The Fulton Center:

design of the cable net

Location
New York City, NY, USA

Authors
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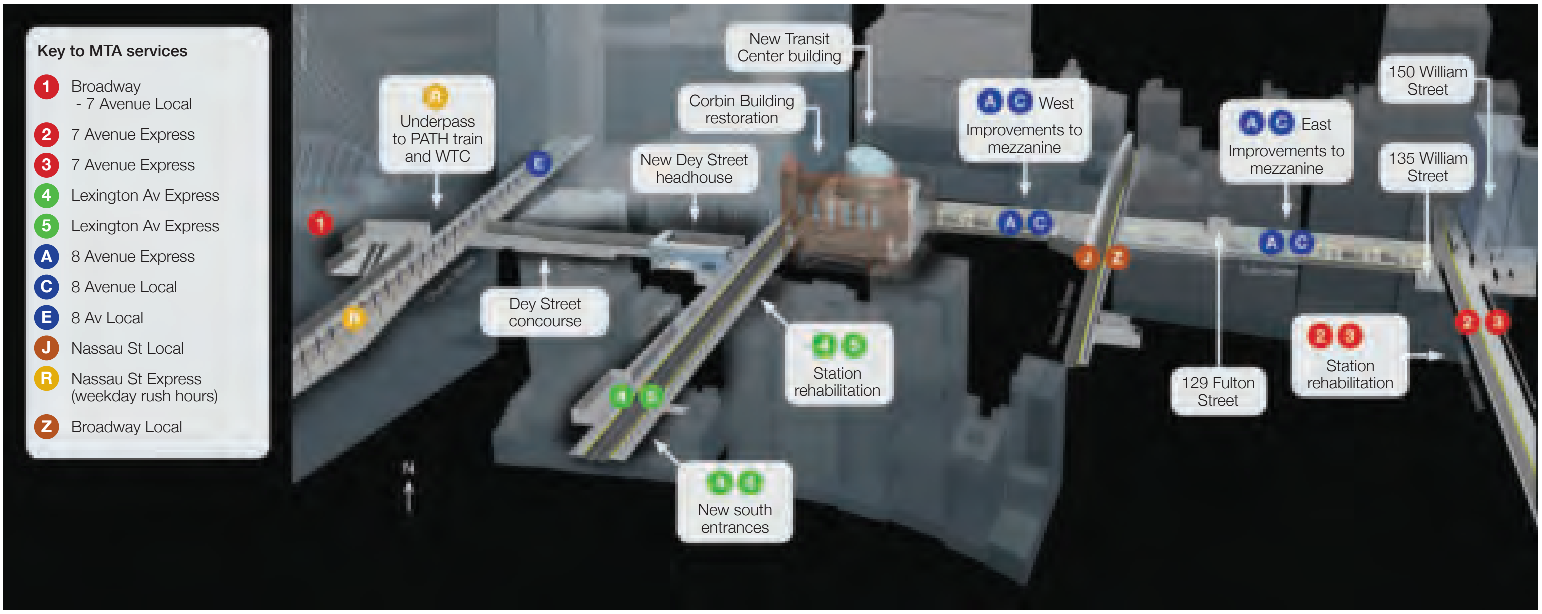
1.

Introduction
At the corner of Fulton Street and Broadway, one block east of the World Trade Center site and two blocks south of City Hall Park, 11 New York City subway lines converge in a hub serving over 300 000 transit riders daily. With their dense tangle, these lines have evaded efficient connection for nearly a century, a legacy of disparate planning and construction practices common to the era of competitive, privatised transit operation — and despite being unified under a single state agency in 1968.

In the aftermath of September 11, 2001, the Metropolitan Transportation Authority (MTA) enacted plans to redevelop this hub into an efficient transfer point, replacing the labyrinth of corridors, retroactively constructed to link existing lines, with an efficient system of pedestrian mezzanines, concourses and underpasses, complete with elevators and escalators to comply with the provisions of the Americans With Disability Act (Fig 2). And at the corner of Broadway and Fulton, the MTA planned a spacious



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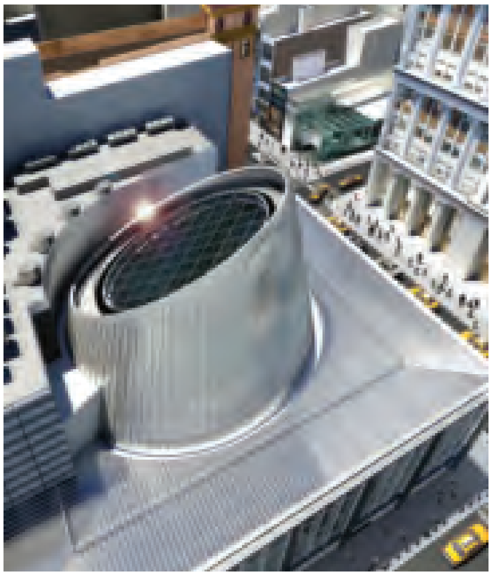

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multi-storey pavilion structure to crown the new underground pedestrian network and form an iconic gateway to Lower Manhattan.

In 2003 Arup was awarded the role of prime consultant for the Fulton Street Transit Center (now the Fulton Center), and has delivered a wide range of multidisciplinary design services since then. As architect for the Center's superstructure, Grimshaw Architects designed a three-storey glazed pavilion set around a central eight-storey dome structure (Fig 1). Topped with an inclined 53ft (16.15m) diameter circular skylight known as the oculus, this large central space serves to collect and redirect natural sunlight through the building to the exhumed sub-levels below, and forms the project's main focal point (Figs 3–4).

The central space beneath the dome and oculus offered a rare opportunity for a large-scale artistic installation to add character and extend the architectural objective of repurposing incident sunlight to illuminate subterranean spaces.

