Photo by Glen Patterson.

Steel Star

Exposed steel HSS and cellular wide-flange beams form the dramatic central atrium of the Gaylord Opryland Hotel Texas.

Dennis R. Tow, P.E., and Shel R. Harrison

Steel-framed atria have become the trademark element of Gaylord Hotels' massive convention centers. The hotels' feature atria that are measured in acres of clear-span skylight-covered space, with lush landscaped themes beneath. For the newest Gaylord Hotel, steel has truly become the star through successful collaboration between structural engineers at the Atlanta office of Walter P. Moore and AISC-member fabricator Hirschfeld Steel Company of San Angelo, TX.

Situated on the southern shores of Lake Grapevine, the new 1,600-room Gaylord Opryland Hotel Texas is located minutes north of the Dallas-Fort Worth International Airport. The new hotel is similar to the recently-completed Gaylord Palms in Kissimmee, FL, in that it features a two-and-a-half-acre atrium in the center of the hotel flanked by two smaller atria, each slightly less than one acre in area. [*Editor's note: Read about the Gaylord Palms in the November 2002 issue of* Modern Steel Construction.] Much of the Florida design team was preserved for the Texas project, with the substitution of Walter P. Moore as the long-span structural consultant. Despite the project similarities, architect Hnedak Bobo Group (Memphis, TN) expressed interest in differentiating the structural framing schemes, so long as there would be no net cost increase for the project. Walter P. Moore worked to devise an innovative and unique structure for the icon of the project.

In order to gain cost confidence and acceptance of the alternate system, Walter P. Moore polled the fabricator from the Florida project (AISC-member FabArc Steel Supply) for preliminary cost-comparisons between the Florida and Texas schemes. With FabArc's quantitative assessment confirming the economic feasibility of the new system, Walter P. Moore produced computerized graphic renderings and fly-through animations for presentation to the architect and owner. Since the guest room balconies around the perimeter of the atrium offer unobstructed views of the entire expanse of the atrium, the architect and owner were sensitive to the aesthetics of the structure, and were pleased with the striking appearance of the structural framing system Walter P. Moore proposed.

STEEL CENTER

The main atrium of the Texas hotel is covered by a skylight in the shape of a regular octagon measuring 135' on each side (more than 352' across the diagonals). Seven of the corners of the octagon bear at the roof level of the surrounding nine-story hotel towers. Due to the effects of the adjacent shoreline of Lake Grapevine on the building geometry, the eighth corner is supported on a nine-story free-standing steel column structure shaped like an oil derrick. A decked roof extends to form corners at two sides of the octagon, and continues along a third side to span the distance created by the altered building geometry.

The octagonal portion of the roof is structured by a tied-arch space frame, with HSS compression struts and tension tie rods, and cellular beams as sec-


Photo by Glen Patterson.

The Gaylord Opryland Hotel Texas, on the shores of Lake Grapevine near Dallas, features a two-and-a-half-acre atrium in the center of the hotel flanked by two smaller atria, each slightly less than one acre in area.

ondary framing. The central octagonal "hub" of the space frame consists of a perimeter tension tie at the base with a compression ring at the main roof level. The only framing inside the perimeter of the hub is the cupola roof at the top–a smaller space frame whose members form a 72'-diameter "Lone Star." The complete framing system is described in detail in the adjacent box.

AESTHETIC STRUCTURE

The structural engineer worked with the architect to ensure that the structure was pleasing to the eye of guests; this was particularly important where guest room views are within 10' of the exposed structure. The primary approach was to maintain consistent spacing and alignment of structural members such that some modicum of order and logic would be apparent in the myriad of oblique angles from which the structure would be viewed.

Since each 135' side of the main octagon aligns with ten 13'-6" guest room sections in the hotel, the geometry of the atrium structure is based on 13'-6" modules. The cellular beams are spaced 13'-6" horizontally, the panels of the tri-chord perimeter trusses are each 13'-6", and the lateral-torsional bracing for the cellular beams align with the 13'-6" tri-chord truss panel points. The web holes in the cellular beams are spaced and aligned on 40½" centers, such that there are four web holes between adjacent lateral-torsional braces. In this manner, a hotel guest's view from the atrium-side balconies readily exposes the attention to aesthetic detail prevalent in the structural design, as opposed to a myriad of non-parallel planes of joists and trusses, with disjointed or segmented bracing and bridging.

