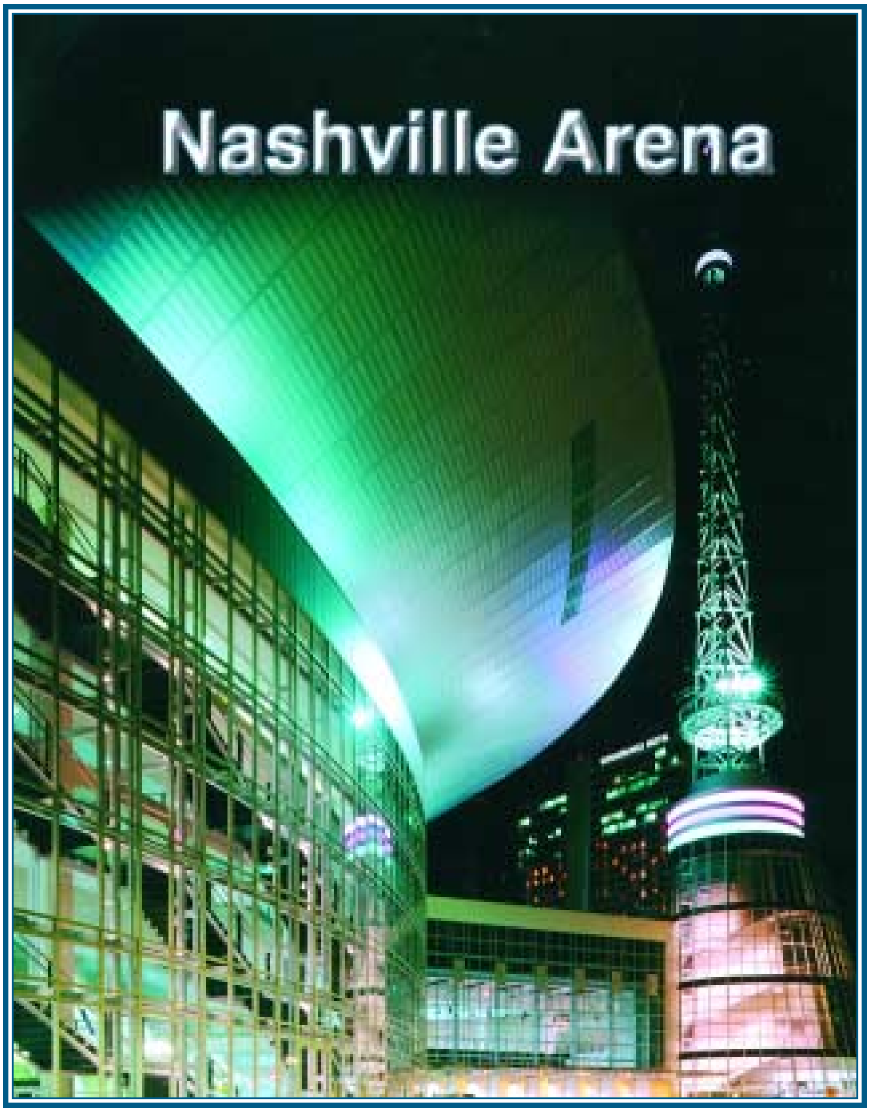
Photo by Bob Greenspan Photography, Kansas City, MO



Arena features a "music box lid" to evoke Nashville's image as the Music City

By Thomas Z. Scarangello, P.E.

The competition directive from the Metropolitan Government of Nashville and the blue-ribbon panel charged the competing design teams to create an arena/entertainment complex which would "enhance the entire downtown district, ignite development in the area and also serve as a landmark for the image reputation and identification of the city." It was the third challenge that spurred the structural design team at Thornton-Tomasetti, working closely with the design architects at HOK Sport, to develop a unique amalgam of structural systems that would achieve this exciting mandate.

The winning concept utilized familiar and evocative forms framed by highly visible supporting structures. Among the major components were a "music box lid lifted slightly to let sound escape", "a symbolic 300 foot high radio tower with a base shaped like the form of an angled spotlight as it lights a stage" and "a horn heralding the renaissance of Nashville, The Music City." The resulting engineering challenge was to develop these concepts into efficient, constructable and elegant structural solutions that would also create a balance between the design and the functional requirements for a 20,000-seat state-of-the-art entertainment complex.

From the outset it was clear that traditional long-span arena roof structural systems would not be able to address these challenges. At the same time however, it was recognized that to meet the facility's tight budget requirements, structural solutions would have to be seen as familiar and buildable to the contractors who would bid on them. In addition, the geometry (which included complex curved, elliptical and conical forms), would have to be documented and detailed in a way that would allow for standard fabrication, transportation and erection procedures to be used for the structural elements.