The client and design team identified artistic potential in the architectural gesture planned for the Transit Center atrium, and responded to this opportunity with a public art competition held by MTA Arts for Transit and Urban Design in 2003. This led James Carpenter Design Associates (JCDA) being selected as collaborating artist for the atrium installation. Over the next two years, an engineer/architect/artist collaboration between Arup, Grimshaw and JCDA developed and designed an independent reflective lining, offset from the dome's interior, to direct sunlight down (Fig 5). The final design involved a steel cable net structure supporting nearly 1000 coated aluminium infill panels using flexible, universal node connection assemblies.

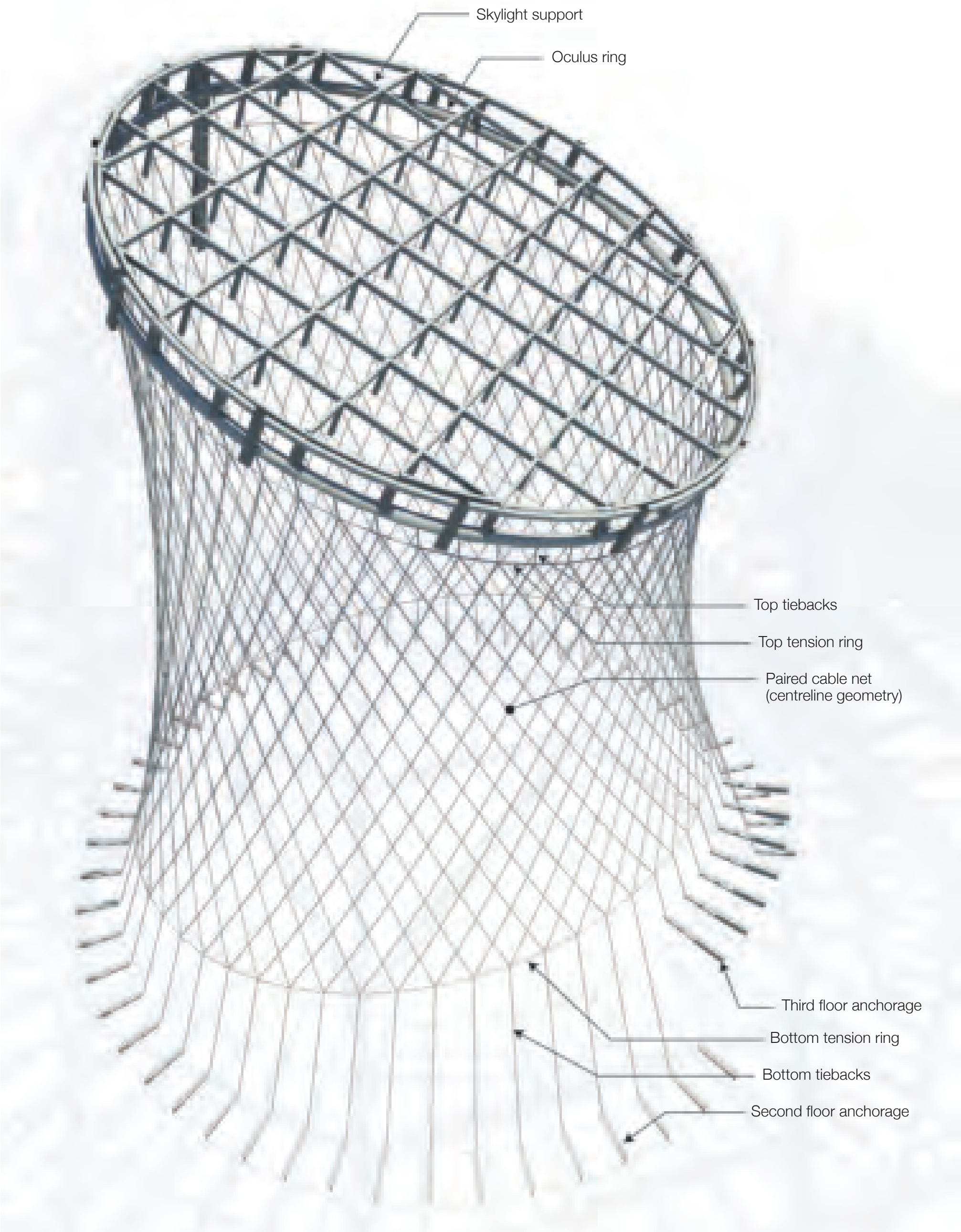
1. Architectural rendering of the Fulton Center pavilion with dome.

2. Extent of the new Fulton Center complex.

3. Rendering of the dome and oculus interior.

4. Rendering of central public space beneath the oculus.

5. Rendering showing cable net and oculus.



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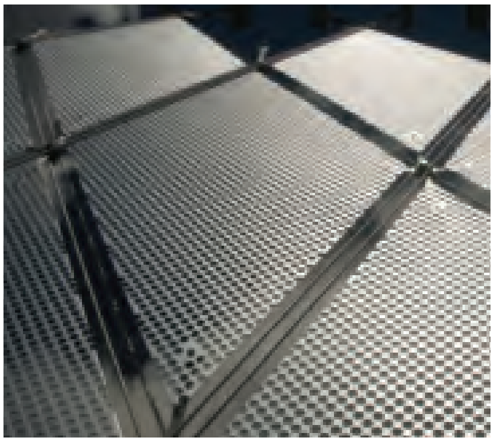
6. Cable net components and boundary support.

