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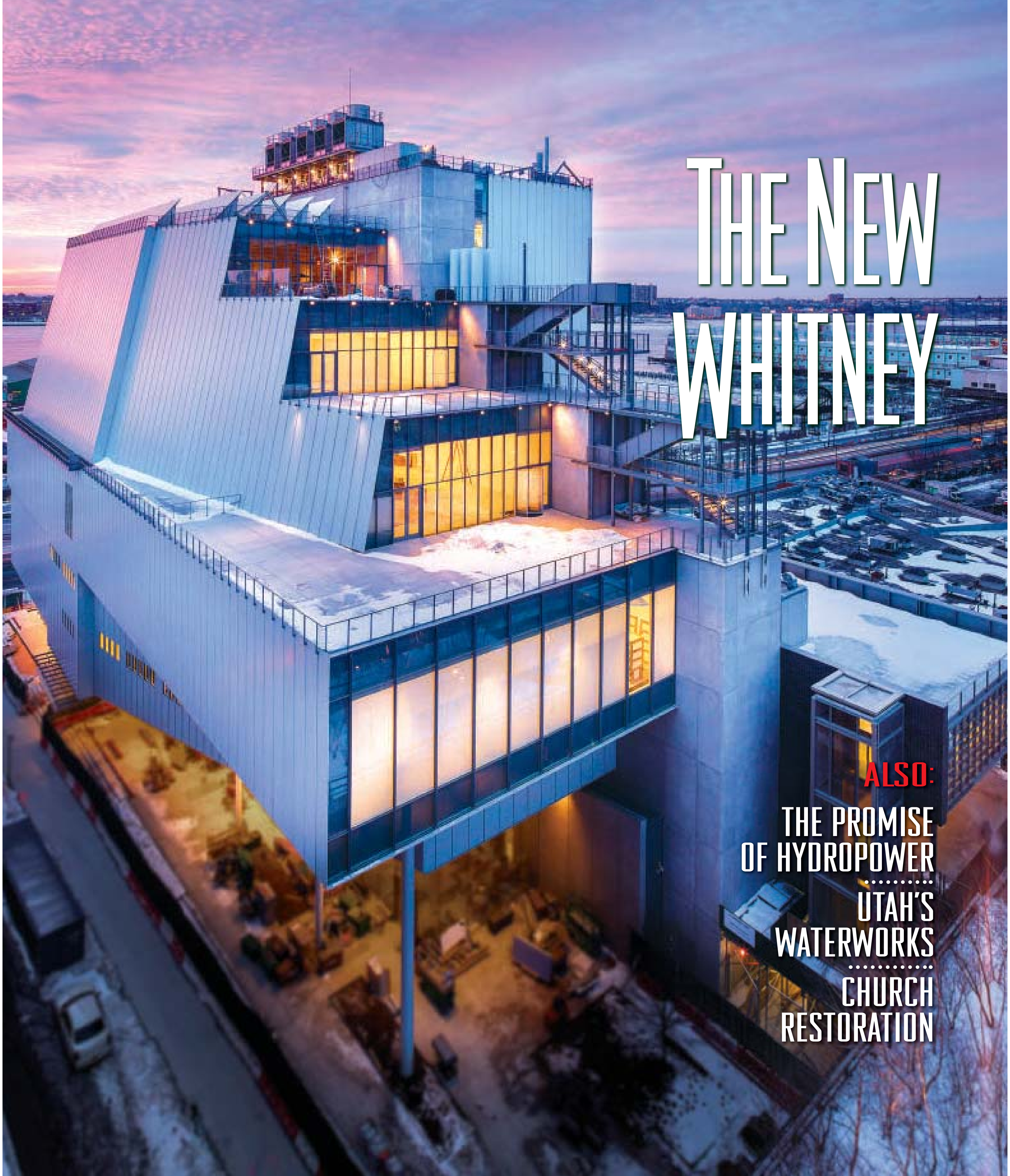

THE NEW WHITNEY

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DESIGNING THE NEW

The Whitney Museum of American Art, a Renzo Piano–designed triumph that proudly displays its complex structural engineering elements as functional works of art, has moved into its new home, in lower Manhattan.

