ARCHITECTURAL RECORD

Gaining Urban Space With Structural Steel

eBook Brought to you by Steel Institute of New York

Architects know that their buildings start with the core structural elements and this eBook offers great examples of well-designed buildings built with steel that are simultaneously structurally sound and aesthetically pleasing. I encourage you to explore this special edition, earning one AIA LU/HSW each for three of the articles, which also qualify for Canadian learning hours and IACET CEUs.

Alex Bachrach, Publisher
ARCHITECTURAL RECORD

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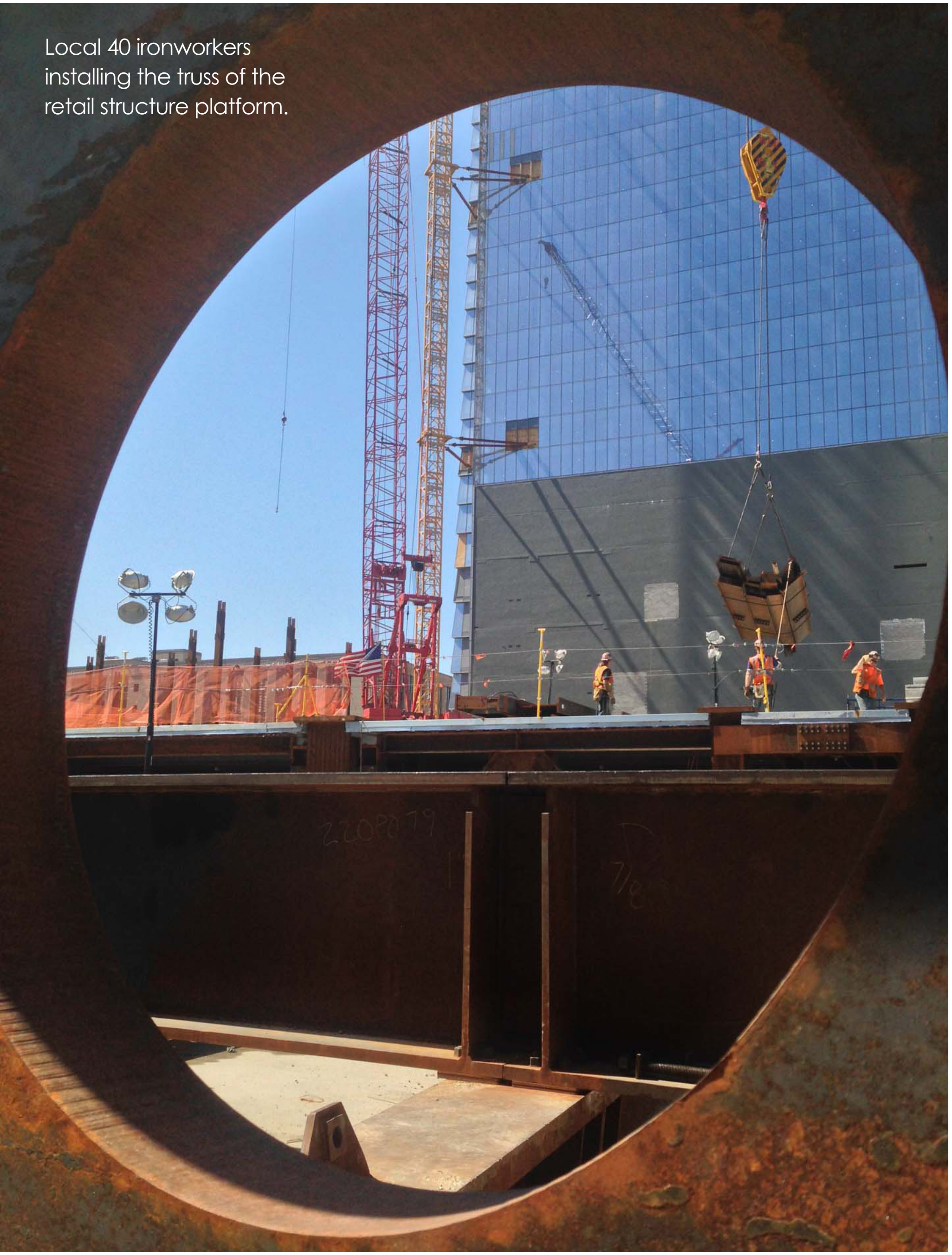
With no overtime or contingency allowed because of the tides and FDR closure window, “You couldn’t be an hour late. It’s a remarkable compliment to the team that did the erection.”

—Jay Bargmann, Vice President and Managing Partner of Rafael Viñoly Architects, on the complex steel erection process for Rockefeller University's River Campus. *Metals in Construction* magazine, Spring 2020

Steel Institute of New York



Local 40 ironworkers installing the truss of the retail structure platform.

PHOTOGRAPHY: GEOFF BUTLER

Hudson Yards East Platform

Structural gymnastics abound as a city on stilts is constructed on Manhattan's West Side, all while hundreds of trains come and go beneath.

NEW YORK HAS NOT SEEN the likes of a real estate development project on a par with Hudson Yards since Rockefeller Center's fourteen buildings were constructed in the 1930s. A mixed-use real estate venture developed jointly by Related Companies and Oxford Properties, the site will include more than 17 million square feet of commercial and residential space, a cultural venue, 14 acres of open park space, a 750-seat public school, and a 200-room luxury hotel. Slated for completion in phases over the next several years, the new development is anticipated to draw more than 65,000 people daily. But almost none of them will be aware of one of the site's greatest feats: Nearly all of it sits atop two massive platforms that bridge 30 active Long Island Rail Road (LIRR) train tracks, three subsurface rail tunnels used by Amtrak, and a fourth passageway named the Gateway tunnel, which will help to double train capacity into New York City.

Of the two platforms, the structure over the Eastern Rail Yards does the most heavy lifting, supporting Hudson Yards' four massive skyscrapers and its main cultural, retail, and residential attractions. Those building foundations will extend through the platform and allow the new buildings to tower over it, totaling 11,340,000 gross square feet of new construction when completed. The Eastern Platform, and the structures overhead, are supported by a total of 288 caissons, ranging from 4 to 5 feet in diameter and 20 to 80 feet in depth, which are drilled to reach bedrock in strategic locations between existing railroad tracks. The platform over the Eastern Yard uses 25,000 tons of structural steel.

The undertaking has required a rolodex of the construction industry's experts—many of whom worked together at a similar scale and level of coordination on the World Trade Center redevelopment in Lower Manhattan. Thornton Tomasetti is the platform's structural engineer, and Langan Engineering & Environmental Services is its geotechnical and environmental engineer. Arup is the site's life safety systems engineer.

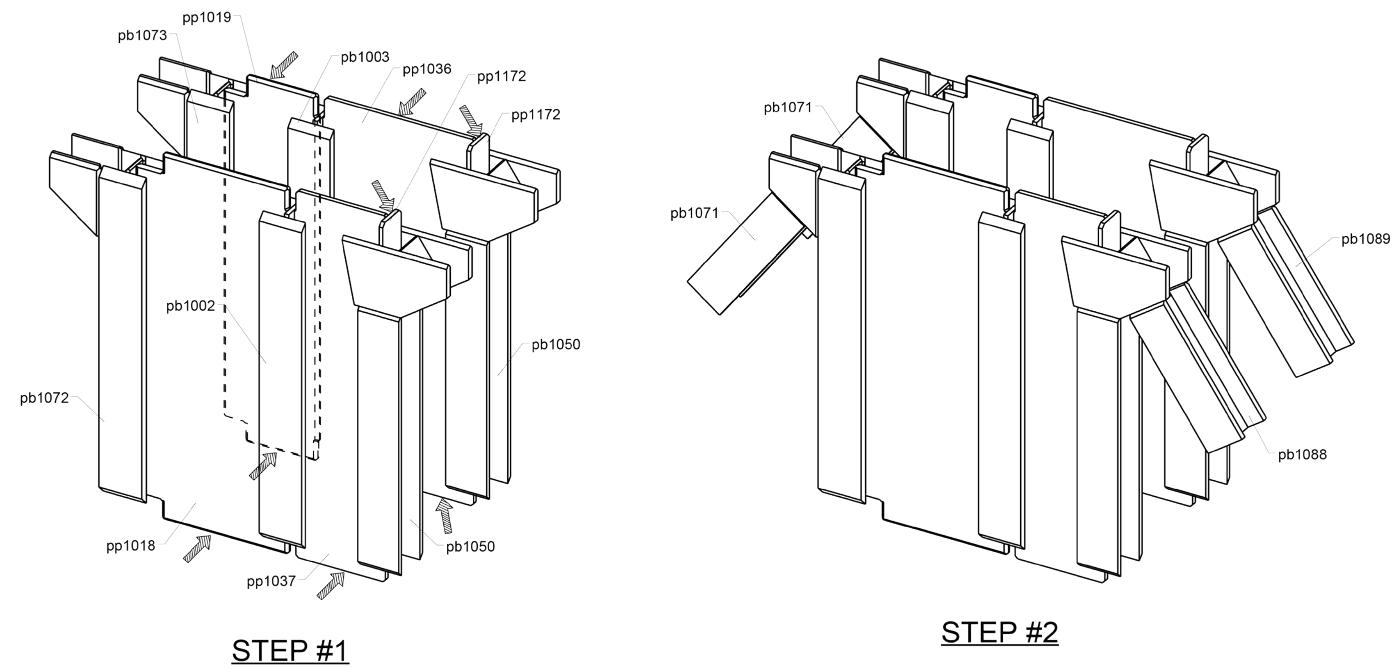
Building what is essentially a small city within a city, the team had to deal with a layer cake of complicated site conditions and constraints. "Thornton Tomasetti didn't

The development of Hudson Yards will create more than 23,000 construction jobs. The Hudson Yards platforms will cover approximately three-quarters of the Eastern and West-ern rail yards.

PHOTOGRAPHY: JENNIFER KRICHELS

have a blank slate to start with," says Jeff Brown, vice president of operations for Tutor Perini Civil Group, the general contractor for both Hudson Yards and the Gateway project. "They had a lot of restrictions on where to put the foundations."

Over seven million square feet of construction are now underway. Preliminary preparations on the Eastern Yard platform began at the end of 2013 and caisson drilling started in March 2014. Erection of the structural steel columns, beams, and trusses began in Fall 2014, and the Eastern Yard platform will be completed soon.

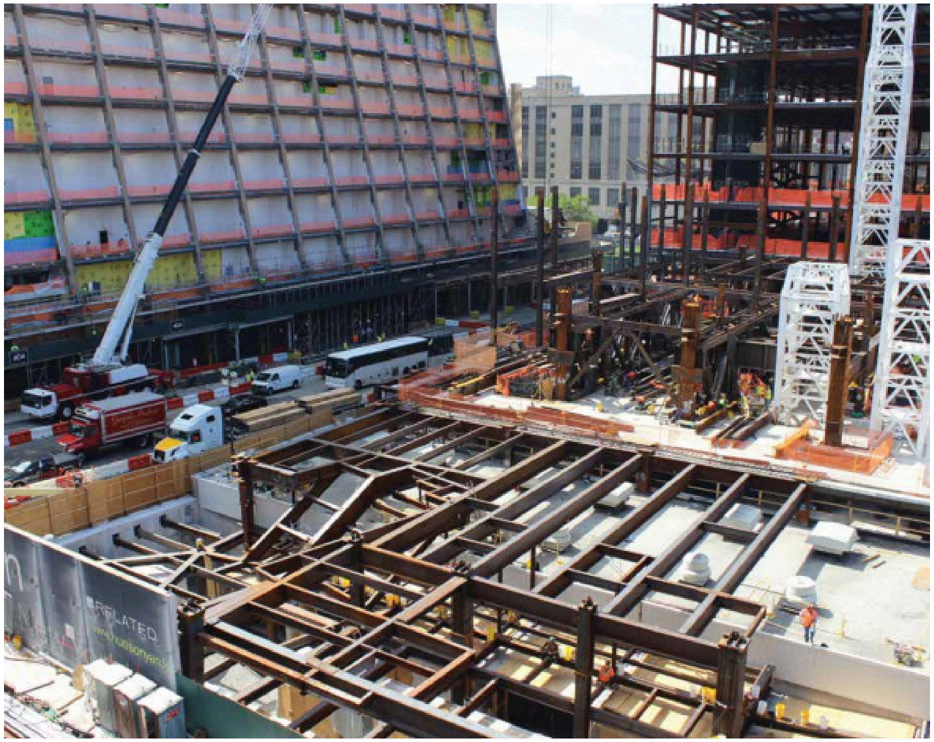


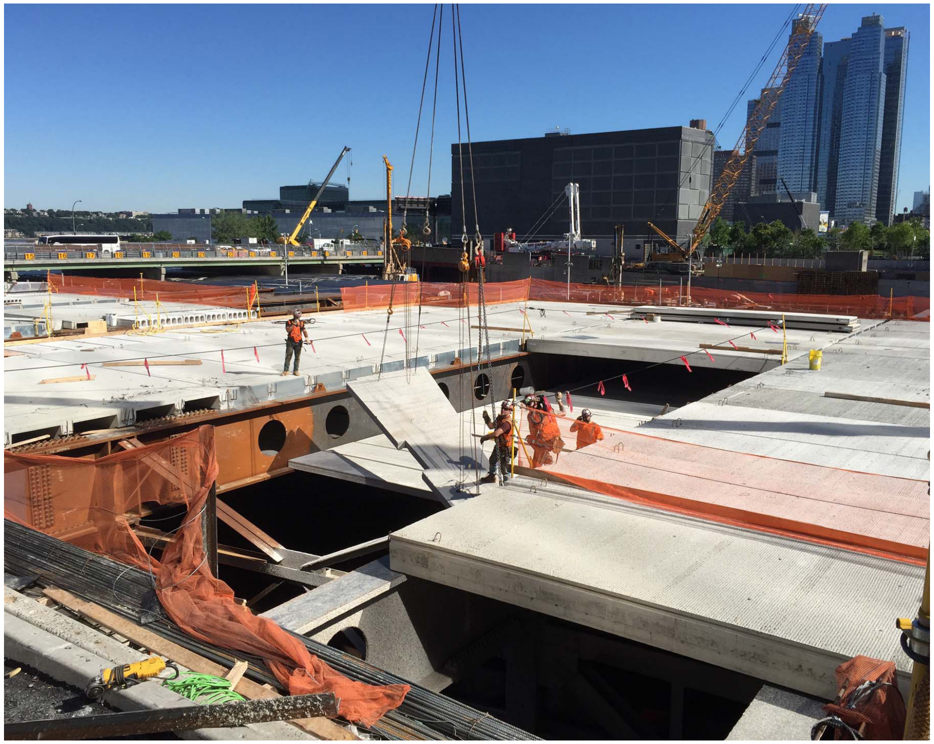
Diagrams of the platform's D10 node.

DIAGRAM: TUTOR PERINI CORPORATION

One of the project team's biggest feats was maintaining the operation of the railyards at all costs—throughout all of the project's construction, the LIRR and Amtrak trains remain operational. To accomplish this, the site was divided into segments: In areas where the train tracks are straight, the team could take four adjacent tracks out of service continuously, leaving drills or other equipment in place. In other areas that are required for switching trains between tracks, they could sometimes drill a caisson for only two hours each night due to train schedules. It could take days or weeks to achieve the 30- to 40-foot depth required for some holes. Because any emergency at all in the train system, like a switch failure, could shut down construction, the Tutor Perini team credits a good working relationship with LIRR for the smooth progression of caisson drilling.

A web of utilities below the tracks added even more complexity. "The utilities are more dense than the trains," says Brown. He estimates the handdrawn, ca. 1987 site drawings that were available prior to the project were accurate, at best, to within 5 feet. Added on top of that





PHOTOGRAPHY: JENNIFER KRICHELS (LEFT), GEOFF BUTLER (RIGHT)

Construction progress in August 2015.

were complications involving the organizational, and legal, separation of the site's operators.

