Music in the Park

By A. Abdelrazaq, P.E., S.E., H. Iyengar, P.E., S.E., C. Rockey, S.E., R. Sinn, P.E., S.E., and J. Zils, P.E., S.E.

The newest addition to Chicago's lakefront is an outdoor performance venue featuring Frank Gehry's signature curving metal panels and a large-scale HSS trellis.

Chicago's skyline is known for its innovative architecture. The new Millennium Park outdoor music pavilion reflects that vitality. Designed by architect Frank O. Gehry, the pavilion features a lawn and fixed seating area for up to 11,000 patrons, and a celebratory orchestral stage area framed by soaring, ribbon-like metallic forms. The great lawn and seating area is spanned by a woven network of exposed arched steel members creating a three-dimensional open-air "trellis" above the level of the spectators. A serpentine pedestrian bridge across Columbus Drive linking Millennium Park and lakefront areas to the east represents Gehry's first realized bridge design.

Band Shell and Metal Elements

The music pavilion is composed of a south-facing band shell housing the stage and related support facilities, which in turn supports the metallic forms. The forms are shaped and located to improve the acoustic characteristics of the performance venue. The central portion of the band shell roof over the stage cantilevers up to 100′ beyond the proscenium door. There are a total of 12 individual metal-clad assemblies arranged around and above the central stage, forming an overall composition about 300′ wide and 120′ tall. Behind the upper metal surfaces, a system of inclined steel pipe struts connected to the band shell structure stabilize the metal elements.

Above the stage, the band shell roof framing consists of a three-dimensional steel platform that includes 12 built-up steel trusses spaced at 9′-8″ on center that vary in depth from 11′-3″ to 5′-0″ at the end of the cantilever. The trusses are composed of wide-flange and tee sections with welded and bolted joints; and are supported on an 11′-3″-deep by 8′-6″-wide built-up box truss girder spanning the 87′ opening over the stage. Overall, the band shell structure is fabricated from 800 tons of structural steel.

Framing the complex geometry of the various metal-clad elements surrounding the stage required careful consideration. The system had to be versatile enough to respond to the significant variety of shapes and sizes of metal forms. Lateral stiffness was particularly important because some of the lower forms cantilever as much as 40′ from their base without lateral supports. Structural rigidity also was required to minimize the potential for wind-induced flutter. Since the structural frame served as the primary support for the architectural stainless-steel-clad surfaces, it also was necessary for the framework to be fabricated and erected within stringent tolerances to install the cladding. Finally, these considerations had to culminate in a structure that could be detailed, fabricated and erected economically within a mandated budget established for the project.

A steel grid/ribbed frame concept was developed for the support of the metal elements, which responded well to the structural system requirements of the project. The structure was configured to closely follow the curvature of the shapes and take advantage of the inherent geometric stiffness of each form. Where required, metal elements were stabilized by steel pipe struts (varying in diameter from 8″ to 14″) framing to the band shell roof. The basic structural system concept was applied and refined through computer-based surface modeling integrating the combined efforts of the architectural and structural engineering teams. First, a structural working surface was generated 2′-0″ behind the clad surface. Vertical slicing planes at 9′-8″ centers and horizontal planes at 10′-0″ centers were electronically passed through the structural working surface, and the intersections created the structural work points. Straight-line segments connecting the work points formed an electronic wireframe representing the centerlines of the structural grid/frame members. Diagonal members were added between work points as required for lateral rigidity.

For this type of structure with relatively few (450) steel tons, considerations other than least weight were more important in terms of overall economy. To promote repetition and control of steel-connection detailing and fabrication, and coordination with cladding systems and attachments, member sizes were standardized as follows throughout the metal elements:

- vertical (inclined) ribs—W12×40 (ASTM A572 – Grade 50)
- horizontal members—HSS 8×8×¼ (ASTM A500 – Grade B)
- diagonals—WT6×15 (ASTM A572 – Grade 50)

Individual member sizes only were increased as determined by the structural analysis (approximately 10%) and never decreased. Independent, parallel structural analysis and design checks were done using two software programs: S-FRAME (CSC-SOFTEK) and SAP2000 (Computers and Structures, Inc.) for a complete loading regime including wind, temperature, snow, ice and live load.