By Shinjinee Pathak, P.E., and Victoria G. Ponce de Leon, P.E.

FOUNDED IN NEW YORK CITY'S Greenwich Village in 1931 by Gertrude Vanderbilt Whitney to showcase the work of living American artists, the Whitney Museum of American Art moved to its Marcel Breuer–designed home, on Madison Avenue at 75th Street, in 1966. By then its collection encompassed some 2,000 pieces, but today the museum has more than 22,000 modern and contemporary works. To better showcase these and to provide additional programming space, the museum commissioned a new building in Manhattan's dynamic Meatpacking District. Its new home is nestled between the Hudson River and the High Line, the pioneering elevated park created from a disused rail line.

Designed by the renowned architecture firm Renzo Piano Building Workshop (RPBW), which has offices in Genoa, Italy, and Paris, in collaboration with Cooper Robertson, of New York City, the new museum is meant to be an imposing yet inviting urban structure. The nine-story asymmetrical building features tiers of terraces and glazed walkways that step down to the High Line. It cantilevers dramatically over a public gathering space along Gansevoort Street, and its setback entrance there opens into a nearly 10,000 sq ft lobby that features a gift shop, a restaurant, and exhibition space. A theater, an office, and support spaces, as well as expansive new galleries, are located on the floors above. At 18,000 sq ft, the fifth-floor gallery is the largest column-free museum gallery in New York City. On the top floor a

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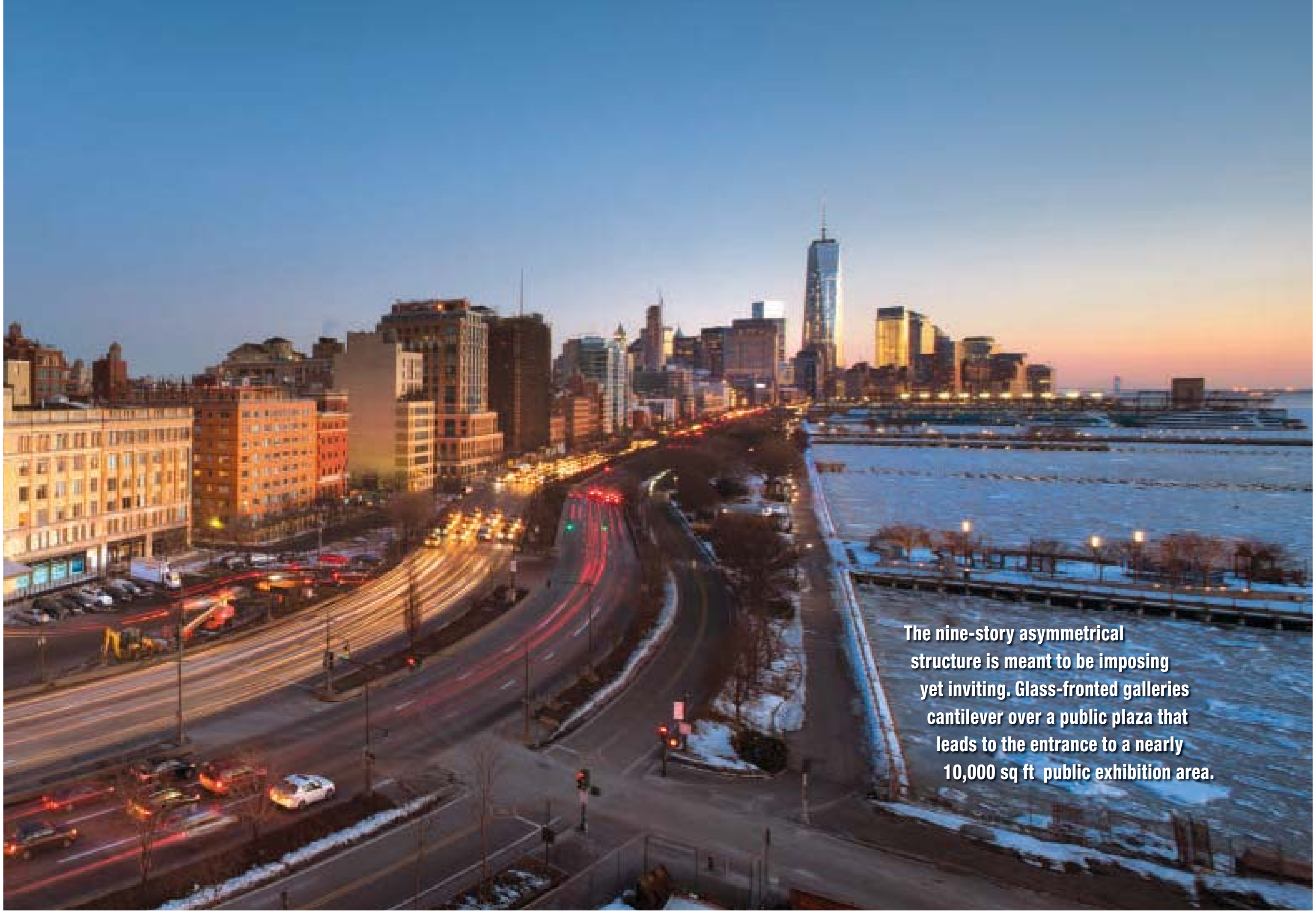

