Building in Beijing

BY MARK SARKISIAN, P.E., S.E., NEVILLE MATHIAS, P.E., S.E., AND AARON MAZEIKA, P.E.

Steel provides the support for two new high-profile atriums in China's capital.

IT'S NO SECRET THAT CHINA'S ECONOMY HAS BEEN ON THE RISE IN RECENT YEARS, AND PROMINENT STRUCTURES HAVE BEEN GOING UP AT A RAPID PACE. And as expected, this construction surge has provided some unique structural design opportunities, especially in the country's larger cities. Two recently completed projects in Beijing, both designed by Skidmore, Owings & Merrill LLP, illustrate this phenomenon. The first, the New Beijing Poly Plaza, is a composite office tower incorporating the world's largest steel cable net-supported glass façade. The second is Beijing Finance Street, a mixed-use development consisting of 700,000 m^2 (7.5 million sq. ft) of framed office, retail, and residential space. The centerpiece of this development is a retail mall enclosed by a 300-m (980 ft) skylight supported by architecturally exposed steel trusses.

New Beijing Poly Plaza

Taking a look at the New Beijing Poly Plaza, the project is prominently located at a major intersection along Beijing's second ring road, northeast of the Forbidden City. The site's primary orientation is northeast towards the intersection and beyond to the client's existing headquarters building. The triangular form minimizes the perimeter surface area exposed to the elements, while a series of atria provide additional interior surface area to give office areas maximum access to daylight. The result is a simple "L" shaped office plan that cradles a large atrium. The exterior walls of the atrium are comprised of minimal glass membranes supported on two-way cable nets in order to maximize visual and solar transparency. In order to accelerate the construction schedule—and to accommodate the complex geometry of the building form—SOM selected a composite structural system employing both reinforced concrete and structural steel. The base building structural system consists of three reinforced concrete cores acting compositely with structural steel moment resisting frames. Floor framing consists of structural steel trusses at 13.5-m (44.2 ft) spans and rolled sections at 9-m (30 ft) spans. Moment resisting frame beams and columns used ASTM A913 grade 65 steel imported from Europe, while locally produced steel was used in gravity framing.

Tim Griffith

An Exotic Solution?

While conceptually simple, cable-net systems may still be considered an exotic solution for the structural support of glass curtain walls. However, the completion of several major walls around the world has established a proven track record of an achievable scale and level of transparency. Planar two-way cable systems support and stabilize glass façades through the resistance to deformation of the two-way prestressed net. Gravitational loads from the glass elements are carried through the attachment nodes to the vertical cables, and up to a transfer structure in the base building above. Lateral deformations due to wind and seismic loadings are resisted by the tendency of each of the horizontal and vertical cables to return to its straight line configuration between supports, while being subject to a perpendicular force. The flexible nature of a planar cable-net under lateral loading means that the critical design goal is limiting deflection through adjusting axial stiffness of the cables, as well as the cable pre-stress. Deflection limits of L/40 to L/50 are generally set for the design loading condition (typically, a 50-year wind event) to protect the integrity of the glass and sealants and to minimize a perception of weakness by the building's occupants.

For more on cable-net walls, please see "Getting Started with Cable-net Walls" from the April 2007 issue (available in the Archives section at www.modernsteel.com).

