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TRANSFORMING CHALLENGES INTO ASSETS: DESIGN OF ARTS AND EDUCATION FACILITIES WITH POST-TENSIONED CONCRETE

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TRANSFORMING CHALLENGES INTO ASSETS: DESIGN OF ARTS AND EDUCATION FACILITIES WITH POST-TENSIONED CONCRETE

BY JON WACKER

Facilities designed for the promotion of arts and education take a multitude of diverse forms, housing elements ranging from concert halls to art galleries to interactive classrooms. These forms can rarely be accommodated using uniform, repetitive structural bays, making the selection of an efficient structural system more challenging. Post-tensioned concrete is an appealing choice for the structural system of many of these facilities. This article will provide an overview of several key considerations for the structural design of arts and education buildings and demonstrate through case studies how post-tensioned concrete can transform challenges into assets for the facilities. Key considerations include: accommodating irregular, non-rectilinear building forms; allowing unique adjacencies of space; providing durability for landmark buildings; controlling deflections and vibrations; and promoting aesthetic forms and finishes. Through exploration of these considerations, the versatility of post-tensioned concrete to create incredible arts and educational facilities will be showcased.

IRREGULAR, NON-RECTILINEAR BUILDING FORMS

The spaces in arts facilities are commonly delineated between public, front-of-house spaces, and private, back-of-house spaces. Front-of-house spaces for arts typically lack repetitive elements such as apartment units, office bays, and parking stalls that translate well into uniform, repetitive structural bays. For example, performing arts centers require large, multi-level spaces for concert halls and theaters and signature lobby spaces for pre-function events. Gallery spaces in museums often desire to have varying sizes and unique configurations to optimize user experience. These facilities, however, also have a significant amount of back-of-house space for storage, dressing rooms, offices, and collection storage that mesh well with a uniform bay layout and need to be addressed with an efficient structural system to promote the economic viability of the facility. Education facilities at the post-secondary level face similar challenges in that they require highly efficient structures for repetitive classroom and office layouts, but also need to accommodate student breakout areas, maker spaces, and connecting common spaces. Post-tensioned concrete provides an option for addressing the diametric space requirement of needing a combination of signature, architecturally driven space and uniform, highly efficient space for back-of-house function without having to change systems.

Bruininks Hall (formerly Science Teaching + Student Services building) at the University of Minnesota is an example of this versatility (Fig. 1). Located on the banks of the Mississippi River, Bruininks Hall meets multiple needs, including lecture space for basic science curriculum and a one-stop location for student services, while creating a gateway to the east portion of the University's campus. The architectural design addressed these needs by

Fig. 1—Bruininks Hall, University of Minnesota.

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congregating and stacking classroom and office spaces on east side of the building while using curved slab edges of varying configuration on the west side to create a multi-level atrium with views of the Mississippi River Valley. The curved slab edges continue into the south end of the building, where a free-form lobby hosting a spiral stair and student break-out spaces connect the building to campus.

A post-tensioned concrete structure provided an effective solution for addressing these varied building forms. The classroom areas were structured with an efficient beam and one-way slab system with 54 in. wide x 24 in. (1370 x 610 mm) beams spanning 48 ft at 22.5 ft (16.4 m at 6.8 m) on center (Fig. 2). Selecting the beam size was complicated by an architectural desire to expose the concrete beams and have every beam in the building be an identical size. This required considerable iteration to determine a beam size that was efficient for the typical spans but didn't result in excessive precompression stresses or overly congested anchorage regions for the longest beams with the greatest demands. The undulating structural form at the atrium on the west side of the classroom area was accomplished by cantilevering the 54 in. wide x 24 in. (1370 x 610 mm) deep beams by varying amounts. To prevent the slab edges from appearing wavy from within the atrium, the tendon profile in each cantilever was determined to achieve similar deflections at the end of each cantilever. Because the locations of the anchorages at the tips of cantilevers were fixed to impart the anchorage force at the centroid of the beam section, the tendon elevation at the supporting column was lowered as needed to obtain appropriate load balancing effects. In many structures, this can significantly penalize the economy of the backspan due to the reduced tendon profile; however, these slabs were laid out with shorter bays for the student support spaces directly behind the cantilevers, resulting in no loss of economy due to the lack of full tendon drape.