The nine-story asymmetrical structure is meant to be imposing yet inviting. Glass-fronted galleries cantilever over a public plaza that leads to the entrance to a nearly 10,000 sq ft public exhibition area.

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WHITNEY

gallery and a café are naturally lit by a sawtooth skylight system. The new building provides approximately 50,000 sq ft of indoor and nearly 13,000 sq ft of outdoor gallery space for the museum.

The structural design for the new Whitney building was developed by the New York City office of Silman beginning in 2007. The structural system was engineered to provide flexible, open-plan galleries for the museum and to realize the architect's vision. The typical challenges of coordination were even greater for the design of the Whitney, where high-end architecture was to meet high-profile artwork. To meet the needs of the institution, adhere to the concept of the architects, and satisfy the demands of the mechanical and electrical systems, all while keeping in mind the limitations of the construction site, Silman was heavily involved in coordination with many professions and worked collaboratively to maintain the aesthetics of the design.

The superstructure of the museum involves composite steel framing with concrete on metal deck slabs. Steel was chosen to achieve the design's long spans and open spaces. The south half of the building houses the four main galleries (on the fifth through eighth floors), each having a larger floor plan area than the one above. The open-plan layouts programmed by RPBW provide flexibility for movable partition walls and for displaying large art installations. The gallery floors were also designed for loads of 50 to 100 psf, in addition to the minimum 100 psf occupancy live loading, to accommodate heavier works of art atop the floor framing or extra loads from installations hanging from beneath the floor structures. Three of the four outdoor terraces were treated as extensions of the interior gallery spaces, so allowances were made to support art that would be displayed in these areas.

Construction began in 2010. Given the site's proximity to the Hudson, water was a concern during excavation and in designing the permanent foundation. Moreover, the western half of the site sits on landfill, which meant that there was a higher probability of obstructions to work carried out in support of excavation. Along the west side, these conditions ruled out the traditional approach of using sheet piles and made a tangent pile system necessary. The contractor for the work carried out in support of excavation—Urban Foundation/Engineering, LLC, of East Elmhurst, New York—decided to use traditional soldier piles and lagging on the east side along the High Line, with tiebacks where possible and cross-lot bracing in the north–south direction. Given the depth of the foundations, additional wales were used here. Conventional tangent walls built against the

existing meatpacker buildings at the northwestern edge of the site were used to support the excavation.

Independent of the work carried out in support of excavation outside the building, conventional cast-in-place interior concrete foundation walls were designed around the entire site. These walls were designed to withstand not only the 9.15 ft design flood elevations (with respect to the North American Vertical Datum 1988 [NAVD 88]) required by the Federal Emergency Management Agency but also the lateral earth pressures. The project's geotechnical engineers, from URS Corporation (now part of Los Angeles–based AECOM), determined that the site's soil was of poor quality and recommended a structurally reinforced concrete mat slab atop 621-ton minicaissons. The minicaissons are steel casings 13.75 in. in diameter filled with high-strength grout and reinforcing bars of size 24. The caissons reached lengths of 100 ft and had a 16 ft rock socket to accommodate both tension and compression loading.

