WORLD TRADE CENTRE
TRANSPORTATION HUB-OCULUS

PROJECT LOCATION: LOWER MANHATTAN, NEW YORK

CATEGORY A: BUILDINGS

PROJECT OWNER: PORT AUTHORITY OF NEW YORK, NEW JERSEY, NEW YORK

Buckland & Taylor International, Inc. New York, NY (an affiliate of COWI North America) proposed bridge engineering methods to construct this unique building. A free cantilever segmental errection scheme allowed the contractor to significantly reduce the amount of falsework and provided opportunities for geometry adjustments where needed.

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COWI

PROJECT INFORMATION

Project Name: World Trade Center Transportation Hub (Oculus)

Location of Project: 185 Greenwich Street, New York, NY, USA

Completed by: 2016

PROJECT DESCRIPTION

The World Trade Center Transportation Hub (Oculus) is owned by the Port Authority of New York and New Jersey (PANYNJ). Designed by Santiago Calatrava and the Downtown Design Partnership engineers, the Oculus pushed the boundaries of structural engineering and required innovative construction solutions. Skanska (the Contractor) approached Buckland and Taylor International, Inc. (an affiliate of COWI North America Ltd.) (the Erection Engineer) and collectively they determined applying bridge engineering concepts and first principles was the ideal approach to erecting Oculus.

The World Trade Center Transportation Hub (Oculus), Manhattan Island, New York.

The World Trade Center Transportation Hub (Oculus) is the new transportation hub located at the tip of Manhattan Island in New York, that serves over 200,000 daily commuters.

1) Innovations

A pair of hands releasing a white dove inspired this eye-catching and iconic structure. The World Trade Center Transportation Hub (Oculus) is striking in its architecture, yet was extremely complicated to build.

Project Solutions and Achievements

As erection engineers B&T (COWI) worked closely with Skanska (the Contractor) and PANYNJ (the Owner), and the design team, to introduce innovative applications that improved the erection schedule. These included:

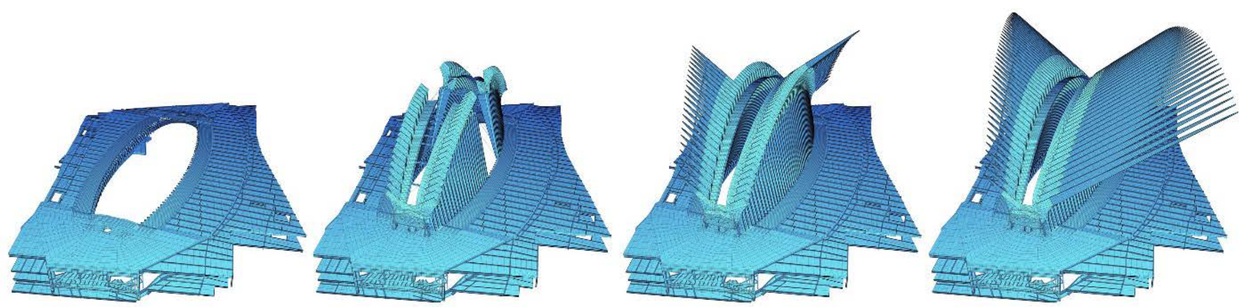
Segmental Construction: Applying bridge engineering concepts and first principles to the erection of the Oculus allowed this complex structure to be constructed safely and accurately.

A free cantilever segmental erection scheme allowed the Contractor to significantly reduce the amount of falsework, and provided for geometry adjustments as needed. Starting at both ends (abutments) of the building, long steel columns were lifted into place by crane; arch segments were then installed and attached on top - one in front of the other, until the arches finally met at the high point in the middle. After successful installment of each segment, B&T and the Contractor were able to survey each segment and further assess the as-built geometry. This ongoing feedback allowed the team to maintain the target geometry of this complex structure.

This decision saved both time and money, and reduced risks associated with the intricate design and glazing tolerances required.

Segmental construction of the steel columns and arch of the Oculus from both abutments. Maintaining construction within tolerance so the opposing sides of the arches meet.