The Challenge

The New Beijing Poly Plaza project is 110 m (360 ft) tall with a 90-m-tall (300 ft) atrium enclosed by a cable-net glass wall, 90 m high by 60 m wide (300 ft by 200 ft). The scale of this wall greatly exceeds those that have been built before, introducing specific challenges that are not critical in smaller walls. SOM's preliminary analysis showed that the cable-net spans were too large to be economically achieved using a simple two-way cable-net design. We determined, however, that the cable-net could be achieved by subdividing the large cable-net area into three smaller zones by folding the cable-net into a faceted surface, and introducing a relatively stiff element along the fold lines. The faceted cable-net solution allows the individual sections of the cable-net to span to a virtual boundary condition at the fold line, effectively shortening the spans. Rather than introduce a beam or truss element to stiffen the fold line, a large-diameter cable under significant pre-stress was used. The largest of these primary cables is 275 mm (11 in.) in diameter and consists of a parallel-strand cable bundle of 199 individual 1x7 strands (a strand consisting of six wires twisting around a single straight wire), each strand being 15.2 mm (0.60 in.) in diameter. The largest cable is pre-stressed to 17,000 kN (3,800 kips) and experiences a maximum in service loading of 18,300 kN (4100 kips) during a 100-year wind event. Using the faceted design solution, the typical horizontal and vertical cables are limited in diameter to 34 mm and 26 mm (1.3 in. and 1.0 in.) respectively. The composite base building structure proved well-suited to the cable-net installation, as two of the three reinforced concrete cores were located at the sides of the cable-net to act as stiff boundary conditions resisting the cable pretension forces, and also providing an ideal location to access the cable anchorage points and to facilitate tensioning operations. The remaining boundary conditions were provided at the bottom of the net by the concrete structure at ground level, and at the top by a three-story-tall structural steel truss spanning 60 m (200 ft) between the top of the two cores.


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"Rocker Mechanisms"

By introducing the large-diameter diagonal cables, one problem is created while another is solved. As the base building structure is subject to seismic and wind loads and experiences inter-story drifts, connecting a point on one floor slab to another point 45 m (150 ft) higher up the structure with an axially stiff element, the diagonal cable behaves as a brace and tries to resist the base building drift. Thus analyzed, the brace forces were too great to be resisted by the main cables or the attachments to the base building structure. However, when the base building drifts in a direction that causes one diagonal cable to go into tension (tries to lengthen), the other cable that forms part of the "V" configuration goes in compression (tries to shorten). A pulley analogy was developed that allowed the "V" cables to be considered as a single element, with rotation at the base of the V allowing the length increase of one cable to be offset against the length decrease of the other cable. This allows the base building to drift without significantly increasing or decreasing the level of prestress in the main cables. The pulley analogy was realized in a buildable form as a cast "Rocker Mechanism." By crossing the cables and connecting to the rocker casting arms, the need to provide curved pulley surfaces and curved sections of the main cable were eliminated. Each of the two rocker mechanisms consisted of six unique steel castings, each weighing up to 8 tonnes (18,000 lb), with solid material thicknesses of up to 800 mm (32 in.).

Construction

The installation of the cable-net wall required that the base building structure be topped out before any cable installation operations could occur. The base structure was constructed with the structural steel floor framing following several stories behind the concrete cores. Once the boundary elements were in place, the installation of the rocker mechanisms began. Each of the castings were hoisted into place, then connected together to form the mechanism. With the rocker mechanisms temporarily shored in place, the main V cables were installed and tensioned. Using technologies developed for the installation of cable-stayed bridge cables, each of the 199 strands were tensioned in a carefully planned sequence to result in an even distribution of force in the final condition. With the V cables installed and tensioned, the smaller cable-net cables were then loosely located in place and incrementally tensioned up to the design pretension level, then the glass support nodes were tightened and the glass was installed and sealed.

Performance

The critical service level load condition (the 50-year wind event) was determined through careful wind engineering studies performed by Beijing University. The wind studies included a traditional rigid model of the building massing, as well as that of the surrounding building fabric, and an aero-elastic wind tunnel study performed on a flexible model of the actual cable-net configuration. This latter study used wires and a membrane to replicate the anticipated dynamic response of the cable-net system. This study, likely the first of its kind to be performed on a cable-net curtain wall system, was used to verify and modify, where appropriate, the results of the rigid model. Analysis and testing shows that the New Beijing Poly cable-net wall behaves very much as conceived. The results from the static non-linear (large displacement) analysis clearly show that the strategy of subdividing the wall into facets with shorter individual spans was indeed successful. This strategy allows the overall displacements to meet the L/45 deflection limit between hard boundary conditions established for the project, while maintaining the economic viability of the project. MSC

Architect and Structural Engineer
Skidmore, Owings & Merrill LLP, San Francisco

Local Design Institute
Beijing Special Engineering Design & Research Institute, Beijing, China

Tim Griffith

The buildings in this carefully planned development are decidedly modern, reflecting Beijing's strong position in international commerce. Beijing Finance Street's many architectural and landscape elements are all clustered around a park, which is the project's core. Opening onto the park is the Great Urban Atrium. This crescent-shaped building—the most engaging component of the project, with a sharply slanting roof and exposed diagonal trusses—provides a vibrant indoor urban space and, being adjacent to the park, enhances the complex's role as a gathering place.

