## Beijing's National Grand TheatreTransforms the Cityscape

### *Innovative cladding and deep foundation are firsts for the city*

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By Janice Tuchman, Peter Reina and Andrea Ding Kemp

Global Projects

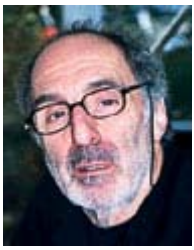
In a clear signal of openness and modern tempo, China's National Grand Theatre has taken shape in the heart of Beijing, just blocks from the Forbidden City. The futuristic titanium and glass-clad bubble–600 meters in perimeter–is one of the new buildings by international designers that are changing the dynamic of the capital's generally modest cityscape.

A labor-intensive array of welded steel arches, economical only with China's low-cost work force, supports the cultural center's shimmering enclosure. Inside the immense dome, an opera house with curving walls and deceptively cunning acoustics, likely will be the center of attention.

Elliptical in plan and section, the roughly 212 x 143-m dome is 46 m high at its highest point, the same height as the People's Congress Hall just across the street. The dome's 35,800-sq-m surface envelopes an opera house that will seat 2,416, a concert hall big enough for 2,017 and a theater that will seat 1,040.

***Views.*** *From the Forbidden City just blocks away, the new arts complex is modern, mysterious and abstract. (Rendering courtesy of AXYZ)*

Titanium sheeting covers the dome on either side of a transparent wedge that tapers from 100 m wide at the bottom in the front to a narrow band over the crown and widens down the back. No doors are visible from the surface, and access will be through an 80-m-long transparent tunnel under a water-filled moat that will surround the building.



***Andreu***

The theater is among the projects Paul Andreu took with him into private practice from his former post as chief architect at the French government's Aéroports de Paris. His decision to take part in the theater's international design competition was driven partly by his urge to show that he could do more than airports, which he has designed worldwide. "I didn't like being put in a box," he says.

Andreu found the competition, with its shifting rules, stressful, and he almost walked away. He was particularly concerned by the official decision to move the building away from the Forbidden City, with little attention to urban planning. The complex "is not a piece of furniture. You don't just push it," he says.

Emboldened by the belief that he would not win anyway, Andreu disregarded official opposition and proposed changes to the overall plan. To his surprise, he won (ENR 9/20/99 p. 12).

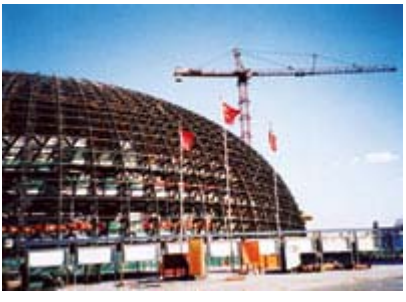
Francois Tamisier, the architect who supervised work on site for Andreu on loan from ADPI, says their government client told Andreu, "You have the vision, but we have the courage to give you the commission." He adds that while the Forbidden City is now open to the public, the residences of current government officials are not. They are tucked away from view in a parklike setting. They are, however, now visible from the upper levels of the theater, which Tamisier describes as modern, mysterious and abstract.

The architecture of the theater evolved from a cluster of separate buildings to halls under a single roof, plotted in the pages of the small sketch- book Andreu keeps with him. In unifying the venues, he wanted to create a popular space for people who would not normally be drawn to the opera, he says.

***Curves.*** *Fluid geometry in the opera hall brings audience closer to the performers.*

**Strong Ideas**

Though supported by subconsultants, Andreu was involved in all aspects of the design. "I want to control everything," he says. "I need everything to be consistent." Andreu had a "strict idea about the structural concept," says structural engineer Jean-Marc Jaeger, a director at SETEC TPI, Paris. Jean-Paul Vian, the project's lead acoustician agrees about the control issue. "Andreu has very strong ideas and



***Indoor Space.*** *Arching steel trusses welded in place resemble ladders that converge on a compression ring. They create a soaring indoor atrium shared by*

[working with him] is quite difficult," he says (see box p. 24). Vian works for France's government-owned building technology organization called Centre Scientifique et Technique du Bâtiment, Grenoble.