Computer Analysis Model: Essential to the segmental erection scheme was the finite element (FE) analysis model created for the project. The glazing tolerances for the structural steel were especially tight. To allow the glazing to fit properly, the steel in the arch and the columns had to be within ±½ in. of the theoretical design location – including both fabrication and erection tolerances. The FE analysis model was used to determine the cambered shape of each individual steel segment, as well as to compute the stresses in the structure and the position of the geometry control points during each stage of the erection. With the installation and survey of each new steel segment, the team monitored the geometry of the building and determined if it had remained on track. Slight alterations and adjustments were applied as needed before construction progressed. From the FE analysis model B&T prepared a geometry control spreadsheet that provided target coordinates to the surveyors for the steel segments as they were maneuvered into place. The FE analysis model helped to define the erection sequence, maintain tight geometric tolerances, achieve schedule, and reduce costs.



An Finite Element (FE) model was created to analyze the Oculus structure. Erection stages were then defined to compute the construction sequence. Four erection stages are shown in Photo 1.

B&T used the FE analysis model to determine the cambered shape of each individual steel segment, and to compute the stresses in the structure and the position of the geometry control points during each stage of the erection. From the FE analysis model, B&T prepared a geometry control spreadsheet that provided target coordinates to the surveyors as each steel segment was maneuvered into place. After each installment, the team assessed the as-built geometry and applied slight alterations and adjustments as needed before construction progressed.

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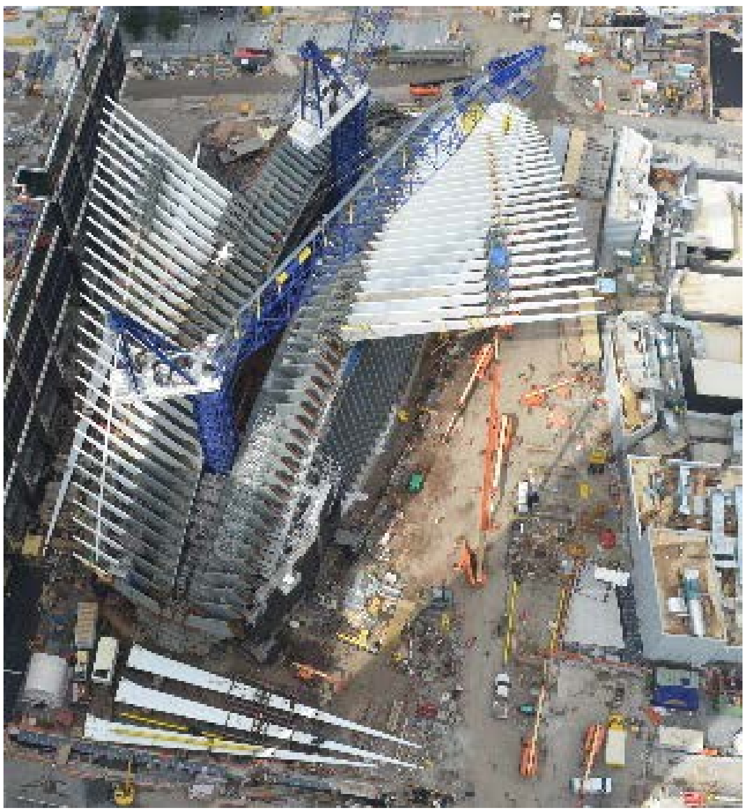
Welding vs Bolts: The project team identified that significant risks were associated with field welding (cost, time, and weld shrinkage distortions). B&T helped to mitigate these risks by replacing welded splices in the arches with bolted connections. A fully connected arch piece required almost three weeks of field welding. By comparison, the bolted connection required only two days. Not only did this drastically reduce the erection schedule, the bolts also made it significantly easier for the Contractor to install the arch segments and achieve the desired geometry.