The attention to detail continued through the design and detailing of the skylight mullions and connections. The skylight mullions are spaced at 4'-6", so that there are three panes of glazing across each 13'-6" module. The lateral-torsional bracing for the cellular beams resists the down-slope dead loading induced by the intermittent thermal breaks in the mullions. All members that are attached to skylight and curtain-wall elements are at least 3/8" thick, in order to facilitate drilling and tapping for threaded connectors. Although all of the glazing is tinted green and fritted, the interior of the Lone Star is tinted blue to further distinguish the icon.

ECONOMY AND FLEXIBILITY

The total weight of the octagonal space frame, including the perimeter tri-chord trusses, is approximately 26 lb. per sq. ft. The dead load of the 88,000- sq.-ft octagon includes nearly 2.3 million lb. of structural steel, 175,000 lb. of aluminum mullions, more than 660,000 lb. of laminated glass and more than 30,000 high-strength structural bolts.

In addition to 50,000 lb. of total rigging capacity at the bases of the queen posts and a single 1,500-lb. rigging point at the center of the Lone Star cupola roof, there are a total of twenty-four, 1,500-lb.-capacity rigging points arranged at joints along the eight tension ties. This provides a robust total rigging capacity of 87,500 lb. for the main atrium, which will be used for such things as hanging decorations during holiday seasons and supporting lighting and equipment for shows within the atrium.

OTHER DESIGN FEATURES

Additional modifications were made to the framing of the remaining portions of the atria roof structures, including the two lesser atria and the decked connector roofs between them. The most obvious difference in the

STAR STRUCTURE

The main atrium of the Gaylord Opryland Texas Hotel is structured by a tied-arch space frame, with HSS 36.000 × 0.750 compression struts along the eight ridges and tension-tie rods underneath. The tie rods slope downward to a 90'-diameter octagonal tension ring at the center of the atrium, approximately 84' above the ground level. All tension-tie elements consist of two 4"-diameter A36 rods, with #8 clevises and 4"-diameter pins at the connections.

The compression struts frame into an octagonal W14 tri-chord truss compression ring at an elevation of 135', directly above the tension ring below. At each of the eight corners of the central hub are HSS 18.000 × 0.500 queen posts. They continue from the tension ring up through a HSS36 "joint can" at the compression ring to an octagonal ring of HSS 12.750 × 0.500 at the cupola above, more than 152' above the ground. Imbalanced gravity and lateral loadings on the overall tied-arch space frame are resisted by HSS 10.750 × 0.365 X-braces below the compression ring and HSS 8.625 × 0.322 chevron braces above the compression ring, on all sides of the octagonal hub assembly.

A "Lone Star" space frame at the cupola roof level covers the open space inside the compression and tension rings at a peak elevation of 165'. The Lone Star space frame consists of 10 HSS 12 × 8 × $^5/_8$ spokes with 10 HSS 10 × 8 × $^5/_8$ members framing diagonally between adjacent spokes along the edges of a five-pointed Texas Lone Star. The points are inscribed on a 72'-diameter circle. Ten small HSS 5.563 × 0.258 tension ties frame from the five outer points of the stars to the bottom end of 8'-tall HSS 6.625 × 0.432 queen posts at the five inner corners of the Lone Star, and continue to form a pentagonal tension ring between the queen posts. Five stabilizing HSS 3.500 × 0.216 members frame from the bottom of the queen posts up to the central intersection of the 10 HSS12 × 8 spokes. The central intersection consists of a vertical 2'-tall HSS 24.000 × 0.500 keystone block, with a clear unobstructed height of 163' underneath. The outer tails of the 10 HSS 12 × 8 spokes bear on the octagonal ring of HSS 12.750, with two 10-sided rings of HSS 8 × 8 × $^5/_8$ serving as mullion supports for the skylight framing.

The outer ends of the main compression struts frame into HSS 24.000 × 0.750 supports with HSS 18.000 × 0.500 knee braces from the base of the support posts up to the point on the compression struts where the tension ties terminate. The support posts are connected by a tri-chord truss which frames around the perimeter of the octagon. The tri-chord consists of a 12'-6"-deep vertical truss, composed of W14 chords and webs, with a W36 × 135 third chord connected by HSS 8.625 and HSS 5.563 web members to the W14 chords. In addition to a cantilevered perimeter gutter, a 17'-tall perimeter closure wall is framed off of the vertical W14 web members of the tri-chord truss.