In October 2012 the construction of the museum was in full throttle, the foundations substantially completed and the superstructure under way. It was then that Hurricane Sandy struck New York City. With only the West Side Highway as protection from the Hudson, the site was quickly flooded.

Given the site's proximity to the Hudson River, water was a concern during excavation and construction of the deep foundations. On the east side, cross-lot bracing was used in the north–south direction.

The building lobby had been strategically established above the design flood elevation at 11.65 ft with respect to NAVD 88 to avoid having to contend with the possibility of floodwaters and debris loading the lobby's facade system, which would be a glass cable wall. Sandy delivered a reported flood elevation of 12.95 ft with respect to NAVD 88, exceeding the lobby elevation and the design flood elevation. The museum mobilized the design team to address flood mitigation and brought on a specialist for flood analysis and mitigation services, WTM Engineers, a German firm with offices in the city. Rather than model the site, WTM collaborated with the Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering—part of Germany's Leibniz Universität Hannover—to analyze potential flood levels on the basis of historical data. From this, the design team decided on a flood level of 18.15 ft with respect to NAVD 88, which is the level that would probably result from a hurricane of category 2 on the Saffir-Simpson scale. This level was even higher than the elevations specified in the revised Federal Emergency Management Agency maps released a few months later.

As WTM analyzed the flood elevations, Silman discussed the effect of the different flood elevation levels on the existing ground-floor structure and the public gathering space along Gansevoort Street. Because the ground floor was nearly

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finished, it was clear that simply reinforcing the floor structure and the glass cable wall for the 18.15 ft elevation would not be sufficient; the building required a robust system of barriers, gates, and flood doors. This system was designed by Walz & Krenzer, Inc., of Oxford, Connecticut. Silman helped design the attachments of this system, collaborating with Cooper Robertson and RPBW to architecturally integrate these points of attachment into the building design. Drainage configurations in the public gathering space along Gansevoort Street were altered, waterproofing details were amended, and hidden concrete beams were added under the plaza's topping slab to support the new flood loads.

Walz & Krenzer's flood barrier system was designed for hydrostatic pressure, the action of nonbreaking waves, and debris impact. With the exception of the flood doors, which are permanent fixtures at the staff entrance and at the loading dock at the west side of the building, all of the barriers and their connections to the building were designed so that they could be stored off-site and brought in prior to a flood event.

Although New York City is not generally thought of as an area of significant seismic activity, the Whitney's new location on poor soil and its irregular geometry meant that seismic factors would control the lateral design. Because part of the site was once a landfill, the area was considered a seismic site of class E as defined in the 2008 edition of New York City's building code. As a result, the building would have been assigned a seismic design category of D (high seismic vulnerability). However, by performing a dynamic response spectrum analysis, Silman took advantage of a

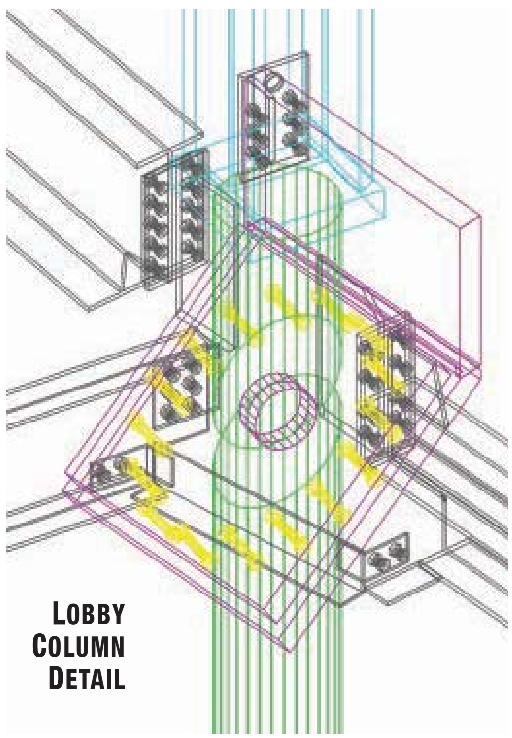
Architecturally exposed braced frames and cantilevered plate girders support a two-level space, the plate girders transferring loads to setback columns below.