AISC Codes: Each arch segment weighed approximately five tons and had to be safely secured for crane release during a single day shift – a project goal was to minimize night shifts and the impacts on crane usage. A490 high strength bolts were required for the design of the bolted splices, and AISC Codes required these bolts to be fully tightened in order to be relied upon. B&T identified that given this AISC Code requirement, an arch segment could not be released from the crane and bolted into place within a single eight-hour shift. Since the full stress was not on the splice at release, B&T believed that the bolts could be relied upon in a 'snug tight' condition versus fully tourqued. B&T contacted the authors of the AISC Code and obtained concurrence that an adequate number of bolts snug tight would provide the necessary strength for the erection scheme. With this endorsement, the Owner was convinced and erection proceeded.

Erection Engineering Solutions: Erecting the arches, the columns, and the rafters involved very tight erection tolerances to ensure the glazing would fit properly. A staged erection scheme was key to overcoming these challenges. Erecting the arches segment by segment, in the free cantilever segmental construction method commonly used in bridge erection, made this project possible. It saved time and money, and allowed the geometry of the structure to be monitored and adjusted throughout construction.



Aerial view of Oculus during rafter construction. The rafters are being erected, from the shortest to the longest, starting on opposite sides of the structure.

Aerial view of Oculus after completion. The unsymmetrical length of the rafters added to the overall complexity of construction.

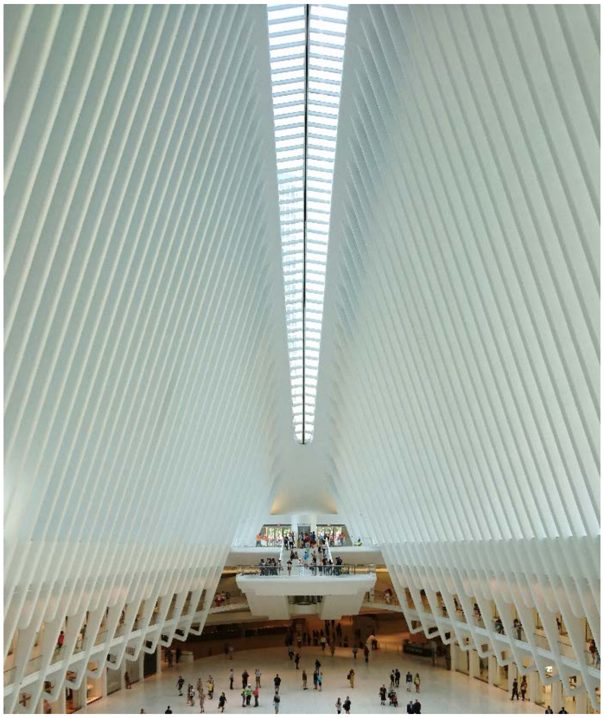
Construction engineering concepts are typically applied to similar projects. Applying bridge engineering concepts to the erection of Oculus was an innovative solution that saved time and money, and reduced risks associated with the intricate design and glazing tolerances.

2) Complexity

Site and Scheduling: Due to its location at the heart of the World Trade Center, the Oculus construction site was very constrained. The site had a limited laydown area for storing the large steel components prior to installation. B&T looked at solutions on how to reduce the number of steel components stored onsite throughout the construction schedule. Through detailed research and modeling, B&T determined the allowable balance and limits of forces on the structure - without arch pieces installed. An erection schedule was then developed for faster installation of the long steel columns and an increased installation from two to four of the large upper portals without the capping arch piece. These innovations reduced the storage requirements, optimized the erection sequence, and accelerated the schedule to help make the project a success.

Preparing the site for construction ("setting the table"). Located at the World Trade Center, the site had a very limited laydown area for storing the 11,500 tons of large steel components.

Materials: Due to the extensive use of glass, the steel structure had limited tolerances which enhanced the complexity of the project. Further complicating the issue, fabrication and installation of the glass was procured under a separate contract, and the glass was being manufactured while the steel structure was being constructed. With little margin for error, an enormous level of analysis, monitoring, and adjustment was required throughout erection to achieve the tight tolerances.



The soaring arches of Oculus reach a crowning height of 100 ft. The extensive use of glass between the steel columns allows natural light to illuminate the main transit hall.

