The REACH at the Kennedy Center

The form and forming of a living monument

by Yvonne Nelson

As reported in the November 2020 issue of *CI*, the REACH, a 72,000 ft² (6700 m²) expansion of the John F. Kennedy Center for the Performing Arts in Washington, DC, USA, received the Overall Excellence Award in the 2020 ACI Excellence in Concrete Construction Awards program. The REACH is comprised of three prominent pavilions connected by studios, classrooms, and a parking structure below an interwoven green roof (Fig. 1). This article provides insights into the execution of some of the project's outstanding features.

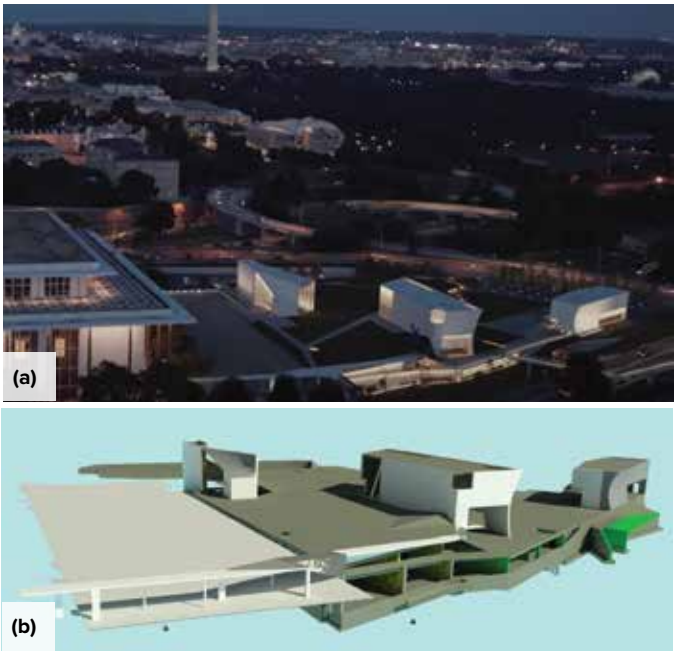


Fig. 1: Prominent exterior features of the REACH at the Kennedy Center include three pavilions and a covered walkway: (a) an aerial view shows the pavilions (right foreground) relative to the Kennedy Center's original building (left foreground); and (b) a rendering from the concrete building information model (from the left: the Welcome Pavilion, Skylight Pavilion, and River Pavilion) *(images courtesy of: (a) the Kennedy Center; and (b) Scott Hover, then BIM Manager at Lane Construction)*

Overview

At first glance, the three pavilions of the REACH—the Welcome, Skylight, and River Pavilions—appear to be three independent structures planted within a terraced landscape covering about 5 acres (2 ha). However, upon further inspection, the terrace is a green roof above two levels of interconnected corridors, performance spaces, practice halls, and a parking structure below.

The green roof is supported by a post-tensioned slab incorporating Cobiax void formers to minimize dead load (Fig. 2). Void formers greatly reduce the nonstructural concrete from the middle of the slab, effectively decreasing

Fig. 2: A post-tensioned slab incorporating Cobiax void formers

the dead load and maximizing overall slab span. During the construction phase, some of the voids had to be eliminated to ensure enough anchorage capacity for formwork loads without impacting the original design parameters for span and deflection. The post-tensioning was also reviewed to ensure adequacy for construction loads.

Throughout, the REACH complex features a variety of exposed concrete finishes and structural and architectural components. The base of the structure is supported by a 2 ft (0.6 m) thick mat on existing caissons and new H-piles, whereas the level above comprises solid slabs (both one-way and two-way), two-way voided slabs, and two-way post-tensioned voided slabs. The green roof structure primarily contains one-way post-tensioned voided slabs except for the roof structure over Studio K, which is a post-tensioned one-way slab with a sawtooth soffit.