"Butterfly Trusses"

The roof of the cavernous 300-m-long (980 ft) atrium retail space is intended to establish a theme of transparency that is present throughout the development. Exposed structural steel "butterfly trusses" are key components. Each is formed by tipping two planar single-kingpost trusses towards each other, resulting in a three-dimensional "V" kingpost butterfly truss. Spanning up to 30 m (100 ft), the single-kingpost trusses provide a long-span solution using a minimum number of structural elements. As the top chord of each truss is effectively point-supported at its ends and at one point within the span (at the ⅔ point along the length of the truss when viewed in plan), bending forces on the top chord are significant. Large-diameter steel circular hollow sections, specified per American Petroleum Institute standards for pipe sections, were used to resist the combined axial and bending forces resulting from this truss configuration. The lack of bracing elements between the top and bottom chord, as well as the visual weight of the 457-mm-diameter (18 in.) pipe truss top chords relative to the 25-mm- to 37-mm-diameter (1 in. to 1.5 in.) cable bottom chords, results in the appearance of slender parallel beam elements spanning the atrium.

The reinforced concrete retail buildings that support the retail roof are subdivided into independent structures with a maximum dimension of 90 m (300 ft). The structures were also subdivided by the natural building break that occurs at the atrium. As a result the roof needs to span between six independent structures. A typical solution to this type of relative movement issue is to provide sliding supports at one end of each of the trusses. However, due to the slope of the roof trusses, the high end of the trusses are supported atop free-standing columns that extend up to 11 m (36 ft) above the roof of the supporting concrete structure. This condition reduces the applicability of a sliding detail.

Ultimately, the high-end columns were also the source of the design solution to the "dynamic" support issue. By providing articulated ball-and-socket joints at the top and bottom of the high-end columns, the columns and trusses become components in a three-pinned arch roof system. Relative

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movement between the supporting structures is accommodated by the articulation of the joints. When the supporting buildings move closer together and further apart along the axis of the roof trusses, the enclosed angle at the apex of the roof closes and opens. The glazing system is jointed to allow this rotation without damage. When the relative movement between supports is perpendicular to the axis of the truss, the top of the high-end columns effectively moves with the low-end support point due to the diaphragm bracing in the plane of the sloped skylight. The bottom of the high-end columns conversely moves with the high-end support point. This causes the south wall of the roof system to rack in-plane.

The glazing for the south wall is supported in horizontal courses that are allowed to slide relative to each other as the columns rack. Due in part to the dynamic nature of the support conditions, the kingpost truss arrangement was developed to result in the three-dimensional truss configuration that has additional out-of-plane stiffness. Lateral forces induced in each of the roof sections are transferred to one of the supporting structures (through the low-end columns) by the use of diaphragm bracing rods.

Construction

Originally designed to allow for the fabrication and tensioning of each of the butterfly trusses at ground level, the truss design could accommodate the lifting and installation of each three-dimensional truss without any requirement for shoring. However, after construction of the reinforced concrete supporting structures was completed, the contractor elected to install a scaffolding system filling the full volume of the retail atrium, allowing each of the truss top chords to be installed independently with continuous gravity support along its length. The truss elements were then connected together, and the steel cable bottom chords were installed and tensioned in-situ. MSC

Architect and Structural Engineer
Skidmore, Owings & Merrill LLP, San Francisco

Local Design Institute
China Academy of Building Research, Beijing

Mark Sarkisian is a partner, Neville Mathias is associate director, and Aaron Mazeika is an associate with Skidmore, Owings & Merrill LLP in San Franciso.