The drawings together with the computer wireframe were issued to the contractor as part of the project documentation. The steel detailer converted the wireframe electronic data into Tekla Xsteel for use in the preparation of shop drawings for the structural steel. The fabrication/erection concept was to prefabricate vertical sections of each metal element in the shop, trial fit and pre-assemble each section to neighboring sections in the shop, prepare the members for shop painting, and ship them to

Over the Top

The Millennium Park Music Pavilion integrates the space and audio quality of an indoor performance theater with the openness and ambiance of an outdoor musical venue. A three dimensional shell-shaped trellis structure, formed by a grid of arched steel pipes, defines the audience space and connects the stage to the great lawn. The trellis structure supports a system of computer-controlled audio speakers to create the effect of surround sound. This speaker system hovering above and around the audience eliminates the need for speaker towers found in many outdoor concert venues.

The trellis shell encompasses an area approximately 625’ by 325’ in plan. It is truncated at the stage end with a few of the northernmost pipes woven between the metal elements, ending adjacent to the stage walls. The arched trellis frames are supported on 24, 6’-diameter reinforced-concrete pylons, 16’ high, spaced approximately 60’ apart. Twelve arches originating from each side of the lawn span in an inclined direction, creating a distinctive skewed and gridded form.

The trellis structure behaves fundamentally as a discretized shell under gravity loads, with primarily axial compression in the members and secondary flexure near the supporting pylons, node points and midpoint of the segments. Imposed loads considered in the design included the suspended speaker system, wind, ice, temperature, and maintenance live loads.

The number of radii required to define each arch were rationalized such that each piece between splice points had one radius and involved pipe bending in one plane only. The arches intersect at common node points on the shell surface. Each pylon typically supports arches in two diagonal directions; one flatter, the other steeper. This results in a symmetrical diagonal pattern defining the shell surface. Individual arches range in overall length from 230’ to 400’. There are 120 sections of pipe in all, 50’ to 105’ long. The height of the trellis reaches 60’ above the lawn at its highest point. The entire trellis represents approximately 320 tons of structural steel pipe.

At each intersection, one pipe member is continuous through the joint and is outfitted in the shop with stub members to receive the two other pipes at the node. The steel pipes vary in diameter from 12” to 20” with wall thicknesses ranging from 0.375” to 0.750”. All pipes are ASTM A500 with minimum yield strength of 42 ksi. Splices are full-penetration-welded in the field with an internal back-up ring, but without external brackets, to maintain the smooth outer form of the pipes. Where pipe diameter transitions occurred, an external collar ring was shop-welded to the smaller pipe, which was then field-welded to the larger pipe.

At the pylon supports, intersecting internal stiffener plates extend from the pipe intersection down to a base plate, which is then anchored to the top of the concrete. The pipes overhang at least 3’ beyond the face of the pylon, promoting an appearance of a floating trellis structure.

Chicago Metal Rolled Products, a subcontractor to AISC-member fabricator ACME Structural Inc., used a cold-bending technology to bend the large-radii pipes with good control on ovality, which resulted in tight tolerances suitable for the architecturally exposed structural steel (AESS). All pipe chords are bent in a single plane with few tangent arcs, with radii varying between 125’ and 5,100’. The bending process started with very low curvatures and progressively increased to the desired value.

Erection proceeded from both north and south ends of the trellis frame. Shoring towers supported the trellis at each intersection point (48 towers total). The towers were located slightly off of the node point to be able to survey and set it for the correct elevation. The pipes were temporarily suspended by a short adjustable sling from a cathead beam of the tower above the node point. This method allowed for accurate setting without the use of bearing-type supports and jacks. The trellis frame was advanced several lines with cross pipes set, before final field-welding of the splices.

The permanent overhead speakers are suspended from the trellis pipes by a system of ⅜”-diameter stainless steel cables, which allow flexibility in speaker locations. TryPyramid Structures, Inc., Westford, MA supplied the cable system and its related hardware.