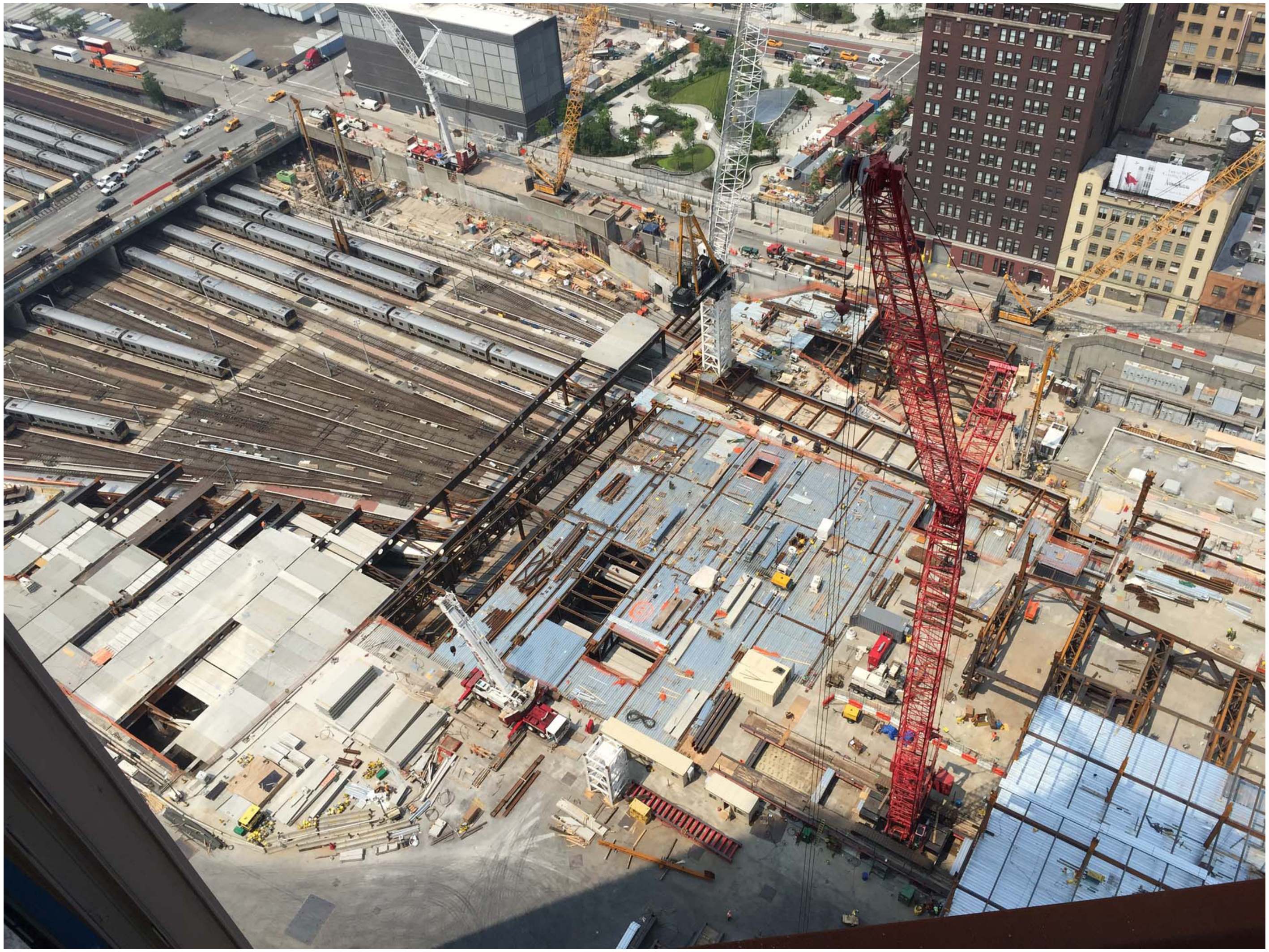
Even before finalizing a contract to construct a platform, Tutor Perini's Civil Group convinced its client, Related, to pre-excavate the site in order to understand the true layout of utilities located there. Looking at a diagram of caisson locations marked by green dots, Brown notes "every one of these was hand excavated—there was something in every single one." The project's utility relocation budget alone is estimated at $12 million. Each time a new obstacle was discovered, Thornton Tomasetti altered structural designs for the frame of the platform to accommodate a new caisson location that avoided conflicts with both the existing tracks and the utilities below. This real-time design approach made another midstream change possible: Work was originally planned to begin at 11th Avenue and move east, toward 10th Avenue, but the plan was reversed to allow an early start on 10 Hudson Yards.

Taking into account the location of tracks, underground tunnels, and utilities, only 38 percent of the site may be used for structural support of the 10-acre platform. With so much weight bearing on fewer than 300 columns, in some cases columns are as large as 32x32 inches, built up of 4-inch layers of steel plate that satisfies ASTM A572-65 and ASTM A1066-65. While a typical 4-inch, A572 plate produced in the United States has a yield strength of 50 ksi, steel plate manufacturer Dillinger uses a fabrication process that allows them to produce the same 4-inch plate with a 65 ksi yield strength. The column structures vary in diameter from 1 foot to 5 feet, 6 inches, and are drilled into the bedrock beneath the railroad tracks at an average depth of 40 feet below the surface.

Approximately 3,300 tons of solid steel cores, the largest of which was 30 by 30 inches square, were fabricated from the 4-inch-thick

Hudson Yards construction in September 2015.

PHOTOGRAPHY: TYSON REIST



PHOTOGRAPHY: GEOFF BUTLER

Platform trusses set west of the throat platform support the plaza.

Of the two platforms, the structure over the Eastern Rail Yards does the most heavy lifting, supporting Hudson Yards' four massive skyscrapers and its main cultural, retail, and residential attractions.

plate; the longest is 87 feet; the heaviest weighs a whopping 71 tons.

The platform's base structure clears the tracks by at least 17 feet, and ranges in thickness from less than 3 feet to up to 7 feet, depending on the architectural features of the planned plaza. For example, to meet city building requirements for resiliency, a truck-loading dock adjacent to 10th Avenue is fortified with W14x500 steel beams topped by 2-inch blast-resistant plate and an 8-inch concrete slab. In many areas, the platform houses a network of tubing carrying cooling liquids that will buffer the plaza's landscaping from the heat of the train yard below, which can reach up to 150 degrees.

On top of this, tall trusses support hung sections of a podium structure that connects 10 Hudson Yards and 30 Hudson Yards and will house a collection of shops and restaurants on multiple floors. Columns and other support structures for 30 Hudson Yards land between the rail lines below it, while trusses supporting the tower's south face span the tracks up to 115 feet. Here, site constraints came into play yet again: Because railroad operations required the use of a tower crane to erect the throat trusses, and the weight of the throat trusses exceeded the capacity of the Favco 1280 (the largest tower crane currently available), Thornton Tomasetti split the trusses into a pair of trusses, allowing them to be set one at a time by the Favco 1280, and then tied together to form a box truss.

From a design and fabrication standpoint, the area of the platform called the D10 Node also required detailed coordination, says Terry Flynn, vice president of engineering for Tutor Perini Civil Group. "It's a large steel box with trusses connecting to it, and a column below it," he describes. "Because of the node's complexity, structural steel fabricator Banker Steel Company created a presentation of their fabrication plan for the node as, simultaneously, Thornton Tomasetti developed the design in a Tekla model."

As a general contractor, Tutor Perini has found itself in the midst of an alphabet soup of agencies: LIRR, MTA, and Amtrak, as well as the City of NY, the DOB and the DOT. Basically, one could joke, every public entity that a contractor might have to deal with to make a project successful for its client. But, motivated by a sense of progress, not to mention the unprecedented revenue the plan should bring the city, the players involved have created a cohesive operational machine that is driving the project forward, relatively on schedule. As a result, the Hudson Yards development holds the promise of a new model for urban development, one in which buildings, public amenities, and utilities work together to create a cohesive community on the previously disparate landscape of Manhattan's West Side.

HUDSON YARDS EAST PLATFORM

Location: Hudson Yards, New York

Developers: Related Companies and Oxford Properties Group, New York, NY Structural **Engineer:** Thornton Tomasetti, New York, NY

Geotechnical and Environmental Engineer: Langan Engineering & Environmental Services

Life Safety Systems Engineer: Arup, New York, NY

General Contractor (Hudson Yards Eastern **Platform and the Amtrak Gateway project):**

Tutor Perini Corporation, New York, NY

Structural Steel Fabricator: Banker Steel Company, Lynchburg, VA; (caisson cores) Owen Steel, Columbia, SC

Structural Steel Erector: Tutor Perini Civil Group, New York, NY

Adjacent to the new building, the East River Esplanade was reconstructed with new landscaping, furnishings, and a sound barrier between the highway to provide a safe and resilient environment for the public realm.

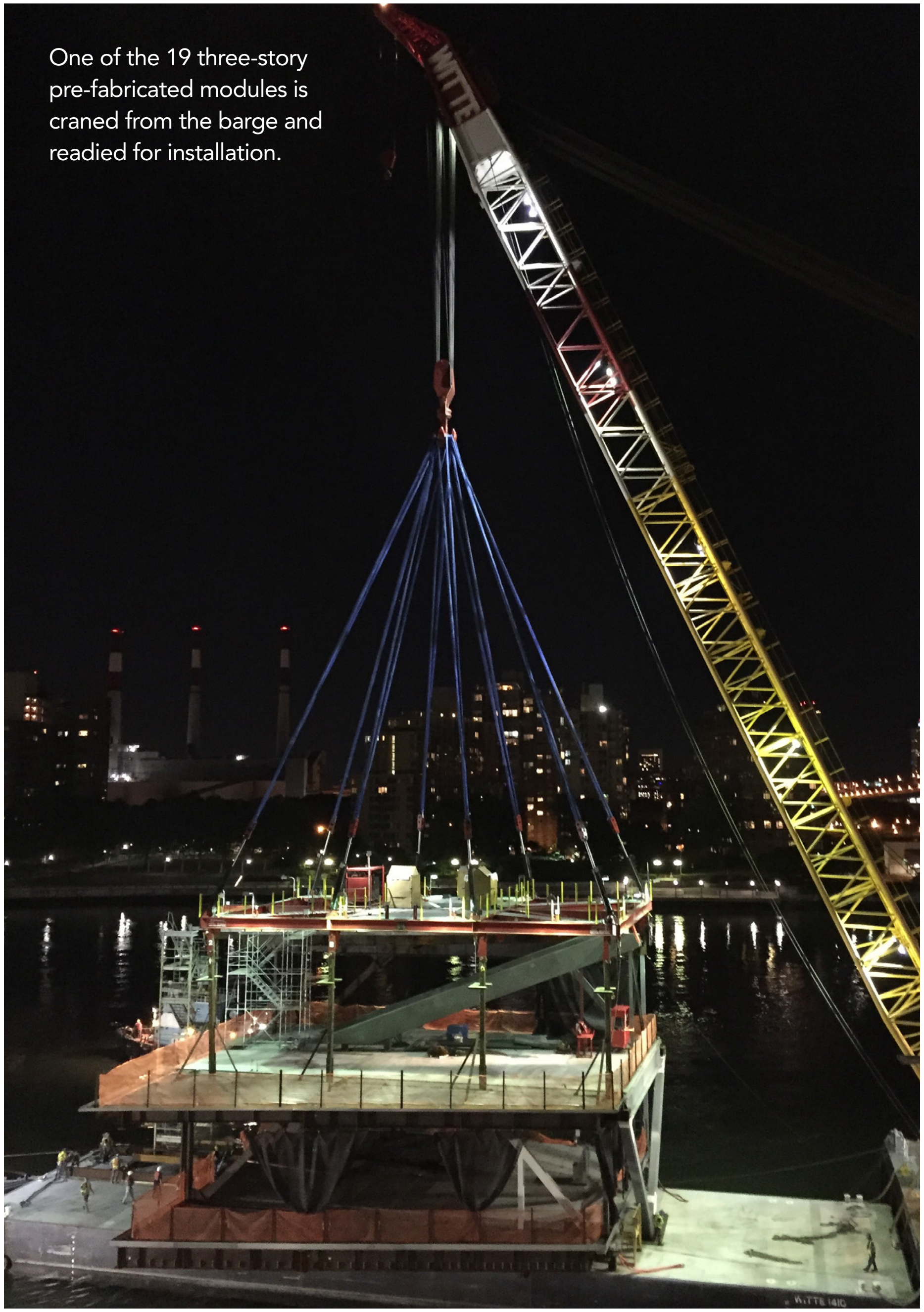
ROCKEFELLER UNIVERSITY

Rockefeller University's new state-of-the-art laboratory facility was assembled in 19 midnight installments as 19 prefabricated steel modules were transported across the East River.

ROCKEFELLER UNIVERSITY WAS facing a quandary. As a leader in biomedical research, it sought to significantly expand with new state-of-the-art laboratory facilities, but was essentially out of real estate. Fortunately, the university owned the air rights on FDR Drive's east side, which allowed it to commission the design of a 900-foot, three-story building, designed by Rafael Viñoly Architects (RVA), that would rise along and over the highway.

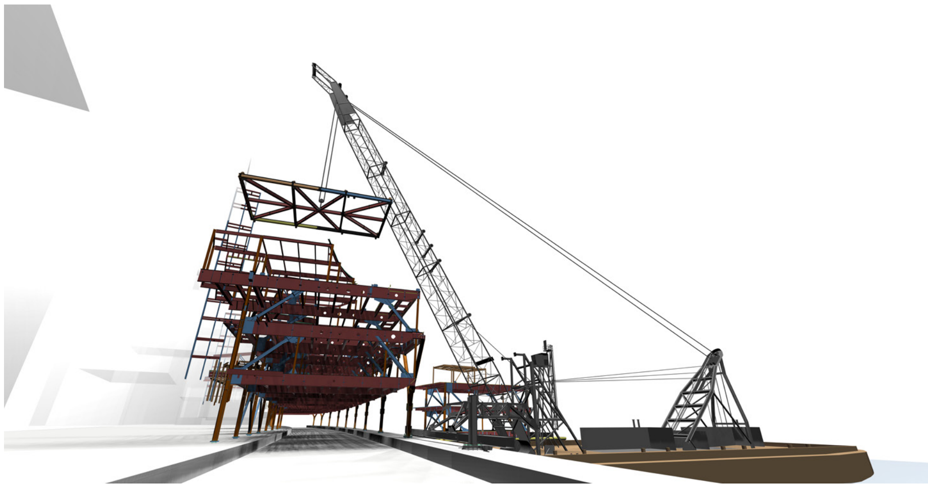
The new 180,000-square-foot building, known as the Stavros Niarchos Foundation–David Rockefeller River Campus, spans almost three and a half city blocks and aggressively addresses the vibration- and thermal-control needs of the laboratory. But perhaps the most unique challenge was erecting the large, long structure on a site with the East River on one side and a limited staging area on the other.

"We basically had to build a bridge over a hundred-foot stretch of the FDR," says Jay Bargmann, Vice President and Managing Partner of RVA. "It was our idea to prefabricate the building. It seemed to me very odd that you could build a temporary bridge over the FDR and then stick-build a building over it; you were still jeopardizing traffic and having to transport materials to a difficult site with that method." Bargmann says the project's structural engineering team at Thornton Tomasetti jumped on the idea of prefabricating the building off-site. Construction manager Turner also came on board with a project manager, Curt Zegler, who "really pushed the idea forward once he understood it," he says.



One of the 19 three-story pre-fabricated modules is craned from the barge and readied for installation.

PHOTOGRAPHY: © HALKIN MASON



Above is a model of the installation.

The building team's creative solution involved prefabricating 19 steel-framed modules at the off-site staging area—each approximately 92-feet by 48-feet on three-levels, complete with cast-in-place concrete on two levels, fireproofing, sprinkler systems and conduits—and then transporting them on a barge across the river. Because the modules already weighed close to 800 tons each, ductwork and concrete deck were installed on-site.

The prefabricated approach, "was the safest way to build the building and it was the least disruptive to the community and the city as a whole," says Bargmann.

"Reducing construction time also reduced the cost," says Bargmann. In a traditional construction workflow, materials would have had to come across the George Washington Bridge and across the one point of access from the FDR to Rockefeller's Campus. But prefabricating the modules off-site shaved approximately 12 months off the project schedule and saved $20 million to bring the total project cost to $500 million. In addition, this approach minimized risk—i.e., exposure to passing vehicles during construction—and created a highly integrated environment with RVA, along with Thornton Tomasetti, Turner, construction consultant Lehrer, and steel fabricator Banker Steel, working closely together to fine-tune the design and complex prefabrication, transport, and erection processes.

"Over two and a half months in the summer of 2016, one module was lifted each of 19 nights using a Chesapeake 1000–a rare, 1000-ton barge crane," explains Sherry Yin, an associate principal for Thornton Tomasetti. To optimally stabilize the modules during transport, a temporary support system was installed and anchored to the deck of the barge. "The barge crane was only able to operate during a steady slack tide, and since the lift had to coincide with the FDR closure from 12 a.m. to 5 a.m., there were specific days on which the lifts could take place."