The eight facets of the main skylight are framed with 42"-deep cellular beams, which span between the compression struts. These cellular beams, manufactured by SMI Steel Products, are expanded-web W27s with circular web openings, which range in span from 45' to 112'.

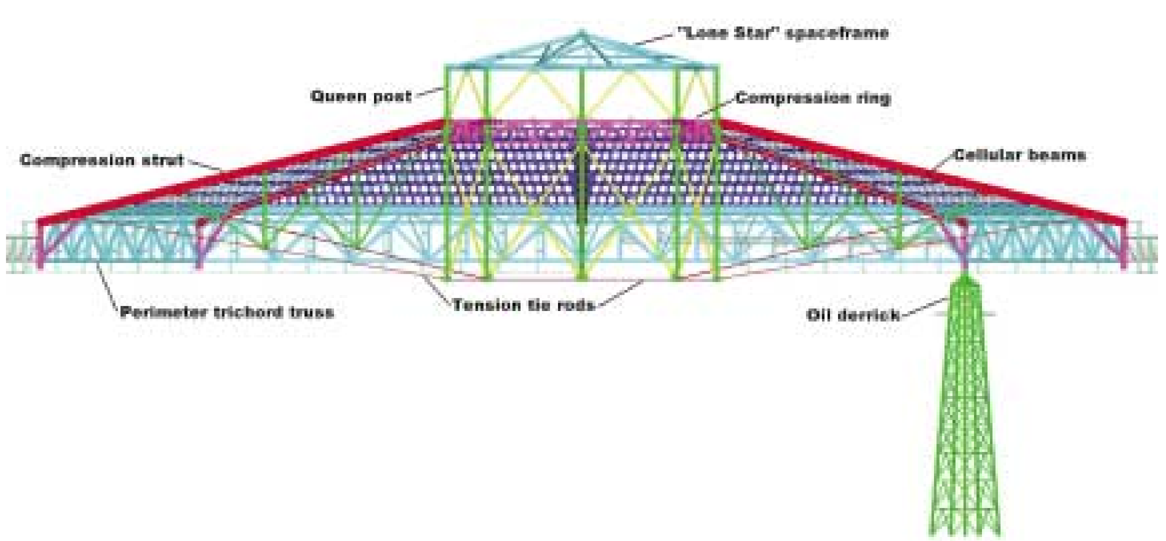
Since each facet of the roof is sloped 15° off horizontal, the cellular beams are oriented such that their webs are perpendicular to the 15° plane of the glazing, which subjects them to biaxial bending. Top and bottom flange bracing is provided for the cellular beams to prevent lateral-torsional buckling and to minimize weak-axis bending due to vertical and down-slope loads. This bracing consists of HSS 4.000 × 0.226 members bolted directly to each flange, extending from the compression ring at the top of the slope to the perimeter tri-chord truss at the bottom. Overall torsional stability is provided between the perimeter tri-chord truss and the compression ring at the central hub by HSS 12.750 × 0.375 diagonal diaphragm bracing in each facet, with the connections being coincident with the lateral torsional braces.

The shear connections at the ends of the cellular beams create bending in the compression strut. The struts are stiffened by a king post assembly near their midpoint. At each strut, an HSS 12.750 ´ 0.500 king post extends down to the midpoint of the tension tie, with HSS 10.750 ´ 0.500 diagonals connecting back up to the compression strut at a point above each quarter point of the tension tie.

The 84'-tall Oil Derrick column consists of battered HSS 10 × 10 × $^3/_8$ legs on each of four corners, with HSS 4 × 4 × $^1/_4$ horizontal and diagonal lacing at each story of the surrounding hotel buildings. Although a cantilevered platform surrounds the ninth floor level of the derrick, it is not accessible.

To accommodate differential wind and thermal movements between the steel atrium roof structure and the three concrete hotel buildings below, PTFE-coated slide-bearing assemblies were provided at most of the bearing interfaces. Only one corner bearing is fixed in both plan directions, and the bearing at the opposite corner is restrained in only one direction to provide overall lateral stability of the roof structure.

Total steel weight for the octagonal space frame is approximately 26 lb. per sq.ft of plan area.



