Engineering an EXPERIENCE

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At the brand-new National Museum of African American History and Culture in Washington, the building itself is a striking and enduring part of the exhibit.

THIRTEEN YEARS AFTER IT WAS ESTABLISHED by an Act of Congress in 2003 and nine years after the design was selected through an international competition, the Smithsonian Institution's new National Museum of African American History and Culture (NMAAHC) was dedicated on September 24 by President Barack Obama and a host of dignitaries and benefactors.

Located on the National Mall in Washington, D.C., the museum chronicles and memorializes the African American experience in a new 376,000-sq.-ft building that itself becomes part of the story. The structure uses steel throughout (just over 4,000 tons) to achieve the sweeping programmatic and aesthetic goals and enhance the visitor experience.

Two-thirds of the museum's space is below grade, extending 65 ft underground on four different levels. The below-grade structure is primarily framed in cast-in-place concrete, including the mat slab and pile-supported foundations, concrete floor slabs and concrete columns. The museum's main permanent historical exhibition, located below grade with a green roof above it at grade level, was originally to be framed in cast-in-place concrete as well. However, due to the fast-track schedule and in conjunction with the owner, exhibit designer and contractor, the roof was redesigned in structural steel after construction of the facility had already begun.

Long-span steel beams and custom plate girders with only two lines of columns create the interior open space critical for gallery exhibitions for this level, and a central steel-framed oculus allows light


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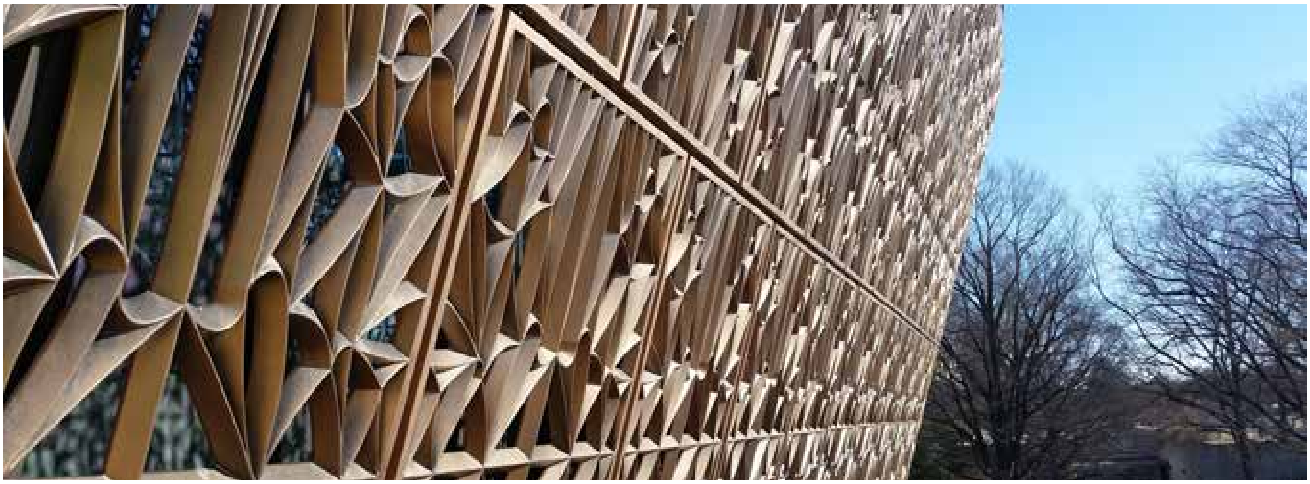
The steel-framed history gallery roof (at grade). The plywood box at right is temporary protection around the installed Pullman train car.

The oculus from below.

The museum's delicate cladding system resembles an African carved wood crown, or corona.

The Corona frames into the building structure only at level 5 and at the base of the museum, thus creating a continuous atrium surrounding all sides of the museum.



into the exhibition space from grade level. The oculus is framed with rolled W40×183 steel beams at the first floor, and the pop-up roof is built from tapered plate girders that radiate out. Steel also eliminated the need for complicated shoring within the gallery during concrete curing, which would have inhibited ongoing work below. It also allowed for the installation of large exhibit items—such as a Pullman train car and a Louisiana State Penitentiary guard tower—without delaying roof construction. This level was quickly redesigned as construction progressed to allow enough time for steel fabrication while maintaining the overall schedule.