A transition from the beam and one-way slab to a two-way slab system was used to accommodate the free-form geometry and column layout at the south end of the building. The two-way slab provided significant flexibility for accomplishing the geometric complexity with only a handful of columns, an elevator core, and a perimeter row of closely spaced columns for support. Thanks to the ease with which post-tensioned tendons can be curved horizontally and the relative simplicity of placing curved bulkheads on flat deck formwork, the complex geometry and signature form of the levels was accomplished without a significant loss in economy over a more traditional two-way slab layout. A rather hefty 14 in. (360 mm) slab thickness was used to accommodate the spans and concentrated loadings from the spiral stair. An alternate design for this area using upturned beams and slab was considered during the schematic phase, but was dismissed due to the

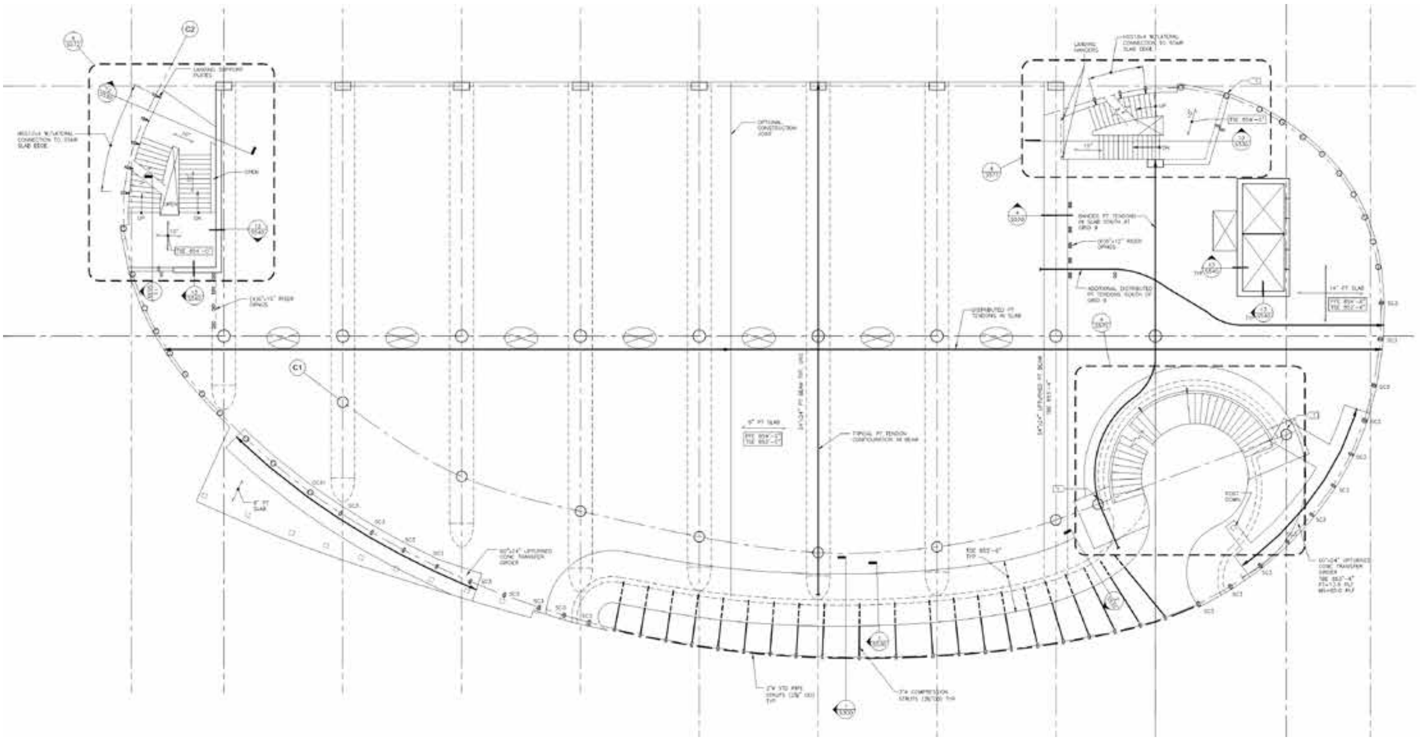

Fig. 2—Bruininks Hall floor plan.

significant labor costs associated with forming curved, upturned beams.

