motion. Many of the outermost columns in the concrete bowl are inclined in order to echo the chaotic feel of the exterior steel structure.

Construction began on December 24, 2003, and for several months proceeded apace. Five months later came an event that shocked the con-

struction world and gave pause to everyone involved in the project: the partial collapse of Paris Charles de Gaulle International Airport.

Designed by the French architect Paul Andreu, the airport had opened to critical acclaim in the summer of 2003. Its breathtaking design emphasized long spans and wide open



The stadium's exoskeleton, a dynamic arrangement of crisscrossing lines, is designed to evoke a sense of movement and excitement. Many of the outermost columns inside the building also lean at unexpected angles, echoing the chaotic feel of the exterior structure.



Steel proved the ideal material for the roof and facade structure of the stadium. Structurally, its load-carrying capacity was well suited both to the long spans of the roof and to the shorter, curving girders that bridge the gaps between the primary members and give the structure its random appearance. Just as important, by employing steel the design team took advantage of the unique strengths of China's construction industry. In fact, every detail of the steel roof design, down to the sizes of the individual plates, was designed with constructability in China in mind. Construction began in December 2003 and was completed in plenty of time for the Olympics, despite a five-month hiatus during which the building was partially redesigned.

spaces. On May 23, 2004, a 30 m long section of Terminal 2E—a tube-shaped building composed of concrete, metal, and glass—suddenly collapsed, killing four people. Two of the dead were later identified as Chinese.

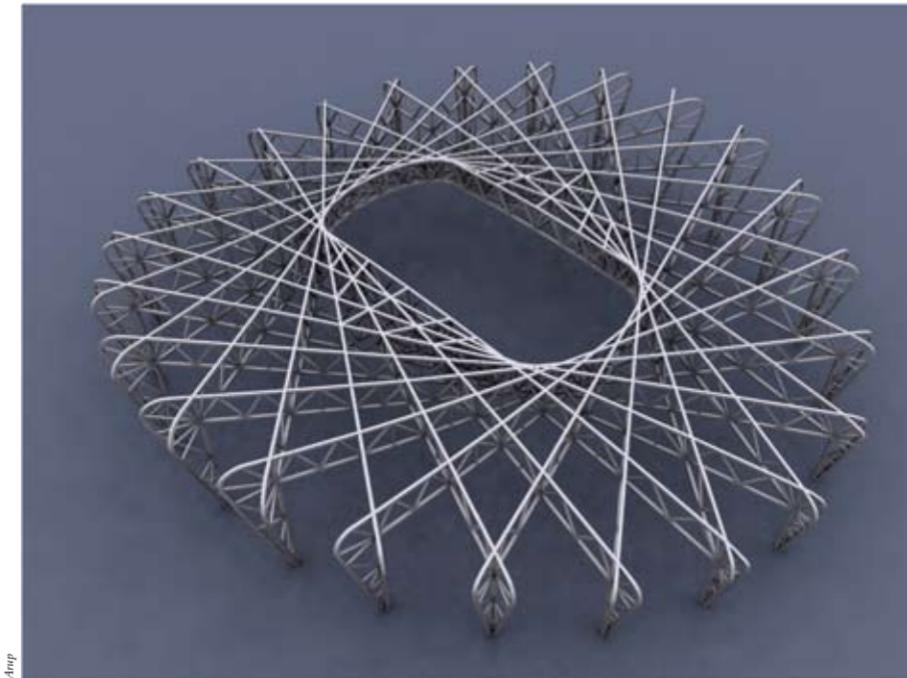
At the time, the National Stadium was just one of many high-profile building projects in Beijing, a city in the process of remaking itself. For many in China's capital, the airport collapse raised serious questions. Had everything necessary been done to ensure the structural integrity of the city's own construction projects? Panels of experts were convened to review the designs of every major project. On July 31 construction of the National Stadium came to a temporary halt.