It was important to the architects that the exposed connections at the top and base of the lobby columns be true working connections, not just aesthetic representations.

provision in New York City's building code to design the building under category C (moderate seismic vulnerability). In addition to a modal analysis, Silman performed a lateral pushover analysis to confirm that the trusses, which act as lateral elements as well as systems supporting gravity loads, were stiff enough to withstand a seismic event.

The building's lateral system was effectively designed as having separate north and south halves, a core spine separating the diaphragms of the two halves. The large open galleries on the south left limited locations for lateral frames. Two braced frames were therefore accommodated, and these remain exposed for use as architectural elements. Limited locations for the lateral braced frames introduced discontinuities into the load path and required transfer elements at nearly every floor. The geometry of the building created torsional irregularities, diaphragm discontinuity, a weak story, a soft story, and both in-plane and out-of-plane offsets in the lateral system. For this reason, most of the elements in the building were designed for seismic forces amplified by an overstrength factor, resulting in several very large members. W14 sections were used for the majority of the columns and braces, the largest section being a W14 × 500.

The building's large, visible cantilevers are also architectural and structural points of interest. The uppermost five stories transfer loads at the fifth-floor gallery, which cantilevers in two directions over the lower four floors and is free of interior columns. The 25 to 80 ft long cantilevers are achieved with a full-story truss that spans along the south side of the fifth-floor gallery. This truss is supported by two-story trusses that span in perpendicular fashion, their top chords being built-up plate girders 46 in. deep. These trusses were left exposed in the office spaces on the fourth and third floors, adding to the aesthetic appeal of the interior.



Lobby Column Detail

At the front of the building the north–south trusses are supported by architecturally exposed structural steel columns of circular cross section. These slender columns vary in height from 15 ft to 55 ft and are 15 in. in diameter, with the exception of the tallest column. To maintain the small diameter of the majority of the columns relative to their heights while still providing the required structural support, most of the columns were designed as customized circular hollow steel sections. The more heavily loaded columns were solid steel. The column at the building's southeast corner is 55 ft long and 22 in. in diameter. This custom-designed steel pipe is filled with high-strength (8 ksi) concrete and contains two vertical reinforcing bars of size 11 (150 ksi), the concrete and bars acting compositely to strengthen and stiffen the section. The lobby columns alone account for approximately 150 tons of steel.

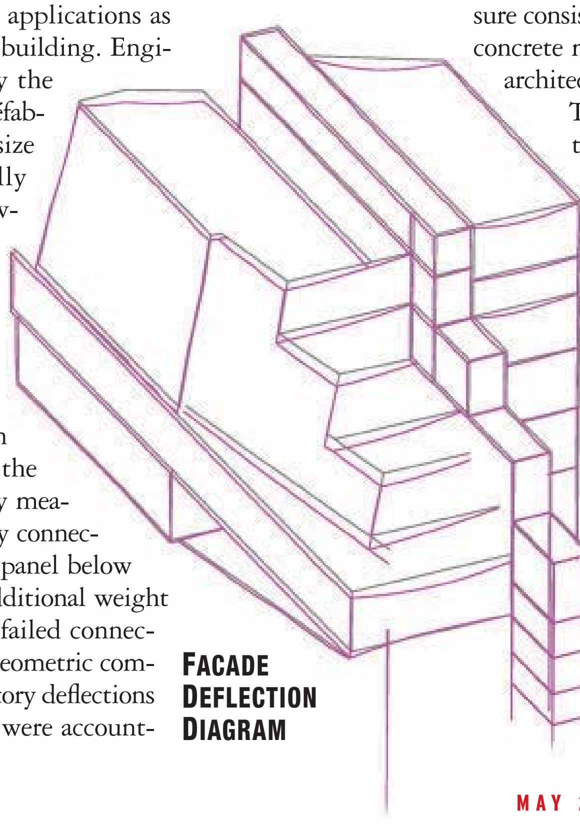
These columns and their connections contribute both to the structure and to the architecture of the lobby. It was important to RPBW that the exposed connections at the top and base of the columns be true working connections, not just aesthetic representations with the actual structural connection hidden above. The slope and skew of the building facade extend to the column splice plates, creating complex three-dimensional connections that link the interior and exterior spaces. Silman used Rhino software, developed by Robert McNeel & Associates, of Seattle, to analyze the geometry and detail the plates, bolts, and thermal breaks. The engineers also worked closely with the project's steel detailer, WSP Mountain, Inc.—a division of the Canadian conglomerate WSP | Parsons Brinckerhoff—and the steel contractor, Banker Steel, of Lynchburg, Virginia, to optimize constructability.