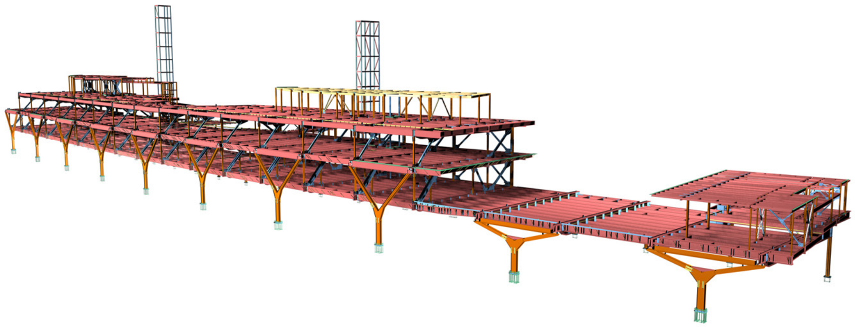
During each crane hoist, a module was supported by 16 computer-controlled cables that would keep the load completely level, explains Bargmann. "That was tested on the staging site in New Jersey so the computer knew what tension or load had to be carried in each level. They repeated that when they got to the site." With no overtime or contingency allowed because of the tides and FDR closure window, "You couldn't be an hour late," he adds. "It's a remarkable compliment to the team that did the erection."

During the day, strict safety measures were employed during construction to ensure the safety of the more than 175,000 vehicles driving down one of Manhattan's busiest roadways on a given day. Dictated by the vehicle clearance on FDR and the need to match existing campus elevations, two-story Y columns were spaced at 96 feet on center on the building's east side. They are supported on pile caps with multiple mini piles, in place of large caissons, due to limited capacity for equipment on the esplanade. The columns on the drive's west side are spaced at 48 feet on center, according to Yin.

"The primary superstructure consists of two levels of high-strength plate girders spanning up to 92 feet over the FDR Drive that are linked by diagonals so that both plate girders, each approximately 5 feet deep, act together like a truss," she explains. "This also supports a green roof on the third level."

In all, the David Rockefeller River Campus has added two acres, four buildings, expansive laboratory space, landscaping and beautiful East River views to Rockefeller University's existing 14-acre campus. Two curvilinear glass pavilions—one housing dining facilities and the other for offices—emerge from the gardens that cover two levels of labs below. The structure's long, slender form is accented by horizontal brisesoleil that shield the glass curtain wall, best viewed by Roosevelt Island's shoreline on the East River.

The floor-to-ceiling glass provides a great view of the River while carefully calibrated ceiling heights enable daylight to enter deep into the interior where automated



PHOTOGRAPHY: COURTESY RAFAEL VIÑOLY ARCHITECTS, © HALKIN MASON

Supported by 10 "Y" columns overlooking FDR Drive and the East River, Rockefeller University's new 180,000-square-foot laboratory building spans almost three and a half city blocks (Top). A Tekla model of the three and a half block expansion facing south (Above).

roller blinds shield the scientists from glare.

Although the zoning of the University's land would have permitted a more vertical solution, the architect opted for a stretched-out, horizontal design for optimized research collaboration and flexibility with future laboratory changes and needs. The layout consists of two open floor plans, approximately 740 feet long. They are divided by a lounge space for informal meetings and coffee breaks to encourage interaction amongst researchers.

Offices and common spaces feature beautiful views of the river and the Queensboro Bridge.

For specialized equipment requiring enclosed rooms, those are positioned along the wall adjacent to the existing campus with the scientists' offices reserved for the prime real estate facing the water. Meanwhile, a middle zone with roughly 90-foot-deep floor plates are used for lab benches. Under the raised floor sits the extensive power, data and gas infrastructure required of a 21st century laboratory. The casework and floor system are designed on a 2-foot-by-2-foot grid for a readily reconfigurable, "plug and play" setting.

While the new addition is primarily used as laboratory space, the University has added a health and wellness center and an interactive conference center with a glass facade facing a broad lawn.

As noted, minimizing vibration was a major issue for the

Extensive power, data and gas systems under the raised floor meet the lab's current and future infrastructure needs.

world class laboratory. With its long spans, the building was particularly vulnerable as issues like rumbling vehicles along the highway and indoor foot traffic could easily impact sensitive equipment and skew research results.

"The rules of thumb frequently employed for vibration analysis were not going to be adequate," relates Lin. "We approached the design by performing detailed dynamic analyses of the overall structure and tuned the sizes to satisfy the vibration limits required by the laboratory."

The long-span structure also presented a thermal movement issue. Addressing this involved ensuring a complete load path for thermal and lateral loads which consists of a 1,000-foot-long diaphragm resisted in the short direction at four middle points. "A comprehensive thermal analysis was performed to ensure no excessive stress induced in structural components," she explains. "The two shorter Y columns at the northern end are released from diaphragm constraints via application of a spherical sliding pad."

Thornton Tomasetti also developed a special drag member using plates welded to the top of steel beam/girder to eliminate conflict and minimize the connections.

In addition, the team faced a few challenges in working with the west-side foundation, which was on the rock adjacent to an existing schist wall. Close and extensive collaboration with the Turner and subconsultants on-site solved issues such as higher rock elevation, overlapping with the Schist wall, and circumventing conflict with existing underground utilities and fixtures.

Lending some perspective on the magnitude of this project, Thornton Tomasetti Senior Structural Engineer Thomas McLane, P.E., says that before the steel could be moved and put into place, the initiative involved years of designing and thousands of shop drawings requiring careful review. "You don't see too many projects of the same scale with Y columns, cantilever diagrams, and modular construction," he explains. In terms of the prefabrication, module transportation and on-site erection, the team describes the project as a Herculean effort.

Bargmann echoes this sentiment: "Necessity is the mother of invention. This was the only way to make it happen in a safe, cost-effective way." And ultimately, exemplary projects don't happen without enthusiastic clients. "The university should be congratulated for having the vision," he says. Recognizing the project's most innovative building and design, the Society of American Registered Architects granted it a 2019 Nation Design Merit Award.

ROCKEFELLER UNIVERSITY

Location: Rockefeller University, New York, NY

Owner: Rockefeller University, New York, NY

Architect: Rafael Viñoly Architects, New York, NY

Structural Engineer: Thornton Tomasetti, New York, NY

Mechanical Engineer: BR+A Consulting Engineers, New York, NY

Construction Manager: Turner Construction, New York, NY

Construction Consultant: Lehrer, New York, NY

Curtain Wall Consultant: Entuitive, New York, NY

Structural Steel Fabricator: Banker Steel, South Plainfield, NJ

Structural Steel Erector: New York City Constructors, New York, NY

Miscellaneous Iron Fabricators and Erectors: FMB Inc., Harrison, NJ; Empire City Iron Works, Long Island City, NY

Architectural Metal Fabricator and Erector: David Shuldiner, Brooklyn, NY (trellis and handrails)

Ornamental Metal Fabricator and Erector: Champion Metal & Glass, Hauppauge, NY

Curtain Wall Fabricator: Oldcastle Building Envelope (Levels 1 and 2), Hauppauge, NY; Sentech Architectural Systems (Level 3), Austin, TX

Metal Deck Erector: New York City Constructors, New York, NY

Stavros Niarchos Foundation-David Rockefeller River Campus at The Rockefeller University | New York | Rafael Viñoly Architects

THE HIGH ROAD

A research institution ingeniously extends its leafy campus over a busy expressway.

BY JOANN GONCHAR, FAIA

OUT OF THIN AIR By taking advantage of air rights over the FDR Drive, Rockefeller University was able to create two acres of real estate and expand its hemmed-in campus.

PHOTOGRAPHY: © HALKIN | MASON

PHOTOGRAPHY: © HALKIN | MASON

POP-UP PARK On the roof of the new laboratories are gardens where the plants, including ornamental grasses and flowering herbs, have been selected in part for the rustling sound they make in the wind. Curvilinear glass pavilions for offices (top) and dining pop up from the garden level, while an amphitheater is scooped out of it (bottom).

"WE'VE ADDED 160,000 square feet of new space, and you can't see any of it, making it one of our best buildings," jokes Jay Bargmann, senior vice president at Rafael Viñoly Architects (RVA). He is referring to the firm's expansion of Rockefeller University, the highly regarded biological- and medical-research institution that occupies a verdant campus along the East River on Manhattan's Upper East Side.

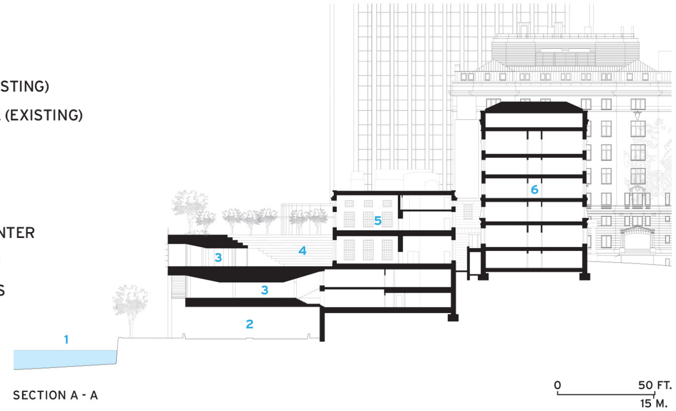
The approximately $500 million endeavor, which has a cumbersome formal name—The Stavros Niarchos Foundation-David Rockefeller River Campus at The Rockefeller University—consists primarily of new laboratories. But the project, which totals 220,000 square feet, also includes new administrative offices, a dining commons, a conference center, and renovations to existing laboratories and offices. And as Bargmann's remark indicates, the expansion is mostly hidden, at least as one approaches from the existing campus, concealed under two acres of inviting roof gardens. The camouflaged structure, which stretches the equivalent of four city blocks along the river, provides a sharp (and ironic) contrast to another of the firm's recent New York projects—432 Park Avenue—a pencil-thin skyscraper located less than a mile away that, for the moment at least, is the world's tallest residential tower, at 1,397 feet high.

The institute was able to pull off its disappearing act because it owned air rights over the FDR Drive—a six-lane highway at the river's edge that once defined the now 16-acre campus's eastern boundary. The rights were granted by the city in the early 1970s to the university and nearby hospitals, all of them hemmed in and cut off from the water by the often-congested roadway. To take advantage of its virtual real estate, RVA, its consultants, and the construction team devised a solution that depended on sophisticated engineering, off-site fabrication, and hair-raising acrobatics: during the summer of 2016, 19 prefabricated steel-framed modules, each unique and weighing up to 800 tons, were lifted from a river barge out over the roadway onto already placed columns and foundations (see sidebar on next page).

The resulting long and low structure is of course not entirely invisible. Two curvilinear glass pavilions—one for the dining facilities and the other for the offices—pop up from the gardens that cover two levels of labs below. At the northern end of the extension and at a lower level, a glass-box conference center adjoins a broad lawn. (The roofs of the three protruding elements will eventually themselves be covered with sedum, in part because they are visible from nearby towers.) The arrangement is a continuation of earlier campus planning strategy, says Bargmann. The Rockefeller grounds, which include traditionally classical structures dating from the early 20th century, and midcentury additions by such firms as Harrison Abramovitz, appear as isolated objects surrounded by a Modernist landscape by Dan Kiley that includes leafy malls, courtyards, and water features. While the older buildings appear to be separate, explains Bargmann, many are connected below grade.

RVA's contribution to the campus is best understood from the shoreline of Roosevelt Island in the East River, opposite the uni-

1 EAST RIVER
2 FDR DRIVE
3 LOUNGE
4 AMPHITHEATER
5 WELCH HALL (EXISTING)
6 FOUNDER'S HALL (EXISTING)
7 LAB SERVICES
8 LAB BENCHES
9 WRITE-UP AREAS
10 CONFERENCE CENTER
11 ADMINISTRATION
12 DINING COMMONS



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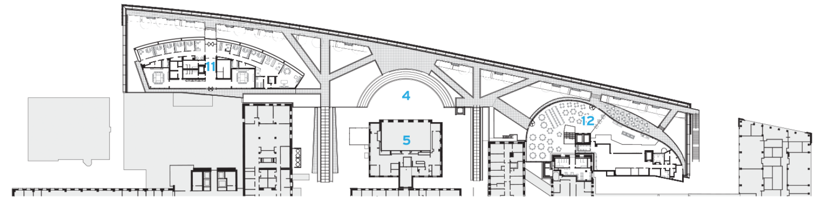
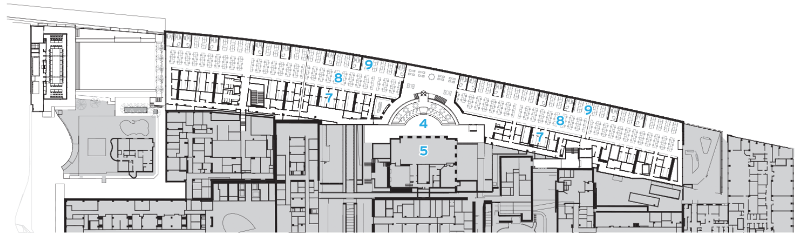
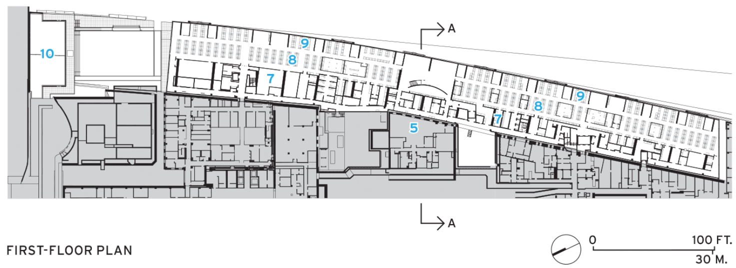


THIRD-FLOOR PLAN



SECOND-FLOOR PLAN



FIRST-FLOOR PLAN

versity. From that vantage point one can clearly see the two stories of labs stretching along the FDR on Y-shaped columns, the building's sleek and subtly arced form accentuated by horizontal brisessoleil that shield the glass curtain wall. The basic outlines of this scheme, including its long and low organization over the highway, were determined in an earlier master-planning phase led by RVA. Although zoning would have permitted a vertical solution, the idea of a tower didn't have much appeal, says Timothy O'Connor, the university's executive vice president. Not only are labs in high-rises difficult to rearrange as research needs evolve, he says, they also can hinder collaboration among different teams. "Scientists with workspaces in tall buildings tend to take the elevator to their labs and stay there."

With the goal of encouraging interaction among researchers, both organized and spontaneous, the new facility has open-plan floors, each about 740 feet long and divided roughly in half by a lounge space for informal meetings, relaxing, or group study. The areas to the north and the south are organized so that specialized equipment requiring enclosed rooms is located along the wall adjacent to the existing campus, and write-up desks, where scientists work at computers, are positioned along window walls facing the water. The zone in the middle of the roughly 90-foot-deep floor plates is devoted to the lab benches. These sit on top of a raised floor, below which runs the extensive infrastructure essential for scientific research, including that for power, data, and gas. The casework and the

PHOTOGRAPHY: © HALKING | MASON (TOP); BRAD FEINKNOPF (BOTTOM)

STUDY HALL Lounges (top), intended to encourage collaboration, divide the laboratory wings (bottom) roughly in half.

PHOTOGRAPHY: ELIZABETH FELICELLA

Brises-soleil on the floor-to-ceiling window walls help bounce daylight into the interiors and emphasize the building's horizontality.

floor system are designed on a 2-foot by 2-foot grid so that the research spaces are "plug and play" and readily reconfigurable, explains Bargmann.

This layout is smart and functional, but what makes the scheme stand out is the way it takes advantage of the proximity to the river. Floor-to-ceiling glass gives the scientists a view of the water's constantly changing surface and reflections, and, because the ceiling heights step up from 8 feet at the west to 18 feet near the river, daylight penetrates deep into interior (automated roller blinds activate to prevent direct morning sun from creating visually uncomfortable conditions). Appropriately utilitarian and durable finishes, including rubber flooring and carpet tile, are all light-colored to enhance the airy and open feeling.

The planning of the new outdoor space—which sits at an elevation about 20 feet above the original campus, to accommodate the laboratory floor-to-floor heights and the required clearance above the FDR—also capitalizes on the river. "Placing trees at the edge of the gardens, along the water, seemed wrong," says Signe Nielsen, principal of MNLA, the project's landscape architect. Instead, the perimeter of the lab building's roof is devoted to a balustrade-protected pathway. This approach allows Rockefeller community mem-

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Learning Objectives

1 Discuss strategies for balancing a desire for transparency—as an expression of an educational institution's pedagogical mission—with the need for energy efficiency and occupant comfort.