Curved stainless steel panels frame the stage opening at the Millennium Park band shell.

the site. The prefabricated steelwork sections then would be assembled on the ground into as large a sub-assembly as could be erected. The pre-assembled geometry was surveyed at key points with any discrepancies adjusted on the ground prior to erecting the steelwork sections. The band shell-roof cantilevered trusses were shored during erection of the metal elements.

AISC-certified fabricators LeJeune Steel and ACME Structural (both have the P1-Sophisticated Paint Endorsement, Enclosed) applied a Carboline four-coat paint system to all exposed steelwork for the metal elements and trellis. The primer and undercoat were applied in the shop over near-white blast-cleaned surfaces. The final color and clear coat were applied in the field after completing the erection of the structure. All site bolting of metal element joints were performed with 1″-diameter A325 galvanized bolts designed with a Class A friction coefficient.

Following survey confirmation of the erected geometry of the structural grid/frame, the aluminum support panels and stainless-steel cladding were applied. The cladding panels, curved to follow the final architectural form, were attached at various locations along the primary horizontal members of the structural frame on steel outrigger arms.

Columbus Drive Pedestrian Bridge

The Lakefront Millennium Park pedestrian bridge provides a pedestrian crossing over Columbus Drive between the park area above the East Monroe Underground Garage (construction circa late-1970s) to the newly built Millennium Park above the Millennium Park Garage to the west. The bridge not only follows a complex curvature, but also includes a superimposed cladding system of stainless steel and secondary cladding support structure similar to an enclosed building. The aesthetic concept is based upon a continuum of the metal-clad form projecting out of the ramping curvilinear abutments that spans across the roadway as a sleek, tapering bridge with minimum depth at the center support.

The approach spans east and west of the Columbus Drive span are curvilinear and framed in reinforced concrete supported directly on the existing underlying garage structures.

The two-span bridge over Columbus Drive is framed in structural steel supporting a cast-in-place reinforced-concrete slab walkway deck. The two-spans over Columbus Drive are on the order of 100′ each and are curved in plan. The structural design for the Columbus Drive crossing had to limit the effects of vibration due to pedestrian walking motions. The high stiffness-to-unit-mass characteristics of a steel design were crucial, particularly because of the limited available architectural envelope within the cladding. Structural calculations provided a minimum fundamental vertical frequency of 3 Hz, per AASHTO *Guide Specification for Design of Pedestrian Bridges*, with sufficient separation between vertical and horizontal modes. Primary longitudinal members include a central structural-steel box girder, transverse outrigger girders, and intermediate longitudinal purlins as required to support the walkway and metal-cladding system. The two-span bridge structure is supported with fixed bearings at the center of Columbus Drive on a new support pylon, and with horizontal expansion bearings at the east and west ends of the span.

The east and west ends of the two-span bridge over Columbus Drive are supported on structural steel, three-dimensional, four-chord cantilevered trusses supported directly on the existing underlying garage structures. These trusses are variable in depth and width, and curved in plan to match the architectural envelope. The supporting truss cantilevers approximately 10′ on the west of Columbus Drive and approximately 25′ on the east. The cantilevered trusses are composed of circular pipe sections for all chords, 20″ in diameter, 1.25″ to 2.0″ wall thickness.

Relatively short lengths (5′ to 10′) of pipe were robotically spliced-welded. The American Pipe Bending Company in Tulsa, OK then electric-induction bent them to the correct radii before shipping the pipes for fabrication. All pipe chords are bent in a single plane with a few tangent arcs, with radii varying between 50′ and 130′.

All steelwork connections for the bridge were designed by SOM and were included in the bid documents. As part of the project documentation, SOM submitted a colored electronic wireframe (AutoCad .dwg format) defining all member geometries and sizes. This file was directly loaded in Xsteel software to create the assembly and individual piece drawings for review. Since the engineer of record designed the connections, and the geometry was submitted electronically to the steel fabricator, 90% of the steelwork shop drawings were approved quickly without any additional review comments or resubmission.