The mechanical, electrical, and plumbing (MEP) systems for an art museum are by necessity extensive and can be very heavy. Silman coordinated with the architects and the MEP engineers—Jaros, Baum & Bolles, of New York City—to keep the main ducts aligned with the structural framing and sized beams to allow for large web penetrations spaced evenly apart; this was especially important in the main gallery, where the structural framing overhead would be exposed.

The two-story basement space is nearly filled with MEP units and piping, much of which was laid out only during the construction phase of the project. To avoid overstressing the slab-on-metal-deck construction, anchor points and loading for all hanging MEP equipment were individually reviewed for their effect on the structure. Here Silman and the construction manager—Turner Construction Company, of New York City—coordinated their efforts.

The structural supports for the building's large cantilevers remain visible as points of interest within the museum.

The unique and engaging facade of the Whitney consists of precast-concrete panels, steel panels, and glass. Precast panels were used in both interior and exterior applications as architectural elements of the building. Engineered and manufactured by the Canadian company Béton préfabriqué du lac, they varied in size and shape but were typically 5 in. thick. Each panel is gravity supported at the top and laterally supported at the top and bottom. Redundancy of the panel connections was taken into consideration by accounting for the weight of the panel above in the design of the gravity connection of the panel below. This redundancy measure ensures that if the gravity connection of a panel ever fails, the panel below will be able to support the additional weight of the panel above until the failed connection is addressed. Given the geometric complexity of the building, interstory deflections and projected building drift were accounted for in the panel joint and panel connection design as well.



FACADE DEFLECTION DIAGRAM

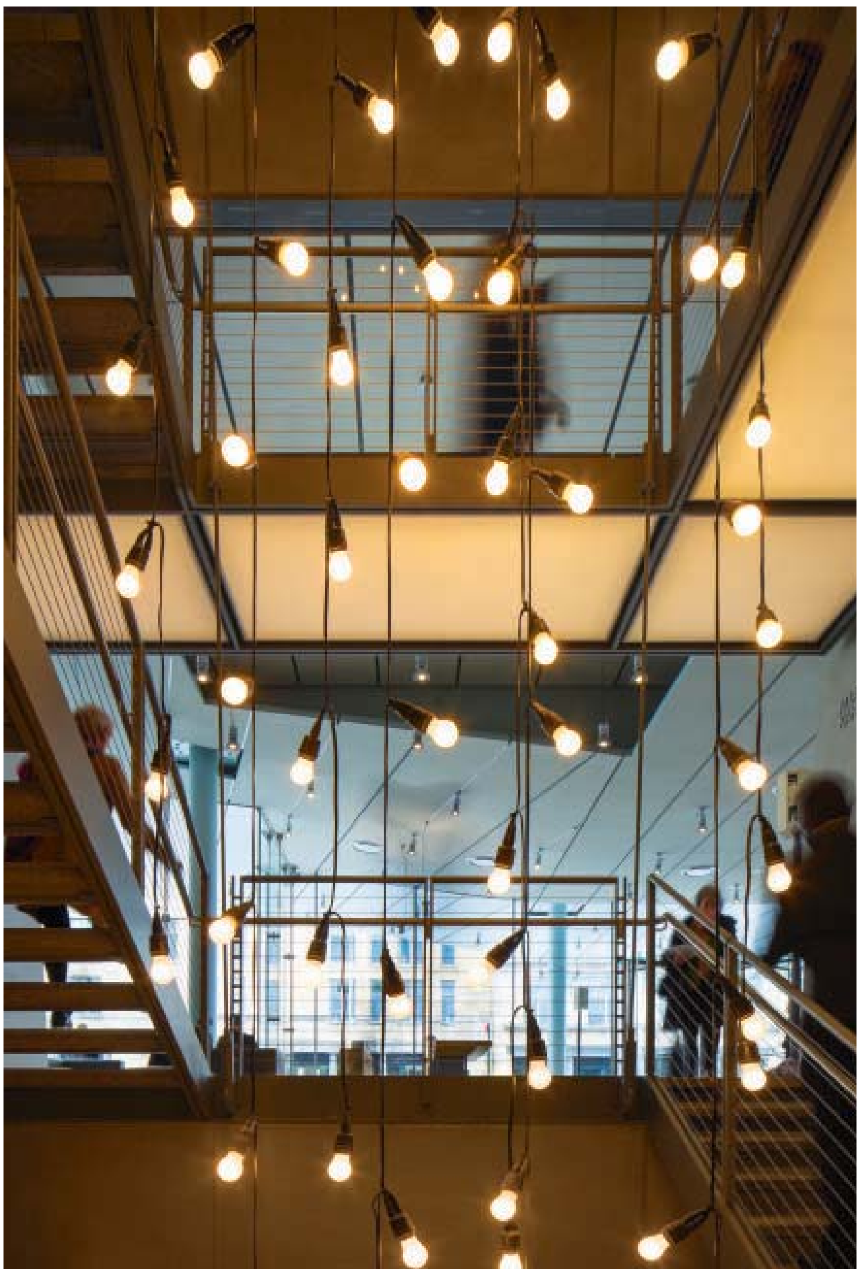
The architectural finishes of the precast panels were of great interest to the design team, so mock-ups of the panels were fabricated to ensure consistent quality and to confirm that the concrete mix designs achieved the prescribed architectural specifications.

