The operable Oculus skylight will be opened annually on September 11.

World Trade Center Transportation Hub

Cost/benefit calculations aside, Santiago Calatrava's beam-sculpture may be seen as one of New York's great public spaces, thanks to ingenious engineering.

RARELY HAS A MAJOR PIECE of transit infrastructure drawn as much press, before even opening, as the World Trade Center (WTC) Transportation Hub. First unveiled in its original design in January 2004, then revised, security-hardened, and value-engineered over a decade of design and construction work in a densely politicized atmosphere, the Hub held its "soft opening" in March 2016, with Port Authority Trans-Hudson (PATH) trains in service, then unveiled its retail component later in the year.

On one level, it's a PATH terminal, and New Jersey commuters are so unaccustomed to civic elegance that the Hub's soaring beams, white marble floors, and cantilevered observation decks, with nary a straight line in sight, can seem outlandish. On another, it's part of the WTC complex, burdened with a complex history. People died here; anything built here, not just the Memorial and Museum, should honor them. Spaces here should inspire ongoing generations to move with purpose, dignity, and reflection, not simply pass through. It's easy to forget this whenever a bean-counting scribe pounces on Calatrava for indulgence, and charges that X number of dollars might have been redirected from artistic intangibles to Y number of subway upgrades, salaries, or potholes repaired.

With those perspectives acknowledged but not overemphasized, questions about how the Hub achieves its effects remain fascinating. Its Oculus, the elliptical transit hall named for its signature feature, a 330-foot-long, 160-foot-high arching glass aperture intended to open on special occasions and temperate days, is a column-free, self-supporting composition of steel ribs (reports of total tonnage vary from about 14,000 tons to 15,250 tons, the Calatrava office's official figure). "When you look at it, it's hard to envision how it holds itself up," says James Durkin, senior vice president at AECOM's Tishman Construction and project manager on the Hub, "but it really is a kind of bridge." Under the unique conditions of a site whose grade-level plaza had to be completed by the 10th anniversary of the 9/11 attacks, constrained by the position of PATH and Metropolitan Transit Authority (MTA) tracks, working around operating train service, and responding to midstream security mandates, the Hub's design and construction team achieved feats improbable enough to border on miraculous.

The Hub comprises three chief components: the Connector from the Fulton Street station, the Oculus, and the Concourse leading to the PATH hall and, beneath Route 9A (West Street), to Brookfield Place, the former World Financial Center, which will finally be accessible without vehicle-pedestrian conflict or lengthy searches for scarce skyways. The Concourse, like the Oculus, features the signature steel ribs, painted bright white with Interchar, a two-part epoxy intumescent fireproof coating by International Paints, a material derived from the aerospace industry ("it was used on the butt end of the Apollo capsule," says architect James Howie, professor of construction and facilities management at Pratt Institute, who served as project manager for fireproofing at the Hub for Composite Technologies.

"Early on in the design, it was contemplated that Calatrava wanted to use concrete," reports Durkin. "The steel itself is extremely complicated to fabricate"—so much so that only a handful of firms in the world, all foreign, could handle the job. Above-grade steel members for the Oculus were custom-fabricated by the Venetian-area firm Cimolai, test-assembled to check the precise fit before shipping 4,700 miles from Italy to the Red Hook port, then escorted to the site. Below-grade steel and some of the decorative steel were by the Spanish firm Urssa. New York-based Skanska fabricated and erected approximately 11,000 tons of structural steel, including the Hub's portals, arches, and rafters.

Pieces were extremely large, Durkin recalls, to minimize the number of field connections; constant, challenging calculations by Vancouver-based erection engineers Buckland and Taylor ensured "extremely tight tolerances" onsite, he reports, "about a quarter of an inch" amid constant temperature-driven fluctuations. "It was extremely challenging to erect those tight tolerances. There's no fake structure; there's no covering structure between the steel and the glass. The ribs are the mullions for the glass." Moreover, "the fabricated pieces don't necessarily fit until they're all put together, so as you're setting the structures, the underlying supporting structure is deflecting. That's really some fantastic engineering that was done by

AECOM that predicted the amount of deflection; when you're adding these 14,000 tons of steel on top of an existing structure, you know it's going to deflect."

Steel overcomes its reputation as a rectilinear material in this space, offering both elegance and feasibility. Projects like this are often first contemplated in concrete because of the shapes possible with that material. But structurally those would have added too much weight and been structurally unachievable. Howie was initially surprised at the material choice: "Until I got to the area above the Concourse where he was doing these significant spans and doing his gymnastics with the shapes of them. And that's obviously why it had to be done in steel."

