



Fulton Center Sky-Reflector Net

Lower Manhattan's bustling transit hub is crowned with an ambitious tensile structure that required rigorous collaboration between designer, fabricator, and installer.

NAVIGATING AMONG NINE SUBWAY lines and the streets of Lower Manhattan, 300,000 people converge daily to walk through Fulton Center, which opened to the public on November 10, 2014. Just as stunning as the number of users is their initial reaction to the new transit hub's atrium pavilion. Spotting the artwork *Sky Reflector-Net* that crowns the eight-story hall, they turn from hardened commuters into tourists: Travelers pause under, photograph, and orient themselves by the skylit cable-net structure cradling 952 Alanod-coated perforated anodized-aluminum panels, each measuring 0.145 inches thick.

The varied responses bear out the installation's multiple functions. As Arup's Zak Kostura, structural engineer for the project, explains, "The artist came to the table wanting to create an experiential effect; the architect wanted people to use it as a wayfinding

device; and the engineer wanted to make sure, quantitatively, that daylight could penetrate Fulton Center's lower levels."

Kostura adds, "In a normal project, you can almost get away with dividing up the systems that support the interests of different stakeholders. Here, achieving our goals required intensive collaboration."

Sky Reflector-Net was conceived by James Carpenter Design Associates (JCDA) in response to Arup and Grimshaw Architects' initial 2003 design of the Fulton Center pavilion. While that scheme would go through multiple iterations for value engineering, the three-story structure consistently featured a dome whose south-facing, 53-foot-diameter oculus would top out at 108 feet tall. JCDA namesake James Carpenter imagined suspending a skewed hyperbolic paraboloid—or hyper—armature from the dome's sloped oculus, and tracing its double curvature in panels that brighten and, evoking the New York subway system's historical reliance on sunshine, reflect natural light into subterranean circulation zones.

Carpenter's vision was compelling enough to win the public-art commission for *Sky Reflector-Net*. Developing it beyond concept required interdisciplinary support. "That hyper shape didn't



Above Three teams of contractors performed the panel installation, connecting each panel to nearby cruciform at its four corners.

Below A skylight at the top of Fulton Center sends light into the atrium below, much like the subway-illuminating sidewalk skylights that used to punctuate New York City streets.



This page top and opening spread: Zak Kostura; this page bottom, facing top and center and following page: MTA/Patrick Cashin; Jennifer Krichels; concluding page: James Ewing

Right Tightly choreographed fieldwork required two boom lifts and a swing stage operating simultaneously.
Below center A form-found structure, the net adopted its final geometry once 56 tie rods at its base were tensioned on-site.
Below Cruciforms connect panels. Rod segments have serial numbers to ensure proper placement.

assume the weight of the panels, the connections, or the position of the boundary form, which would all dictate the final design," Kostura explains of the myriad factors that would have to be calculated to realize the complex geometry. JCDA subsequently worked with Grimshaw as well as Arup, which was tapped as prime consultant to the MTA in 2003, to bring the idea to life.

While Carpenter did not originally picture it as such, budgeting dictated approaching the hyper as a purely tensile structure. Arup reverse-engineered tensile forces and node positions according to Carpenter's preferred geometry by executing more than 113 iterations of a computational model. Next, modeling yielded the unstressed length of each cable segment, along with 1,056 x, y, and z coordinates that would ultimately position the 952 infill panels into 17 rows.

All but the top and bottom rows comprise rhomboid panels, and Kostura notes that a traditional hyper-shaped net would have included horizontal banding to panelize it into stiffer triangles. "Jamie [Carpenter] and Grimshaw made an adamant assertion that the panels should be diamond-shaped and not triangulated. That posed an immense structural challenge of creating a soft net from rigid, delicate panels, which would waft in the intense amounts of sun and airflow in the atrium."

The panels are bolted to one another via paddle connectors, held between 112 quarter-inch-diameter steel cables that crisscross to form the 17 rows. The integrated team had to treat a seemingly minute detail of *Sky Reflector-Net*—the left, right, and bottom holes where each panel would receive the paddle connector—with the same scrutiny as its cable lengths. Indeed, if attached with less tolerance than the maximum billowing of the net, then extreme movement could rip the aluminum piece from its source.