2 Describe low-energy climate-control systems suitable for tropical climates.

3 Describe how universities are transforming former industrial buildings and disused academic buildings for new educational uses, and discuss methods for structural retrofit and seamless incorporation of new mechanical systems.

4 Discuss off-site fabrication as a strategy for building on constrained urban campuses, and outline the challenges to such an approach.

AIA/CES Course #K1911A

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bers and staff of the neighboring hospitals (the campus is not accessible to the public) to enjoy unobstructed views, but it also acknowledges the exposed nature of the new real estate, which has a completely different microclimate from that of the more sheltered, older part of the university grounds, points out Nielsen. The newly planted trees, including Japanese black pines, are pulled away from the roof's edge, and have small leaves, so theyaren't prone to toppling over in strong winds. Throughout, there are spots to sit and relax, including an amphitheater sunk below the garden level and benches integrated into the edges of the planting beds.

In creating a low-rise, horizontally oriented laboratory building disguised by landscape, RVA has added new space for cutting-edge research and for scientific collaboration, both indoors and out. And it has ingeniously—and somewhat counterintuitively—managed to integrate its addition into the existing campus while completely, and nearly invisibly, transforming it.

CREDITS

Architect: Rafel Viñoly Architects — Rafael Viñoly, Jay Bargmann, Charles Blomberg, David Hodge, Bassam Komati

Consultants: Thornton Tomasetti (structure); Ocean and Coastal Consultants (marine); Langan (geotechnical, civil); BR+A Consulting Engineers (m/e/p/fp); AKRF (environment); Convergent Technologies Design Group (audiovisual); Entuitive (curtain wall); One Lux Studio (lighting); MNLA (landscape)

Construction Manager: Turner Construction

Steel Fabrication: Banker Steel

Steel Erection: New York City Constructors

Client: The Rockefeller University

Size: 220,000 square feet

Cost: $500 million

Completion date: April 2019

SOURCES

Curtain Wall: Oldcastle Buildingenvelope, Agc Interpane, Tvitec

Interior Glazing: Tgp, Cristacurva

Thin Brick: Endicott

Built-Up Roofing: American Hydrotech, Carlisle

Wood Deck: Bison Innovative Products

Doors: Kawneer, Oldcastle Buildingenvelope, Fleming, Scanga, Vitrocsa, Mckeon, Dorma

Hardware: Allegion, Crl, Assa Abloy, Fritsjurgens

Acoustical Ceilings: Armstrong, Conwed

Paints And Stains: Benjamin Moore, Sherwin-Williams

Wallcoverings: Construction Specialties

Plastic Laminate: Formica

Floor And Wall Tile: Daltile, American Olean, Atlas Concorde, Nemo, Mosa, Stone Source, Tectura Designs

Carpet: Bentley, Mohawk, J+J Flooring

Resilient Flooring: Johnsonite

Raised Flooring: Tate Access Floors

Wire Mesh: Cascade Architectural

Outdoor Furnishings: Landscape Forms, Streetlife, Janus Et Cie, Uhlmann

Plumbing Fixtures: Toto, Elkay

Interior Lighting: Axis Lighting, Acuity Brands, Sistemalux, Litelab, Hubbel, Vibia, Legrand, Kreon, Bicasa

Exterior Lighting: Bega, Lightolier, Erco, Eaton, Acuity Brands, Lumenpulse

“Studies proved the economic viability of incorporating certain minimally invasive techniques of connecting to the existing structure, and quickly we realized that something very compelling could be done.”

—John Cerone, Director of Virtual Design and Construction at SHoP, on the process of designing a structural steel armature for the Nassau Coliseum. *Metals in Construction* magazine, Summer 2019

Steel Institute of New York

GAINING URBAN SPACE: PLATFORMS OVER RAIL YARDS

By creating large platforms over rail yards, urban locales are now tapping into new spaces for building, as pictured here at Manhattan's Hudson Yards

PHOTO COURTESY OF HUDSON YARDS NEW YORK/RELATED OXFORD

Land-strapped cities are starting to erect massive steel overbuilds on top of rail yards to spur much-needed urban development

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AS URBAN populations continue to surge, space-starved cities are seeking creative solutions to continue developing the commercial, institutional, and residential buildings vital to these metropolitan centers.

To meet this growing need, technological advancements and economic feasibility are merging to support the amazing notion of constructing huge platforms over cities' rail yards and transportation corridors. These several-acre platforms can then anchor new development in city centers.

A number of cities are already capitalizing on these ideally located air spaces—on the heels of New York's Hudson Yards development, Philadelphia's Schuykill Yards, Paris' Rive Gauche, and several more sites have serious proposals and feasibility studies in the works.

"While developing platforms and infrastructure over active rail yards requires significant engineering and investment, it is a way to develop land in dense urban areas," explains Eli Gottlieb, managing principal, Thornton Tomasetti, New York. "This can have multiple advantages, knitting back urban fabric that is currently cut by the transit infrastructure as well as capturing large footprints that may not be available on other sites."

In a similar vein, Juan Estevez, vice president, AECOM Tishman, New York, says, "A great advantage of developing these large areas that have sat silently in what are now densely populated, prime locations is that it allows designers to create a space that is boundless from the usual urban constraints; to create a new city within a city."

Consider New York City, for example. According to Chris Jones, senior vice president and chief planner for New York's Regional Plan Association, urban revival has greatly increased the value of well-positioned property—particularly near transit hubs and where rail yards tend to be located—that can be converted to high-density, mixed-use development. "This mismatch of supply and demand is making it profitable to develop even costly and complicated projects."

While New York's rail yards were originally built at the city's edges, there is now a large population living around the tracks, as is the case in many urban areas. As a result, real estate values are high enough to justify the expense of decking over, explains Jack Robbins, AIA, LEED AP, partner, director of urban design, FXCollaborative, New York.

With extremely limited undeveloped site locations, these railroad yards represent large parcels of untapped land.

Steel Anchors Platforms

To technologically enable these mega platforms, experts name structural steel as the material of choice due to its relatively lightweight, high-strength, large-spanning abilities and availability.

"The driving force for material selection for building around active tracks is to maximize the load capacity of the structure while minimizing disruption to the railroad," explains Estevez. "Steel is certainly a stronger material and has the advantage of reducing the area taken up between tracks to support high-rise buildings above. Steel further has the advantage of the pieces being customizable offsite for a perfect fit that can be set quickly and minimize disruptions."

A prime example is Hudson Yards, which will ultimately house more than 17 million square feet of commercial and residential space, a public school, and a luxury hotel on top of 30 active Long Island Rail Road train tracks, three Amtrak subsurface rail tunnels, and fourth Gateway tunnel. Here, steel columns were the only solution to meet the hefty column loads—as high as 51,000 kips service—that had to come down between the tracks with only 24 inches of width for clearance.

"By using 65 ksi steel plates laminated to form the full columns, the loads could be efficiently carried in the limited dimensions," Gottlieb says. Furthermore, "spans range from 35 feet up to 155 feet with the large variety in spans and the grids that shift to the curve of the tracks and switches. Steel was a key material to provide this flexibility."

While the concept of decking over has been around for a long time, technology is now making it a reality. For the Hudson Yards project, laminated steel columns were fabricated from layers of high-strength steel made from special steel plates manufactured in Europe.

And advances in construction technique (e.g., use of heavy crane equipment, special gantries, etc.) make erection of heavy and long structural members both possible and economical on the project, according to Yefim A. Gurevich, senior vice president, building structures, WSP, New York.

High-strength steels, such as A913 and A992 65 ksi material, were used for the columns and beams at Hudson Yards. This enabled a significant reduction in material use and more critically, a reduction in the pick weights for the cranes that allowed the project team to fabricate and set larger elements at larger reaches. "This maximized the ability to cover the yard quickly by reducing crane picks and reducing pick complexity," Gottlieb says.

Robbins points out that today's structural modeling programs make these designs much more efficient, particularly when dealing with irregular column grids and/or modeling with a time dimension, whether it's looking at train traffic, pedestrian movement, or vehicular traffic.

Similarly, advanced BIM tools support a greater level of detail and coordination. "This also allows for tighter designs fitting all the required parts together as well as faster construction, as everyone knows how every piece will fit together from structure to MEP to final architectural elements," Gottlieb says.

Meanwhile, Estevez praises BIM for its ability to clearly show how every trade and system interacts with the one another. "For New York City, our greatest cost is in field labor, so everything we can do to make that work on-site as safe and efficient as possible is a savings to the project," he says.

Furthermore, with platform projects, decreasing or eliminating disruptions to the railroad is of utmost importance.

"Preplanning and microplanning of activities associated with rail outage times in BIM provides crystal clarity to all parties and greatly decreases risk," he adds.

The Structural Details

There are many complex details that go into designing and installing these massive platforms; the process begins with large caissons that are drilled into the ground.

"While foundation selection is highly dependent on soil and rock conditions, large-diameter caissons with structural steel shafts inside will take up minimal space and provide enormous capacity for vertical loading," Estevez explains.

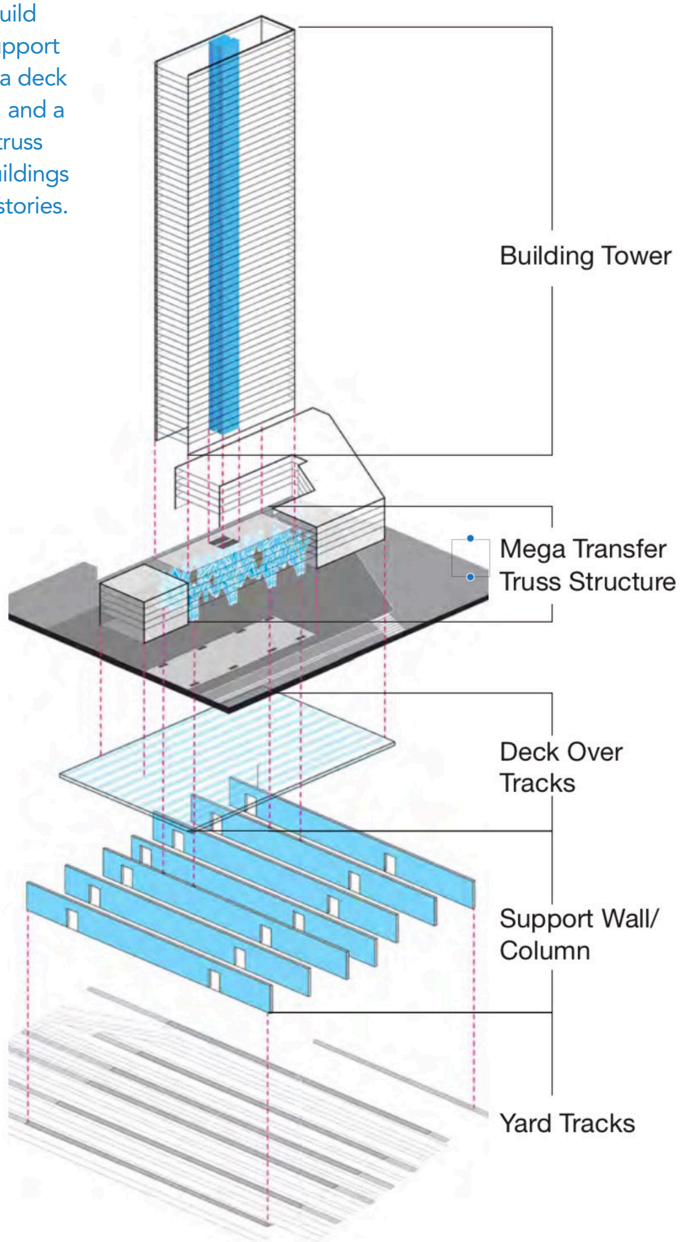
When working within the confines of a rail yard, those foundations become limited by the available space between tracks to drill in those caissons. Similarly, the diameter of the foundation shafts is limited by the clearance between the rail tracks.

For Hudson Yards, "we used a 60-inch-diameter steel casing on the shafts," Flynn says. "We placed a solid laminated steel core inside the casing and concrete between the casing and core."

Each caissons' capacity was maximized to limit the number of foundations that had to be installed. In some cases, 65 ksi steel cores, as previously mentioned, and built-up plate were used to support individual loads of as much as 25,000 kips service, according to Gottlieb.

Another issue was navigating between the rail utilities and other obstacles that came to the surface as construction progressed. For example, the team insisted that the site be

A typical overbuild incorporates support walls/columns, a deck over the tracks, and a mega-transfer truss structure for buildings taller than five stories.



TOWER AND TRACK STRUCTURE RELATIONSHIP

IMAGE COURTESY OF SUNNYSIDE YARD FEASIBILITY STUDY

PHOTO COURTESY OF HUDSON YARDS NEW YORK/GEOFF BUTLER

Shown is column, truss, and girder construction at Hudson Yards.

pre-excavated in order to minimize surprises.

The project's utility-relocation budget alone is estimated at $12 million. This includes altered structural designs for the frame of the platform to accommodate a new caisson location in order to avoid conflicts. In all, a total of 288 caissons, ranging from 4 to 5 feet in diameter and 20 to 80 feet in depth, support Hudson Yard's Eastern Platform and structures overhead.

Columns, Trusses, and Girders

It's important to note that a typical 4-inch, A572 plate produced in the United States has a yield strength of 50 ksi. So in order to deliver the required 65 ksi yield strength with a 4-inch plate, a large European steel plate manufacturer was tapped to leverage a fabrication process to produce the laminated plates.

The column structures vary in diameter from 1 foot to 5 feet 6 inches and are drilled into the bedrock beneath the railroad tracks at an average depth of 40 feet below the surface. Approximately 3,300 tons of solid steel cores, the largest of which was 30 by 30 inches, were fabricated from the 4-inch-thick plate. The longest is 87 feet, and the heaviest weighs an amazing 71 tons.

When placed between the tracks, the columns often have size limitations imposed by the "train dynamic envelope," which is the clearance required for unobstructed train movement, explains Patrick Chan, senior vice president, building structures, WSP, New York.

"Moreover, even the shape of the columns is sometimes dictated by this clearance where the tracks are not straight but curved," he adds. "The fact that these columns often are tall and slender—usually there is no room for any type of bracing inside the yards—also adds to limitations imposed on column design."

Ultimately, the goal is to lay out the columns to fit the track alignments while creating as uniform a grid in one direction as possible to allow for the standardization of many of the deck elements, explains Gottlieb.

To illustrate the structural and spatial dynamics of the platform, Robbins explains that much of the support is actually created by walls, as opposed to the individual columns.

"What you essentially end up doing is creating walls in between the tracks which act as a kind of continuous column to support the deck," he says. "Because those structural elements run parallel to the tracks, it means that you have very good structural support in one direction, and it tends to dictate the orientation of the building."

As a result, the buildings on top of the platform end up running perpendicular to the tracks so that they get the most support.

Spanning in between the columns are steel plate girders and steel trusses. For Hudson Yards, steel plate girders support the plaza area and vary from 35-foot spans up to 120-foot spans, with depth ranging from 4 feet to 6 feet.

"These girders also are designed to incorporate the mechanical plenums for smoke and air ventilation of the yards as well as incorporate all the other MEP services within their depth," Gottlieb says. "By providing regular openings, similar to castellated beams, the girders were an ideal way to stack all the structural and mechanical systems together and minimize the depth of the entire system sandwich."

The plate girders were also used where vertical space was limited and were coordinated in dimension to incorporate all the platform ventilation systems, including fan rooms and ducting, while minimizing the vertical dimension from rail clearance to the top of the finish grade, he adds.

Generally speaking, trusses and beams need to be shallow enough to provide the vertical clearances required by railroad authorities, and the roof over the yards should meet street-grade requirements. In many cases, this can be challenging, as rail yards built at the turn of 19th century are relatively shallow. Using steel helps address this shallow depth issue, in addition to meeting lightweight, long-span, and high-capacity construction needs.

At Hudson Yards, the platform's base structure clears the tracks by at least 17 feet and ranges in thickness from less than 3 feet to up to 7 feet where special features have been incorporated into the design. For instance, in many areas, the platform houses a network of tubing carrying cooling liquids that will buffer the plaza's landscaping from the heat of the train yard below, which can reach up to 150 degrees Fahrenheit.

Mega-Transfer Truss

Trusses were used for the largest spans and where there is a lack of interior/intermediate support for overbuild construction.

"A prime example of this type of condition is closely spaced tracks within the yard that do not allow for column placement between them," explains Jeffrey Smilow, F.ASCE, executive vice president and director of building structures, WSP, New York.

