



Technology

Letting in the Light

I.M. Pei's modular space frame for the Miho Museum in Japan makes the most of an earthbound site.

By Eric Adams

With 80 percent of the \$216 million Miho Museum built deep into the earth of a nature preserve outside Kyoto, Japan, it's no surprise that light-loving architect I.M. Pei chose glass to dominate the 20 percent of his design that remains visible. The finished product is pure Pei: an artfully designed, glazed space frame that offers views of surrounding forests, withstands the region's high wind loads, and, most importantly, bathes interior lobbies and hallways in natural light.

"When you think of space frames, you usually think of steel and struc-

ture," says New York structural engineer Leslie Robertson, who collaborated with Pei on the Rock and Roll Hall of Fame and Museum in Cleveland, the Bank of China in Hong Kong, and the Meyerson Symphony Center in Dallas. Robertson conceived the Miho's space frame but credits its ultimate success, both technological and esthetic, to Pei's guiding hand. "Here, I think of warmth and people and softness and elegance," he explains of the slatted louver system that provides the space frame's color and texture. "It has little to do with engineering and lots to do with Pei's whole composition."

Following site limits

At 1,830 square feet, the space frame constitutes about 10 percent of the museum's roof. The rest, composed of double-reinforced concrete, supports soil, up to 2 meters deep, to comply with the program's strict site limitations on the amount of visible structure. Local government restrictions on the site stipulated that the museum, which opened in November, could rise no higher than 13 meters above grade. Any visible components over 2,000 square meters in area had to be separated by 5 meters of land.

Though there was flexibility underground, these constraints made the visible roof a challenge. Pei intended the steel and glass structure to resemble the hipped roofs typical of historic Japanese temples but with a lighter and more transparent feel than its historic ancestors. The space frame's angles follow the shape of the building's concrete foundation walls, which in turn follow the contours of the mountain.

The tetrahedral modules forming the roof's dynamic peaks, gables, and cantilevers are composed of 6-meter-long steel pipes connected by 119 spherical cast-steel nodes. The 19-centimeter-diameter spheres act as universal joints for 35-millimeter-thick steel tabs, which were part of the node castings. The tabs connect to the silver-painted steel pipes via two outer tabs that cap the pipes. These are welded so carefully that no seams are visible and are fastened with six flush bolts.

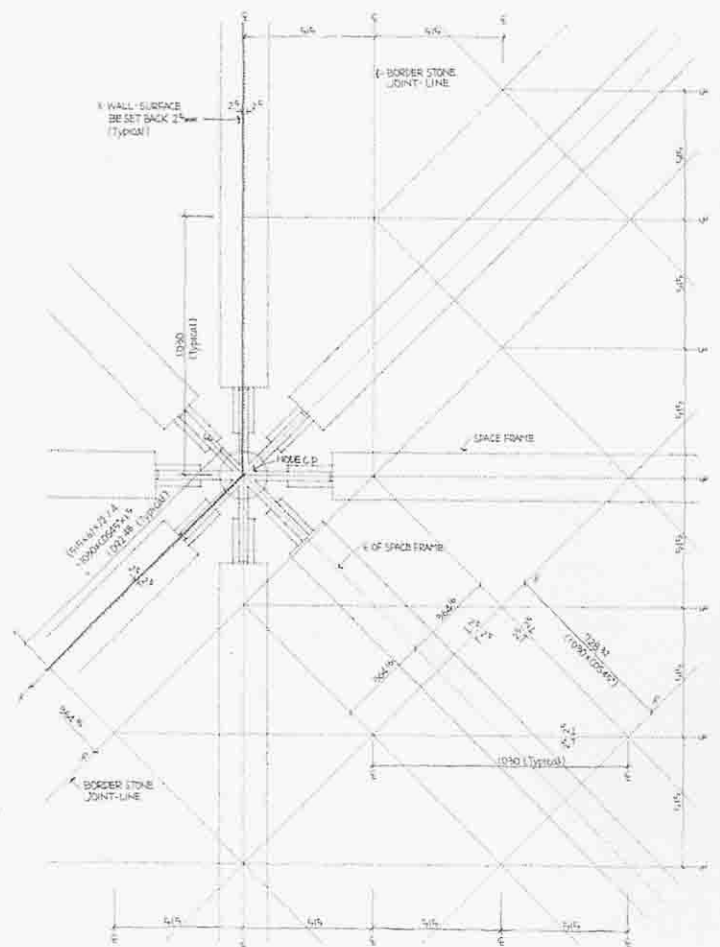
Given the various angles required of the space frame, Pei, Robertson, and Japanese structural engineer Yoshihiro Okabe of Tokyo's Whole Force Studio had to devise 83 different configurations for the nodes. Each receives between three and 10 steel struts extending at varied angles from other nodes and some are welded to steel plates within the 45-centimeter-wide concrete walls to anchor the structure.