Using computational fluid dynamics to model the cable net under 815 different conditions, the team arrived at peak width and height values for the holes of 0.23 inches and 0.08 inches, respectively. Hole dimensions were set with construction tolerances. A similar parametric design process also generated the cruciform-shaped paddle (see diagram), which swages the crisscrossing cables with a through-bolt; the paddle's horizontal and vertical pieces measure 0.25 inches thick at their ends, and taper to 0.125 inches at that bolted midpoint. All elements freely rotate around the bolt axis to account for panel movement. Bolts at the tips of the horizontal and vertical pieces connect paddle to panel.

The meticulous engineering of *Sky Reflector-Net* might suggest a direct file-to-fabrication approach to execution. But this project's delivery required overlapping digital efforts. "We engage in modeling before we even sell a project," says Jeff Vaglio, a Los Angeles-based associate director of Enclos' Advanced Technology Studio, which assumed oversight of fabricating and erecting

the artwork in summer 2010. He continues, "On many projects, it is not until after contracts are awarded that we're able to exchange model information."

Enclos and Arup used the same software platforms in modeling the cable net and its panels. They did not necessarily incorporate the same criteria. Namely, "We set up our tools to anticipate field conditions that are not absolutely precise, but are within construction tolerances of adjacent trades," Vaglio says.

Strength of panel-to-paddle bolts was one inconsistency that arose from the different perspectives. In turn, Arup and Enclos discussed the movement tolerances associated with a more robust bolt, forecast the network-wide ramifications of individual adjustments, and then identified the exact locations to increase bolt size. All of the cable net's bolts are stainless steel ASTM Grade F593 316, and nuts are stainless steel ASTM Grade F594 316. Eighth- and sixteenth-inch-thick Neoprene and Teflon-coated washers separate the panel and paddle materials to avert galvanic reaction.

The enlarged design team relished further opportunities to ensure accuracy. Enclos and Schopfheim, Germany-based panel manufacturer Durlum conducted parallel engineering to validate production of the 8,524 square feet of anodized aluminum. Similar quality control was performed during the mockup of 13 panels at the Westford, Massachusetts, workshop of contractor TriPyramid, with one engineering team manually deriving the panel geometry and a second team automatically generating it from the parametric model.

Finally, Enclos deferred fabrication of tensioned AESS stainless-steel tie-back rods until site surveys confirmed as-built data: Each 0.375-inch-diameter rod addresses construction tolerances via adjustability. At the oculus, for example, rod segments were connected by couplers set within a hole at the base of each kingpost—the vertical member that connects the tension rods to the oculus's upper lattice of tube sections. "The rods had to be free to slide through the kingpost holes so the contractor could tension the rods evenly, but to resist skylight

This spread Work on the surrounding pavilion building continued throughout cable net installation. Work was performed carefully to ensure the relatively delicate cable net system was not compromised by construction activities nearby.

deflections we needed to be able to lock each kingpost to the rods once tensioning was finished," Kostura explains. "So we came up with a novel detail involving cylindrical nuts that could be torqued against external threads on the coupler until they bear on a flange within the pocket of the kingpost. Those nuts were left loose on the rod assembly until tensioning was complete. The result was a stable system with compact, almost invisible connections between the kingpost and rod."

"It makes me feel very safe that, as a group, we're taking the precautionary steps to ensure a prudent structure," Vaglio says of

the redundancy. And while that diligence clearly paid off—the *Sky Reflector-Net* cable net was installed in one piece during a single morning for minimal disruption to adjacent work, for example—Vaglio adds, "We learned that no matter how precise our modeling, there's always a point when the reality—the construction site—decouples from the model and craftsmanship is paramount." Double- and triple-checked in the field, *Sky Reflector-Net* spins its transformative effect on commuters, and elevates Fulton Center from public transit node to a jewel for the people. □

FULTON CENTER SKY-REFLECTOR NET

Location: **Fulton at Broadway and Cortland Street, New York, NY**
 Owner: **MTA Arts for Transit and Urban Design and the MTA Capital Construction Company (MTACC), New York, NY**
Sky-Reflector Net Artist: **James Carpenter Design Associates (JCDA), New York, NY**
 Architect: **Grimshaw Architects, New York, NY**
 Structural and Mechanical Engineer, Facade Consultant: **Arup, New York, NY**
 Construction Manager: **Lend Lease**, part of a joint venture with **PB Americas, New York, NY**
 Structural Steel Erector: **Imperial Iron Works, Bronx, NY**
 Architectural Metal Erector: **Jordan Panel Systems Corp.** (exterior/interior metal panels), **East Northport, NY**
 Ornamental Metal Erector: **Capco Steel Erection Co., Providence, RI**
 Curtain Wall Fabricator and Erector: **Enclos, New York, NY**