The steel-framed portion of the bridge comprises 260 tons of structural steel. The steel fabricator completely pre-assembled the entire cantilever trusses and central box-girder span in the shop prior to shipment to the site. The Columbus Drive crossing was erected in a single weekend, with two welded air splices performed in the field. All steelwork for the bridge received an inorganic zinc-rich primer supplied by Carboline, over near-white blast-cleaning of the bare steel. All

Getting a Lift

Eighteen JLG® boom lifts were used to build the complex band shell at Chicago's Millennium Park. Ironworkers relied on the JLG boom lifts to build the structure, which extends to 145' above ground and is 320' across. Rented from Illini Hi-Reach of Lemont, IL, as many as 30 machines with platform heights ranging from 60' to 150' were used on the job at one time. Three of the JLG Model 150HAX articulating, telescoping boom lifts were used for the high-reach work. They are the tallest self-propelled booms available in the United States, with 150' platform height and the capability of reaching 79'-3" horizontally. For the majority of their work envelope, they have a platform capacity of 1,000 lb.

Most of the boom lifts were JLG's new Ultra-boom lifts, including the Model 1350SJP (The JLG Ultra-boom lift was awarded an Honorable Mention in this month's *Modern Steel Construction* Hot Products award competition. See p. 59 for more). It has a 141' working height and could lift workers to most of the overhead areas of the band shell. The Model 1350SJP boom lifts' features were well-suited for the crowded site. Extendible axles could be deployed by driving the machine forward or backward in as few as 8', an important feature for setting-up a machine in minimal space. It also meant that no outriggers occupied extra area. The Model 1350SJP has three steering modes: two-wheel front-wheel steer, four-wheel coordinated steering, and crab steering when maneuvering around the site.

"We needed boom lifts that give workers the flexibility to reach into the structure to set the steel and that could do it with speed because of our tight timetable," said Larry Ferris, Danny's Construction Company superintendent for the band shell. "All of the steel needed rustproof coating and that had to be done at temperatures above 40°. With winter approaching, we needed the work done!"

JLG lifts also helped install the aluminum panels and skin for the surface of the structure. With their compound curves, the panels look like a segment of an airplane wing and are built within a ±1/16" tolerance. Once the steel structure was completed, the panels were bolted to the arm plates using boom cranes and the JLG boom lifts.

bolts are A325 galvanized bolts designed as slip-critical with the primer faying surface supplying a Class A slip resistance. ★

Ahmad Abdelrazaq, P.E., S.E. is a former associate partner, Hal Iyengar, P.E., S.E. is a retired structural partner, Christopher Rockey, S.E. is an associate, Robert Sinn, P.E., S.E. is an associate partner and John Zils, P.E., S.E. is an associate partner at Skidmore, Owings and Merill, LLP.

Owner
City of Chicago

Structural Engineer
Skidmore, Owings & Merrill LLP, Chicago

Architects
Gehry Partners LLP, Los Angeles

General Contractor
Walsh Construction, Chicago

Steel Detailers
Dowco Consultants, Ltd., British Columbia, Canada (Band shell and Metal Elements) (NISD members)
Industrial Detailing, Inc. St. Louis (Trellis) (AISC member)
Mountain Enterprises, Inc., Sharpsburg, MD (Pedestrian Bridge) (AISC member)

Steel Fabricators
LeJeune Steel Company, Minneapolis (Band shell and Metal Elements) (AISC members)
ACME Structural, Inc., Springfield, MO (Trellis) (AISC member)

Steel Erectors
Danny's Construction Company, Inc., Shakopee, MN (Metal Elements and Trellis) (AISC, NEA member)
Imperial Construction Associates, Joliet, IL (Pedestrian Bridge)

Metal Cladding
A. Zahner Company, Kansas City (Metal Elements)
Permasteelisa Cladding Technologies, Ltd., Mendolta Height, MN (Pedestrian Bridge)

Structural Engineering Software
S-FRAME (CSC-SOFTEK)
SAP2000

Detailing Software
Tekla Xsteel
Design Data's SDS/2