Texas hotel is the prevalent use of cellular beams in the framing. In fact, there are no joists in any of the Texas atria roof structures. In using cellular beams extensively in the project, Walter P. Moore was able to specify the size and spacing of the circular web holes. The resulting hole alignments create visual interest in the roof structure from all angles, and lend a complete and interesting appearance to the overall design.

The connectors between the atria are nine-story gaps between hotel buildings. These spaces are bridged with 38"-deep cellular beams spanning from 56' to 72'. A four-story curtain wall at the outer edge of each connector is supported by a W40 girder at the roof level, and provides vertical closure between the main atrium and the smaller side atria.

Due to the site constraints imposed by the lake, the two lesser atria are asymmetrical. The west atrium is approximately 162' wide and 108' long, and peaks at a height of nearly 72'. The east atrium is generally square, with a large chamfer on one corner. It is approximately 162' wide and more than 160' long at its maximum, with a peak height of nearly 87'. Each atrium is framed by two trusses 54' apart spanning the length of the atrium. The 12'-6"-deep trusses consist of W14 chords and webs, and support gable frames at each 13'-6" panel point. Each gable frame has a 30"-deep cellular beam spanning 54', with a WT 12×31 top chord following the profile of a 30° gable with doubled L4 $\times$ 4 $\times$ $^1/_4$ web members. At the middle bay of each atrium, the cellular beams are moment-connected to the trusses to provide lateral-torsional stability for the truss.

The front of each atrium is a multi-story curtain wall. Each truss bears on a "cluster column," consisting of four HSS $6 \times 6 \times {}^3/_8$ columns with HSS 4×4 horizontal and diagonal bracing. The curtain wall is braced at alternate stories by HSS Vierendeel trusses which distribute lateral loads back to the cluster columns.

Overall lateral stability of the atrium structure is afforded by diagonal diaphragm HSS bracing around the perimeter. The attachment of the northern ends of the trusses to the roof of the concrete hotel buildings, coupled with the base attachment of the cluster columns, provides support against lateral loads without generating thermal restraint.

DETAILING, FABRICATION, AND ERECTION

With critical aesthetic features designed into the steel structure, communication and coordination were essential to successful execution of the project. With a keen sense of teamwork for this project and a history of cooperation and collaboration on other major projects, Hirschfeld Steel and Walter P. Moore worked hand-in-hand to ensure another successful delivery.

Since designs for nearly all of the bolted truss connections were provided on the contract drawings, Walter P. Moore was able to control the connection configurations and enforce aesthetic consistency among the gusset plates. Overall connection economy was also achieved by iteratively modifying truss member sizes during design to avoid many of the expensive and labor-intensive supplemental plates at the reduced net section of the bolted members.

Most of the complex connections involving round HSS members were not completely designed on the contract drawings. These connections required intensive coordination and collaboration among the structural engineer, fabricator, detailer, detailing consultant and erector. To support development of the shop drawings by NISD-member Consteel Technical Services in England, frequent trans-Atlantic conference calls were conducted, including Walter P. Moore in Atlanta, Hirschfeld's project manager in San Angelo, TX, and Fort Worth detailing consultant / connection engineer Structural Solutions, Inc. Also participating was Hirschfeld's Abilene, TX plant. An essential focus was the sequencing of the welds in the "joint cans" and the coordination of shop member splices with welding access. Several of the "joint cans" at the intersections of the 36"-diameter HSS members required internal stiffeners where external reinforcement was aesthetically impractical. In order to place the internal stiffeners in the "upper joint can" at the upper end of the compression struts, Hirschfeld split the HSS member open longitudinally and welded it back together. Circumferential complete-joint-penetration-welded shop splices were also used to place diaphragm stiffeners within the compression struts at connections.

In order to efficiently and accurately produce shop drawings for the structure, Consteel utilized Tekla's XSteel software to produce a virtual three-dimensional model. Taking advantage of symmetry when possible, Consteel modeled the entire atria structure, using as many as 14 detailers simultaneously on a single database. Despite the physical distance between fabricator, detailer, and engineer, the use of e-mail and the model's computerized graphics and renderings helped communicate clearly. Issues such as bolt clearances, welding accessibility and bevel conflicts could be resolved quickly. In fact, some of the compound bevels and stiffeners required for the structurally complex and aesthetically critical pipe connections would have been impossible to accurately describe and detail without the use of the computer. Consequently, Consteel's accuracy in detailing and Hirschfeld's precision in fabrication resulted in smooth and rapid erection with minimal field modifications for AISC-certified erector Petersen-Beckner Industries (PBI).