The steel panels that clad much of the exterior of the building are $^3/_8$ in. thick, 3 ft 4 in. wide, and up to 60 ft long and were manufactured by the German firm Josef Gartner GmbH. Each panel is hung from the top and braced laterally at each floor. The beams above support the panels' gravity loads and were designed for the full weight of each panel, and the lateral connections provide redundancy by also being able to support the weight of the panel in the unlikely event that an upper connection fails. Because the steel panel facade was integral not only to the building's aesthetic character but also to its performance, performance mock-ups for structural strength and thermal and water infiltration were developed, in addition to visual mock-ups for the painted finish on the steel.

The glass curtain wall at the east and west ends of the gallery spaces—designed by the facade consultant Heintges & Associates, which has offices in New York City and San Francisco, in collaboration with Josef Gartner GmbH—admits natural light and provides expansive views of the city. The building's structure was designed for the deflection limitations of the glass curtain wall, which were particularly strict at the fifth floor's operable glass wall, which was provided by NanaWall Systems, Inc., of Corte Madera, California. Here the limitations were designed to prevent the door track from binding.

A glass wall supported by a cable system wraps around the ground-floor lobby and restaurant. Following the sloping profile of the lobby ceiling, the cable wall ranges in height from 24 ft to 45 ft, the corresponding cable tension loads ranging from 20 kips to 85 kips. Silman and Heintges & Associates coordinated the work involved in the initial design of the glass cable wall and the structural support system. Silman provided the load path assumptions, deflection expectations, and stiffness values of the primary building structure, and in return Heintges & Associates provided the tension forces in the cables and the resulting loads imposed on the structure above and below. After several iterations to fine-tune the cable wall system and the supporting structure, the connections were designed so that adjustments could be made in the field to the prestressing of the cables.

The often-photographed winding stairway from the lobby to the fifth floor surrounds an art exhibit by Felix Gonzalez-Torres.



While the building's long-span beams and cantilevers were designed to meet standard deflection criteria, the structural analysis model revealed that the absolute deflection in some locations was of sufficient magnitude to warrant tracking based on construction sequencing. Silman recognized early in the design phase the value of sharing this information with the design and construction teams, particularly as doing so would make it easier to accommodate postinstallation movements of the facade and the curtain wall. As part of the construction documents, Silman provided deflected-shape diagrams of the building and deflection values at critical points under each type of loading separately to enable the contractor to estimate the expected building movement at any point during installation. (See the figure on page 55.)