The use of elastic finite element analysis was essential for designing the irregular south portion of the building due to the multiple feasible load paths present. Mapped shear distributions were used to determine the lines of zero shear through slab in both directions. Zero-shear lines representing an area of significant stiffness within the slab (that is, shear diagram transitions from positive to negative as it would in a continuous beam over a support) were used as locations for banded tendons where the balancing load from the tendons would have the most direct impact on the slab. Zero-shear lines representing where load diverges from one support towards another (similar to the shear diagram of a continuous beam between supports) were used to determine the boundaries of the design strips used for averaging moments to check codified stress limits within the slab. This approach allowed for development of a rational tendon layout and application of code limitations for the irregular form. The finite element model also provided an accurate means for determining the deflections of the slab and ensuring design requirements were met.

The post-tensioned concrete structure proved adept at providing the economical structure needed for the regular portion of Bruininks Hall while easily accommodating the areas with irregular plan geometry. In arts facilities, irregularity rarely exists only in plan but often presents itself in the section of a building due to required adjacencies of spaces (Fig. 3).

Project Details

Project: Bruininks Hall (formerly Science Teaching + Student Service Building)
Location: Minneapolis, MN
Owner: University of Minnesota
Design Architect: KPF
Executive Architect: HGA
Structural Engineer: HGA
Construction Manager, Concrete Contractor: McGough Construction
PT Supplier: Amsysco
PT Installer: AMSYSCO, Inc.

ALLOWING UNIQUE ADJACENCIES OF SPACE

Arts facilities require many different spaces such as galleries, theaters, concert halls, and lobbies. Maximizing a facility's impact in terms of both user experience and financial viability often requires locating different spaces in proximity. This can require significant structural gymnastics to accommodate as demonstrated on the Ordway Center for the Performing Arts Concert Hall Addition in Saint Paul, MN (Fig. 4).

The Ordway Center for the Performing Arts, located in downtown Saint Paul, is a premier arts destination anchoring the Minnesota Opera, Saint Paul Chamber Orchestra, and the Schubert Club in addition to hosting traveling Broadway productions. Built in 1985, the center originally consisted of a 1900-seat Music Theater and a 300-seat McKnight Theater. The McKnight Theater was demolished and replaced with an 1100-seat Concert Hall. The significant space constraints of trying to build an 1100-seat concert hall in the space of a 300-seat theater and the necessity of matching the floor-to-floor heights of the existing facility made post-tensioned concrete the material of choice.

One location where the tight site and required adjacencies of the arts programming created the greatest structural challenges was the proximity of the upper balcony of the concert hall to the adjacent lobby. As with most theaters/concert halls, the upper balcony needed to cantilever out from the supporting columns to prevent them from blocking the sight-lines of patrons on the level below (Fig. 5).

Fig. 3—Interior of Bruininks Hall.

Fig. 4—Ordway Center for the Performing Arts Concert Hall Expansion.

The balcony continued to extend upwards at an incline past the support column to achieve the required seat count for the hall. It was not possible to place a column support at the top of the balcony as the columns would sever through the lobby space tucked below the balcony in an unacceptable manner. Instead, the balcony structure needed to turn horizontal and extend out over a large lobby space with only a single additional line of columns providing support. As the structure was laid out, it became clear that the balcony and lobby roof would need to be structured with kinked raker beams supported on only two columns and cantilevered at each end. To make things more challenging, the raker beams needed to support the concrete wall at the back of the concert hall, which transferred a portion of the concert hall roof load to the rakers. Post-tensioned concrete was the optimal solution for making these kinked, cantilevered transfer beams a reality.

Designing the raker beams (Fig. 6) required a thorough understanding of the mechanics associated with post-tensioned concrete, as no commercial design software available at the time could accommodate post-tensioned concrete beams with the anchors located on different levels of a building. A series of simplified thought problems were used to develop an understanding for the design of the beams. First, a straight beam with a straight tendon running perfectly along the beam's centroid was considered. Because the tendon has no eccentricity to the beam, it only imparts forces at the end and therefore, the beam is in pure compression. Next, this beam is taken and kinked with the kink in the tendon matching the kink in the beam. The tendon can only apply loads to the beam at the ends and the location of the kink. The force applied at the kink is found using statics and it is found that the beam remains in pure compression. The next challenge is accounting for the parabolic draping of the tendons. For a straight beam with a parabolically draped tendon, the determination of the representative balanced loading is well established. Now take this beam and kink it. The eccentricity of the tendon relative to the centroid of the beam remains unchanged at all locations along the beam length, indicating that applying the same balanced loading to the kinked beam is appropriate. Combining the axial and balanced load effects provides the post-tensioning demands on a kinked beam.