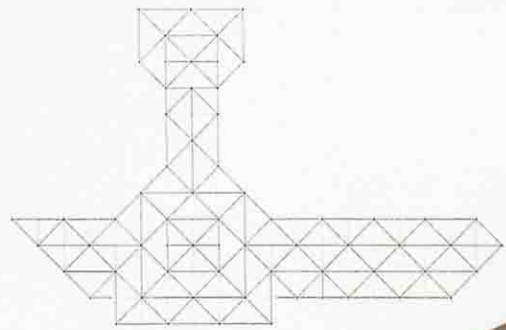
Project architect Tim Culbert explains that these node configurations and the roof's geometry have little direct precedent in Pei's previous work. "They're nothing like the glass pyramids at the Louvre, in

TIMOTHY HURSBLET PHOTOS



In north corridor (left), horizontal steel members of tetrahedron conceal emergency lighting and uplighting. Typical 19-centimeter-diameter cast-steel node (below) is positioned on center line of module. Wall position is represented by darker line at left.





Roof plan of space frame (top) shows main building's 6-meter-spanning tetrahedral space frame; flush bolts attach steel struts to node tabs (left); node diagrams (below) show variety of tab configurations.



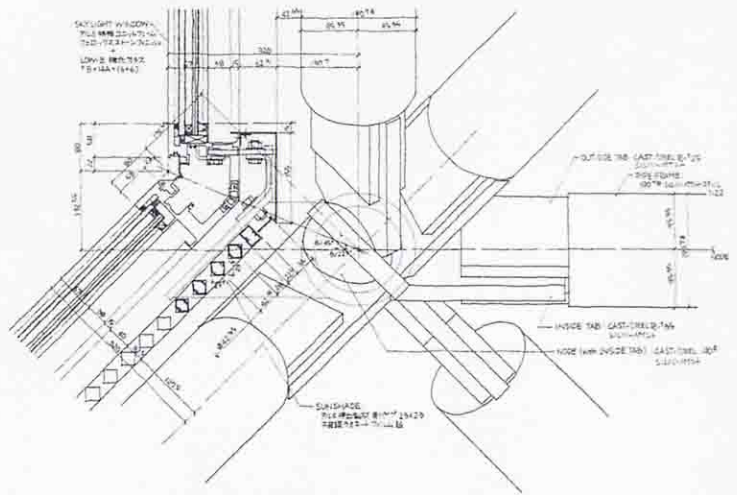
which each glass panel represents a module of structure." At the Miho, Culbert continues, the space frame supports the glass, which is not structural, and derives its strength from its own three-dimensional geometry. "The space frame modules are quite large, but only two points of the tetrahedron have to be supported. That allows for significant cantilevers."

Multiple variations

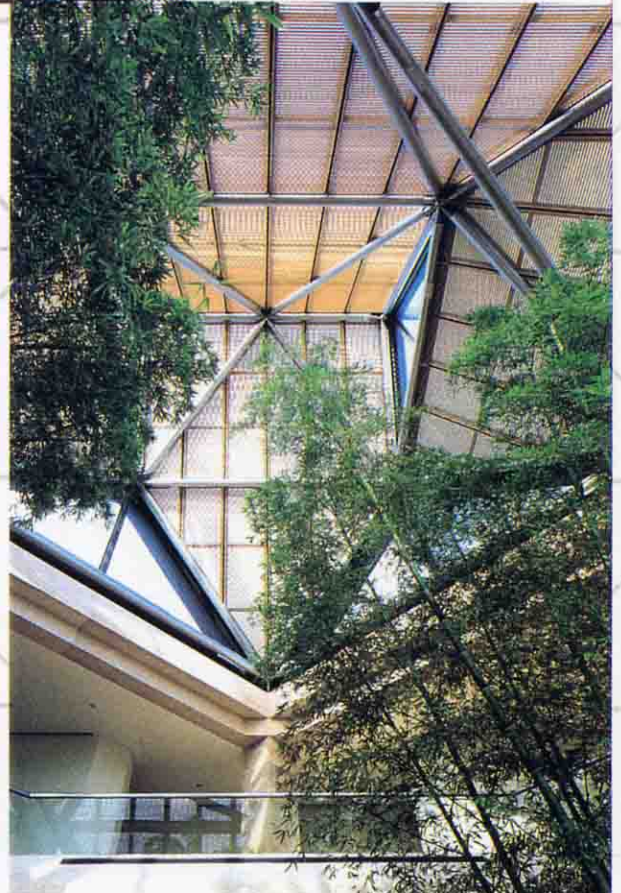
Working in collaboration with Tokyo-based Aoki Structural Engineers and general contractor Shimizu Corporation of Osaka, the design team guided the space frame through numerous iterations, experimenting with different connective tab thicknesses, node and pipe diameters, and frame configurations. Pei led the effort throughout, and even ordered a complete redesign when he sensed from a full-scale mock-up that the pipes and nodes were too large. To produce a more subtle effect, engineer Shigeru Aoki used a higher-grade carbon steel to help reduce the diameters of both elements from 21 centimeters to 19 centimeters. "That's less than an inch, but it was significant to I.M.," Culbert says.