7. Reflective infill panels.



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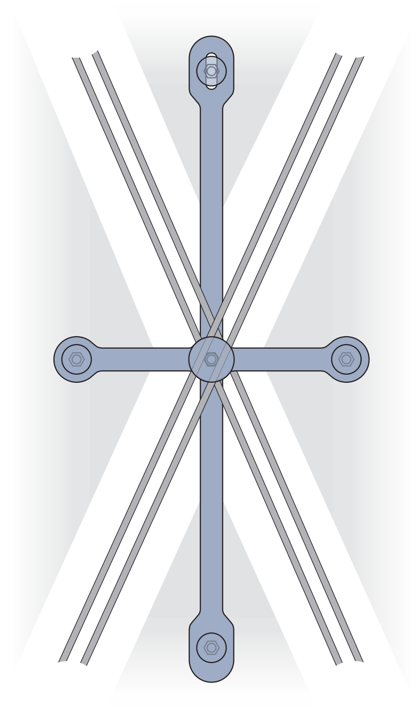
Cable net design
Extending the full height of the central public space, the cable net is suspended from 56 connection points around the compression ring of the oculus and anchored to as many cantilevered beams at levels 2 and 3. It is a skewed hyperbolic paraboloid, or hypar, in form, but unlike a regular hypar, it has double curvature. Moreover, the skewed form has only one axis of symmetry, so each four-sided infill panel has a unique shape, defined by the lengths and intersecting angles of the cable segments along each side (Fig 6).

The reflective infill panels are of 0.125in (3.2mm) thick aluminium substrate with a high-performance coating on the interior faces (Fig 7). They are perforated with a regular circular pattern to control the quantity of light reflected, permit the passage of interior air currents, and reduce loading on the cable net, to which they are linked at each corner by cruciform connectors fixed to the nodes (Figs 8–9).

The strategy to secure them follows conventional cladding practice. Each panel is suspended from its top corner by a pin fed through a standard hole in the corresponding connector, and its angle and position in space are established at the bottom corner, where a pin is fed through a vertically slotted hole that allows for correct positioning with minimum restraint. Holes in connector arms at the left and right corners are oversized to allow for independent movement from changes in temperature across the whole eight-storey net, or air pressure from large air intake grills at its midpoint.

The net is made of 112 pairs of stainless steel 0.25in (6.35mm) diameter cables, mechanically swaged at each node. Swages are through-bolted with cruciform connectors arranged between the opposing cable pairs. Stainless steel rods are used for top and bottom ties as well as ring elements (Fig 10).

Form-finding
Initial assessment of the skewed hyperbolic form proposed by the artist indicated that a form-found tensile system could be developed to fit the desired geometry. This was enabled by using the swages at the nodes to grip the cables tightly, allowing each segment to carry a unique tensile force and dramatically broadening the range of geometric forms achievable using a purely tensile system.



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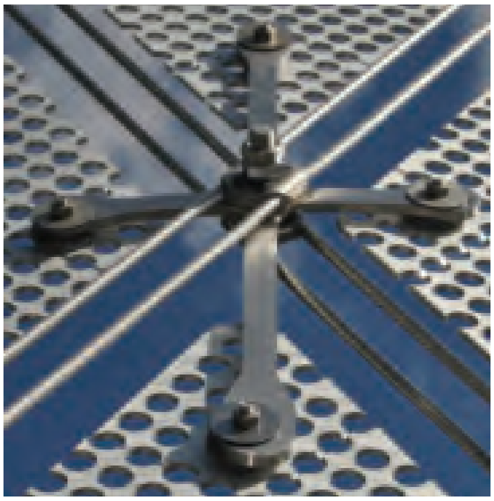

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As the desired final form was known, this "form-finding" entailed ascertaining the tensile force required in each cable segment to achieve that form. Arup developed a computational model of the desired cable net geometry, including all node positions, and initially ran it with a uniform 900lb (4.00kN) tensile force in each cable pair. The resulting found form varied significantly from the initial, desired geometry due to the generalised prestress force: where the force entered was larger than the true prestress, the segment shortened; where the force was smaller, the segment lengthened.

These geometric shifts from the initial geometry, while undesirable in principle, lead to redistribution of the generalised initial prestress, eg shortening of segments that were overstressed leads directly to a reduction in the force in the element after form-finding and prestress redistribution. Put simply, the prestress redistribution inherent in the form-finding process is self-correcting.

These redistributed forces were again applied to the desired architectural geometry. The resulting node displacements were smaller than observed in the first iteration, and the redistribution of prestress from this second form-finding routine further approached the correct prestress values for each cable segment.

Arup then developed a Microsoft *Excel* custom that automatically ran subsequent iterations, each time applying the redistributed loads to the original geometry and performing a form-finding routine. This terminated at the 113th iteration when the convergence indicators were met. The resulting prestress distribution pattern had maximum average values of 906lb (4.03kN) at the top and bottom rows, and minimum average values of 886lb (3.94kN) at mid-height. These were converted into element strains and applied to a new analytical model embodying the desired architectural geometry as well as the actual stiffness properties of the cable net elements.

Non-linear static analysis of this model demonstrated negligible movements in the nodes, confirming the validity of the strain distribution. These strains were then used to determine the unstressed length of each cable segment — data later used for fabricating the cables and swage assemblies prior to installation.

The validated architectural geometry was tabulated and presented as a set of Cartesian node co-ordinates, which in turn became the set-out geometry for the 952 infill panels. Successful execution of the installation's design thus necessitated correct distribution of tensile force throughout the net, with each node positioned so that each panel's shape matched that of the space within the net that it would occupy.

Understanding movements

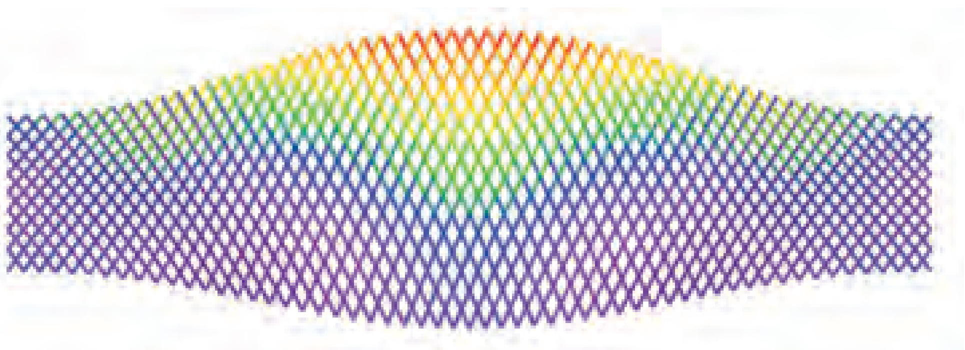
This analysis to establish a suitable strain distribution pattern was predicated on several assumptions about the net's real-world environment, including uniform ambient temperature, no loading from internal air pressure, and an exact match between the prescribed prestress distribution and what would actually be applied to the system.