One of the most celebrated elements of the new structure is its striking interior stairway, which spirals up from the lobby to the fifth-floor gallery; it may be one of the most photographed spaces within the museum, partly because of the ethereal art installation by Felix Gonzalez-Torres that cascades down its central open core. The stair stringers, which are solid routed plates 2.75 thick and 9 in. deep, are supported at two points on each side by steel plates that knife through the precast panel stair walls on three sides. The stair is also supported around its central core by 0.75 in. diameter rods hung from steel beams between the fifth and sixth floors. Two of the four rods are connected to the ground-floor structure by a spring clevis custom designed by TriPyramid Structures, Inc., of Westford, Massachusetts. The rods are also coupled at each floor by a custom connection that also was designed by TriPyramid.

The Catalogna bluestone stair treads

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The glass curtain walls at the east and west ends of the gallery spaces admit natural light and provide expansive views of the city.

are set atop steel plates that span to each stringer. The stone tread and steel support were designed to act compositely to support the required loading of the stairs while realizing RPBW's vision. Throughout the design process, Silman collaborated with RPBW to provide a stair that would be aesthetically pleasing, satisfy the strength requirements of the New York City building code, and be satisfactory to the user.

Anchor points on the terraces and north facade of the Whitney were designed to provide flexibility for hanging or bearing large works of art. Silman collaborated directly with the museum to strategically locate the anchor points and design the system for an acceptable capacity. The Whitney opened on May 1, 2015, and since then it has retained Silman as the structural engineer for reviewing the structural feasibility and effects of displaying works of art and art installations. This extends to sculptures located on the fifth-floor terrace, which is also the roof of the High Line maintenance and operations building, adjacent to the museum. That facility was designed and constructed within the same time frame as the Whitney, and Silman worked with its design team to coordinate work on the adjacent foundations, negotiate around property lines, and understand the loading requirements and allowances for the roof terrace.

As the structural design of the new Whitney building advanced, it became clear that in many situations the structure would be part of the architecture. Silman therefore had to be adaptable and creative in the design and, in many cases, take the lead in acquiring and incorporating information from various parties to optimize the design while preserving the architect's vision. Since its work involved coordination, analysis, design, and production, the organization of the engineering project team was of paramount importance. The Silman team consisted of a leading partner, an advising associate, a project manager, and several engineers. The team members worked together tirelessly to coordinate the efforts of the design consultants and the construction teams and to find solutions to issues without losing sight of project priorities. The result is a building in which the structure is on display, supporting the architectural design and promoting the art within. **CE**

Shinjinee Pathak, P.E., is a senior engineer and Victoria G. Ponce de Leon, P.E., an associate with Silman. Both are in the firm's New York City office.

Pathak

Ponce de Leon

PROJECT CREDITS **Owner:** The Whitney Museum of American Art, New York City **Owner's representative:** Gardiner & Theobald, New York City office **Design architect:** Renzo Piano Building Workshop, Genoa, Italy, and Paris **Executive architect:** Cooper Robertson, New York City **Structural engineer:** Silman, New York City, Boston, and Washington, D.C. **Construction manager:** Turner Construction Company, New York City **Landscape architect:** Mathews Nielsen, New York City **Civil engineer:** Philip Habib & Associates, New York City **Geotechnical engineer:** URS Corporation (now part of AECOM, Los Angeles) **Support of excavation contractor:** Urban Foundation/Engineering, LLC, East Elmhurst, New York **Mechanical, electrical, and plumbing engineer and fire consultant:** Jaros, Baum & Bolles, New York City **Flood analysis and mitigation services:** WTM Engineers, Hamburg, Germany **Flood prevention system design:** Walz & Krenzer, Inc., Oxford, Connecticut **Facade consultant:** Heintges & Associates, New York City and San Francisco, and Josef Gartner GmbH, Gundelfingen, Germany **Steel detailer:** WSP Mountain, Inc., a division of WSP | Parsons Brinckerhoff, Montreal **Steel contractor:** Banker Steel, Lynchburg, Virginia **Lighting and daylighting engineer:** Arup, London **Leadership in Energy and Environmental Design consultant:** Viridian Energy and Environmental (now Vidaris, Inc.), New York City