FABRICATION

Once the connection procedure was resolved on paper, Hirschfeld began the task of fabricating the steel. With so many different geometric shapes converging at various oblique angles, Hirschfeld fabricated and fit-up the various sections in the shop to ensure that the structure would bolt-up in the field. The size of the center compression ring did not allow for shop fit-up, as it is composed of eight "upper joint cans" connected by trusses to form a 90'-diameter octagon more than 20' tall. For this critical element of the building geometry, Hirschfeld relied upon the expertise of their shop employees and the accuracy of their equipment in cutting and drilling the steel. Complex layouts were established and controlled with work points and checks in all directions.

Field-welded rectangular HSS connections were an important component of the design, to maintain "clean" aesthetics. To accommodate the requirements of OSHA CFR 18 subpart R, erection aids had to be provided for all of these welded "tube" connections.

Photo by Glen Patterson.

Cellular steel beams add a visually pleasing rhythm to the complex geometry of the central atrium.

The erection aids consisted of tabs welded to the ends of the connecting members, which were temporarily bolted together to hold the members in correct alignment for field welding. After the connections were welded, each erection aid was removed, followed by grinding and touch-up. Due to the accurate placement required to ensure correct field alignment, Hirschfeld, Consteel, and PBI utilized the XSteel model to establish the location of each erection aid. Shipping constraints, raw material lengths, and erection sequences occasionally required this to be an iterative process.

ERECTION

Instead of building the main atrium's center compression ring / tension ring / cupola roof "hub" in-place on falsework, PBI elected to assemble them on the ground adjacent to the falsework and lift them in two sections, taking advantage of the ample room in the expanse of the atrium. PBI designed, fabricated, and erected a re-usable shoring system for the falsework, and installed it in the center of the atrium. The queen posts, compression ring, and tension-tie ring were assembled on the north side of the falsework, while the Lone Star cupola roof was constructed on the south side. PBI used two 300-ton Manitowac M2250 Series 3 crawler cranes in tandem to perform the lifts. For the lift of the 190-ton compression-ring assembly from the ground to its perch 82' above, the cranes were set with 180' main booms. For the 67-ton cupola roof lift, the cranes were reconfigured with 140' main booms and 130' luffing jibs.

The base of each queen post was designed to have a vertical fin plate with a 3"-diameter hole for attachment of rigging loads. PBI used these holes for keeper pins to hold and lock down the queen post and compression ring assembly to the falsework. Despite the enormity of the erection assembly (nearly 400,000 lb., 67' tall, and 90' diameter), the last of the eight keeper pins was inserted less than 80 minutes after the start of the lift. The cupola roof lift was equally as smooth, and the remainder of the atrium was erected using only one crane, as the other worked on the convention center portion of the hotel.

Prior to removal of the erection shores, skylight manufacturer Naturalite-Vistawall installed all of the aluminum mullions for the skylight framing system. Their sequence of installation followed PBI's. Steel was erected in one of the eight "pie" sections while mullions were installed in the previous section. By installing the mullions before the shore removal, general contractor Centex Construction Company was able to start construction on the ground plane features of the atrium sooner and take six weeks off the critical path of the hotel's construction schedule. This amounted to six weeks of additional revenue-generating operation of the hotel for the owner.

The Compression Ring was set on July 25, 2002, and the shores were removed on November 25, 2002. During removal of the shores, the deflection of the bases of the queen posts measured 3½", which agreed with Walter P. Moore's predictions.

For the three atria, the total material quantities were as follows: 1,827 tons of structural steel; 25,763 pieces detailed; 17,437 ¾" bolts; 34,114 1" bolts; and 156,000 sq. ft of clear-span space. Although the statistics can be staggering, the true measure of the project will come when the hotel's guests gaze skyward and enjoy a starry Texas night framed by a 6-million-lb. canopy of steel, aluminum and glass.

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DESIGN SOFTWARE
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STEEL DETAILER
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DETAILING CONSULTANT–CONNECTION ENGINEER
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DETAILING SOFTWARE
Tekla Xsteel

STEEL ERECTOR
Peterson Beckner Industries, Inc.,
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EXPANDED-WEB BEAMS
SMI Steel Products, Hope, AR
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