The roof of the Concourse had to be built from the top down to avoid deep excavation disturbing Memorial Plaza construction, without columns supporting the MTA 1 line, which runs down the middle of the project. Steel "micro-piles" were driven down about 100 feet, Durkin reports, as the crew excavated four levels in 15-foot segments, pouring concrete slabs at each level. "The original concept would have been to put a temporary structure all the way down to the bottom and then build back up. That probably saved at least a year, if not more.... That had been done before outside New York; it's the first time to my knowledge it was done in New York City."

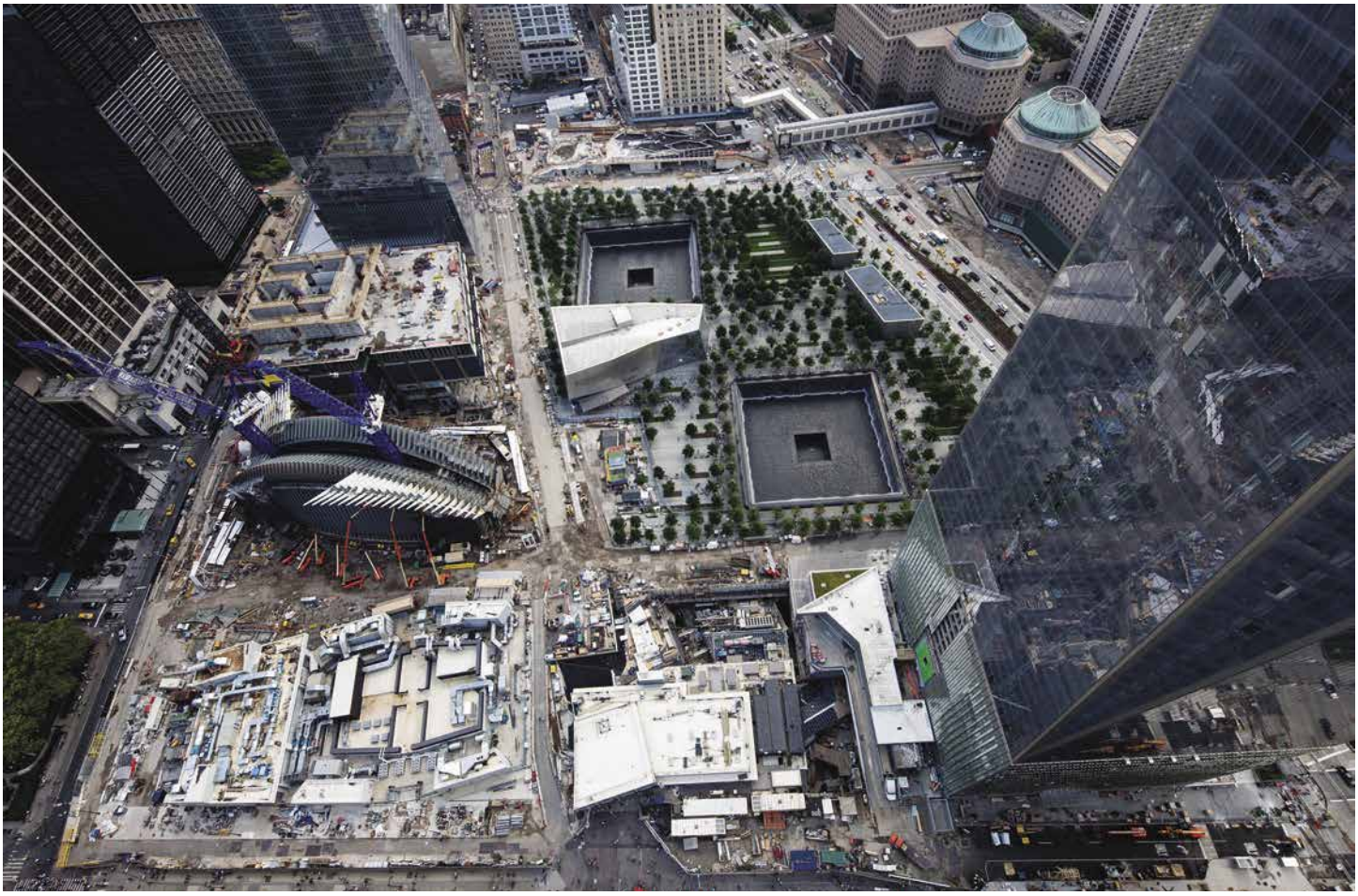
The Oculus beams needed support from portal frames resting on a compression ring, with all the temporary supports in place until the assembly was complete. "The major structural piece, the Vierendeel truss [that] runs down the center, was the last piece to go in the rafters," Howie says. "They jacked down the structure from its temporary shoring and placed the load on the actual structure, and then they took out the temporary steel. There was another building underneath all of this; no one recognizes the complexity of building this.... Although it may seem very light and open, it's actually a very complicated structural and construction problem."