This change in dimensions was ordered after construction had begun, and all relevant agreements concerning Japan's conservative fire and safety codes had to be renegotiated as a result. This renegotiation was typical of the labyrinthine approval process required at each phase of the project. But because construction of the museum was still proceeding around the space frame, the amount of time lost in the effort was minimal.

Culbert attributes this ability to absorb major changes during building to the nature of the Japanese construction industry, which relies on prototyping for complicated structures and is more tolerant of mid-construction changes than the U.S. construction industry. Robertson agrees, adding that this tolerance comes from a slower construction pace set by the input of the Japanese construction ministry,



Typical space frame node (above and left) offsets glass and aluminum sunshade layers from structural chords. Peak of space frame (below) rises 1.4 meters above double-height tea court in south wing.



Space frame attaches to concrete wall through limestone cladding (right and below), face of which is on center line of space frame node.



erected afterwards in only 2½ months in 1994, after the last concrete pour and at about the midpoint of the museum's construction.

Glass and louvers

The laminated low-E glass panels that hover 10 centimeters above the space frame are supported by vertical aluminum web plates welded to the steel pipes and carefully concealed. They were manufactured in 1.2-meter-wide modules, each up to 5 meters long, that were dropped onto aluminum rafters. To mimic the tile roof vernacular, the color of the rafters is similar to that of the tile manufactured in local kilns. "The local government only allows tile roofs, so we had to get a variance to use glass as the roofing material," remembers Perry Chin, who oversaw most of the technical specifications for the museum. "That was something of a breakthrough."

The gap between the inside face of the glass and the outside of the steel pipes allows enough space for the aluminum louvers, which filter sunlight and are designed to mimic the appearance of honey-colored laminated wood, but not wood's vulnerabilities. "The problem with wood is that radiant heat and humidity would cause the slats to bend and discolor," Culbert points out. "We also needed something that would be compatible with conservation and fire-safety issues."

With the help of Toyama-based manufacturer YKK (known worldwide for making zippers), the design team developed a woodlike louver consisting of a computer-generated grain pattern designed by Pei and photographically printed on polyester film. At 1.2 meters square, the widths of the louver modules match those of the window panes and are triangular in places to conform to the shape of the space frame.

Beyond their esthetic success, the louvers speak to cultural tradition through the dramatic, sharp shadows they cast in the museum's lobbies and corridors. "Shadow culture is very strong in Japan," notes Culbert, who marvels at the serendipity. "This effect wasn't entirely expected."

which oversees all building. "As an engineer in the United States, I could just wave my arms and say 'do it this way,'" notes Robertson. "But here, everything that is not conventional must be thoroughly tested and approved before it can be built."

Strength testing

Pei's crystalline roof also needed to accommodate Japan's strict national codes governing seismic forces, high winds, and snow loads. Fortunately, the space frame's light weight required only minimal seismic reinforcement and its high-compressive-strength members brace the walls in the double-level main hall, contributing to the building's overall stability. (A retaining wall, separated from the building by a 3½- to 7½-meter-wide air space, handles most of the seismic pressures.) The prefabricated glass panels above the space frame were designed to resist seismic activity by allowing movement between the modules, focusing it in aluminum gaskets that also maintain weathertightness. To withstand the wind and snow loads, a model was tested in a wind tunnel at the University of Western Ontario to compensate for wind effects on the envelope and space frame structure. Additionally, the roof system was further tested by the manufacturer in its laboratories against wind, water, and structural deformation.

Although it took close to nine months for Osaka-based Sumito Heavy Industries to manufacture the node castings, the space frame was