In reality, the eight-storey space inevitably has thermal gradients, as warm air collects near the oculus and cool, conditioned air is diffused within the occupied space below. The ventilation strategy for the building relies on developing air currents that must pass through the panels, resulting in pressure drops across the perforated surface and generating loads that will influence the net's shape. Realistically, tensioning the net had to acknowledge errors inherent in the final values, and a review of industry standards suggested variations in applied tension loads of ±20%.

Because of its scale, the cable net must be viewed as a dynamic structure whose form constantly changes corresponding to the sum total of loads — the weight of panels, thermal strains, air pressures, and applied prestress forces — that will vary over time. Consequently the position of each node will also vary, and thus it was essential to understand and quantify the maximum conceivable movements in the nodes under all realistic environmental conditions.

8, 9. Universal node assemblies, with cruciform armatures and cable swages.

10. Stainless steel rod tie and connections to panels.



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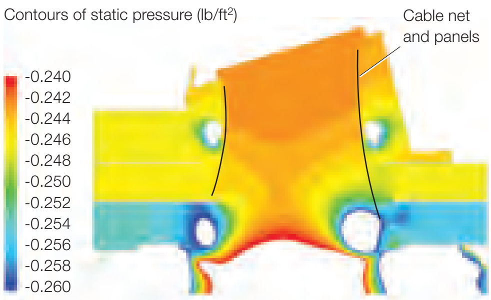

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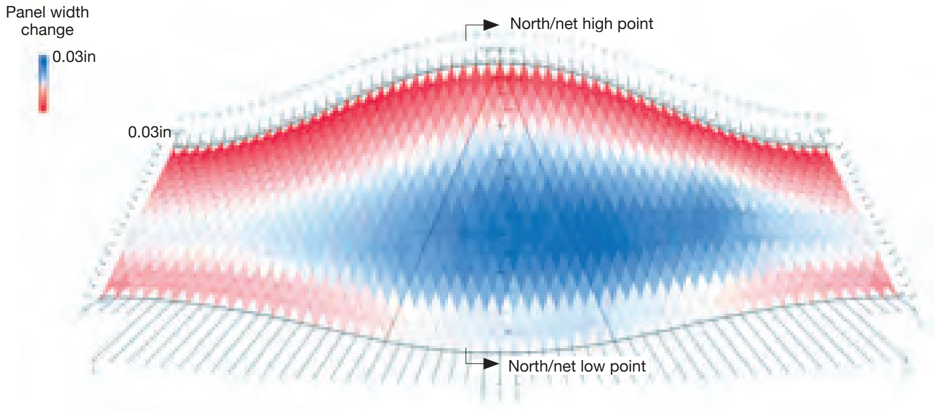

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11. Axial force in cable pairs under nominal panel loading and prestress.

12. CFD model generated to determine air pressure on each panel.

13. Assessment of individual node movements for a single load case. The component of node displacement measurement normal to the surface of the net was denoted as "node-surface deviation".

Should any of these movements transfer tensile forces to the infill panels, they would quickly overwhelm the delicate aluminium elements. The cruciform connector arms thus hold each panel in place with minimal restraint to allow for unrestrained movement of adjacent cable net nodes, enabled by the slotted and oversized holes in the arms on the left, right and bottom corners of each panel. The dimensions of these non-standard holes had to be co-ordinated with the maximum conceivable movements to provide sufficient freedom of movement and avoid transfer of force into the panels (Fig 11).

Arup studied each environmental characteristic and developed realistic scenarios to cover the range of corresponding load conditions. To determine the magnitude of pressures from interior air currents, a computational fluid dynamic (CFD) model was developed in the *ANSYS* program to identify the pressure drop across panels, given the known volumetric flow of intakes and diffusers throughout the building and the degree of permeability in each area of the cable net (Fig 12).

The scenarios for each environmental characteristic were then superimposed to generate 815 unique load combinations, each with a presumed unique cable net shape, and static non-linear analysis conducted for each combination. A custom subroutine was written to interrogate the position of each node under each load case and determine the largest changes to the support conditions of each panel. Increased distance between left and right corner supports was referred to as "panel width change" — the peak value implied the required dimensions of the oversized holes at these support points. Correspondingly, increased distance between top and bottom corner supports was "panel height change", which provided information on the necessary dimensions of the vertically slotted hole at the bottom connection point.

Analysis revealed that the largest resolved movement of any node under any perceivable load combination is around 2.06in (52.3m). Broken down, however, this maximum movement results in a change of only 0.23in (5.8mm) in panel width and 0.08in (2.0mm) in panel height. The dimensions of oversized and slotted holes were thus set to accommodate these movements in addition to acceptable construction tolerances of 0.25in (6.35mm) in either direction (Fig 13).

Modeling a universal connector

Working with the architect, Arup developed the universal cruciform connector for adequate panel support in the various configurations that result from the skewed hypar shape. Each connector comprises a horizontal and vertical armature, linked by a bolt at the midpoint and set between swaged cable pairs. All elements are free to rotate about the bolt axis, to allow the connector armatures to conform to the various required configurations. The armatures, nominally 0.25in (6.35mm) thick, taper to 0.125in (3.2mm) at their midpoints to minimise the effective thickness of the assembly, and the corresponding eccentricity between opposing cable pairs.