*multiple venues. (Photo left by Janice L. Tuchman for ENR, right by John Kosowatz for ENR)*



With so much focus on Andreu, the Beijing design came under scrutiny again after the collapse of a section of a vaulted concrete concourse at a year-old terminal Andreu designed at Charles de Gaulle Airport in Paris (ENR 5/31 p.10). Jiang Zhi Quan, chairman of Shanghai Construction Group, one of the three companies in the Beijing project's joint venture contractor, says he got a lot of calls after the collapse, but he is "sure there are no problems" at the theater because its unusual design went through extensive review by code authorities and by engineers working for the construction team.

The French engineers presented the design to a panel of Chinese experts for their approval. About 100 people questioned SETEC's team over a week, Jaeger remembers. "It was a very difficult meeting from a structural point of view" because the structure is so unusual, he says.

Potential buckling was the reviewers' main concern.

Weighing nearly 22,000 tonnes, including cladding, the dome is formed by 148 radial trusses rigidly fixed to a concrete base and to a compression ring beam close to the crown. The dome springs from 20-m-deep basement walls cast within a slurry trench perimeter. The entire structure is supported, without piles, on a roughly 4-m-deep cellular base slab.

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**Transparency**

The arching trusses resemble curved ladders with distances between the "uprights" ranging from 3.8 m at the base of the longest span to 1.5 m at the top. Trusses are set nearly 4 m apart at ground level, converging to 1 m at the upper compression ring. The roughly 1.1-m-dia tubular ring beam encloses a small elliptical roof with 14 ladder-like trusses crossing its shortest dimension to support the glass. H-section radial

...girders frame the remaining clad area. Because of Andreu's demand for transparency, "we used a lot of steel," says Jaeger. The extent of cutting and welding in the field would have been cost prohibitive in other countries. At peak, the joint venture had 4,000 workers on site.

***Extensive Welding.*** *Array of field-welded connections possible with low-cost work force. (Photo courtesy of SETEC TPI)*

The 46 arches that are behind the dome's glazing are made of 6-centimeter-thick flat plate to reduce their visibility from outside. Rungs and uprights are up to 45 and 36 cm deep respectively. Arches hidden by the titanium skin are made more economically of wide flange girders. To reduce clutter, Andreu ruled out diagonal bracing. Instead, chords of adjacent arches are linked at intervals by horizontal tubes nearly 20 cm in diameter in the glazed areas.

The dome's stiffness required balancing seismic and wind considerations, says Jaeger. "From the seismic point of view, it is useful to have flexibility, but for wind it is the opposite," he adds. Seismic forces are handled by separating the dome's concrete base beam from the substructure with elastomeric bearings.

Having at first anticipated that seismic accelerations would be the dominant design factor, the engineer later calculated a greater need for stiffness. The dome's stiffness comes also from cross-braced bays of nine arches at four locations, one on either side of the glazed areas.

The project required Beijing's widest and deepest foundation to date, at 32.5 m. The deep excavation allowed support facilities for the theaters to be located below grade so that the dome's overall height did not exceed that of the People's Congress next door. Peng Chengjun, chief engineer for Beijing Urban Construction, the contractor for civil works and concrete in the joint venture, says his crews had to build a diaphragm wall because the city's water table is 18.5 m below grade. They used 26 dewatering wells to pump 28,000 cu m of water per day during construction. A water-resistant concrete mix design was used for the foundation's submerged caissons.

***Deep Excavation.*** *Dewatering removed 28, 000 cu m of water per day. (Photo courtesy of SETEC TPI)*

Shanghai Construction Group began dome erection in July 2003 with the top ring assembled on falsework. Then, the contractor erected the arches, supported by two concentric rings of scaffolding. Three 10-m-long sections were assembled on the ground and lifted into place by crane–a tricky procedure because of their slenderness and curve. Three of these assemblies make up each radial truss. Temporary bracing prevented localized buckling.

To limit erection stresses, base plates were set on rockers and fully fixed later. To ensure that the final shape matched Andreu's expectations, SETEC computed how the dome would deflect progressively as it took shape. It recommended precambering the truss elements because under self weight alone, deflection was calculated at up to 23 cm.