In the case of Hudson Yards, four tracks on the east side branch out into 30 tracks on the west side, and within this track configuration, switches are used to navigate trains in between the tracks. Because the railroad couldn't tolerate any disruption to the switches, the structural engineers had to span these long spaces between the foundations with large trusses.

The trusses were also coordinated to be the "basement" of the retail building and incorporate services, mechanical rooms, and storage as well as the loading docks for the project.

One advantage with these trusses is that the absence of support columns minimizes construction and time and coordination inside the rail yard. However, this lack of intermediate supports increases the depth of the truss. So ultimately, the fabrication, transportation, and installation is more complex and costly compared to a simple beam/girder system.

As noted, when building these platforms, there's a misconception that the deck is like a skirt around the building, with a rail yard going through the building basement. In reality, the skirt around the building acts like an extremely large basement, which is the rail yard, explains Robbins.

"You're trying to figure out how to land the building, and the structural load, to the ground, to terra firma, and the transfer truss ends up being the most efficient way to do that," he says.

Essentially, the structural engineers are dealing with a set of support points coming up from the foundation and the building coming down on top of that. "You've got to figure out how to marry the structure loads coming down and support them, and the transfer truss is what accomplishes this," Robbins adds.

To do this in the most economical way, engineers try to minimize the span between those touchdown points. Alternatively, if the spans get too large, the design will not be economically feasible.

That said, for Hudson Yards, there are points below the 10-story retail complex where trusses had to span lengths are long as 155 feet and support uniform loads of nearly 4,500 psf. "The trusses required close architectural mechanical and structural coordination to maximize the structure, achieve a usable space, and fit the required systems into them," Gottlieb explains.

While these mega-trusses do solve the challenge of dealing with large spans, it should be noted that their diagonal structural members need to cut through the building core, which makes the space in the podium of the building a little less useable. For example, within Hudson Yard's retail complex, the truss is installed between floors one and three, and it does take up a portion of the real estate.

Sharing some more details about the truss design, these elements were sized based on erection weight and crane capacity, and many were designed as two side-by-side trusses, which were tied together after erection. "Had a single truss been used, it would have been too heavy to lift over the railroad tracks," Flynn says. "By splitting the trusses, we could erect one truss at a time and tie them together later. This minimized the impacts to the railroad below."

The stable box truss assembly formed by these double trusses supported a fast, lightweight installation of precast planks to cover the tracks.

"The trusses were each installed during a 2-hour window once a week in the afternoon over the tracks, allowing all the trusses to be installed in a six-week period, covering half the yard and all the complex switching tracks," Gottlieb says.

As noted, the structure had to be fully optimized so that all the structural elements could be fitted to the architectural design and the limited dimensional volumes but without using any additional material that would drive up pick weights for the cranes. "Minimizing weight was critical to allow the cranes to efficiently erect the project and minimize crane positions for the project," Gottlieb adds.

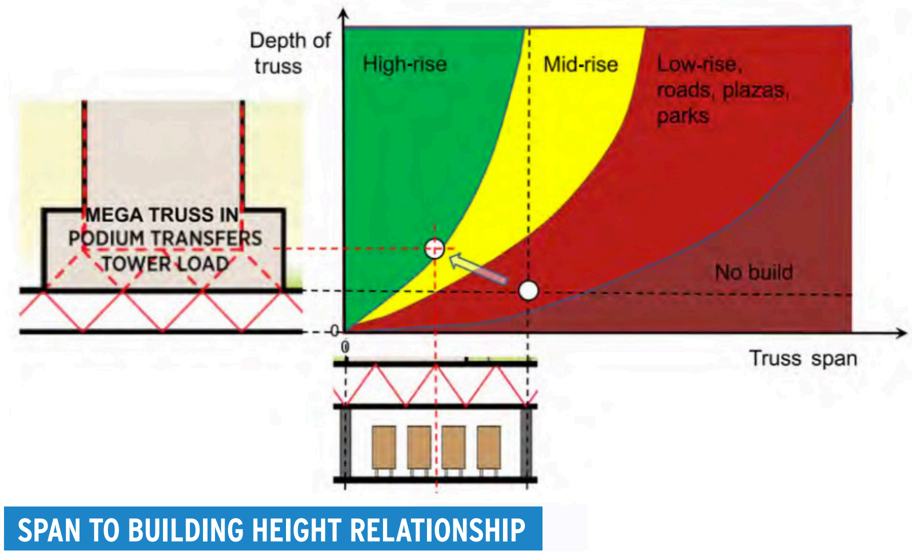


IMAGE COURTESY OF SUNNYSIDE YARD FEASIBILITY STUDY

Truss depth increases in relation to the height of the buildings.

Complex Coordination

While a sophisticated level of engineering and architectural design goes into these platform projects, one of the most challenging aspects is the extremely high level of coordination required. Projects of this nature are highly interdisciplinary; transit companies, engineers, architects, cost estimators, financial modelers, urban designers, and municipal officials must all work together.

"These projects cannot be built efficiently without full dedication and collaboration of the private and public entities involved," Estevez says.

As opposed to a greenfield project, the notion of coordinating construction with ongoing train operations, yard underground activities, security, ventilation, etc. is a daunting task. "To tackle these challenges [for Hudson Yards], our structural engineering team worked closely with around 20 different consultants representing various engineering fields as well as contractors and clients," says Silvian Marcus, F.ASCE, director of building structures, WSP, New York. "To add to this mix, every step of design had to pass a rigorous review by city authorities, railroad authorities, police and fire departments, etc."

Just the issue of taking trains out of commission during construction alone is a difficult and costly endeavor. For example, at Hudson Yards, in areas where the train tracks were straight, the team could take four adjacent tracks out of service at a time, allowing drills and other equipment could be left in place. However, in some areas with switches where trains change tracks, the team was permitted to drill a caisson for only 2 hours each night.

Similarly, the erection and stabilization of steel members could often only proceed within in limited time frames. "These time windows ranged from 20 to 90 minutes, depending on the number and location of tracks affected," reports Flynn.

Furthermore, the cranes had to be located in "off-track areas," which increased the distance from the crane to the final location of the piece being erected and made the use of very large cranes necessary.

"We used the largest cranes that were available and then needed to configure the steel members so their weight was within the crane capacity," he explains. "This led to the side-by-side steel truss concept and also the location of field splices in the laminated steel columns."

Another challenging issue with these platform projects is the fact that developers are working with a transit company whose primary job is to make the trains run. "They're not developers, they're not urban planners," Robbins explains. "There can be some individuals within the organization who have the vision to see that if you do an overbuild, it can help fund rail operations, but it's not how these transit companies are used to thinking or doing business, so that's a paradigm shift for them."

Project Process

In terms of how to best execute these complex projects, Flynn explains that the first step is addressing the big picture, discussing project needs, and evaluating the ability of the railroad to tolerate some disruption and maintain the necessary level of service.

Before starting the design, the team must collect as much existing information about the existing underground facilities as possible.

If information is limited or unavailable, then an attempt is made to conduct a survey. This survey can be visual for above-ground utilities, or it may use ground-penetrating radar or X-ray techniques for underground utilities.

At Hudson Yards, a detailed 3-D BIM model was developed following a comprehensive study of all existing conditions. The model then served as part of the preliminary design, also helping the project team to determine what items needed to be field-verified.

"The schematics need to be presented early to the operations division of the public entities to assure that the work is feasible and the best solution for the project," Estevez says. "Subsequent design development and construction documentation needs to be created with collaboration from all entities."

The building team must also develop a detailed understanding of train operations, as working with preexisting conditions and active train lines is a delicate balancing act. For example, the team could be dealing with an underground foundation and column directly above it.

"Often, due to tight track layout and multiple underground conduits and utilities, individual footings literally have to be carved out to allow for passage of these conduits," Gurevich explains. "Columns above sometimes must be shaped to accommodate curved train clearance outline and other limitations."

In terms of ensuring access during these tight time windows, close coordination with the railroad staff is essential. To best enable this, Flynn recommends bringing more railroad personnel into the building team's project meetings, as these sessions progress from ideas to details.

"It is important for all parties to understand each other's goals and concerns," Gottlieb adds. "By having regular interface with the rail design teams, Hudson Yards was tailored to address their concerns, including vertical and horizontal clearance to track outages to meet the rail infrastructure's needs while allowing the project to be completed."

Ultimately, the only way to make these complex projects work is with a high level of planning and frequent meetings. "The key is constant communication between the builder and the railroad," agrees Flynn.

Emphasizing how complex these types of projects can become, Estevez shares a poignant example. At the base of the 30 Hudson Yards 102-story tower, the only place to locate the building core was on a small terra firma area within the northern portion of the site. "The entire building core—including structural lateral load system, elevators, and mechanical systems—had to shift over 80 feet midway up the building to provide full perimeter of window space at commercial floors," he says.

At 100,000 tons of steel, these issues contributed to making 30 Hudson Yards the heaviest and most complex steel high-rise building ever built.

Code Compliance

Another key issue with platform projects is determining which codes and standards apply, which is not so straightforward.

For example, Robbins asks, "If you build a deck over a railyard, does that make the deck a building, so then the building codes apply? Or if there's a building that goes through that deck and anchors into the ground, how much of the deck around the building is counted as part of the building?"

SUNNYSIDE YARD

As New York's Hudson Yards massive decking project moves along, another major metro project may not be far behind. In early 2017, the New York City Economic Development Corporation (NYCEDC) and Amtrak, along with several other agencies and consultants, released a comprehensive feasibility study for Sunnyside Yard in Queens. A master plan is now in the works.

With an anticipated population growth of 80,000 people to the area within the next two decades, the plan intends to deliver 180 acres of new space with up to 24,000 homes, 19 schools, and 52 acres of public space on top of the rail yards.

Zooming in to structural details, the study delineates the following:

- Structural steel construction is preferred for the deck, as it is lighter than precast concrete and therefore easier to maneuver and install in congested areas.
- Structural support walls or columns must be located outside of required railroad track clearances.
- Deck/platform depth—vertical thickness between upper surface and underside—will vary between 9 and 16 feet.

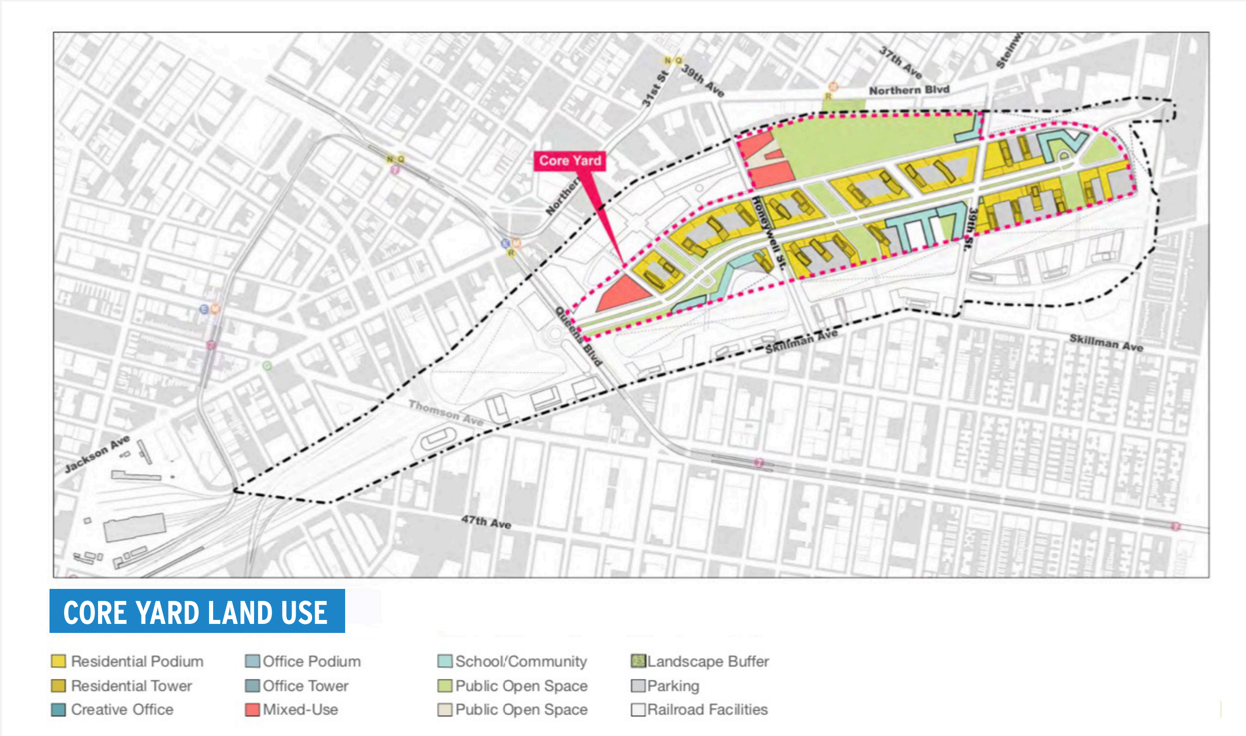


IMAGE COURTESY OF SUNNYSIDE YARD FEASIBILITY STUDY

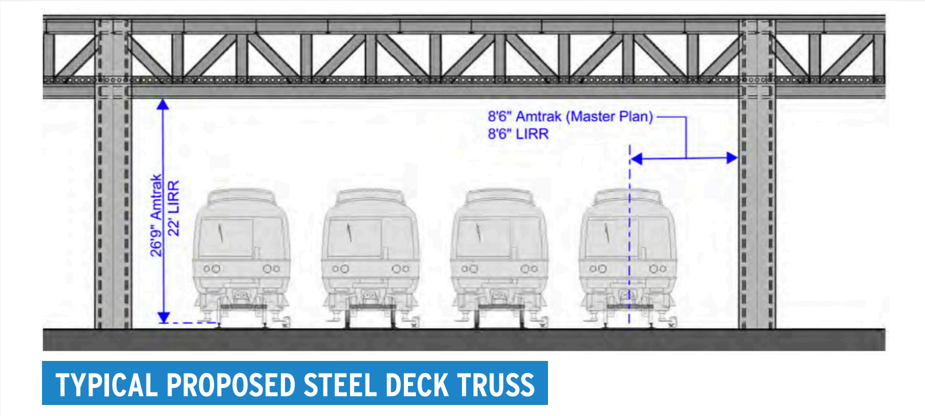
The Sunnyside Yard project hopes to deliver 180 acres of new space with up to 24,000 homes, 19 schools, and 52 acres of public space on top of the rail yards.

"In the study, we found that at five stories, around 60 feet tall, you could support that with a platform, but taller than that, you really need to have the transfer truss in the building," explains Jack Robbins, AIA, LEED AP, partner, director of urban design, FXCollaborative, New York.

Furthermore, for these taller buildings, the study recommends:

- Require full support walls at track level.
- Orientation with the long axis perpendicular to the direction of the tracks, with support walls running between tracks, in order to provide adequate resistance to wind loads.
- Spanning three to four lines of columns, depending on tower length/height.
- A substantial steel truss—a mega-transfer truss—in the building podium to transfer the loads to support walls. The depth

IMAGE COURTESY OF SUNNYSIDE YARD FEASIBILITY STUDY



This proposed steel deck truss for Sunnyside Yard shows a typical height and span.

of the steel deck truss is anticipated to vary from 9 feet for shorter spans to 16 feet for spans greater than 150 feet.

"With the limited structural supports at non-uniform locations, the mega-transfer system situated at podium levels above the deck will allow towers of various sizes and geometries to be located independent of the podium structure, as if they were supported directly on terra firma," says Yefim A. Gurevich, senior vice president, building structures, WSP, New York.

"The concept of mega-transfer trusses presented in the feasibility study is a way to balance the structure of the platform with the towers. This allows for a lighter less expensive platform, but it also provides flexibility by leaving the final layouts and transfers to be part of the building development," adds Eli Gottlieb, managing principal, Thornton Tomasetti, New York. "In some cases, the platform could be designed with a deck that can support light loads, with strong columns to support the buildings. Then a transfer truss could be built as part of the building to support the building on the columns."

In terms of the spans required for the buildings' varying heights, the study delineates the following:

- Low-rise buildings of up to five stories can be located on deck spans of up to 150 feet with no mega-transfer truss required. Longer spans of up to 200 feet can technically be achieved at a cost premium.
- Residential buildings up to 14 stories and commercial building up to 17 stories can be supported on spans of up to 145 feet.
- Residential and commercial buildings between 33 and 43 stories can be supported on spans up to 115 feet.
- High-rise towers up to 69 stories can be supported on spans of up to 85 feet.