Designing the universal connector armature required geometry that incorporated the space-saving taper while facilitating the free rotation of elements to accommodate the various panel configurations, and Arup developed a parametric model in the *Digital Project* program to assess the performance of various designs. All components — armatures, bolt and swages — were individually modelled as discrete parts and then assembled into a single component. That assembly was instantiated into a global model containing the 896 cruciform connector nodes (Figs 14–15).

Set-out instructions intrinsic to each connector facilitated its rapid configuration, given the position of adjacent nodes in all directions. A separate clash detection program was then used on the solids to confirm the rotational adequacy of the universal part design.

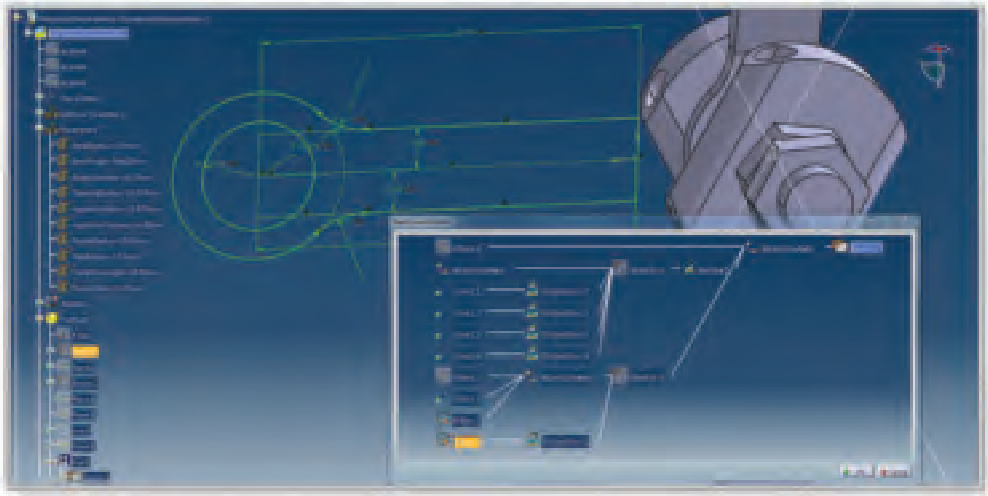
Limitations to computing power then available led to instantiation routines that took days to complete. The design team observed that the instantiation of solid components was by far the most time-consuming; points and lines that established the location and orientation of the components were much faster to instantiate.

To accelerate the process of studying each armature design, solid components were removed and only set-out lines instantiated. A custom script was written to interrogate the relative angles between each armature pair, and the most severe angles were then modelled using the solid components to test their suitability. This modified approach to parametric modelling proved exceptionally fast, and instantiation of armatures on all 896 points was completed in a matter of seconds.

The geometry of the armatures for the universal connector was optimised for visual and performance criteria through the parametric model, and the final design was extracted from the individual part models and presented as simple 2-D sections and elevations in the contract drawings.

14. Parametric definition of horizontal armature.

15. Custom routines instantiate the connector prototype throughout the node cloud.



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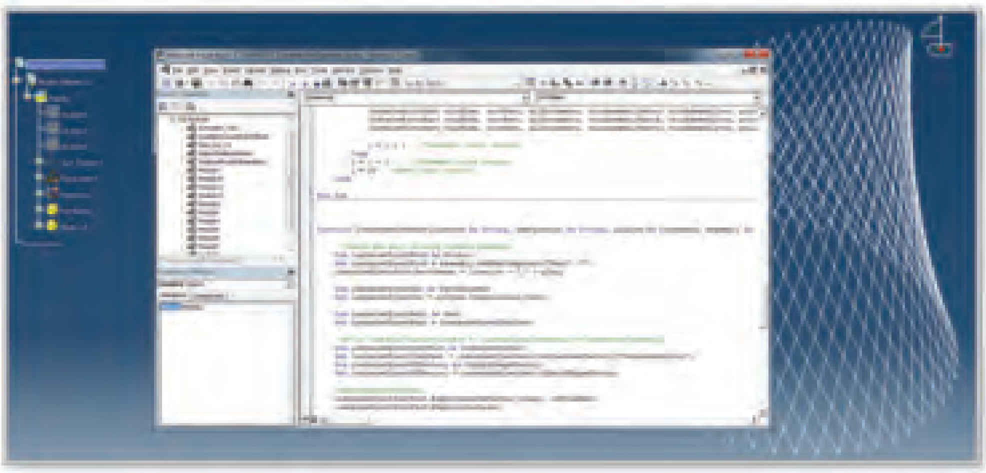

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Documentation

Throughout the design process, the cable net system seemed to wear two masks simultaneously: one of an intricately detailed sculpture in which the architect and engineer had both laboured over the aesthetics of every pin, clevice, armature and connector; and one of a form-found system with discrete performance metrics tied to a range of building disciplines such as structure and lighting. It was thus imperative to adopt an approach to documentation that would ensure conformance to the geometric characteristics intrinsic to the sculptural piece while promoting a performance- based approach emphasising ends rather than means.

The design team therefore employed a hybrid approach to documentation, largely embracing prescriptive design but also integrating performance criteria to ensure the selection of a specialist subcontractor knowledgeable and experienced in the construction of such a system.

In addition, Arup incorporated performance requirements so as to facilitate a productive dialogue with the contractor that would allow the designer to more effectively monitor and observe the contractor's co-ordination, shop drawing preparation, fabrication, and assembly. The resulting working environment promoted open dialogue on potential construction issues and a balanced approach to risk management.

The design team's extensive form-finding analysis yielded comprehensive data on the characteristic node co-ordinates and element strains in the cable net system. Because these data remained available to the team members, who were highly confident of their validity, a prescriptive approach to documentation became the team's baseline. Nodes were given unique identifiers, tabulated and presented in the contract drawings with explicit 3-D co-ordinates.