The beams were analyzed for the forces due to the post-tensioning tendons, dead loads, live loads, and snow loads using two-dimensional stick models. Hyperstatic demands were determined by deducting the primary post-tensioning moments due to tendon eccentricity from the moment demands due to application of the balanced load. Fortunately, because the beams were only supported on two columns that had minimal bending stiffness relative to the beams, the hyperstatic effects were minimal. The resulting demands on the beam were combined using applicable load combinations, and used to check stresses in the beam and determine appropriate amounts of reinforcement. It was determined that a series of four 36 x 36 in. (915 x 915 mm) beams with effective tendon forces of approximately 324 kip (1440 kN) most appropriately supported the balcony and lobby roof.

The Ordway Concert Hall Expansion showed how the unique space adjacencies of arts facilities can be accommodated with post-tensioned structures. Another area where post-tensioned concrete structures provide benefits to arts and education buildings is through addressing serviceability considerations, notably control of deflections and vibrations.

Project Details

Project: Ordway Center for the Performing Arts Concert Hall Expansion
Location: Saint Paul, MN
Owner: Ordway Center for the Performing Arts
Architect: HGA
Structural Engineer: HGA
Construction Manager, Concrete Contractor: McGough Construction
PT Supplier: DSI
PT Installer: DYWIDAG-Systems International, Inc.

DEFLECTIONS AND VIBRATIONS

Careful consideration of serviceability criteria, including deflections and vibrations, is critically important to the design of arts and education facilities. The design of performing arts centers need to consider both the vibration response of stage areas, for high-energy excitation from dance performance, and the response of seating areas, including balconies, for crowd-induced vibrations. Education buildings often require enhanced vibration analysis to ensure they create environments conducive to student learning and well-being. Many arts facilities also incorporate brittle finishes such as plaster, large-format tile, and brick that require significant control of deflections, often complicated by the unique configurations of these buildings. The ability of post-tensioned concrete to maintain the gross section properties of the concrete elements under service loading conditions and limit long-term creep deflections by balancing out a significant portion of the structure's dead loads make it an ideal material for arts and education buildings.

The expansion to Weisman Art Museum at the University of Minnesota is a prime example of how the deflection control capabilities of a post-tensioned concrete system enable great design (Fig. 7). Four new, interconnected galleries were added on the east side of the museum. The galleries were constructed from steel roof systems supported on load-bearing masonry perimeter walls. These load-bearing walls were in turn supported off large, 10 ft (3.0 m) square central columns by the floor structure. The floor plan had a highly irregular, angular shape to accommodate the desired spatial relationship of the galleries with cantilever lengths of up to 19 ft (5.8 m) (Fig. 8). There was also a need to minimize the structural depth of the floor system to provide sufficient clearance for Delaware Street traveling below the southernmost edge of the galleries.

Structuring the floor of the galleries with a post-tensioned concrete slab was the natural choice based on the large cantilevers, desire to minimize depth, and large loads applied at the perimeter of the slab by the bearing walls above. In addition, slab deflections had to be rigidly controlled to prevent cracking of the exterior face brick and/or plaster interior. Based on multiple design iterations, it was determined that a 40 in. (1020 mm) thick post-tensioned concrete slab reinforced with over 800 0.5 in. (13 mm) diameter tendons provided the optimal design for the museum expansion. Similar to Bruininks Hall, analysis and design of the floor plate using elastic finite element analysis was crucially important to understanding the most effective layout of post-tensioning tendons and determining accurate estimates for the long-term deflections of the slab (Fig. 9). By balancing nearly 100% of the slab dead load, it was possible to limit the long-term deflections at the perimeter to less than 0.5 in. (13 mm). Significant consideration was given in the design to whether the slab should be designed to incorporate staged stressing or not. Staged stressing had the potential to permit the use of a thinner slab by allowing a portion of tendons to be stressed at distinct stages during construction, such as at initial slab construction, after masonry wall construction, and after roof construction.

Fig. 5—Interior of Ordway Hall.