The Welcome Pavilion

The form

The Welcome Pavilion provides a spacious main entry and visitor lobby for the REACH. Prominent features include 40 ft (12.2 m) tall, board-formed concrete walls, cantilevered concrete stairs, a conical roof over the uppermost entryway, and a vaulted lower ceiling near the lower entryway (Fig. 3). The latter feature creates a contoured region in the green roof adjacent to the lobby (Fig. 4).

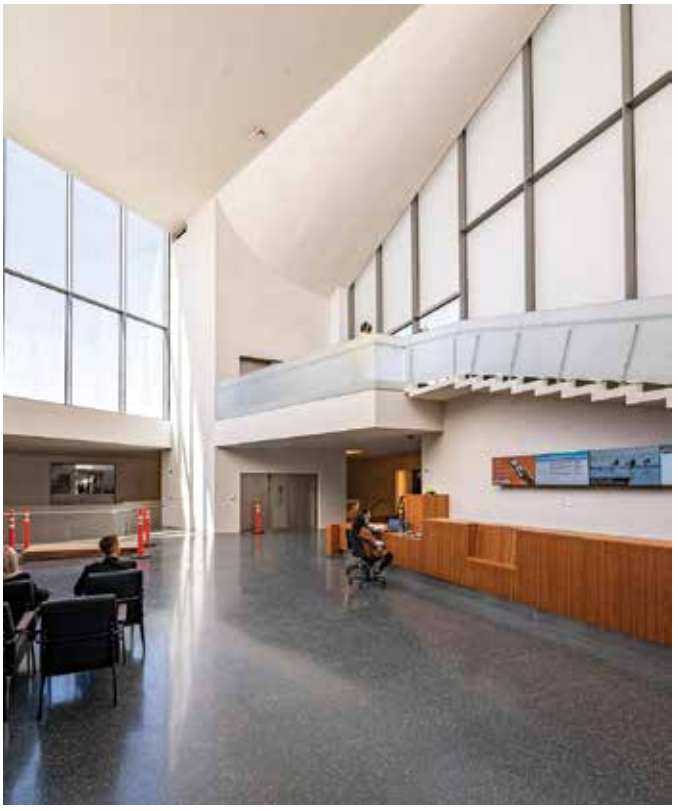


Fig. 3: A conical roof slab and cantilevered concrete stairs provide distinctive features in the atrium of the Welcome Pavilion

The forming

The upper roof slab and beams of the Welcome Pavilion were cast on elevated forms supported by shoring that was up to 40 ft tall (Fig. 5). The conical section of the upper roof created many unique design and construction challenges because the shoring had to resist both horizontal and vertical forces. Additionally, the distinctive shape required a dampproof membrane in between two layers of concrete and an architectural concrete finish (Fig. 6).

After much consultation, the construction team opted to place the two layers using both a conventionally placed low-slump concrete mixture and shotcrete without using a form for the exterior face of either layer. The custom formwork for the interior structural layer was fabricated with the aid of a computer numerically controlled (CNC) router using data from Lane Construction Corporation's three-

Fig. 4: The green roof near the Welcome Pavilion follows the contours of a vaulted ceiling in the pavilion below

Fig. 5: Shoring and formwork at the Welcome Pavilion. In the background, 40 ft (12 m) tall shoring is in place for the elevated roof slab that forms the upper atrium ceiling. In the center of the image, variable-height shoring was erected for the 92 ft (28 m) long post-tensioned concrete beam needed to support the vaulted slab that forms a lower ceiling in the pavilion. The contour of the vaulted slab was formed on boxouts fabricated using a CNC router. The boxouts were supported by the orange deck members in the foreground

Fig. 6: The conical slab comprises a gray structural concrete layer, a roofing membrane, and a white exterior layer. The form was achieved using both formed concrete and shotcrete placements.

dimensional (3-D) building information model (BIM) of the pavilion. After the interior gray structural layer was placed, fiber composite connectors were installed and an elastomeric roofing membrane was applied. The connectors penetrated the membrane to ultimately connect the two layers of concrete. On top of the membrane, an outer white layer of concrete was placed—again using both a low-slump mixture and shotcrete. This approach enabled Lane Construction to manually produce a smooth architectural finish and follow the roof's curvature to form a consistent shape.