For wind and seismic loads, the study recommends tuned slosh dampers.

Overall, Gurevich points out that Sunnyside Yard, with its multiple train operations, creates a situation where the track layouts are nonuniform in nature. This means there are limited locations for vertical structure and large deck spans.

"The limited touch-down locations create the need for major structural transfers of building loads above deck," he explains. "This nonuniform structural grid also creates additional challenges when using gantry systems for erecting deck over the operating tracks."

Furthermore, the feasibility study notes that installing deck over the Main Line tracks and other critical tracks will be a constructability challenge, requiring multiple tracks out of service, large cranes, and significant advance planning.

One way to reduce risk, and the length of track outages, could be to incrementally launch the deck from previously constructed sections, rather than exclusively using cranes.

This is a grey area with a lot of ambiguity and needs to be carefully evaluated on a project-by-project basis.

Take Hudson Yards. Here, the trains are an Metropolitan Transportation Authority facility that is governed by the New York State Code, in addition to other rail codes set by the Federal Railway Agency. However, the buildings on the site are all governed by the New York City Building Code.

"While the codes are similar and have similar performance goals, there are differences and all parties need to be aligned to avoid conflicts between codes and requirements for the projects," Gottlieb says. "Making sure that everyone is aligned on which codes the project is following and the critical overlaps is important to the success of the project."

The sheer number of regulatory documents involved shows the extent to which codes impact design requirements. Ultimately, the platform must satisfy all applicable codes, regulations, and requirements that include, among other things, building, transportation, railroad codes, fire, smoke exhaust, security/blast, and train impact regulations. "Sizes of structural members, their location within the yards, and sometimes even their shape are all affected," Chan says.

In addition to the issue of codes, these overbuild projects must address a few unique design requirements. For instance, the platforms need to account for heat buildup from the trains. In order to address this for Hudson Yards, an extensive CFD analysis was conducted, and passive air intakes were located and designed to allow the heat buildup to stay within acceptable limits. The heat is then dissipated through this ventilation; three fan plants exhaust the air while three plants provide fresh air to the facility.

The decks are open on the sides, providing some fresh air, "but you still need the supersized fans hung on the ceiling of the deck to help move the air around and provide the ventilation," Robbins adds.

Maximum and average temperatures of the structural elements were also derived from the CFD analysis, which, in turn, impacted the structure's fire protection design, Smilow adds.

Another unique issue is emergency egress. In the planning and design, the building team must ensure there are multiple ways that people can exit from under the deck to the surface.

Designers must address the issue of stormwater retention. For another project where FXCollaborative performed a feasibility study, the rail yards' locale required the proposed project to conform to stricter stormwater standards. Consequently, the design had to incorporate stormwater retention tanks. Such tanks tend to be fairly large and can encompass a significant part of the infrastructure.

The Future of Platforms

With urban population growth not anticipated to slow down any time soon, urban planners and designers anticipate that platform building over rail yards and

PLATFORM BUILDING AROUND THE WORLD

With growing infrastructure needs and little space left to develop in urban centers, cities are struggling to meet the residential, business, shopping, cultural, and leisure-based needs of its residents.

"Densely populated areas are starving for the space to build near their centers or near highly valued real estate. As the value of real estate increases and the space gets more limited, we have seen a shift to develop areas that will require more costly and risky investment," says Juan Estevez, vice president, AECOM Tishman, Los Angeles.

Estevez is referring to the concept of decking over rail yards and transportation corridors to create new space for real estate development. While the materials, engineering, and construction required to build and structurally support mega platforms upon which new buildings can be constructed is very costly, such developments are being carefully vetted in a number of urban locales around the world.

Most projects are still in initial evaluation and planning stages. Among those that have broken ground is Parcours Paris Rive Gauche, one of the largest developments in the history of Paris. Out of the 320 acres under development, 60 acres are platforms being built over rail lines.

One of the largest developments in the history of Paris, out of the 320 acres under development, 60 acres are platforms being built over rail lines at Parcours Paris Rive Gauche.

Located in the City's southeastern 13th Arrondissement on the left bank of the Seine River, 6,300,000 square feet is slated as residential, 8,000,000 square feet will be office space, 4,400,000 square feet is designated for commerce, and 7,200,000 square feet is being developed as public spaces.

While a number of buildings and public spaces have already been built, the developer, Sempara, anticipates that the full development will be completed by 2023.

Another European project, Earls Court Development, is looking to deck over 77 acres on the Western edge of central London to build 1,300 new homes with 1,800 square feet of community, health, and leisure facilities.

In the United States, Philadelphia's $3.5-billion Schuylkill Yards platform project is already under construction, with the goal of transforming 14 acres of Drexel's University City into an innovation hub.

Together with Brandywine Realty Trust, the University plans to build 2.8 million square feet of office space, 1 million square feet of laboratory space, 1.6 million square feet for residential use, and 6.5 acres of green space.

Involved with the project's feasibility plan, Jack Robbins, AIA, LEED AP, partner, director of urban design, FXCollaborative, New York, compares Philadelphia to Sunnyside Yard in Queens.

"Sunnyside was much more constrained, with much less space to bring the structure down to the ground," he says. "In Philadelphia, we had more space to work and a little more flexibility to bring some building cores down to the ground."

"The cores act as a spine for taller buildings and really provide a lot of the structural support and structural stiffening of the building," he adds. "So that greatly reduces the structural gymnastics, the size of the transfer truss, etc. and reduces the cost considerably."

Also in New York, Pacific Park, formerly referred to as Atlantic Yards, is looking to take the area next to Barclays Center and build 6,439 new apartments, 250,000 square feet of retail space, 360,000 square feet for offices, and 8 acres of open space.

Meanwhile, at South Station Tower in Boston, the city is reviewing plans to build a 51-story mixed-use tower of office, residential, and retail space, a 17-story tower, and a nine-story building.

Two decking projects are currently undergoing review in Atlanta. The Stitch proposes to construct a 3⁄4-mile platform over the Interstate 75/85 Connector, thereby "stitching" back together this area in downtown Atlanta and delivering 14 acres of new space to the city.

An even more ambitious development sits near State Farm Arena and is known as the Gulch, a field of parking lots and rail lines below surrounding viaducts. The proposal would build a $500-million steel and concrete platform approximately 40 feet above the active rail lines to street level, where 1,000 residences, 1,500 hotel rooms, and a mall-sized retail space would potentially be built.

On the other side of the country, Seattle's LID I-5 proposes to build a "lid" over the freeway in order to reconnect communities severed by I-5. "This provides a unique opportunity to create more land and more space...open space for schools and other community amenities like community centers as well as affordable housing, which we desperately need," says Riisa Conklin, executive director, Freeway Park Association, Seattle.

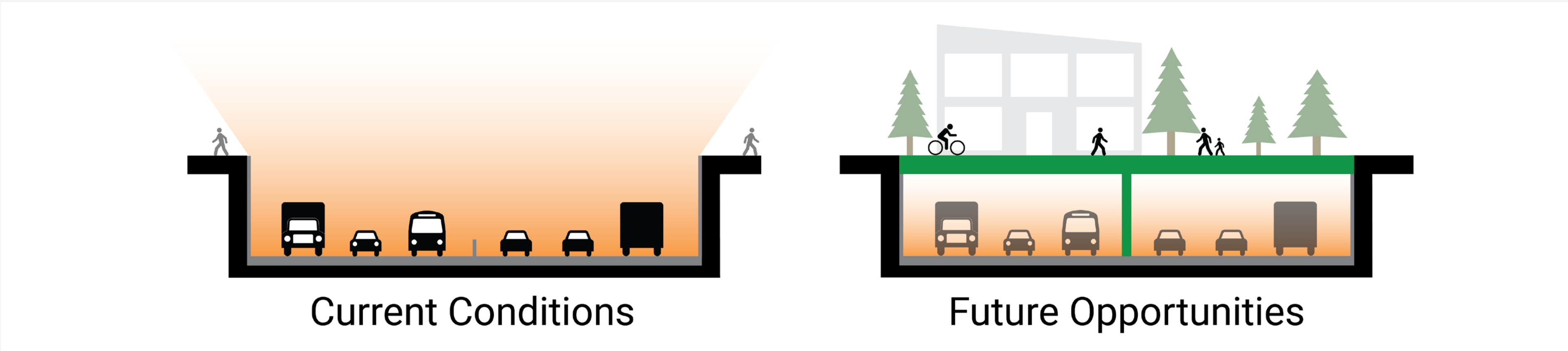


IMAGE COURTESY OF LID I-5 STEERING COMMITTEE

To create additional building and green space, Seattle is considering building a "lid" over I-5, which would also reconnect communities severed by the freeway.

transportation corridors will really take hold.

In fact, Estevez sees a new set of factors converging. City and state agencies have realized the value of leasing the air space above their properties to private developers; railyards are being sought as a way to renew cities and turn a profit; and the initial investments, risks, and logistics of these projects are starting to make financial sense.

"I think this is going to very much be a growing area," agrees Robbins.

While these initial overbuilds will struggle with this new way of developing real estate, like any new venture, the more it's done, the more efficient it will become, and the less costly it will be.

"These current projects are building a knowledge base, so it will become a little easier and more feasible for future projects," Robbins says. "My hope is that it changes the way some of the transit companies who own large amounts of real state start to think about their real estate and the integration of development and infrastructure."

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Learning Objectives

1 List the factors driving urban interest in developing new real estate on top of platforms covering rail yards and transportation corridors.

2 Identify the numerous reasons that make structural steel the material of choice for building these platforms.

3 Gather design and installation details about the columns, girders, trusses, and mega-transfer trusses that support the platforms.

4 Review various details surrounding New York's current Hudson Yards project and the Sunnyside Yard Feasibility Study.

5 Discuss the complexities and high level of coordination required by these unique projects.

AIA/CES Course #K1906C

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PHOTO COURTESY OF THORNTON TOMASETTI

With its flexibility, adaptability, high strength-to-weight ratio, and ability to support long spans, structural steel—like that used for Barclays Center in Brooklyn—is a material of choice for today's multipurpose arenas.

ADAPTING TO CHANGE: ARENAS RELY ON STEEL

Structural steel delivers the flexibility and adaptability required by today and tomorrow's multipurpose arenas

SPONSORED BY THE STEEL INSTITUTE OF NEW YORK | BY BARBARA HORWITZ-BENNETT

IN THE battle for fans and audience members, today's multipurpose arenas are boasting bigger and better scoreboards, over-the-top amenities, and unique and varied seating options to lure spectators out of their homes (and off of their smartphones) and into the arenas to watch the games, competitions, and concerts.

Arenas, as opposed to larger stadium venues, have the nimbleness to support the quick and varied changeovers required by the variety of events and attractions utilizing the spaces. However, to optimally support current and future venue needs, these arenas must have the ability to adapt and upgrade.

One key aspect of this equation is the roof design. "The roof often comprises the largest surface area on an arena, and the vast, unobstructed program space it shelters below offers maximum flexibility for reconfiguration and reuse," states John Cerone, principal, SHoP Architects, New York.

In fact, seating bowls and support spaces are constantly being reinvented to support trending fan behaviors, says Bart Miller, PE, principal, senior project manager, national sports market leader, Walter P. Moore, Houston. Tasked with frequent renovations, it behooves arenas to anticipate future structural support and flexibility needs from the onset.

"Effective planning and informed decision-making early in the design process can save millions in construction costs and generate millions in future revenues," Miller explains. "Structural steel allows for the most flexibility in structural modifications, as it can be economically configured for optimal column locations and structural framing depths that allow for contiguous open spaces and increased ceiling heights, and it can be easily reinforced or removed in the future if necessary."

In addition to sporting events, infrastructure must be built to accommodate top music performers and tours.

"Concerts are asking more of arena roof structures with each new tour by applying heavier and more numerous loads, often that move, distributed over much larger areas than ever before," Miller reports.

High-Capacity Rigging Grids

Consequently, one of the critical design decisions for a long-span roof system is the evaluation of loading assumptions for concert rigging and scoreboards, explains Jeff Callow, PE, LEED AP, principal, Thornton Tomasetti, New York. "No one wants to have tours turn their facility away because they are limited on what they can do and hang from the roof," he says.

As venues compete for concerts and other events, arenas that have suitable show rigging capacity, frequent and useful points to rig from, and are easy and safe to access are at a great advantage, confirms Brian A. Dickson, PE, SE, senior principal, Magnusson Klemencic Associates, Seattle.

"A clever, experienced arena roof design will integrate the catwalk provisions and rigging points seamlessly into the roof design from the outset," adds Peter Aryes, global service leader, structural, for Aurecon, an engineering firm active in the Australian and South African market with a specialty in arenas and stadiums.

Putting things into perspective, venues designed as recently as 10–15 years ago can generally support rigging grids of up to 100,000–120,000 pounds concentrated over the center and end stages only. Now those grids are proving inadequate, as today's heaviest arena shows—such as Kanye West, Drake, and Game of Thrones—can exceed 250,000 pounds with loads distributed widely across the entire venue roof structure.

In response, many venues are now looking to increase their rigging grid capacity and coverage, which often necessitates the addition of rigging beams and may require strengthening of their primary roof structures. "In planning a new facility, owners should consider proportioning their rigging grid to extend across the entire event floor, be configured for optimum speed and accessibility, and provide far more capacity than they think they will

Retractable roofs offer the best of both worlds—an authentic outdoor fan experience and a comfortable, temperature-controlled environment on cold, rainy, or exceptionally hot days—as shown here at Atlanta's Mercedes-Benz Stadium.

need," recommends Miller. "The construction costs associated with additional capacity and coverage are nominal, making it much wiser to build it now than to retrofit later."

Structural Steel Roofs

In addition to supporting high-capacity rigging loads, structural steel for long-span roof structures is arguably the "right system" for arena and event centers, asserts Dickson.

"Structural steel is familiar and readily available in nearly any market, can accommodate nearly any desired shape, and can span distances of 300 feet to 400 feet with ease," Miller states.

Additionally, steel structures can be retrofitted by selective structural strengthening of the existing shapes and/or connections to achieve greater capacity.

As a lightweight material with a high strength-to-weight ratio, structural steel supports long spans, which is ideal for fabrication and erection. By manufacturing the members into smaller pieces, they are easier to transport and move onto the job site, where they are then attached. "The versatility of using either bolted or welded connections provides fabricators and erectors with ultimate flexibility in selecting fabrication processes and installation techniques that fit their equipment, capabilities, and often limited project schedules," Miller explains.

Steel can also be attached to existing concrete structures, or in many cases, columns can be threaded through the existing structure to provide support for new roof elements, adds Cristobal Correa, PE, principal, structures, Buro Happold, New York.

The structural steel members can be easily modified, strengthened, or removed in the field, which is especially important for multipurpose venues with evolving functional, operational, and aesthetic requirements.

Offering some more insight into why steel is particularly suited for large spans with less distance between the columns/supports, Charis J. Gantes, Ph.D., professor of structural engineering, National Technical University of Athens, Greece, explains that as the span increases, the stresses increase proportionally to the square of the span and the deflections proportionally to the fourth power of the span—or in other words, very quickly. It then becomes very difficult to satisfy the stress/strength and deflection/serviceability constraints.

One strategy is increasing the section, but this is not very effective because then the self-weight also increases. Besides adding to cost, this also adds to the weight that the structure must sustain. Gantes explains that in large spans, the structure mostly carries itself, with little reserve left for live loads, and at a certain span length, the structure cannot even carry itself. "Therefore, for large spans, such as in arena roofs, it is effective to use materials that have high allowable stress to satisfy strength constraints and high modulus of elasticity to satisfy serviceability constraints. This makes steel the best and perhaps only choice," he says.

This issue of minimizing the self-weight of the structure is of primary importance, emphasizes Craig Tracy, vice president, WSP, Montclair, New Jersey, as every pound of self-weight robs capacity from the structure to support external loads, such as snow, wind etc., and each square inch of structure that is added to support self-weight requires more material to support that added weight.

"The inefficiency of this structural tail-chasing is minimized by using materials that have the best strength and stiffness/modulus relative to their density," Tracy states. "Comparing the best materials available for construction today, one finds that structural steel has a 50 percent higher specific strength and 30 percent higher specific modulus than concrete."

Roofing Types

Long span: The majority of today's arenas of up to 25,000 seats are long-span truss roofs. In addition to supporting video boards and concert rigging, the roof will often participate in the acoustic objectives for the facility (i.e., foster good interior sound, address sound escaping the venue, etc.)," says Dickson.