The expert reviewers found no cause for concern with regard to the stadium's structural integrity. During the construction hiatus, however, the client also asked the design

team to examine ways of reducing project costs. After considering a number of options, the team recommended the removal of the retractable roof, leaving in its place a larger, permanent opening. "We felt that was probably the best way of reducing costs without changing the overall design of the stadium," says Kwok.

In August 2004 the retractable roof was officially deleted from the design, a change that left the athletic field open to the elements but brought with it a number of advantages. In the original design, the roof opening had been kept as small as possible to minimize the size of the retractable element. Now, that opening could be enlarged by about 30 percent, shortening the spans in the space frame and greatly reducing the amount of steel required for those spans.

Another consequence of enlarging the roof opening was



A view of the primary members reveals the building's essential structure. Twenty-four perimeter columns rise to join the horizontal trusses that span the roof. The roof trusses follow a diagonal path, crisscrossing each other to leave an opening above the athletic field in the center of the arena. In essence, the columns and trusses form a series of interlocking portal frames that efficiently distribute loads to the foundations.

a significant reduction in the overall weight of the roof. The weight reduction was achieved both by shortening the spans and by removing the retractable roof element, which itself had been quite heavy. Because of this reduction in weight, plate thicknesses in many locations also could be reduced, which saved even more steel. All in all, the elimination of the retractable roof cut the amount of steel in the roof by approximately 30 percent, says Kwok. The result was an approximately 10 percent reduction in overall project costs.

Furthermore, the deletion of the retractable roof enhanced the appearance of the stadium, notes Burrows. In the original design, two long parallel lines extended the length of the stadium, revealing the presence of the long truss beams required to support the tracks of the moving roof. Once the roof had been removed, those lines could be eliminated as well. The roof opening is still defined by a ring-shaped truss 10 m deep, but the parallel lines extending beyond that opening are gone, thus enhancing the random appearance of the exterior structure.

The elimination of the retractable roof would have been nearly impossible without the use of the CATIA model, says Burrows. "Every single part of this building is derived from a mathematical equation. Because of that, if you change something, everything that relies upon it changes as well in the parametric model." The roof design was so complex

that if the team had been working from a set of conventional drawings, it would have been difficult even to determine which drawings needed to change, Burrows says. Instead, changes were automatic and could be shared instantly with the fabricator and contractor, who also had access to the model.

Construction of the stadium resumed on December 28, 2004. Despite the five-month hiatus, the project was completed in May 2008, in plenty of time to prepare the facility for the Olympic Games.

As constructed, the roof structure employs 42,000 metric tons of steel, while the stadium as a whole contains 110,000 metric tons of steel—all of it produced and fabricated in China. While some have criticized the stadium for employing excessive amounts of steel, Kwok finds the criticism misguided. Beijing has always been a cultural and political center, but the unique design of the National Stadium and other recently

completed projects gives the city a new image of creativity and innovation. It will also draw people to the city for years to come. "This is someplace people will want to visit, just like the Great Wall," Kwok says. "The economic benefit is far greater than the cost of the building."

If the finished building has been beneficial, so too has the process of designing and constructing it. As the project moved from conception to completion, team partners in both Europe and Asia were introduced to new methods of design, construction, and information management. "A lot has been learned," says Kwok, "and I think a lot of this knowledge can be applied to other projects around the world." ■

#### PROJECT CREDITS

Client: National Stadium Company, Ltd., Beijing  
 Design consortium: Herzog & de Meuron Architekten AG, Basel, Switzerland; Arup, London; and China Architecture Design & Research Group, Beijing  
 Main contractor: Beijing Urban Construction Group Company, Ltd., Beijing, and CITIC International Contracting, Inc., Beijing  
 Steel contractor: JingGong Construction Industry Group, Zhejiang Province, China; Beijing BUCG JingGong Steel Structure Engineering Company, Ltd., Beijing; Hu Ning Steel Company, Jiangsu Province, China; Jiang-Nan Heavy Industry Company, Ltd., Shanghai; and ZhongZhi Group-BaoYe Construction, Shanghai