**Field Work**

Chen Jianqiu, deputy general manager for SCG, says the contractor decided to precamber steel only within the top ring, preferring to redesign the connections on the arches to allow for adjustments in place. Connections were changed from flange bolts to welded tubes. As built, hollow steel hemispheres welded to the uprights accommodate the changing connecting angles between tubes and arches. Short cast steel end sections of bracing tubes, with cruciform cross sections, are welded to the hemispheres. Middle tube sections are welded to the castings, via telescopic joints, allowing length adjustments to be made.

Hong Kong Construction, joint venture contractor in charge of the enclosure, worked with cladding fabricator and erector KGE Group, Zhuhai. After full-scale mock-up tests of cladding panels, the original design was adapted to solve waterproofing and construction problems without changing the exterior appearance.

Titanium panels are a sandwich of titanium, silicon carbide and stainless steel on an

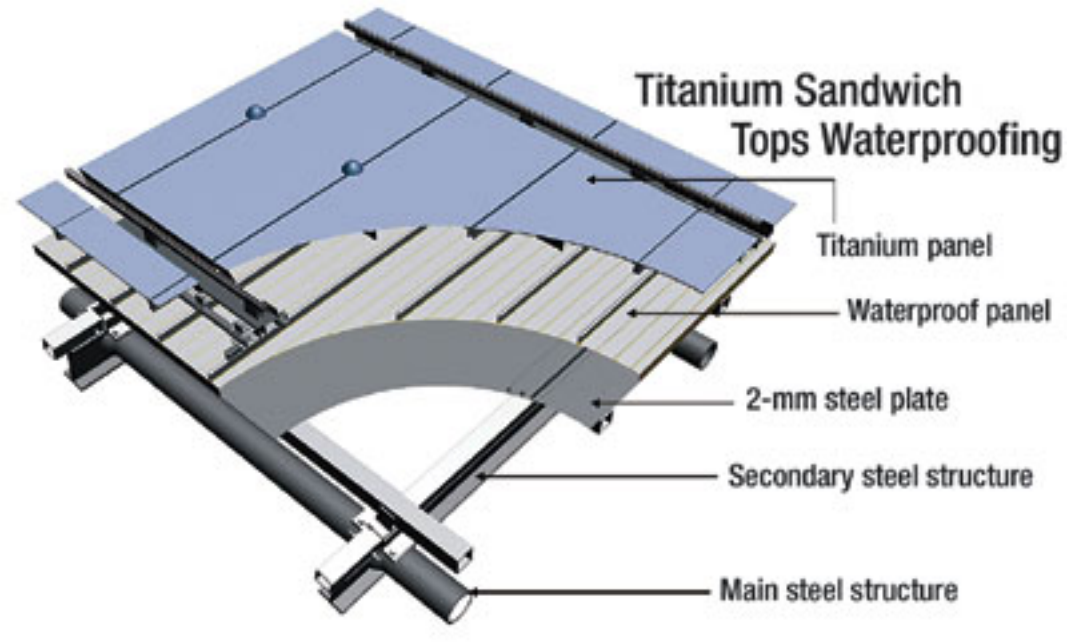
aluminum alloy frame made by Mitsubishi Chemical Functional Products Inc. of Japan. They are clamped to waterproof panels underneath made of aluminum, magnesium and manganese alloy, which in turn are fixed to 2-millimeter-thick steel plates. The roughly 20,000 cladding panels came in 6,250 different sizes to accommodate the curvature of the shell. To protect the structure from storms, a network of 5,000 lightning rods was installed along the tracks that carry cleaning equipment. **Click here to view graph**

***Finishing the Touches.*** *The dome proved waterproof during rainstorms last summer, but it still faces political heat over operating costs. (Photo courtesy of KGE Group)*

Yi Luo, chief engineer at KGE, says the cladding has already proved waterproof: "It survived the rainy summer in Beijing with several heavy storms."

The performing arts center still has to weather political and economic clouds about its operations. The opening is slated for next October, but no decision has been reached about whether the city, the central government or some private enterprise will be in charge. Critics worry that the $325-million project will be costly to operate–and particularly to air condition.

*Reporting for this story was done in Beijing and Paris.*


Titanium Sandwich
Tops Waterproofing
Titanium panel
Waterproof panel
2-mm steel plate
Secondary steel structure
Main steel structure