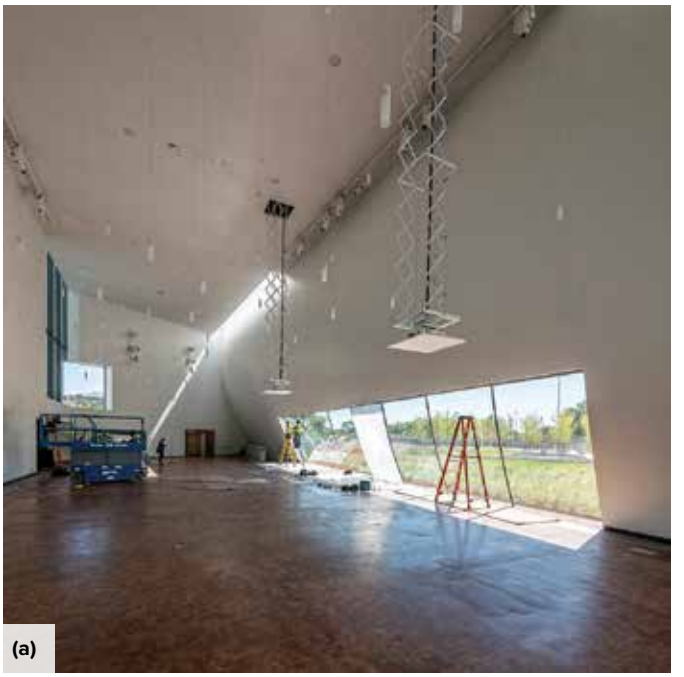
The Skylight Pavilion

The form

The Skylight Pavilion is the project's crowning achievement, featuring an expansive atrium and a 145 ft (44 m) long, 42 ft (13 m) tall, asymmetrically curved wall (Fig. 7). Overlooking the Potomac River, natural light from the slotted roof and large, curved windows in the south-facing wall create an elegant gathering space. On the north face of the pavilion, a vertical exterior wall serves as a large outdoor projection screen for audiences to enjoy movies and simulcasts.

The forming

The Skylight Pavilion is a very complex structure and the largest of the three pavilions. The "wave-shaped" wall is curved and warped, with each spline being unique. At the base, it includes the large opening for the curved window; and at the top, it is loaded and laterally supported by a reinforced concrete roof that is slotted for skylights at each end (Fig. 7). The base of the curved wall was complicated even further because it extends below the historic flood elevation and required a membrane sandwiched between two placements of concrete to prevent flooding of the enclosed space. The high mass, complex geometry, and key design features of the



(a)

(b)

Fig. 7: The interior of the Skylight Pavilion: (a) during installation of the curved glass window overlooking the Potomac River. The glass and the embed forming its frame were manufactured in Germany to match the curvature of the wall. Very tight tolerances were required for the embed installation, so formwork deformations were strictly limited. Note the skylight penetration adjacent to the curved wall; and (b) view of the opposite end of the Skylight Pavilion after removal of the forming and shoring. The roof structure includes transfer beams to accommodate skylight openings

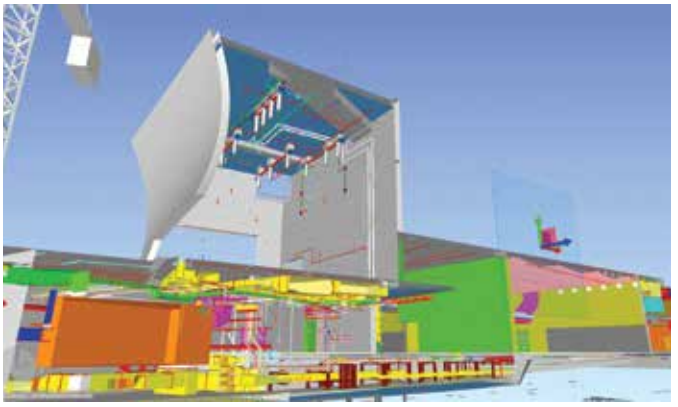


Fig. 8: A section through an integrated BIM model shows the Skylight Pavilion (left) and Studio K (right). The model was used for clash detection with other trades and for communication of issues. The contractor issued hundreds of requests for information (RFIs) in order to create the extremely detailed BIM model. Jim Feezer, then Superintendent at Lane Construction, considered coordination between trades to be one of the biggest challenges on the project