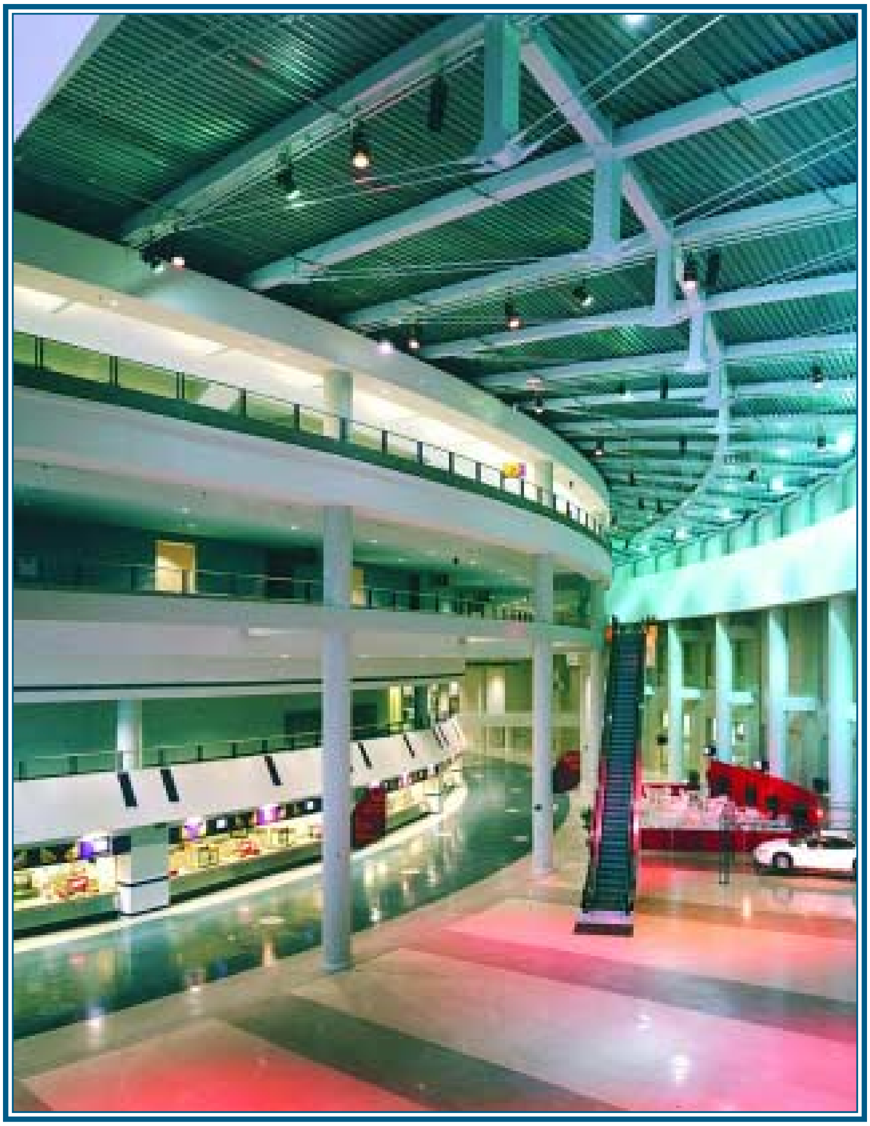
This was particularly challenging given the unique nature of the design. Even the arena bowl superstructure was non-traditional, in that the seating was separated into two clearly defined sections. Unlike typical arenas with symmetrical seating bowls, the Nashville Arena bowl reflected its musical roots with a focus on end-stage concert events. The seating bowl was divided into a horseshoe-shaped section facing the end-stage and a crescent-shaped section behind and adjacent to the end-stage. In addition, the horseshoe seating area gradually reduces in height and in rows as one approaches the stage, focusing the main arena towards the end-stage.

Foundation And Superstructure

The Nashville Arena foundation consisted of spread footings and piers to 75 ton Bigby limestone. The bowl superstructure was designed as a cast-in-place structure with the precast/prestressed seating beams. Concourse floor construction typically consisted of a 5½"-thick slab spanning 12' to 13' between 18"x24" to 24"x24" beams spanning 20' to 44' between 30"x30" girders spanning 18' to 36'. Rakers beams supporting the precast seating were typically 30"x30" spanning 18' to 42'. Columns were typically 30" round.

The precast seating beams were pretensioned, stepped elements with 4"-thick treads and 6"-thick risers, on average, which are supported upon the concrete rakers and precast vomitory walls.