For tensioning, the drawings conveyed to the contractor the precise force to be applied to each boundary element. Average tension forces were provided for each row of cable pair segments, as the standard deviation in any given row of the net was considered low relative to the magnitude of tension forces and the corresponding margin of error intrinsic to the tensioning process.

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16. Full-scale mock-up prepared by fabricator TriPyramid at the production facility in northern Massachusetts, September 2011; a 13-panel section of the net was tensioned and assembled for design team review.

17. The mock-up tested the design configuration and revealed opportunities to enhance the system's configuration while such changes were still viable.

18. Preparing the cable net:
a) As each panel is geometrically unique, to ensure proper installation connector components were marked with serial numbers.

b) Connections throughout the net involve sophisticated assemblies of custom components. Here, a connection between the net cables and lower tension rods is packaged for transport to site.

c) Components — panels and tension rods — are geometrically unique. Where etched serial numbers were not called for, the supplier included temporary identifiers for reference during installation.

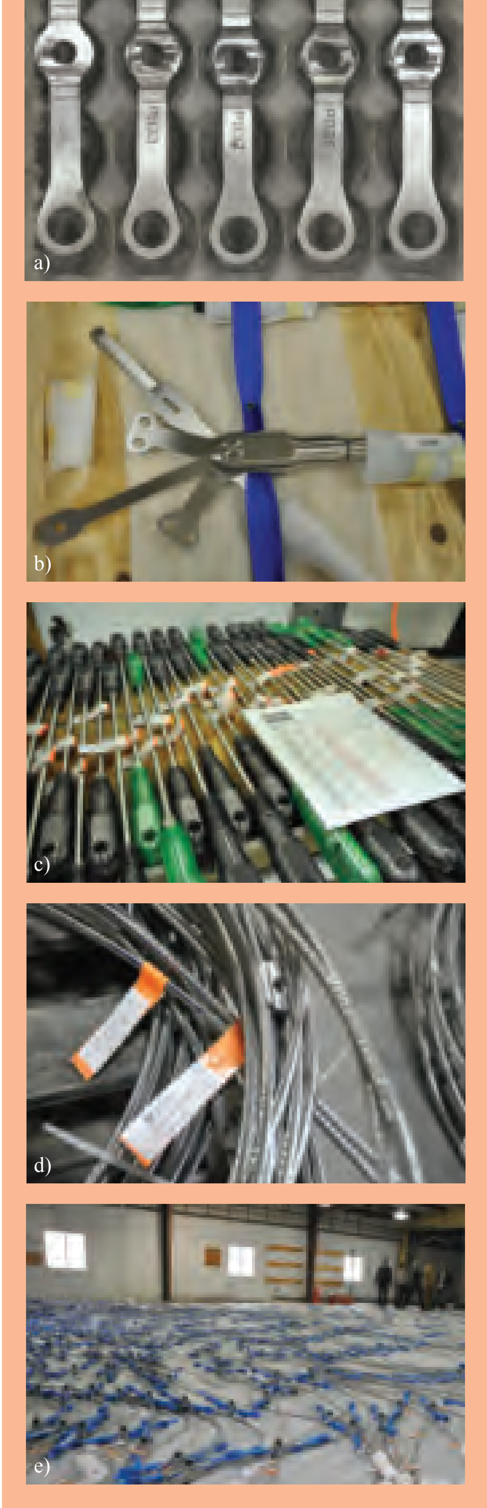
d) Close-up of cabling prior to assembly.

e) The net was assembled at a rented warehouse in a town in rural northern Massachusetts, and then lifted by crane in a field to simulate installation, before transport to site.

The provision of this prescribed set of tensioning data helped ensure that the contractor's system embodies not only an acceptable distribution of tensile forces to achieve the desired form, but also an average level necessary to ensure that movements under environmental loads are kept within acceptable limits.

Had the design team produced a performance-based design, the contractor would have needed detailed information on loading assumptions in lieu of prescribed tension forces, and would have had to perform a far more sophisticated analysis of the system to identify tension forces commensurate with permissible node movements — analysis already conducted by the design team to arrive at a component design that balanced aesthetic and performance requirements.
Such duplication would have been costly and added more tasks to an already complex construction schedule.

Providing the tabulated node co-ordinates on the drawings put the onus on the contractor to ensure that the co-ordinates on the installed cable net matched those in the design drawings within specified construction tolerances. This requirement would thus incentivise the contractor to carry out analysis to ensure that all cable and rod segments were fabricated to lengths appropriate for the specified boundary tension forces outlined in the drawings.



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This analysis yielded specific tension forces in each element that were used by fabricators to prepare shop drawings illustrating cable marking lengths. These were received by the design engineers as submittals, allowing them to check the resultant shape using non-linear static analysis.

The design team was thus reassured that fabrication drawings had been developed from a suitable analytical model, owned by the contractor, that had produced results matching those produced by the designer's model. However, the prescriptive dimensional and force data from the design team eliminated the need for the contractor to undertake complex form-finding. Rather, the tabulated node co-ordinates were used to generate a non-linear static model that could be analysed with the documented tension forces to confirm that any node displacements would remain within the governing performance-based requirements.

Construction

The building's superstructure and fit-out of the area bounded by its enclosure and foundations were packaged into a single construction contract, awarded to a joint venture of Plaza and Schiavone (PSJV) in August 2010. However, the cable net's complex and unconventional nature caused PSJV to engage several specialist subcontractors to fabricate and install it. Co-ordination was managed by Enclos, the subcontractor also selected to supply façade components for the enclosure and the oculus. TriPyramid Structures provided the cables and cruciform armatures, while the anodised aluminium infill panels came from Durlum of Schopfheim, Germany.

Together with the steel fabrication and erection subcontractor STS Steel, all the construction team added skill and expertise to the value of the design through open collaboration. Performance-based provisions in the contract documents, aimed at promoting discourse among team members, generated fruitful if occasionally intense discussion over elements of the design and strategies for its execution.