"Long-span truss roofs can support large loads close to the oculus and facilitate construction by providing a support line without the requirement for temporary works below," states Peter Chipchase, M.Eng., C.Eng., MICE, MIStructE, PE, director, WSP, London.

Because the NBA and NHL maintain stringent temperature, humidity, and sports lighting requirements for their venues, the roofs are typically closed and fixed.

Tension/compression ring system: This is a lightweight, long-span solution that can internalize the inherent forces within itself, much like a bicycle wheel, Correa explains. "This often creates advantages for a sympathetic retrofit of an existing venue by reducing the impact on the current structure, or creating a demountable system that can be removed, replaced, or modified independently—with minimal impact on the internal program—to promote venue flexibility and help future-proof a design," he says.

Retractable roofs: Though not typically found in arenas, retractable roofs offer the authentic experience of playing football, baseball, or soccer outdoors, while maintaining a comfortable, temperature-controlled environment on especially warm, cold, or rainy days.

"A retractable roof can provide the best of both worlds, allowing for the venue to be either an open-air or enclosed stadium depending on the weather and the preferences of the fans," Miller says.

Buro Happold Principal Derrick Roorda, SE, points out that designs must accommodate both open and closed loading conditions and have a mechanism for opening and closing that can be accommodated by the structural system.

Cantilevered canopies: Though more common in stadiums, cantilever roofs are a signature architectural element, enhancing the fan experience with unobstructed views and creating a greater sense of intimacy in the seating bowl, according to Miller.

Offering the benefit of modularization and standardization, this enables mass production. Consequently, the project benefits from fabrication efficiencies, repetitive construction, and extensive optimization to reduce steel tonnage while maintaining performance, explains Chipchase. As self-supporting units, they can be installed on multiple work-fronts, thereby shortening the construction schedule.

Fabric roofs: Also more common in stadiums and ballparks, these lightweight tensile structures utilize membranes to enclose the primary structure. "Clear and translucent roofing and facade materials, such as ETFE and PTFE, create an outdoor atmosphere in a permanently enclosed, conditioned space," Miller says. The lightwweight roof materials reduce structural support requirements and cost.

Fabric and cable roofs are sometimes used in pure sports venues where blackout conditions, acoustic performance, and high rigging loads are less important, but Aryes would not normally recommend them for an entertainment-led, commercially driven venue. These roofing types "tend to come into their own on larger stadium projects where minimizing self-weight is even more important, climatic control is less important, and a lighter, airier structure is more architecturally attractive," he says.

Stadium Roof Considerations

In determining which roofing system is best for a particular project, a number of factors must be taken into consideration.

"The needs of arenas and stadiums and environmental effects (such as rain, wind, snow, and ambient temperature) as well as the future readiness of the venue weigh heavily on the selection of the appropriate long-span roof: fixed closed roof, partially closed roof, or retractable roof," explains Cerone.

Additional factors for determining the ideal solution for a long-span roof, according to Miller, include geometric alignment with architectural design intent, structural efficiency that minimizes materials and self-weight, repetition in detailing and assembly, ease and speed of erection, the capacity, expertise and competitiveness of local contractors, fabricators, and erectors, and site considerations, such as crane access and removal.

While weighing these factors will help guide the design decision, there is no single formula that always yields the best solution.

Offering some general guidance on typical arena configurations, Aryes relates that most modern commercially driven arenas have roofs with a primary span in the range of 100–130 meters (325–425 feet) with an aspect ratio of around 1.2–1.5. "They require a fairly dense node configuration to accommodate rigging, and they tend to be blacked out," he explains. "As a result, they almost always end up being some form of one-way truss, two-way truss, or space frame configuration since these options tend to favor relatively low roof profiles and are relatively easy to build using easily handleable components."

When Aryes' team embarks upon a long-span roof project, one of the first questions it asks is what the roof will look like once it is half built since the cost of erection and temporary works can easily outweigh the material costs. Unlike some roof types that are only stable once complete, the benefit of trussed roofs is that they can be assembled in robust, stable, handleable components and tend to be self-stabilizing with minimal temporary works. Consequently, the roof construction does not paralyze the entire site in the way that a dome or cable-net roof might.

Another major consideration is the roof's ability to support future flexibility and retrofits. As market needs are constantly changing, arena owners are looking to maximize the flexibility of their venues. For example, the infrastructure required for network broadcasting is quickly evolving and needs frequent updating. "Revenue models evolve as well, requiring the rebalancing of fixed seating, suites, concessions, and other spectator experiences," adds Tracy.

That said, steel structures generally add the most flexibility when it comes to renovations. For example, demolition can usually be achieved using cutting torches, diamond saws, and other small tools, Tracy explains. And connections to the existing structure can be made through welding and bolting, which are both methods that can be reliably inspected and afford a high level of confidence.

At the same time, it is not as common to retrofit the long-span roof structure itself because accessing the trusses to perform structural work is exponentially more expensive once the facility is opened; the work is highly field intensive, and room for logistics is limited at that point, says Callow. Consequently, it is important for the project team to carefully evaluate the desired allowances for show rigging and potential scoreboard upsizing to strike a balance between minimizing future retrofit work and day-one construction cost.

Barclays Center

Taking a look at the way structural steel was designed and fabricated for a high-profile multipurpose arena project, Brooklyn's Barclays Center, designed by AECOM and SHoP Architects, is home to the National Basketball Association's (NBA's) Brooklyn Nets and one of the home arenas for the National Hockey League's (NHL's) New York Islanders, in addition to a host for concerts, conventions, and other sporting and entertainment events.

The building design was heavily influenced by the Bankers Life Fieldhouse in Indianapolis, which is rated as one of the premier basketball viewing facilities in the country, and provides excellent sightlines, as the roof structure is much higher than the seating, explains Callow, whose firm did the structural engineering for the project.

But one noted difference between the two arenas is that Bankers Life was a concrete superstructure with a conventional arched truss, whereas Barclays Center was more suited for a steel superstructure and a tied-arch system. This determination was based on initial schedule and cost studies that showed the tied-arch system was an efficient way to achieve the 350-foot roof span.

Working on a congested urban site, the choice of steel also eliminated the potential scheduling challenges of having too many trades on location at one time. On the other hand, with limited real estate for on-site building, the steel structure did not inherently have sufficient lateral stiffness to resist the arch thrust forces alone. The solution was introducing a tension tie to balance the arch forces. Consequently, the thrust forces imposed on the superstructure are greatly minimized.

"This strategy also simplified the overall roof system, as two 'super' tied-arch trusses were provided to span the long direction of the arena, while shallow trusses span between the super trusses and the perimeter," explains Callow. "With the pure arch trusses, it was preferable to distribute that thrust across the whole building, whereas the self-contained load path of the tied arch trusses allowed them to be centralized."

PHOTO COURTESY OF FOREST CITY RATER COMPANIES

A 350-foot long-span structural steel roof crowns Barclays Center in Brooklyn.

PHOTOS COURTESY OF THORNTON TOMASETTI

Pictured here is the erection of primary roof trusses at Barclay Center. Four temporary shoring towers were provided to allow for construction of the tied arch truss elements.

Several analytical studies were performed to both understand and design for some component of the overall thrust that results due to the stiffness of the building, he adds. Construction sequencing with member leave-outs were performed to minimize the amount of the thrust that 'leaked' to the primary structure to maximize the superstructure's efficiency.

Two main tied-arch trusses run in the long east-west direction, spanning approximately 350 feet. Each comprises a 12-foot-6-inch-deep arched upper truss, with chords made up of W14s that vary across the section and a tension tie, consisting of a 14x311 wide-flange member, which occurs approximately 50 feet below the top of the arched truss and 10 feet above the lower ends of the truss for optimized sight-line preservation. The truss configuration was largely dictated by the fabricator's shipping limitations. The tie is hung by a series of eight, 8-inch vertical HSF pipes. Sixteen smaller trusses connect with the large longitudinal trusses and provide the free span of the arena with chord sizes varying from 14x90 to 14x159. Dead loads and lateral loads are resolved into the steel superstructure, with thrust forces from the trusses largely balanced by the ties.

Callow explains that one of the project's main structural challenges was connecting the tied arch to the steel superstructure that rings Barclays Center and forms its street-side concourse. In a conventional design, where the tension tie would connect at the ends of the truss, the truss would rest on a roller or bearing support that could allow the truss some movement. However, for Barclays Center, the connection had to be able to transmit some lateral forces to the superstructure. While the introduction of the tension tie significantly reduces the amount of thrust imposed on the superstructure, it does not eliminate it completely due to strain compatibility between the tension tie elongation and the superstructure lateral displacement. To minimize this effect, Thornton Tomasetti specified a construction sequence involving leave-outs of elements to disengage the arch thrust resistance of the superstructure for de-shoring of the roof structure. This forced the tied-arch action to resist the initial dead load. After the roof was de-shored, these leave-out connections were completed, leaving the superstructure to resist thrust forces under future environmental and live load conditions.

Another unique aspect of the design is its cantilevered canopy. To find the balance between the desired geometry and project budget, Thornton Tomasetti and SHoP Architects performed numerous parametric studies. "To create the 85-foot cantilever, backspan trusses were run from the entry structure storefront all the way back to the primary bowl support columns," explains Callow. "The three-story entry structure to the west of the primary bowl was lightly loaded, and thus it was desired to tie the cantilever backspan back to the heavier bowl structure, like the back anchorage of a diving board."

Coordinating the cladding attachments to the cantilevered structure was one of the more challenging aspects. To address this, Callow's team communicated anticipated movements of the cantilever under dead load, snow, thermal, and wind loads to the facade subcontractor to ensure their joints were able to accommodate the movements. The structure was pre-cambered to accommodate some of the anticipated vertical deflection. In addition, three-dimensional models of the anticipated structural range of positions during cladding panel installation was provided to the cladding manufacturer to ensure they had sufficient range of tolerance in attachment points.

"One of the less obvious benefits of the canopy structure was that the creation of the back span trusses that were needed to support the cantilever allowed for elimination of columns in the entry structure VIP restaurant region, as the back span truss was able to span over the region," says Callow.

Barclays Center Green Roof

The second chapter of the Barclays Center story is the arena's 135,000-square-foot green roof addition, also designed by AECOM an SHoP Architects.

"The green roof addition served a dual purpose by providing a visual amenity to the inhabitants of the surrounding new residential construction and a means of improving the acoustic performance to minimize sound transmission outside of the arena," explains Callow.

To achieve acoustical performance targets, the green roof needed to be separated from the main roof structure by an air gap, which also provided the ideal space to locate new structural elements. While the original structural foundations were designed to support the load of a green roof, this was not the case for most of the superstructure, including the long-span roof.

To minimize penetrations to the existing roof and retrofit work to the side trusses spanning between tied arches that would be difficult to access above the bowl, new trusses were introduced in the air gap space above the current roof to span from the existing tied arches to the perimeter of the building, according to Callow.

ach arch was retrofitted with two 33⁄4-inch-diameter, 300-foot-long steel cables, the type and size more commonly used in bridge construction. The cables were pretensioned to relieve some of the load in the existing tie and provide the entire system with more axial capacity. To connect the cables and transfer the load into the existing structure, new 3-inch-thick cable gusset assemblies were welded to each side of the existing 3-inch-thick arch node.

A new arch-shaped top chord was also posted up from the existing tied arches to increase the overall depth of the tied arch system and subsequently improve its load-carrying capacity. This additional chord is 14 feet above the existing arch chord and is tied into the existing arches with a vertical element at each major panel point and diagonal a bracing elements at the ends of the span. In doing so, the effective depth of the arch under live loads and the weight of the new roof increased from 50–64 feet, with a proportionate decrease in member stresses.

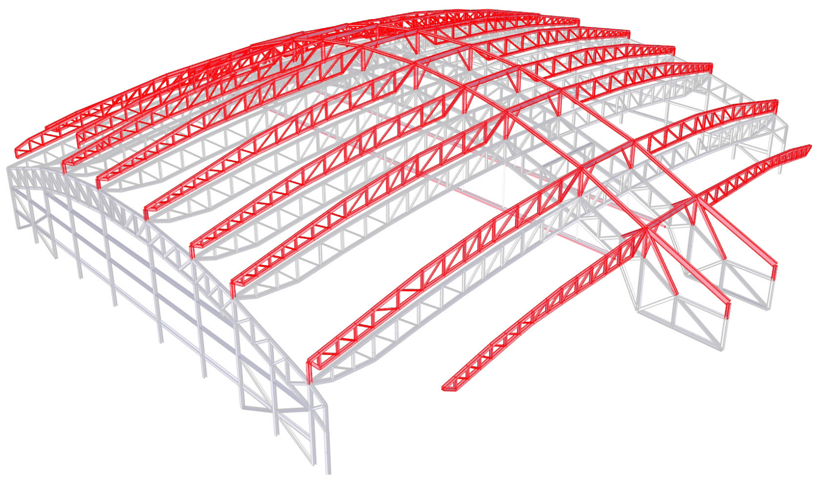


PHOTO COURTESY OF THORNTON TOMASETTI

Supplementary steel trusses are installed above the existing roof to increase the capacity to create the Barclays Center green roof.

In addition to the new elements that were constructed over the existing roof, the existing tension tie was reinforced with a pair of cables on each side of it to increase the tensile capacity of the tie.

To address the erection challenges inherent in transporting the large truss members for installation, ASTM A913 Grade 65 steel was used to reduce their weight. Mid-span shoring posts supported on the existing roof trusses below allowed each of the 170-foot secondary trusses to be erected in two segments with weights under the limiting pick capacity of each crane. Lightweight joists were used to

PHOTO: JAMEY PRICE PHOTOGRAPHY; COURTESY OF 3A COMPOSITES USA

provide infill framing, further reducing the weight of the overall structure and increasing the speed of erection.

Ultimately, a highly integrated building team succeeded in performing green roof retrofit with minimal impact to the arena's busy event schedule.

Nassau Veterans Memorial Coliseum

The Nassau Veterans Memorial Coliseum in Uniondale, New York, a 416,000- square-foot, multipurpose arena best known for hosting NHL New York Islander and American Basketball Association New York Nets games, was recently reclad with

Breathing new life into the Nassau Veterans Memorial Coliseum in Uniondale, New York, approximately 4,700 unique aluminum fins were used to reclad the 416,000-square-foot facility. The canopy cantilevers approximately 85 feet from the primary building and features an open-air oculus in the center with large curved video boards.

approximately 4,700 unique aluminum fins, a move that breathed new life into the 1970s facility.

"Each of the elements in this system varies slightly in profile and dimension to create a subtle flow that reflects the big skies of the flat Long Island landscape," states SHoP Architects, the project's architect, in a description of the project.

Instead of tearing down and rebuilding the facility, the project successfully met the Coliseum's needs to provide a state-of-the-art, regularly used venue at a fraction of the budget.

A highly integrated building team essentially put their heads together to come up with an efficient and effective way to marry the building enclosure's new shape and a new form without forcing that design upon the structure.

One major issue was how to attach the cladding. The initial schematic design employed steel structural channels, but this would have involved going behind the existing concrete siding. Building enclosure subcontractor Crown Corr then proposed a space-frame construction approach. Not only did this circumvent the risk and cost of penetrating the arena, but it embellished SHoP Architects' vision for a reinvented skin.

"Instead of channels and angles installed behind the fins, now there would be tubes and space-frame nodes," relates Cerone. At the same time, SHoP Architects needed to understand the aesthetic implications of this change. Fortunately, it was easy to model the change and the architects were happy with the results. More specifically, the architect utilized a high-fidelity digital process, leveraging LiDAR scanning to survey and model existing conditions, to which design models were tailored, coordinated, and evolved into fabrication. "Structural steel aided the process due to the accuracy of fabrication tolerances," he adds.

Going into more detail about this innovative attachment approach, Thornton Tomasetti's Callow explains that the existing building had 32 radial perimeter concrete columns shaped like a U. "Through coordination with SHoP Architects and Crown Corr, we developed a detail where a short horizontal steel member would be connected between the two stems of the U-shaped column. By utilizing the cavity, we were able to connect the member to the existing concrete column using a shear transfer rather than a direct face mounted tension connection."

Crown Corr then connected their secondary steel elements directly to this new member.

"Two anchors on the top and bottom of each of the 32 piers from which the structural steel space frame allows long spans—approximately 45 feet—support all additional secondary structure and finish cladding," adds Cerone.

PHOTO COURTESY OF THORNTON TOMASETTI

Nassau Veterans Memorial Coliseum's new facade panels contain a secondary steel backup system that spans to existing building columns.