The arena structure was constructed without expansion joints, enhancing its continuity while reducing long term maintenance requirements. Utilizing a three-dimensional model, the structure was analyzed for the anticipated thermal variations and reinforced for the resulting forces. During construction, shrinkage strips were incorpo-



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rated throughout the structure to control short term, thermal, creep and shrinkage effects.

Roof Structure

To achieve the main 400'x500' span "music box" roof design, boomerang, cantilever and crescent shaped trusses supporting a sloping central two-way truss system were incorporated. The system developed was able to support this long-span roof area with virtually all element depths at no more than 13' center-to-center.

The boomerang trusses supported the perimeter of the high end of the roof, with their 7'6" deep (center to center) raked lower leg also serving as the support for the upper precast seating elements. The upper leg of the boomerang truss is 12'6" deep and cantilevers about its main support column, 60' inward toward the arena and 15' to 50' away from the arena. The outer edge of the boomerangs also supported a continuous elliptical 450'-long triangular pipe space truss, which varied in width and depth from 3' to 15' and formed the faceted elliptical upper edge of the roof. A 7,500 sq. ft. mechanical room structure was inserted into the "belly" of these boomerangs, which formed the dramatic "underbelly" which juts out 65' over the main entrance. In addition to its functional use, the permanent dead load of this room was also utilized as a counterbalance to the roof loads to be supported at the tip of the upper leg of the boomerang.

As the upper roof slopes down with the gradually reducing rows of upper seating, the perimeter supporting structure transitions into 12' 6" deep cantilever trusses with cantilevers between 30' and 60' and with backspans between 35' and 80'. The back spans form and support the fin walls featured in the architectural expression of the east and west building faces.

Interconnecting the cantilever elements of the boomerang and cantilever trusses are a pair of interconnecting 12'6" trusses that follow the horseshoe plan shaped layout of these elements. These interconnecting horseshoe trusses are located halfway out and at the tip of the cantilevers. They serve to enforce deflection compatibility and provide load redistribution capability between the cantilever trusses. They also serve to provide substantial redundancy in the overall system that would not be present otherwise, in the inherently non-redundant cantilevers.

A pair of mirrored crescent-shaped stage trusses are framed to two 6 foot diameter architectural columns which define the transition from the horseshoe shaped seating bowl facing the end stage area to the crescent shaped seating bowl behind and adjacent to the end stage area. These stage trusses also act to define the end stage proscenium as well as the stepping down of the roof "lid," with the main roof step formed by the upper half of the 25'-deep front stage truss. These elements complete the perimeter supporting structure. These perimeter structural elements support a 250'x270', 12' 6" and 14'-deep two way truss system that forms the central roof structure.

The curved roof surface is formed by a series of parallel wide flange purlins spaced at approximately 12' on-center supporting standard 3" metal deck for the high and middle roof sections and $1\frac{1}{2}$" metal deck for the low roof section. With a radius of 680', 480' and 500' for the three roof sections, standard straight deck was utilized and easily "walked down" over the purlins to achieve the curving roof surfaces.

This amalgam of structural elements elegantly and effectively formed the unique shape of the arena while also meeting the economic requirements of the project. The roof structure was efficient and economical for the following reasons:

1. The roof structure was designed and detailed with primarily straight, standard shaped wide-flanged and double angle elements. The curved shape of the roof was achieved by utilizing straight shippable truss elements, segmented every 3 to 4 truss bays (35' to 50' long) and varying the wide flange purlin elevations to form the curved surface.

2. Every truss, with the exception of only the proscenium truss, was under 15' deep out-to-out, allowing for complete shop fabrication.

3. Truss connections were simplified by utilizing end plate connections whenever possible for all compression chords. In addition, in the two-way truss elements, the truss depths of the perpendicular trusses were varied by 1' 6" to avoid an intersection of the tension chords, which dramatically simplified their connections.

4. Only four wide flange temporary shore members were required for the erection of the entire roof. In addition, these shores were located over the arena floor so they would not impact any other areas during construction. The minimal use of shoring was in large part accomplished through the inherent stability of the perimeter boomerang and cantilever truss elements as well as the analysis procedure T-T utilized during design. T-T analyzed the roof in an anticipated construction sequence. This involved the separate analysis of eight different computer models, which reflected the distinct erection stages of the partially completed structure. The results of these analysis were then superimposed, utilizing an in-house post processing program, in order to calculate all the member forces and displacements at each stage of construction. By utilizing this approach, T-T was able to virtually eliminate the need for temporary shoring towers that would have been required had only a single standard analysis of the total roof structure been undertaken. T-T's approach even allowed the central two-way truss system to be erected as a one-way system, dramatically simplifying the erection process. This analysis approach also allowed T-T to allow for the early placement of the critical path mechanical equipment in the underbelly mechanical room.