Mock-up

The specifications required a full-scale mock-up of 13 panels, provided by the contractor so as to validate his means and methods and enable the design team to assess the system's performance (Fig 16).

Detailed review revealed opportunities to enhance durability and longevity through minor tweaks in the geometry of perforated infill panels and hardware components such as neoprene washers, spacers and nuts (Fig17). The contractor worked with the design team to realise these enhancement opportunities, and with minimal impact to the construction cost.

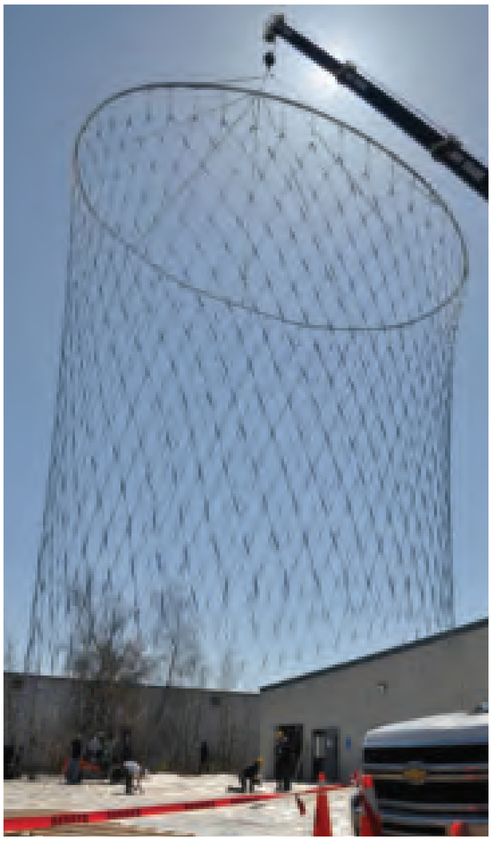
The contractor used tabulated node co-ordinates and a small set of typical details to develop the geometry of each unique infill panel, and automated scripts to rapidly develop shop drawings for each.

These drawings, once approved by the design team, were used by Durlum as electronic instructions in the computer numerically controlled (CNC) process used to fabricate each panel. The panels and cruciform connectors were stamped with a unique identification code to facilitate proper assembly in the field (Fig 18).

Fabrication, assembly and installation

TriPyramid Structures fabricated and assembled the net in a small rural town in northern Massachusetts. Each connector assembly was pieced together and wrapped for protection during transport. Once assembled, the net was lifted by crane in a field outside the assembly facility to simulate its actual installation on site (Fig 20). The net was then lowered and rolled immediately for transport to site by truck.

Once on site, the net was lifted into place using a temporary aluminium lifting ring raised by a set of hydraulic jacks mounted around the perimeter of the atrium at the Fulton Center's upper levels, and lifting cables that doubled back over the oculus above (Fig 21).



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19. Uday Durg, MTA-CC Program Executive, in attendance at test lift.

20. The assembled net crane lifted in a field near the facility, to both simulate installation and review its untensioned form.

21. The untensioned net following installation on site.

22. Contractors on the swing stage complete work on hardware connected to the lower portion of the net.

23. 3-D LIDAR scan of the tensioned net both before and after panel installation; the survey gave detailed information on the as-built position of the cable net nodes.

22.

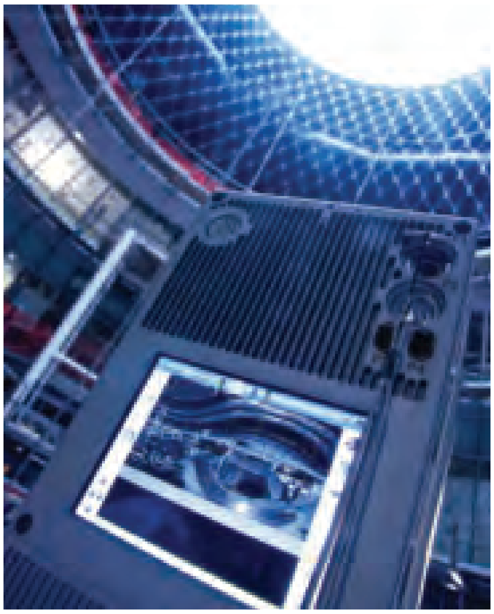
Once all boundary connections were made, the installer, Enclos, tensioned the net through a procedure that involved imposing known and unique displacements on the lower tension rods, inducing target boundary forces obtained through design team analysis and provided on contract drawings (Fig 22).

Panels were then installed with two man-lifts and a swing stage platform suspended from the oculus. Panel installation was completed in about three weeks (Figs 24–29).

Survey

The Arup design team contracted Naik Consulting Group PC to carry out a 3-D LIDAR ("light"+ "radar") survey of the cable net at critical installation milestones. Using remote sensing technology to measure distances, this generated a cloud of several hundred million points, representing the as-built surface geometry of the interior atrium space (Fig 23). The point cloud was used to identify the position of cable net nodes following installation and tensioning, both before and after panels were installed. The design team used the resulting information to assess the conformance of the constructed system to contract performance requirements, and identify regions of the completed net for in-depth, up-close review.

The survey was commissioned by the client during construction administration as an effective risk management tool. Although nothing occurred to prompt extensive use of the LIDAR survey data for corrective action, the availability of this information enabled the distribution of tension forces throughout the as-built structure to be compared to those established through design stage analysis, thereby providing information on system elements requiring adjustments to their tensioned length. The LIDAR results also serve as a permanent record of the as-built net geometry, should any panels require replacement in the future.



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Conclusion

This installation at the new Fulton Center combines two generally disparate structural systems: a form-found cable array prone to movement under varying loads, and rigid, delicate aluminium panels sensitive to strains caused by movement at their support points. To achieve harmony between them, detailed nonlinear analysis was performed to fully understand the magnitude of deflections under all conceivable loadcases. A linear algebraic model of the net facilitated rapid interrogation of deflection components within the plane of the panel surface.