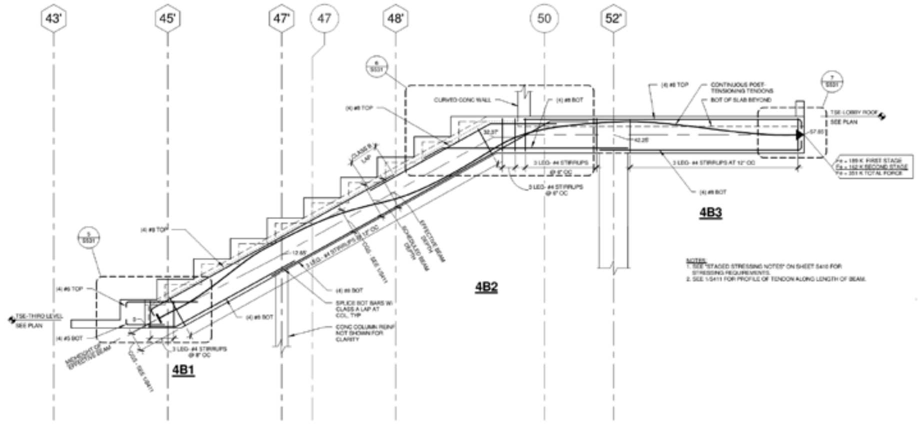

Fig. 6—Raker beam section.

Fig. 7—Weisman Art Museum.

Fig. 8—Interior of Weisman Art Museum.

In doing so, it is possible to balance out nearly the entire dead load of the structure, minimizing dead and long-term deflections. The design team opted to use a thicker slab in lieu of staged stressing to simplify the construction process and eliminate concerns about the slab moving more or less than expected during the staged stressing process.

Project Details

Project: Weisman Art Museum Expansion
Location: Minneapolis, MN
Owner: University of Minnesota
Design Architect: Gehry Partners
Architect of Record: HGA
Structural Engineer: HGA
Construction Manager: JE Dunn
PT Supplier: AMSYSCO, Inc.
PT Installer: Sanders

Limiting deflections was also a crucial consideration for Bruininks Hall. This was most notable at the four-story curtainwall enclosing the atrium on the west side of the building. The curtain wall was supported on a series of concrete and steel columns spaced between 4 and 5 ft (1.2 and 1.5 m) on center that also, in some locations, supported loads from the upper floors and the roof of the building. Due to site limitations and the required program, it was not possible to extend these columns to grade, but rather they had to be transferred by the third-floor structure, which spanned up to 48 ft (15 m). The deflection at the base of the curtain wall was limited to 1 in. (25 mm) maximum and the size of the supporting beams on third floor were constrained to 54 in. wide x 24 in. deep (1370 x 610 mm) to provide aesthetic continuity with the remainder of the building.

Preliminary design indicated that there were no feasible solutions for accommodating the condition using only the third-floor beams as transfer elements. While tendon layouts could be developed that provided sufficient strength, the deflection of the third-floor beam under snow and live loads exceeded the 1 in. (25 mm) maximum allowable. The solution was to introduce columns between the beams on the second and third floor of the building directly below the curtain wall columns. In doing so, the 48 ft (15 m) long support beams on the second and third floors essentially became sistered transfer girders, where loads on the third floor could be resisted by both the second and third floor beams and vice versa. This significantly increased the tributary area of the structure supporting the curtain wall columns allowing the stringent deflection limits to be meet. While the concept of the sistered transfer girders is relatively straightforward, executing the design required a feat of strength as there was no commercially available software at the time of design that could capture the interaction of post-tensioned elements on multiple levels of a structure. Spring elements were used at each level to represent the stiffnesses of the floor system at the opposite end of the sistering columns. Iteration was then required to determine the appropriate spring constant that would result in matching deflections at each level under applied load. Once appropriate spring elements were established, an extensive step-by step analysis was required to determine the amount of load transferred between the floors at each stage and ensure the design stress limits and strength requirements were met.

Vibrations were the critical concern for the Ordway Concert Hall. Modal analysis was used to estimate the response of the balconies to a variety of forcing functions intended to represent crowd induced excitation. While not directly influencing the analysis, the post-tensioned raker beams provided a significant benefit in that they provided basis for the use of gross concrete section properties instead of cracked section properties in design. This increased structural stiffness, resulting in higher natural frequencies of vibration for the structure and reduced the potential for excitation of the structure due to crown movements.