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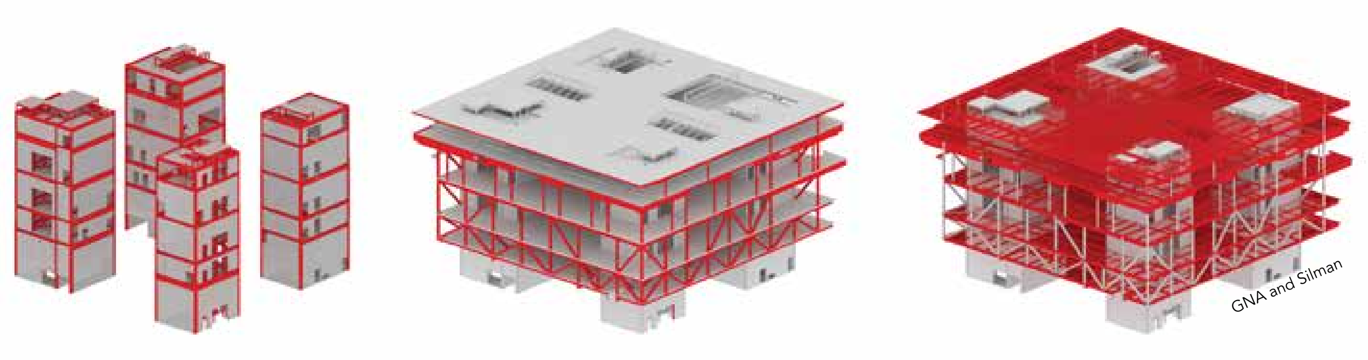


Steel composite cores, perimeter trusses and floor framing.

Steel Composite Cores

The five-story above-grade structure of the museum, including its iconic facade system, is supported entirely from four structural cores in order to create a column-free ground-floor lobby. The four structural cores are composite systems made up of steel floor beams and corner steel columns. These beams and columns are made composite through shear studs with reinforced cast-in-place concrete infill walls and support both the entire gravity load of the building as well as serve as the primary lateral force-resisting system. This composite system provided greater lateral stiffness, allowed for greater flexibility in the coordination of large penetrations through the walls for building services and provided greater resistance to blast loading and progressive collapse than a traditional braced-frame core system. It also allowed for simpler connections between the cores and the long-span and cantilevered steel framing in the building than typical reinforced concrete walls.

The reinforced concrete infill walls vary in thickness from 10 in. to 16 in. depending on the shear force transfer required. They are perforated in numerous locations for architectural openings, mechanical ducts and other utilities. The concrete infill walls are connected to the steel columns and beams with headed shear studs, which allow shear and axial force transfer between the steel frame and walls, and in some locations reinforcing bars are coupled to the steel frame. The boundaries between the steel and concrete where the shear studs are located are heavily reinforced with closed stirrups to provide confinement around the shear studs. A blast-loading analysis was carried out on the core systems to determine out-of-plane pressures on the infill walls and to identify upgrade requirements to steel framing sizes.

Four separate structural models were built in ETABS (v9.7.2) to analyze and design the composite cores:

- Model 1 was a steel-only model with "dummy" diagonal braces used to design the steel core beams and columns for gravity loads and overturning forces due to lateral loads. This model was also used to determine connection design forces for the steel framing.
- Model 2 was a concrete-only model with large openings, explicitly used to determine the required thickness and reinforcement for each infill wall and the total number of shear studs required between the concrete and steel elements.
- Model 3 was a composite model with steel framing elements and concrete shell elements used to calculate the sharing of load between these components and to calculate drift.
- Model 4 was similar to Model 3 except that the stud connector elements were modeled explicitly as nonlinear elements.

Deep composite plate girders span between the structural cores at each level to support the main gallery levels. Additionally, each gallery floor plate projects outward from the cores and is supported by cantilevered steel beams on the north side and perimeter vertical trusses and cantilevered brace "outriggers" framing into the composite cores on the east and south sides.

The Corona

One of the most prominent design features of the museum is its delicate cladding system resembling an African carved wood

The project uses just over 4,000 tons of steel in all.

The level 2 platform with perimeter vertical steel trusses.