These movements were subsequently addressed through the design of a universal, flexible connection assembly that isolates the panels from the effects of the net's dynamic behaviour, through strategically-placed slotted and oversized holes. Flexibility of the universal assembly was tested by parametric modelling, which simulated the geometric configuration of the assembly in each of the 896 intermediate node positions.

The detailed analysis enabled the use of prescriptive design documentation, which provided the contractor with clear geometric and force data. The resulting fabrication, assembly and installation occurred without major incident.

The cable net was substantially completed in June 2013 at an estimated cost of $3.8M. The Fulton Center complex is scheduled to open to the public in June 2014. A year prior to opening, the cable net was already receiving considerable attention in the press including *The New York Times*, as well as in other media.

Acknowledgments
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Erin Morrow is a senior consultant in the Toronto office. He provided 3D modelling support for the cable net design.

Ben Urick was a structural engineer in the New York office, and contributed to the cable net design.

Project credits
Client: *New York City Transit Authority* Architect: *Grimshaw Architects* Artist: *James Carpenter Design Associates* Structural engineer: *Arup — Scott Bondi, Craig Covil, Bruce Danziger, David Farnsworth, Matt Franks, Kristina Moores, Erin Morrow, Ricardo Pittella, Markus Schulte, Jason Shapiro, Tabitha Tavolaro, Ben Urick* Contractor: *PSJV* Specialist sub-contractors: *Enclos; TriPyramid Structures; Durlum; STS Steel*.

Image credits
1, 3-5 *MTA-CC/Arup/Grimshaw*; 2, 6-7, 9-29 *Arup;* 8 *Nigel Whale*.

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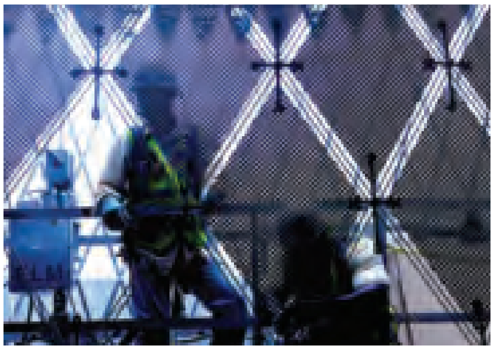

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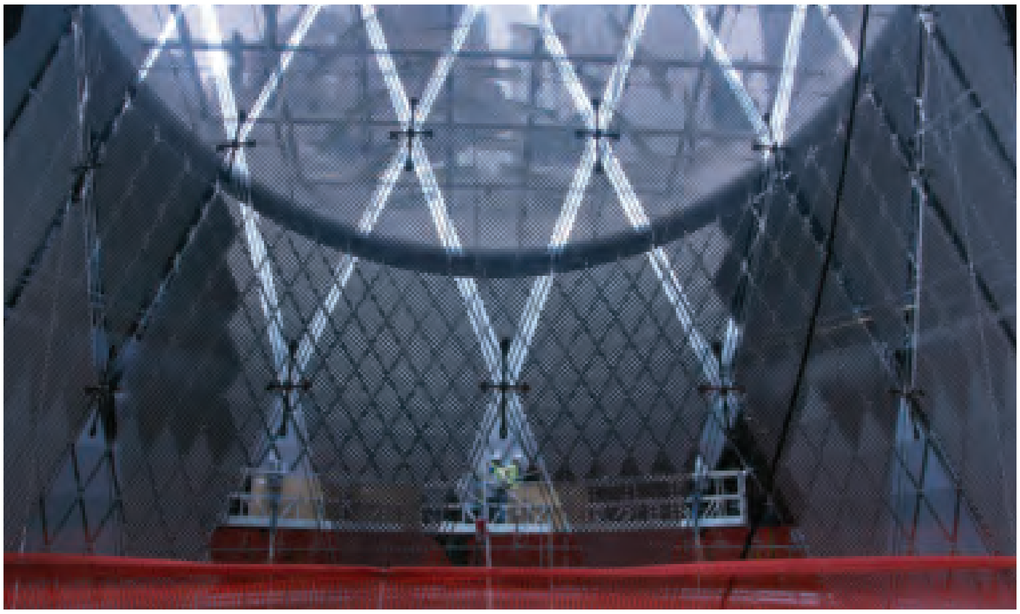

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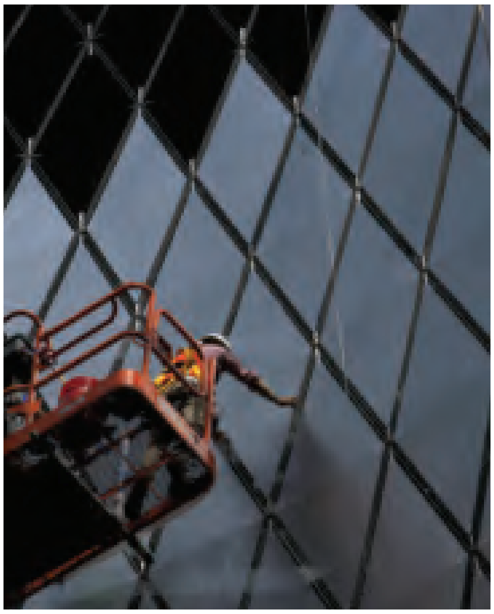

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24. Removal of the panels' protective films.

25. Three teams of contractors installed the panels, connecting each to cruciforms at the four corners.

26. The dramatic lighting effects of the cable net became apparent as panel installation progressed.

27. Panel installation took approximately three weeks.

28. Arup engineers took to the boom lifts to assess the built configuration against service requirements; as the form-found structure will behave dynamically under changing environmental loads, it was necessary to ensure the panel connections retained adequate allowance for associated movements.

29. Contractors' final check of the completed system: art integrated with architecture and engineering.