curved wall provided tremendous challenges for the construction team (Fig. 8).

After being awarded the formwork contract, PERI performed a complete analysis of a 3-D model of the wall formwork to assess the constructability of the curved wall. While the design team had specified that the wall be pumped from the bottom and placed monolithically, PERI was concerned about the high pressures from both the self-consolidating concrete (SCC) and the corresponding resultant forces in the two stop-end systems at each end of the wall. In lieu of a monolithic placement, PERI first considered a two-lift placement and calculated the construction loads to be transferred to the voided slab of the permanent structure below.

The engineer of record (EOR) conducted an analysis of these anticipated formwork reactions, and this showed that the permanent structure below could not support the construction loads resulting from a full-length, two-lift placement. To avoid overloading the supporting structure, PERI recommended a three-lift placement (Fig. 9). This increase in the number of

Fig. 9: The curved "feature" wall of the Skylight Pavilion required an extremely complex formwork system: (a) the initial formwork towers above the site, adjacent to the tower crane; (b) the tongue-and-groove board finish was especially challenging to create on the curved surface; (c) uniform tie spacing was required; and (d) the scale of the wall is made clear by this photo of the crew commemorating the final placement of the wall concrete

placements significantly impacted the material and labor costs. Although the outside formwork could be left in place for all placements regardless of the number, the change from two-lift construction to three-lift construction added about 50% to the quantity of forms and attachments needed for both the outside and inside formwork assemblies.

This modification had the greatest impact on the inside face of the formwork, as each lift of interior forming and falsework had to be stripped and the wall braced before the subsequent lift of forming and falsework could be set. The added formwork created additional engineering challenges. Because each spline of the wall is unique, each panel of formwork also had to be unique, and each connection and bracing condition had to be designed and detailed independently.

Early on, formwork designers anticipated that the curved wall would need to be tied into and placed with end wall returns to facilitate forming the bulkheads at each end and to prevent cracking in the curved wall. Because it could not be reasonably assumed that the wall was self-supporting until the roof slab was tied into the curved wall, it was imperative that much of the formwork and shoring remain in place and that bracing be provided for the stripped inside face of the wall until the roof slab had been placed and gained strength. This requirement added substantially to the rental costs for the formwork and shoring for the outside face, plus the formwork, shoring, and labor for the inside face. Ultimately, leaving the inside face of the formwork and shoring in place also complicated the shoring design for the roof slab and sequencing for the entire operation, including transfer beams bisecting the roof at the top of the wall and supporting the slab edge at the skylights (Fig. 7).

As the formwork design was developed, PERI initially assumed that the form ties would be horizontal. This would have allowed the back of each formwork panel to be fabricated perpendicular to the ties, thus reducing the need for custom detailing of the stiffbacks. However, the design team rejected this concept, as the desired aesthetic instead required each form tie to be perpendicular to the face of the finished concrete. This condition added to the engineering costs for the formwork because it required that each stiffback was chorded between ties rather than simply running vertically for the length of the panel. The articulated stiffbacks required more intricate bracing for each panel, so the complexity of the bracing calculations and associated details increased significantly.

The River Pavilion

The form

Located at the southernmost end of the Kennedy Center campus, the River Pavilion houses a café with views of the Potomac River and a new pedestrian bridge. The smallest of the three aboveground structures in the REACH, the River Pavilion continues the themes of the other structures with a conical roof slab and an asymmetrical curved wall with board-formed finishes (Fig. 10).