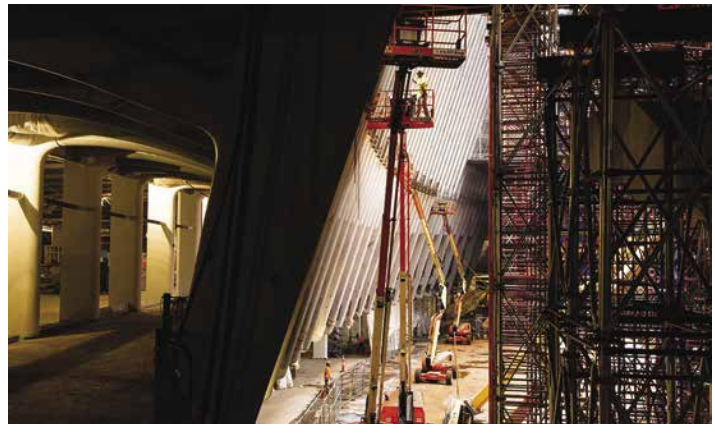
Not all the ribs are necessary to carry the load structurally. The many changes since the initial 2004 design included a doubling of the number of ribs in response to Police Department orders regarding blast safety, reducing 11-foot modules (matching those of the retail areas) to 5 feet, 5 inches, "leaving a glass space of 4½ feet," Howie reports. "The architectural pattern of the roof is at 5½ feet. Now, no one has mentioned that at all, [but] that doubled the cost right there in the steel. Doubled the cost of erection; doubled the cost of temporary structure." The Oculus, one of the project supervisors told Howie, contains "52 miles of welding. In my career, I've specified welding in feet or inches."

Only those who saw the Hub take shape may fully appreciate its scale and sophistication. Howie recalls "a forest of columns that was supporting [the 1 line] until they put these massive girders... 18-20 feet high, basically railroad bridges underground. And only when those were done could they remove the shoring; put in the concourse flooring; put in the

Left Construction at the Hub ca. February 2013.
Above top and bottom Connection joints for the structural steel elements of the Oculus ribs.
Facing clockwise from top An aerial view looking south on the World Trade Center site. Construction of the Hub's bonelike structure. An interior view of the WTC Transportation Hub during construction. View from 7 WTC of construction on the Hub, 3 WTC and completed 4 WTC in the background. A crane lifts one of the 114 rafters that were installed on the Hub.

Opening spread: James Ewing; This page: Steel Institute of New York





This page, clockwise from top: Silverstein Properties (1, 2, 4); Joe Woolhead (3, 5)

underside of the trusses, which is all-concrete; and then start to do all the finishes. So in addition to the structural steel that you see, there are pieces of steel that I have never seen in my career, 4 or 5 inches-thick steel, that are part of this trusswork."

Calatrava, among his official statements, refers to the Oculus as "a piazza for New York, the same way the piazzas were traditionally understood in Europe: as a place for visiting and gathering in which the access to the main locations of the city are articulated." With its high-end retail offerings, the Hub has forever blurred the lines between public space, luxury shopping mall, and transit station.

Skepticism follows opulence as naturally as fresh air rushes into a vacuum. And the Hub alone can't untangle New York's transit dilemmas. The public who ride the trains, traverse the public spaces, and try to assess what it gets for its four billion dollars—no one discussing the Hub omits that figure—expect a lot from this facility. Yet the experience of standing beneath the enormous oculus, among New Yorkers who uncharacteristically drop their freneticism, raise their eyes, and stand as still and respectful as choristers, is a sensation unlike any other in the city. Durkin reads that recurrent response in kinetic terms, generated by the visual rhythm of the fluid, parametrically varied ribs: "If all the pieces were symmetrical, I don't think it would have the same impact. I think that conveys motion."

"No one's seen anything like this before," says Howie. "It is certainly and undeniably an extravagance. But it's a pretty spectacular extravagance."

WORLD TRADE CENTER TRANSIT HUB

Location: **World Trade Center, 290 Broadway, New York, NY**
Owner: **Port Authority of New York and New Jersey**, *New York, NY*
Architect and Structural Engineer: **Santiago Calatrava LLC**, *New York, NY*
Architect, Structural Engineer of Record, Mechanical Engineer: **The Downtown Design Partnership** (STV/AECOM joint venture in association with Santiago Calatrava and Parsons Transportation Group), *New York, NY*
Construction Manager: **Tishman Turner JV**, *New York, NY*
Structural Steel Fabricator: **Skanska Koch**, *Carteret, NJ*
Structural Steel Erector: **DCM Erectors**, *New York, NY*; **Skanska Koch**, *Carteret, NJ*

This spread: James Ewing

The Oculus stands as both a monument on the World Trade Center site and as a functional piece of New York City transit. **Facing** Steel ribs reach 160 feet into the air from the main hall. They are coated in bright white intumescent fireproof coating, a material derived from the aerospace industry.