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Fabricator on the project was AISC-member SMI-Owen Steel Co., detailer was N.C. Engineering and erector was Runyon Erectors.

REHEARSAL HALL

In addition to the main roof, the Rehearsal Hall roof presented its own special challenges. The Rehearsal Hall is a space intended to accommodate a full concert stage setup so that performers can practice and move directly into the arena or prepare for upcoming tours. The Rehearsal Hall also incorporates a backstage tour area. Its unusual conical horn shaped roof provides a dramatic exterior architectural statement and interior backdrop. The structural system selected needed to economically form the roof shape while also enhancing the drama of the interior space.

A series of tied arches were developed to fit the bill. The arches varied in diameter from 45' to 75' and spanned from 80' to 130'. The arches were formed with 8'-deep curved wide flange trusses. The chord sections and orientation for these trusses was selected so that they could be easily rolled to the various diameters. The arch trusses were interconnected by straight radial bridging trusses and tubular purlins. The arches were tied at their base with standard wide flange sections which also hung

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from the arched truss with cruciform angles. The roof surface was formed by precurved 3" metal deck. This design created a dramatic volume of interior space, without the visual and functional obstructions of a standard truss. The tie level also provided a perfect support location for a 5,500-sq.-ft. mechanical room and the rigging steel level for the rehearsal hall. The last tied arch also features an exterior architectural "eyebrow," cantilevering up to 16', mirroring the tied arches inside.

As with the main roof, large economies were achieved by insuring that the arch elements were composed of standard shapes that could be shop fabricated in shippable depths.

ICON TOWER

The 305' visitor's center icon tower located adjacent to the arena was conceived to be symbolic and evocative of radio broadcasts from the historic Grand Old Opry and to help define the arena's civic importance. The 100-foot base of the tower was shaped like the elliptical form of an angled spotlight as it lights a stage. Within this base structure is housed a visitor center, a 100-seat theater and a "music bar" with an elevated hung walkway connecting it to the suite level in the arena. Geometrically the base structure is formed at the base by two opposing 40'-diameter inner and outer circles, with their centers 40' apart. These circles were then connected at their centers by a square with two corners at the circle centers and the other two corners acting as the center of two larger, approximately 90' diameter circles. The complex curve formed by the intersection of these four circles defined the perimeter base geometry. The vertical geometry was then generated by extending the base line perimeter geometry upwards to meet the inner 40'-diameter circle at an elevation approximately 100' above the base.

This shape was developed structurally by using a series of 10" round pipes forming the perimeter supporting structure, at inclinations varying from 0 degrees (vertical) to 22 degrees inward (from vertical). These pipes also served as the main supporting structure for the glass curtainwall structure. Approximately 20' from one end of the base is a 24'-diameter elevator shaft. The shaft walls were designed as a circular concrete shear wall as well as the base support for the 200' triangular tapered steel tower above. Each supported level was designed in cast-in-place concrete and span from the concrete shear wall to the perimeter round pipes.

Pipes were chosen due to the inherent difficulty of casting a sloping concrete column. They also limit creep and the potential lateral movements that creep would generate in the sloping structure. The pipes were filled with concrete to increase their capacity and provide a monolithic connection to the steel tubes. Once in place, the pipes served as built-in formwork for the concrete fill.

As the perimeter pipe columns slope toward the center of the elevator shaft, the area of each higher supported slab level becomes increasingly smaller. At approximately 25' up from the base as the perimeter pipe spacing becomes smaller, half of the sloping pipes are terminated. The remaining pipes continue up to approximately 80' above the base to the roof of the base structure with the circular shaft continuing up another 20' to the base of the steel tower.

The steel tower is a triangular braced tower with 6" to 12" vertical pipes and double angle 3x3 to 5x5 diagonals. The triangular tower tapers from a depth of 22' at its base to 2' at its apex. The tower leg splices were detailed with end plate connections for ease of erection. These design decisions allowed the tower to be shop fabricated in only 5 sections and erected in less than one day.

SUCCESSFUL PROJECT

With the completion of the Arena, the City of Nashville has already accomplished most of the goals spelled out in the challenge of the design competition.

The Arena construction has led to major spin-off development in the downtown area. Witness the revitalization of historic 2nd Avenue, the arrival of well-known commercial ventures such as the Hard Rock Cafe and Planet Hollywood and the start of construction of the new football stadium for the NFL Oilers. Clearly, the project's development has "created an arena/entertainment complex which would enhance the entire downtown district and ignite development in the area."

As for the arena as " a landmark for the image reputation and identification of the city," only the passage of time can cement that distinction. However, given the enthusiasm, energy and innovative spirit that the design team brought to this project, we are confident that the design of the Nashville Arena will stand the test of time.

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