Fig. 10: A conical roof slab is a prominent feature of the River Pavilion. In contrast to the conical slab at the Welcome Pavilion, this feature was placed using a single layer of manually finished white concrete: (a) an interior view; and (b) an exterior view

The forming

As with the curved wall of the Skylight Pavilion, the curved wall of the River Pavilion was constructed with white SCC and tongue-and-groove board form lining. While this shorter wall was constructed in two lifts rather than three, the wall's proximity to the cut for the Rock Creek Parkway made it necessary to anchor the formwork bracing only on the interior side (Fig. 11). Because there was no slab to support the exterior forms, heavy channel strongbacks were used to

Fig. 11: A view of the interior shoring and formwork required to construct the curved wall of the River Pavilion

Fig. 12: Studio K is a multipurpose room that takes its name from the late president's last initial. The space includes acoustic "crinkle" concrete walls and a sawtooth concrete ceiling with integral light fixtures. The concrete slab soffit profile was cast to match the form of the blue covering. Although this slab supported the green roof and was post-tensioned, it did not include void formers

resist the loads of the asymmetrical placement. These channels extended down one level and were anchored into the foundation wall below.

Though the River Pavilion is the smallest of the three structures, it was not without its challenges. Coordination of the construction and a "top-down" formwork sequence was vital to the structural integrity of the building. Once the River Pavilion walls were in place, the flat portion of the roof was placed and tied into the perimeter walls, followed by placement of the conical roof slab. After the roof was in place, high roof shoring and bracing for the perimeter walls was stripped to make way for an intermediate hung slab. Shoring at wall openings remained in place throughout this sequence.

Studio K and the Justice Forum

The form

Over 11,500 ft^2 (1070 m^2) of the interior wall surfaces of the REACH were constructed with a crinkle concrete texture featuring 3 in. (75 mm) deep random folds and angles designed to break up sound waves and avoid reverberation between parallel walls (Fig. 12). Studio K is the largest space with this feature, followed by the Justice Forum auditorium (Fig. 13).

Fig. 13: The Justice Forum auditorium also includes crinkle concrete walls. The steps, door openings, and corner reveals created challenges in laying out the liner panels and forming the bulkheads, as a running bond pattern was required to avoid creating a discernable repeating pattern in the crinkle finish. Further, many of the walls had crinkle liner on one side and board-form finish on the other

The forming

Steven Holl, the REACH's architect, came up with the crinkle concrete's unique form pattern by bending sheets of metal. Subsequently, he worked with Fitzgerald Formliners and Form Services, Inc., to transfer the irregular pleated textures to 4 x 10 ft (1.2 x 3 m) elastomeric form liners. During the liner fabrication process, special care was taken to ensure that the folds in the pattern would not inhibit stripping of the formwork. After Aluma Systems' beam gang system was assembled to form the 22 ft (7 m) tall cast-in-place walls of the interior performance spaces, the form liners were oriented randomly in a staggered bond pattern to avoid any appearance of repetition (Fig. 14). To reduce form liner waste and enable stripping of the forms with the staggered bond pattern, a "split" panel was also manufactured. Instead of "cutting" a 4 x 10 ft panel, two 4 x 5 ft (1.2 x 1.5 m) panels were placed at the end of formwork gangs and "matched" at the seam.

The crinkle concrete walls are not only decorative and sound enhancing but also serve as primary structure supports for the portion of the buildings where they reside. The brilliant use of texture and light combine to create a warm and inviting atmosphere for this monumental project.

As previously noted, the exteriors of the Studio K and Justice Forum auditorium walls were constructed with

(a)

(b)

Fig. 14: Although interior walls were to be painted, the surfaces were complex and required very high attention to detail. To maintain a 5 x 4 ft (1.5 x 1.2 m) tie-hole pattern and enable efficient use of the crinkle concrete form liners, conventional Aluma stud forms were used rather than modular gang forms: (a) exterior formwork for Studio K; and (b) interior formwork and crinkle concrete form liners for the Justice Forum

board-formed surfaces. The forms included proprietary crack inducers to minimize the visual impact of contraction joints (Fig. 15). The 22 ft tall walls were placed full height with a gray, high-slump concrete mixture. The challenges associated with these features are discussed in a following section focused on finishes and formwork.