DURABILITY

Durability is a significant consideration for many arts and education facilities. These facilities often serve as anchors within their communities and designing for service lifespans of over 100 years is common. The pre-compression and reduced amount of cracking present in post-tensioned structures is highly beneficial for providing this durability as represented by the Town Green Bandshell and Pavilions (Fig. 10 and 11).

The Town Green Bandshell and Pavilions in Maple Grove, MN, consist of an outdoor performance bandshell for dance, music, and theater and three pavilions housing support spaces including concessions and restrooms. Inspired by abstract groves of trees and the curved shape of maple seedpods, the bandshell is a curvaceous post-tensioned concrete slab supported on six slender columns, sloping towards the middle and back of the canopy and gently arching towards the sky. The adjacent pavilions have post-tensioned concrete slab roofs that portray a similar design concept. A tapered slab ranging from 18 in. (460 mm) thick at the center to 8 in. (203 mm) thick at the perimeter was used to accommodate the 45 ft (14 m) spans and cantilevers of up to 15 ft (4.6 m) of the bandshell. The roof does not have a conventional roofing system but uses a waterproofing product that can theoretically accommodate cracks. But the idea of water staining through cracks would be unthinkable architecturally and terrible structurally as well. Accordingly, care was taken in design, including ensuring service level stresses remain below levels expected to induce cracking and estimating the amount of restraint provided by the supporting columns to ensure that they do not cause a significant decrease in pre-compression.

Project Details

Project: Town Green Bandshell and Pavilions
Location: Maple Grove, MN
Owner: City of Maple Grove
Architect: HGA
Structural engineer: HGA
Construction Manager: RJM Construction
Concrete Contractor: Northland Concrete
PT Supplier: DYWIDAG-Systems International, Inc.

AESTHETIC CONSIDERATIONS

Aesthetic are of paramount importance for many arts and education facilities. Post-tensioned concrete can provide significant benefits to delivering the aesthetic vision of a

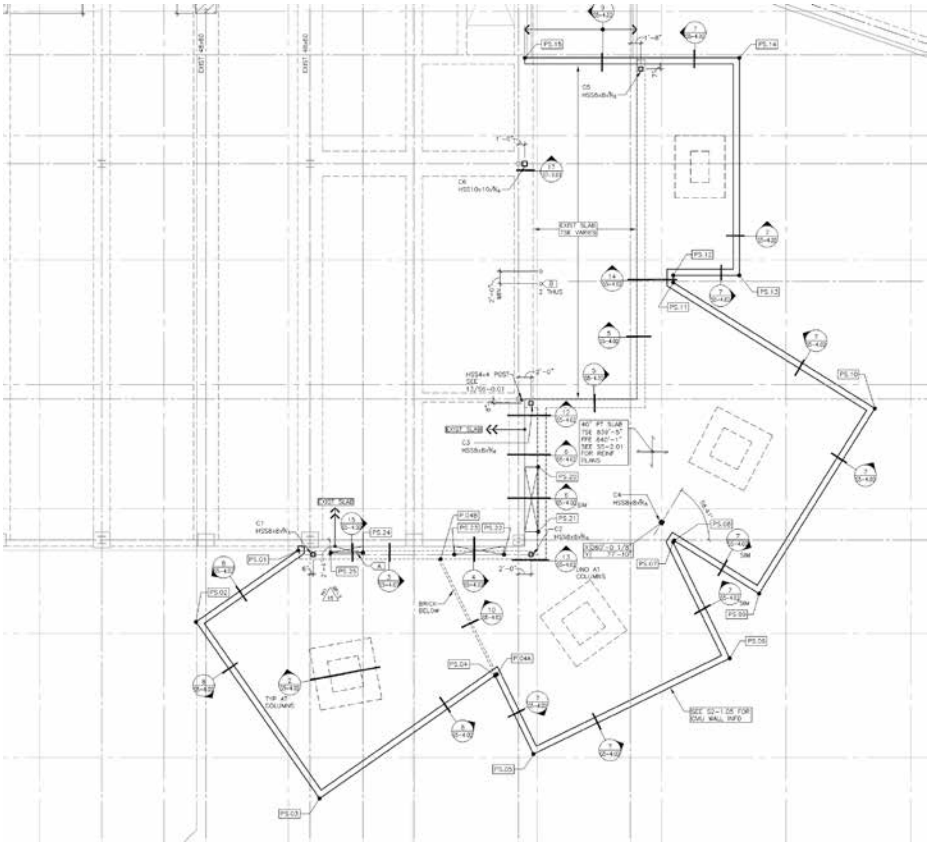

Fig. 9—Weisman Art Museum floor plan.