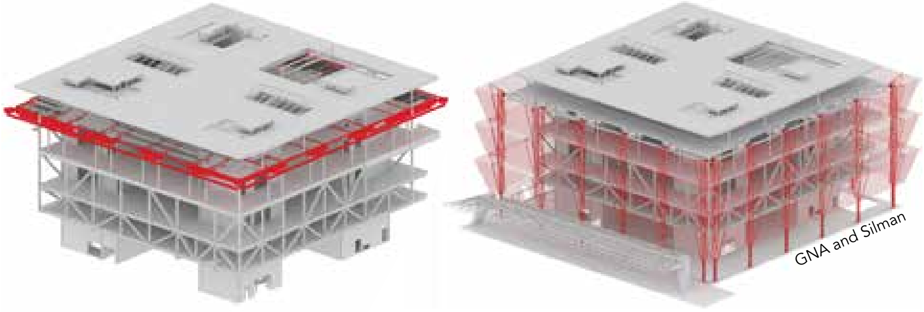
crown, or corona. While conventional building enclosures are typically connected at each floor level of a building, the Corona frames into the building structure only at level 5 and at the base of the museum, thus creating a continuous atrium surrounding all sides of the museum.

Based on several framing studies conducted early in the design process, it was determined that suspending the glazing and cladding support structure from the top of the building rather than from the base would be advantageous in limiting the member sizes of the cladding structural elements, as the self-weight would effectively pretension these elements against compression loads induced by wind and other transient loads. The decision to support the cladding from the top of the museum structure led to a number of complexities in the design of the building's superstructure. These included stringent drift requirements for the lateral load-resisting system, complex base connections requiring fixity and freedom of movement along different axes and consideration of unusual load paths for wind and other transient loads such as blast and seismic acting on the facade system.

The schematic design for the Corona support structure included a series of suspended horizontal trusses supported by vertical cables and braced with in-plane diagonal X-cables. Gravity loads were resisted in tension by the vertical cables, and lateral loads such as wind loading on each face were transferred laterally by the horizontal trusses to the orthogonal faces of the structure, which in turn functioned as inverted braced frames to transfer these lateral forces in-plane to level 5.

However, as a result of value engineering and construction sequencing considerations, this 3D structural system was replaced by hung vertical trusses comprised of architecturally exposed hollow structural steel sections (HSS) spanning approximately 92 ft from the base of the building to level 5 in the final built design. The glazing that provides the enclosure of the building envelope is located on the inner face of the vertical trusses. Perforated cast aluminum panels clad the outer faces, and service catwalks are located in the cavities between these surfaces.

Wind-tunnel testing was conducted for the Corona system to determine wind loading requirements on both the glazing and the cladding, and special analysis was conducted to calculate the significant ice loading requirements on the exposed steel and cladding panels.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▲ Level 5 cantilevers for the Corona support (red at left) and the Corona as it hangs from the overall superstructure (right).


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▲ The porch canopy structure, under construction.

▼ An integrated Revit model showing a perspective view.


GNA

▼ A Louisiana State Penitentiary guard tower is one of the museum's exhibits.


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The Porch Canopy

Approaching the museum lobby from the south entrance, visitors pass below a massive freestanding canopy structure referred to as the "Porch," which is independent from the rest of the above-grade structure and supports an unoccupied green roof. The structure is made up of an approximately 9-ft by 6-ft steel box girder that spans 172 ft between two built-up steel plate box columns supported from below by concrete columns in the below-grade loading dock. Tapered fabricated steel plate beams cantilever from the south edge of the box girder to create a triangular or wing-shaped cross section to the canopy that supports the green roof surface. As a result of this cantilevered geometry, gravity, wind and blast loading conditions induce significant torsional forces on the primary box girder. The entire steel structure is clad in ultra-high-performance precast concrete panels.

Construction and Coordination

The project team performed trade coordination during construction due to the tight schedule; construction began in November 2011 and was completed in September 2015. For both the below- and above-grade core walls, this meant reviewing MEP penetrations on a floor-by-floor basis, often only a few days before construction or even the day that concrete was to be poured. The structural engineering team joined the daily phone calls to discuss open coordination and field issues so that they could be resolved immediately and construction could continue. These included steel coordination issues such as connections conflicting with architectural finishes or headed shear studs conflicting with core wall reinforcement. In addition, because the National Mall is federal land run by the National Park Service—and disrupting the surrounding roads is not feasible except in the most extraordinary circumstances—the contractor crafted a site plan to allow room for steel laydown and erection that was coordinated with ongoing construction.

Thanks to these coordination efforts as well as structural design changes that made for a more efficient structure, the latest Smithsonian addition to the National Mall is now open to share its portion of the ongoing American story. ■

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Smithsonian Institution

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Steel Team

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Erector
Bosworth Steel Erectors, Inc.,
Dallas

Detailer
SteelFab, Inc., Charlotte
Prodraft, Inc., Chesapeake, Va.

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