Challenges

The REACH is a concrete monument in a city of monuments, and its unique features demanded extra attention from the planning phase through execution. Some of these features are discussed in the following sections.

Fig. 15: Tall walls were fabricated with proprietary crack inducers to minimize the visual impact of contraction joints

Concrete color and finish

Fifteen mixture designs were developed for the project—all with the stability needed for delivery in the heavy traffic of the Washington, DC, area. The most visually stunning mixtures were the white concrete mixtures used to form the exterior walls and conical roof sections of the pavilions (Fig. 3, 4, 6, and 10). These mixtures (self-consolidating, conventional, and shotcrete) comprised Aalborg White® cement, titanium dioxide, white sand, and light-colored coarse aggregate.

To provide a consistent color, the producer had to establish that a large quantity of the required sand could be obtained over the long project duration. The self-consolidating and high-slump mixtures were used on the exterior board-formed walls, crinkle walls, and columns to ensure consistent finishes. This introduced the additional challenge of designing the wall and column formwork for higher formwork pressures.

The original contract documents called for vertical elements to be constructed by pumping concrete from the bottom of the form. This was investigated in early mockups to evaluate procedures, formwork pressures, and outcomes.

Mockup, mockup, mockup!

The project required extensive use of mockups in the planning and construction phases. Early in the planning phase, 3 x 3 ft (0.9 x 0.9 m) panels were constructed to evaluate the concrete color and board-formed surface appearance. Several larger mockups were created to assess the overall finish on a larger scale. Using these mockups, three different board form finishes were selected for the project: Douglas Fir tongue-and-groove boards, ripped face boards, and a board-form without a vertical grain pattern.

As the preconstruction planning continued, formwork pressure was also a major focus. In an effort to evaluate

design formwork pressure, concrete mixture design, concrete finishes, and placement method, two 20 ft (6 m) tall mockup walls were instrumented with pressure sensors. Pumping the SCC from the bottom and placement from the top were both evaluated during this process (Fig. 16). While the design team initially required monolithic placements by pumping from the bottom of forms, the construction team favored placement from the top of the form. Through the mockup program, it was found that the desired finishes could be achieved by placing concrete through a pump hose used as a drop chute. Top placement reduced the design concrete pressure for the formwork system and minimized both the cost and the weight of the formwork system.

Fig. 16: Mockups were used to evaluate placement methods: (a) pumping at the base of the formwork; and (b) using the concrete pump hose as a drop chute

Fig. 17: Visual mockups were used to test concepts for formwork, form ties (steel or fiber composite), jointing, embed placement, and patching

In the final step of the preplanning phase, three visual mockups were constructed on the grounds of the Kennedy Center (Fig. 17). Each mockup included a singularly curved wall with returns at each end. The mockups proved worthwhile in evaluating many concerns, including means and methods for bulkheads and concrete placement, vertical and horizontal cold joints, matching color of concrete for different placements, type of tie to be used (fiber composite or threadbar), orientation of the ties, form release on board form, and concrete finish on the face of the curved surface. The design team even performed small mockups of the sawtooth slab for Studio K and the crinkle form liner to mitigate issues with stripping and finish. The lessons learned through these mockups along with weekly conference calls with key members of the design and construction team greatly contributed to the success of the project.

Finishes and formwork

Much of the project comprises exposed concrete walls that define the aesthetics of the REACH. The exterior walls were constructed using self-consolidating white concrete with tongue-and-groove board form on the outside face. The finish on the inside face of the exterior walls varies. Many walls were placed with board form on one side of the wall and "crinkle" liner on the other. These varied finishes created challenges with sequencing and stripping the formwork. The interior walls were constructed using gray concrete that was subsequently painted white. In all cases, the designers required that the boards or liner used to create the surfaces were cut and placed to avoid any discernable pattern or repetition.