Fig. 10—Town Green Bandshell.

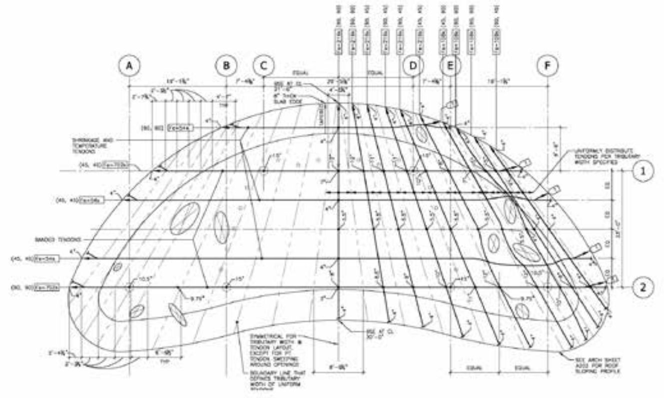

Fig. 11—Town Green Bandshell plan.

space due to the flexibility with which it accommodates curved and angular floor plans, transitions between structural systems such as beam/slab and two-way slab to allow varied column layouts, and limits unsightly cracks. There are several aesthetic considerations created by post-tensioning systems that need to be addressed in the design and construction process. First and foremost is deciding whether to conceal or embrace the stressing pockets of the tendons.

Countless methods have been used to address the stressing heads of tendons in arts and education facilities with exposed structure. The most common, perhaps, is to locate all stressing anchors at exterior walls where the stressing pockets will be concealed by wall finishes, as was done for the Weisman Art Museum Expansion and the Ordway Concert Hall Expansion. While effective, this approach has several disadvantages including that additional construction joints may need to be introduced into the structure to keep the one-ended tendon stressing lengths below 125 ft (38 m) and it is only possible to add tendons on one side of the structure, potentially resulting in less-efficient designs if the structural bays adjacent to the fixed end anchors control the required post-tensioning force. Another approach is to conceal stressing pockets by holding the tendons back from the final slab edge location and using a second concrete placement to cover the stressing pockets after the tendons have been stressed. With appropriate planning and collaboration with the architectural team, details can be developed that look like monolithic construction, as achieved for tendon stressing at the face of the atrium in Bruininks Hall. For some designers, the most appealing option is to embrace the stressing pockets. This was the case on the Town Green Bandshell, where the designer requested to have every other tendon stressed from the opposite direction to create an even spacing of stressing pockets around the perimeter of the structure. The pockets were then filled with a slightly contrasting grout to punctuate them on the face of the slab. Whatever method is selected, consideration early in the design phases of the project to promote collaboration with the architectural team and/or capture costs associated with less-optimized systems is important for success.

High-quality construction processes are also critical for arts and education facilities, especially when exposed concrete surfaces are incorporated into design. Construction crews not only need to avoid leaving any markings on formwork that could transfer onto to finished slab surface, but also must be very careful in profiling tendons correctly, consolidating concrete behind anchors, and installing hairpins at sweeping tendons as any tendon blowouts or anchorage zone failures can result in repairs that detract from the aesthetic quality of the space.

As shown in the case studies, post-tensioned concrete is an appealing structural system for many arts and educational facilities. When applied with thoughtful engineering and creativity, post-tensioned concrete systems not only address the challenges of arts and education facilities, but also turn them into assets that promote the functionality and appeal of the spaces.

Jon Wacker *is Senior Structural Project Engineer with HGA Architects and Engineers in Minneapolis, MN. He received his bachelor's degree in civil engineering from the University of Minnesota and his master's degree in civil engineering from the University of Washington. Wacker has spent the last 12 years at HGA specializing on projects serving clients in the arts, culture, and education community. In addition to post-tensioned concrete, Wacker's professional interests include the design of structures for crowd-induced vibrations and increasing the resilience of the built environment to climate change.*