A wide-flange horizontal beam spanning the inner faces of the U-shaped pier holds the outrigger supports that intricately fits the aluminum cladding fins in the prefabricated metal space frame and attached it to the existing structure. Crown Corr's structural lug comprises a W14x132 flange spanning 4-foot-wide welded end plates, which are bolted and epoxied to the concrete. Welded to the face of the W-flange are two match plates, from which 10-inch-diameter HSS tube frames provide welded 'half-nodes' for attaching adjacent space-frame panels. The attachment points are separated by approximately 9.5 feet of elevation. The space frame was assembled from HSS in diameters that vary from 2.375–3.5 inches according to tuned-to contextual loads and load paths. The chords were threaded into spherical nodes ranging from 3.5–7 inches in diameter.

The aluminum cladding material itself offered a high level of flexibility and was therefore easy to form into precise shapes. This, coupled with the cladding's natural brushed finish, enabled SHoP Architects to create the aesthetic effect it was seeking.

"The aluminum finish picks up the ambient light and color well during different times of day and reflects the sky and sunset," Cerone explains. "As the crowd moves into the Coliseum, colors from their clothes and the surrounding trees also get reflected into the material."

The project's main challenge was the juxtaposition of the existing structure's regular geometry with the new facade's undulating surface, which required the new structural elements to take the form of the new shape and transfer its load back to the existing column grid. "The ability of steel to span the large distances between the existing concrete columns with a lightweight structure was critical to minimizing the cost to the reclad and minimized the load imposed on the existing building," Callow explains.

Mercedes-Benz Stadium

Opened in 2017, Atlanta's Mercedes-Benz Stadium designed by HOK features a pinwheel-style retractable roof—an architectural gesture inspired by the oculus in the roof of Rome's Pantheon—made possible by an intricate and highly integrated feat of engineering.

Made from facade panels clad in single-skin ETFE (ethylene tetrafluoroethylene), the transparent, inflated lightweight material exerts minimal weight on the eight long-span cantilevered moving petals, which open and close in under 10 minutes.

As stated in a Buro Happold blog, as the structural engineer on this massive, $1.6-billion project, "the complex geometry of the facades, framed with elegant lightweight steel, help to create an iconic exterior."

The uniquely designed roof incorporates a two-way spanning truss system, which is unusual for a long-span roof. According to Yasmin Rehmanjee, PE, SE, LEED AP, principal, Buro Happold, New York, each truss is 70 feet deep and reframed with a 12-foot-square top chord truss box

consisting of four chord members, with the tension chord 58 feet below. "The roof structure is framed with four primary trusses that span 723 feet and provide support to the downward force from the cantilevered, moveable panels," she says.

In addition, secondary trusses support the uplift rails for the moving petals. Both 65-ksi and 50-ksi steel were used, which included the newest available jumbo shapes (W14×873) at the time.

From the project's onset, the design team set out to conceive an unprecedented operable roof—using more moving pieces and smaller spans with the intention of creating an opening that operates faster than any other retractable roof in an eye-catching manner.

"Despite giving a visual effect similar to a camera shutter when opening, each of the petals moves along straight tracks on the fixed roof," Rehmanjee explains. "Constant and in-depth information exchange is required between

PHOTOS COURTESY OF AMB SPORTS & ENTERTAINMENT

Atlanta's Mercedes-Benz Stadium features a highly intricate pinwheel-style retractable roof, a unique two-way spanning truss system, and single-skin ETFE facade panels. (top) Mercedes-Benz Stadium's unique roof features eight long-span cantilevered moving petals that can open or close in under 10 minutes. (left) the structural engineer and the mechanization contractor to ensure that the mechanization is capable of handling the loads imposed by the moveable panels."

In describing the intricate engineering that went into achieving this, Bill Darden, president of Darden & Company, the project management firm overseeing development of the stadium, compared the construction to a Swiss watchmaker working with micro-ounce pieces that are so small you can barely even know they are in your hand, with one major difference. In this case, "there are 4,000 tons of steel in these eight petals, and we are trying to accomplish the same exact thing because these pieces have to move at the exact precise time and must have very tight tolerances between the bogies and rails. It is very precise…we are literally talking about 1/16 and 1/32 of an inch," explains Darden in an interview with the Atlantic Journal-Constitution.

In addition to the challenge of supporting eight moving roof panels, the roof trusses had to be placed in such a way as to not block the roof opening but rather frame the 60-foot-tall halo video board at the stadium.

The board itself is quite remarkable. Called the Halo Board, it is a 360-degree, 58-foot-tall, high-definition LED video display delivering an immersive and theatrical experience whether the roof is open or closed.

To create this impressive new stadium with its 72,000 seats, 18,000 tons of structural steel was used for the fixed roof, 4,000 tons went into the retractable portion, another

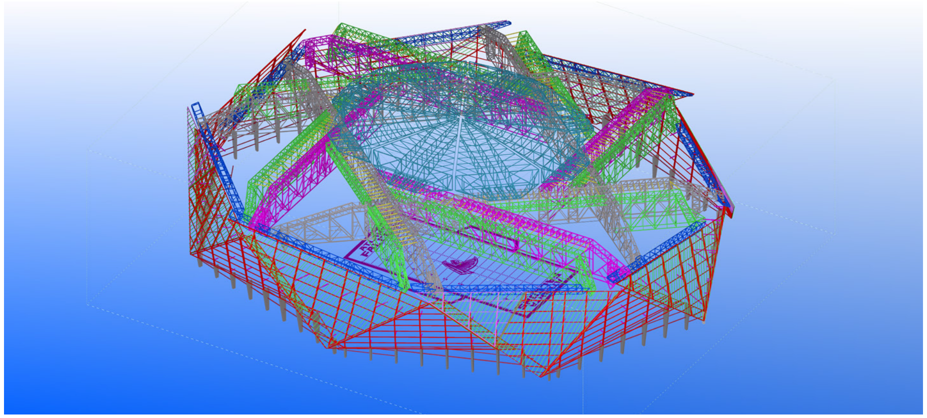


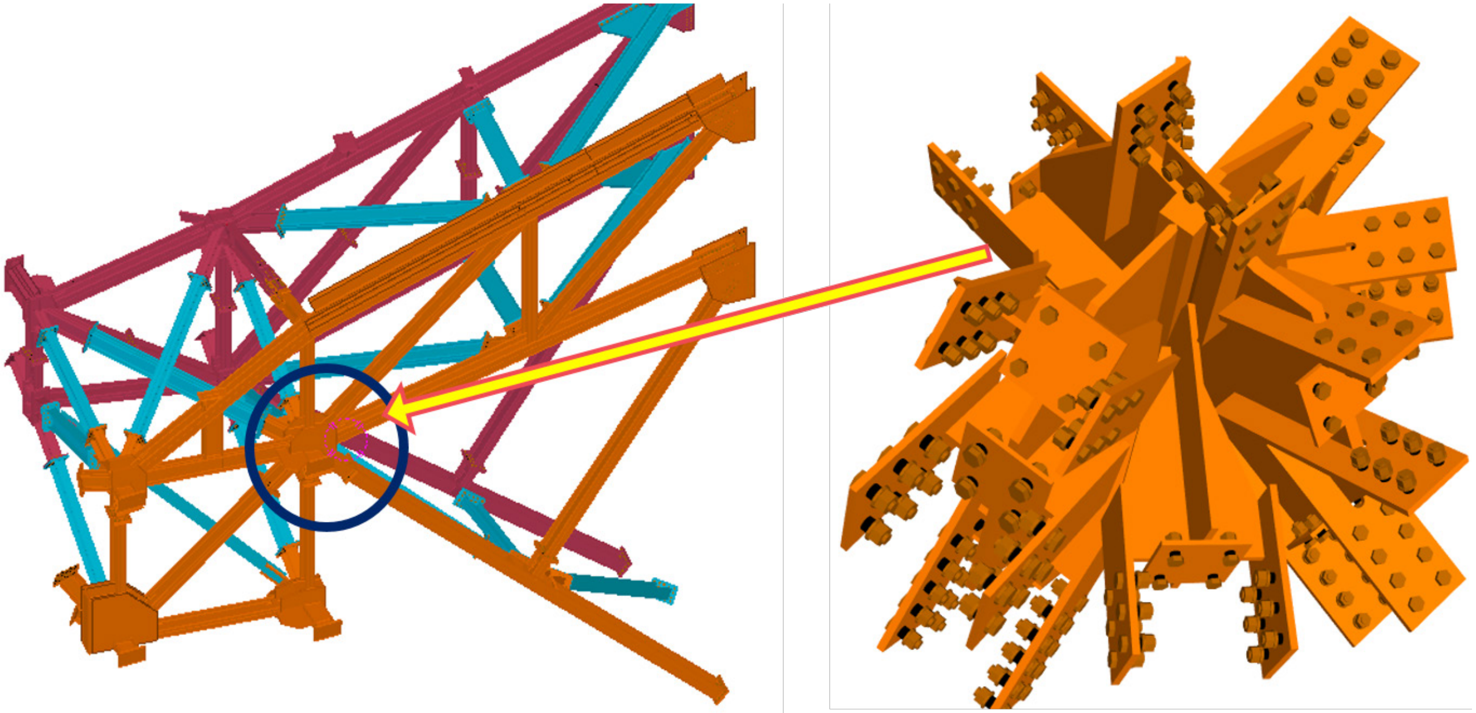
IMAGE COURTESY OF BURO HAPPOLD

This structural steel Tekla model consists of about 70-foot-deep trusses with 12-foot top chord box trusses comprising four chord members, with the tension chord 58 feet below. Four primary trusses span 723 feet to support the entire fixed roof as well as the cantilevered, moveable panels.

4,000 tons make up the 'skin' of the building, and 580 tons support the video board.

Rehmanjee describes the importance of understanding how the structure will be built while correctly accounting for the forces that get locked into the structure during construction—a crucial part of the project delivery process. One part of this equation is the structural engineer making an assumption about construction sequence, which must be communicated to key contractors when they come on board. In the case that the contractor changes the construction sequence to suit their preference, it is of utmost importance that the roof design is reevaluated for the revised sequence to ensure that the members and connections are still capable of resisting any changes to load demand.

IMAGE COURTESY OF BURO HAPPOLD



This 3-D image shows a connection detail of the complex steel nodes for trusses in which several members frame into a single location. The Mercedes-Benz Stadium roof structure includes both 65-ksi and 50-ksi steel, as well as the newest jumbo shapes at the time, W14×873.

On the Horizon

Whether it is more iconic elements, large retractable roofs, mega-size scoreboards, or large-scale operable windows, future arenas will demand bigger, better, and more advanced facilities than ever before.

And as arenas seek to create more unique experiences, designers will be challenged to find that balance between flexibility and authenticity, or as Miller explains, "conceiving a facility that can easily accommodate any event but also provide a custom-designed, event-specific experience for every fan."

To address the challenges that lie ahead, Callow believes that structural steel is well served to achieve the high strength, light weight, and ability to fabricate to form unique geometries that will be demanded. Staying a step ahead of the game, Thornton Tomasetti has started creating and integrating fabricator-ready Tekla (a popular BIM software program well suited for structural design) models into its design process for sports projects constructed with steel. "By doing this, we not only can help owners achieve faster schedules, but we can also work through the complicated geometry using parametric tools and develop connections in lock-step with the architect to achieve more dramatic forms," he explains.

Callow adds that the firm has already been utilizing high-strength 65-ksi steel on numerous long-span projects and anticipates that higher strengths are on the way, particularly with bolted fasteners that may further enhance the efficiency of tomorrow's structures.

PRIORITY ONE: THE SCOREBOARD

As the number-one focal point in any sports arena, the scoreboard captures the play-by-play action in a technologically impressive display.

"No single feature in a sports venue attracts more attention from fans than the scoreboard—a massive, meticulously branded showpiece floating above the event floor with the ability to communicate directly with fans in real time and generate revenue through constant and dynamic product messaging," states Bart Miller, PE, principal, senior project manager, national sports market leader, Walter P. Moore, Houston.

Tracking the trends, scoreboards continue to grow in size and shape, from cylindrical or cube, to elongated and rectangular, and everything in between. Design wise, they incorporate open frameworks, full LED coverage, and venue-specific aesthetics.

And while the new LED technologies and high-strength aluminum framing materials allow the boards themselves to be lighter, the fact remains that the increased overall size, components, and capabilities mean that the entire system is becoming significantly heavier, Miller says.

Case in point, Walter P. Moore is currently involved in the installation of a new, state-of-the-art, kinetic, 4-D scoreboard as part of an ongoing multiphase renovation at the Wells Fargo Center in Philadelphia.

"The transformable scoreboard, which transitions from a conventional square board that can be recessed into the existing roof structure to a massive rectangular board that maximizes area for live-action feeds and sponsorship opportunities, weighs four times more than the original scoreboard installed in the late 1990s," Miller says.

Consequently, the existing roof structure has required extensive strengthening, including reinforcing the primary long-span roof trusses, the replacement of the original hoist platform, and the introduction of new support structures for additional equipment.

"Because the existing structure was composed entirely of structural steel, strengthening was easily implemented through the installation of bracing members and/or supplemental steel plates to overstressed members and additional field-welding of overloaded connections," Miller explains. "Because the platform connections to the primary structure were bolted, framing could be easily removed in the field and new replacement members could be welded into place."

Correa agrees that the high strength and low weight of structural steel makes it the material of choice for long-spanned roofs and cantilevers. "As stadium design evolves to create spaces that are destinations unto themselves, there is increased need to create spectacular design and inviting spaces. In addition, it is becoming more and more prevalent to build arenas and stadiums that can accommodate several weather conditions, and this is done by transparent roofs that open or walls that slide. Structural steel supports these design aspirations well."

Again, the ultimate goal is gaining the flexibility to be able to operate in a variety of event modes. "With the right brief at the outset, it is possible to design an efficient structure in steel that can accommodate flexibility in spectator requirements and behavior, and different event loading patterns," says WSP's Chipchase. "They can also be designed and detailed to facilitate permanent conversion by way of removal, addition, or modification to the primary structure to transform following a major event, for example, where the brief and requirements fundamentally change."

One other emerging trend is what Aryes describes as entertainment-focused, immersive super theatres. While he cannot specify "where this will take us," one thing he is sure of is that the inherent benefits of steel will make it the material of choice for long-span arena structures of all shapes and sizes for many years to come.

Continuing Education

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To earn one AIA learning unit (LU), read "Adapting to Change: Arenas Rely on Steel" and complete the test at continuingeducation.bnpmedia.com. Upon passing the test, you will receive a certificate of completion and your credit will automatically be reported to the AIA. Additional information regarding credit-reporting and continuing-education requirements can be found at ce.construction.com, under "Resources and Requirements."

Learning Objectives

1 Summarize multipurpose arenas' evolving needs for adaptability and flexibility to service a variety of venues.

2 Discuss the benefits of structural steel roofs for arenas, including their light weight, high strength-to-weight ratio, and ability to support growing high-capacity rigging load requirements.

3 List key factors that must be considered when designing a long-span arena roof.

4 Review the structural design details of noteworthy steel roof retrofit projects.

AIA/CES Course #K2005E

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“The driving force for material selection for building around active tracks is to maximize the load capacity of the structure while minimizing disruption to the railroad. Steel is certainly a stronger material and has the advantage of reducing the area taken up between tracks to support high-rise buildings above. Steel further has the advantage of the pieces being customizable offsite for a perfect fit that can be set quickly and minimize disruptions.”

—Juan Estevez, Vice President of AECOM Tishman, on the task of constructing structural steel platforms over Manhattan’s active rail yards.
Architectural Record, June 2019

Steel Institute of New York

The projects in this eBook are visual testimonials not only to the sophisticated level of engineering and architectural design involved, but also to the contractors who specialize in the challenging, highly interdisciplinary work of building them. Those who erected the structural steel, mostly contributing members of the Steel Institute of New York, were key to the expansion of usable urban space that characterizes each project. What sets them apart is their reputation for delivering high-quality work on the complex projects you have read about, and their knowledge of how best to execute them. Construction is extremely deadline-driven, which is why general contractors look for experienced subcontractors who can devise and implement innovative solutions to overcome challenges. Those they seek out deploy technology platforms that enable them to undertake every aspect of the work. For the projects featured here they wanted to be confident that on-time completion would be achieved, even when the erection and stabilization of steel members could often only proceed within limited time frames. This kind of performance by subcontractors leads not just to winning more work, but to winning the jobs they want with the general contractors they want to work with. We look forward to covering more of their noteworthy projects in future eBooks. You can also read about other innovative solutions to the challenges of building in New York by visiting our website www.siny.org.

Gary Higbee, AIA
Director of industry development

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