3) Social and/or Economic Benefits

As the primary transportation hub in downtown New York, the Oculus is at the heart of environmental and social sustainability. It is a hallmark structure for public transportation within Manhattan and the boroughs beyond, and serves as a meeting place for those who pass through. The creation of this high quality public space encourages people to gather and admire this signature railway station design.

During construction, B&T was ever mindful of time and project costs. The project team identified that significant risks were associated with field welding (cost, time, and weld shrinkage distortions). B&T helped mitigate these risks by replacing welded splices in the arches with bolted connections. A fully connected arch piece required almost three weeks of field welding. By comparison, the bolted connection required only two days. This solution drastically reduced the erection schedule, made it easier for the Contractor to install the arch segments, and helped achieve the desired geometry. The use of bolts rather than welding increased efficiency, reduced risks to geometric distortions, and reduced cost. From an environmental perspective, B&T minimized the footprint of steel fabrication by selecting the segmental erection approach. This eliminated major use of falsework, and significantly reduced excessive energy expenditure for associated steel production and field welding.

The project's steel production footprint was further reduced by re-using temporary bolted connections to erect the ornamental rafters. Rather than fabricating individual temporary connectors for every ornamental rafter (which would have required 108 unique connectors), B&T designed a re-useable connection, in conjunction with a partial welding sequence, that maximized efficiency and speed of construction. This saved on materials, cost and energy usage for the manufacturing of the temporary steel connections.

4) Environmental and Sustainability

From an environmental perspective, B&T minimized the footprint of steel fabrication by selecting the segmental erection approach. This approach eliminated major use of falsework, and significantly reduced excessive energy expenditure associated with steel production and field welding. The project's steel production footprint was further reduced by re-using the temporary bolted connections to erect the ornamental rafters. Rather than fabricating individual temporary connectors for every ornamental rafter (which would have required 108 unique connectors), B&T designed a re-usable connection, in conjunction with a partial welding sequence, that maximized efficiency and improved speed of construction. The re-usable connection saved on time, materials, cost and the energy usage required for the manufacturing 108 temporary steel connections.

5) Meeting Client Needs

The Client and Owner's main object was to develop an erection engineering concept to construct the Oculus while minimizing schedule delays. This challenging and complex structure required innovative solutions to address constructability issues, site lay down limitations, and time constraints, while addressing the requirements of maintaining the tight geometric tolerances. B&T (COWI) and Skanska met the client/owner's goals through the following innovative solutions:

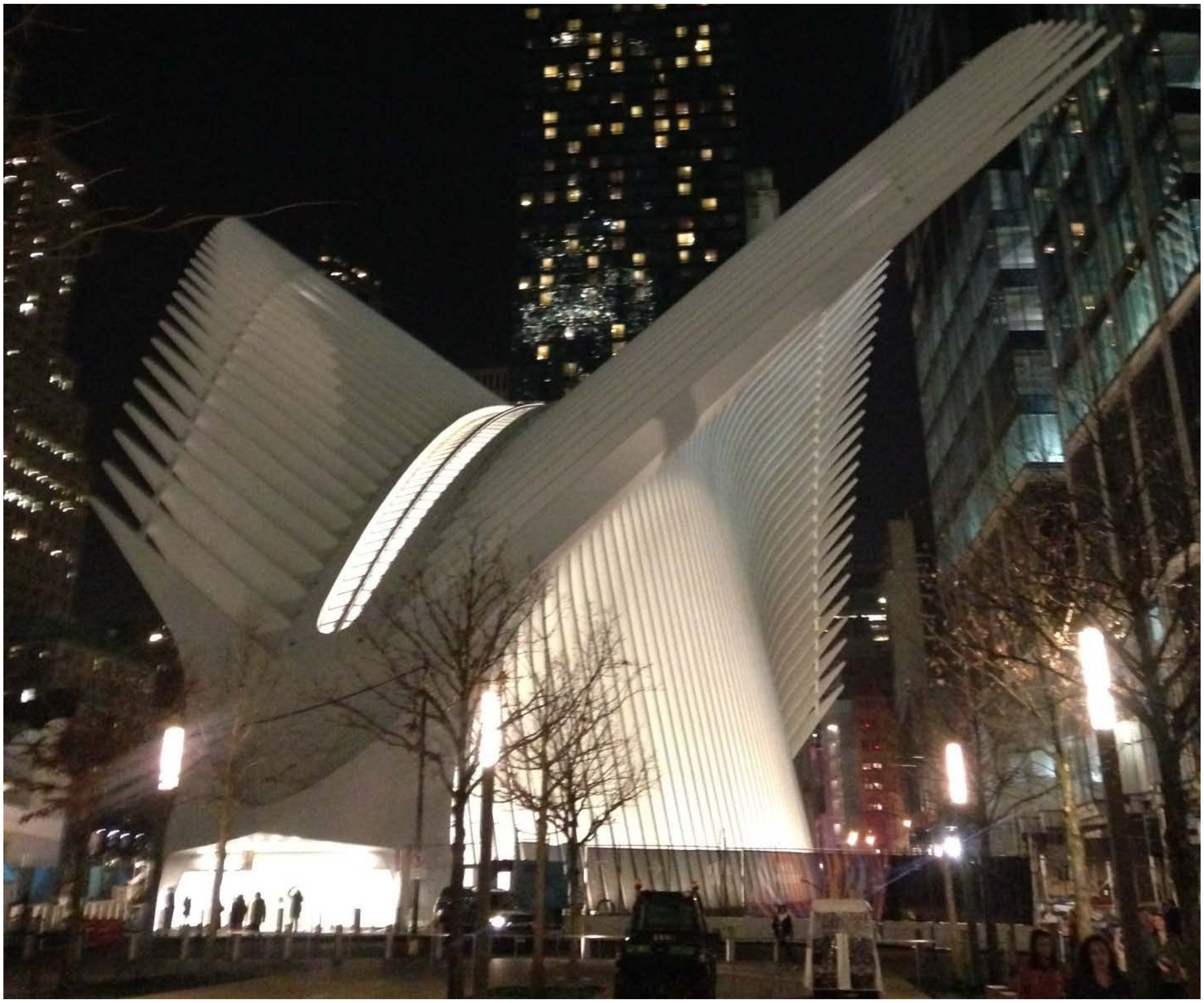
Segmental Erection: The free cantilever segmental erection scheme was the ideal approach for construction. By applying commonly used bridge construction methods, this innovative application meant the project could be completed without extensive falsework. This crucial decision saved both time and money, and also allowed the structure to be monitored and adjusted throughout construction. It also reduced risks associated with the intricate design and the required glazing tolerances.

*Scheduling and Staging:*The limited site layout also required unique scheduling and staging solutions. After extensive research and modeling, an erection schedule was developed for faster installation of the long steel columns, arch segments and rafters.

Extensive Analysis and Monitoring: A high level of analysis, monitoring, and adjustment was required throughout erection to achieve the tight tolerances of the steel structure required by the extensive use of glass.

Innovative Engineering Solutions: The Oculus is an example of the successful application of a traditional bridge erection engineering technique as an innovation solution in building construction.

Client/ Owner needs were successfully achieved through innovative erection engineering. Applying bridge engineering concepts and first principles to the erection of the Oculus allowed this complex structure to be completed safely and accurately. The innovative use of bolted arch connections instead of welded joints expedited construction and minimized schedule delays.



The striking Oculus architecture as seen by over 200,000 commuters every day.

KEY PARTICIPANTS

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Downtown Design Partnership (DMJM + Harris, STV Group and Parsons)

About Buckland & Taylor International, Inc. (an affiliate of COWI North America, Inc.)

Buckland & Taylor International, Inc., together with COWI North America, provide specialized bridge engineering services to clients worldwide. B&T (located in New York) and COWI (across North America) provide specialty bridge, tunnel and marine engineering services. Founded in 1972 with the goal of providing the highest standards of bridge engineering, B&T and COWI are recognized as leaders in the design, evaluation, rehabilitation and construction engineering of all types and sizes of bridges and structures. Buckland & Taylor International, Inc. and COWI North America are part of the COWI A/S group.