Further, tie holes had to be laid out in a regular pattern—aligning both vertically and horizontally. This was difficult to achieve on irregular shapes and at corners, as they resulted in high reaction loads. Construction joint locations were limited to wall corners, and this resulted in the need for large quantities of formwork and form liner materials,

particularly boards used to create the board-formed finishes.

The length, height, and asymmetrical shape of the curved wall on the Skylight Pavilion required careful analysis of its effects on the void slab below. Placement height and formwork pressure affected construction loads, labor and formwork costs, and schedule. The position of the curved and asymmetrical wall in the River Pavilion created another set of challenges, as a steep embankment made it impossible to brace the formwork on the concave side of the wall.

Assembly of the formwork panels for the curved walls required large amounts of space and labor. Many of the components in the wall formwork were fabricated in Germany to take advantage of a large CNC router that was able to cut oversize sheets of plywood. The machine was also able to automatically and efficiently lay out the pieces on each sheet as well as label the CNC-cut gussets for each formwork component. Labeling was important in the project's quality control process and helped with the assembly schedule.

The shapes of mockup panel assemblies were verified at the fabrication plant and jobsite using laser scanners. When formwork was placed for the feature wall of the Skylight Pavilion, a laser scan was also performed to ensure proper geometry. A final scan was performed on the cast concrete to verify the formwork had not moved during placement.

The walls were not the only features that demanded close attention to detail. Even the soffit of the slab above the parking level had to meet strict finish requirements. Newly faced modular panels were installed in a layout that was approved by the architect. The result is a sleek and uniform finish on the underside of the deck that provides continuity with the meticulous detail demonstrated throughout the project.

Demonstrated Excellence

The REACH at the Kennedy Center excels at many levels. Outside, its brilliant and sculptural forms create striking icons both day and night. Inside, its textured walls provide aesthetic features as well as acoustic function. It truly is a demonstration of excellence in concrete construction.

Want to learn more about the REACH project? Join us on March 30, 2021, for Architect's Day at the upcoming ACI Virtual Concrete Convention. With presentations by key members of the project team, you will learn more about various aspects of the architecture, structural design, formwork design, and concrete mixture design for this complex project. Want more? The Kennedy Center will present the journey through the construction process from mockups to completion and take you on a behind-the-scenes virtual tour through the final product. Don't miss this in-depth look at excellence in concrete construction. Register today at **www.aciconvention.org**. CEUs available.

Project credits

Architect: Steven Holl Architects
Associate architect: BNIM Architects
Landscape architect: Edmund Hollander Landscape Architects
Civil engineer: Langan Engineering & Environmental Services
Structural engineer: Silman
Façade consultant: Thornton Tomasetti
Acoustic/AV/IT/security consultant: Harvey Marshall Berling Associates
Design project manager: Paratus Group
Preconstruction manager: James G. Davis Construction Corp.
General contractor: Whiting-Turner
Concrete contractor: The Lane Construction Corp.
Formwork and shoring suppliers: PERI and Aluma Systems, Inc.
Form liner suppliers: Fitzgerald Formliner and Form Services, Inc.
Concrete consultant: Reg Hough Associates
Ready mixed concrete producer: Vulcan Materials Co.
Polishing contractor: Cuviello Concrete and Terrazzo Polishing

Selected for reader interest by the editors.

ACI member **Yvonne Nelson** has designed and managed formwork in the Washington, DC, USA, region for 14 years. She is a member of ACI Committees 301, Specifications for Concrete Construction, and 347, Formwork for Concrete, as well as Chair of ACI Subcommittee 301-B, Formwork and Formwork Accessories - Section 2. Nelson was the Formwork Engineering Manager for the concrete subcontractor, The Lane Construction Corporation, during the construction of the REACH.