Under Glass

Photo by The Harman Group

BY MALCOLM BLAND, P.E., LEED AP, AND CHRISTOPHER CONN, P.E., S.E.

AT 2,400,000 SQ. FT, GAYLORD NATIONAL is the largest privately financed combined hotel and convention complex on the East Coast.

The complex is the cornerstone of the newly developed National Harbor development overlooking the Potomac River in Prince George's County, Md. The hotel contains 2,000 guest rooms, meeting space, and two ballrooms. The 800,000-sq.ft convention center portion includes a 180,000-sq.-ft exhibition hall, two ballrooms of 50,000 sq. ft and 35,000 sq. ft, and approximately 400,000 sq. ft of flexible meeting space.

Structural steel was used in many areas of the project, such as the hotel and convention center ballrooms, theater space, mezzanines, façade support, canopies, an 8,000-sq.-ft pool building, and a porte cochere, for a total of 5,400 tons.

Marquee Space

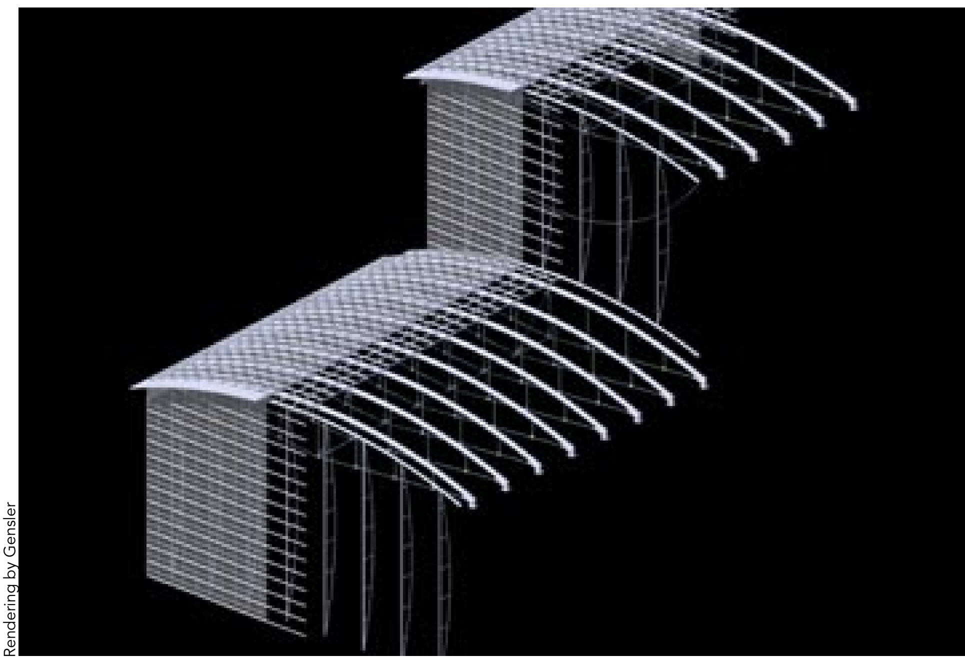
The centerpiece of project is the 2,400-ton structural steel bow-string truss roof skylight structure over the 1.6-acre hotel atrium. Providing 120,000 sq. ft of glass walls and roofs, the atrium connects the wings of the central hotel tower and the two lower hotel towers. As the feature space of the project, and in deference to the view to the Potomac River, the objective for owner Gaylord Entertainment was that the skylight must have less structure and more openness than its previous projects, thus maximizing the benefit of the project's premier location. The design team developed multiple schemes for the structure to achieve Gaylord's goals, eventually selecting the bow-string truss structure, as it achieved both the aesthetic and functional requirements for the atrium.

The final result was a design in which the horizontal surfaces of the atrium are spanned with exposed bow-string (tied arch) trusses and hollow structural section (HSS) purlins, while the vertical curtain wall façades that span between the upper and lower roof and from the lower roof to the ground were supported using Vierendeel vertical trusses at the walls with HSS girts, and a hung catenary upper wall.

The bow-string trusses consist of curved 40- and 42-in.-diameter pipe top chords, vertical pipe web members and double 3-in. and 4-in. rod bottom chords. The trusses at the upper atrium roof are 28 ft deep at mid-span and span 195 ft, while trusses at the lower atrium roof are

2008© Photo by Alan Karchmer, courtesy of Gensler

A glass-and-steel-encased atrium meets the goals of less structure and more openness, and provides great views of the Potomac River in the process.



Rendering by Gensler

opposite: The 19-story atrium is topped with a 2,400-ton steel bow-string truss roof skylight structure.

top of page: The Gaylord National contains 2,000 guest rooms and a 180,000-sq.-ft exhibition hall.

mid-page: This cutaway of the atrium depicts the hierarchy of framing.

32 ft deep at mid-span and span 220 ft. Stability of the trusses, which include round HSS king posts, is attained with the use of bridging located at the center king post.

The HSS purlin frames that support the glazing system connect to the top of the bow-string truss top chord and provide lateral bracing to the trusses and act as the diaphragm for distributing lateral forces to the hotel towers. Lateral wind forces were determined through boundary wind layer testing performed by Rowan Williams Davies & Irwin, Inc. (RWDI) by combining mean wind load distributions with appropriate fluctuating dynamic load distributions, including an allowance for dynamic amplification resulting from inertial effects. An IBC Exposure Category of D was used as the basis of design due to the proximity to the Potomac River, which is 2½ miles wide at the location of the complex.

Efficiency of Design

To increase efficiency, fabricator Banker Steel Company suggested using spiral welded steel pipe at all but the two heavily loaded trusses. A mock-up of the top chord was prepared to determine the acceptability of the spiral seam. Gensler determined that while the seam was visible at close range, it did not need to be ground smooth, given that the trusses are viewed from a distance. However, at splice locations, the seams had to be within the top 20 degrees so the seam would appear continuous from below. One significant challenge for Banker was curving the 40- and 42-in.-diameter top chord members. A shop-performed heat curving procedure, developed by Banker, accomplished this successfully. The process involved building a track device so that gas "rosebud" heat torches would gradually move along the pipe and heat the steel so that it would curve under its own self-weight.

In order to eliminate structural columns impeding the use of the atrium floor, the roof structure was designed to be supported directly on the top of the hotel's structural framing. The layout of the hotel wings, with a U-shaped 19-story building and two 8-story sections—all separated with expansion joints—required careful consideration of slide bearing supports for the atrium structure and hinging of the upper wall. Thoughtful design of slide bearing connections, plates, and bearing pads at each end of the trusses, capable of transmitting the

Photo by The Harman Group

2008© Photo by Alan Karchmer, courtesy of Gensler

The upper atrium wall is designed as a catenary truss hung from the top of the U-shaped 19-story hotel tower.

gravity loads and resisting lateral loads induced by wind or seismic events, allow the hotels tower to move independently.

To accommodate the differential movement between the towers, slide bearing connections were detailed to allow movement in certain directions while resisting forces in other directions. This allowed adjacent towers to move out of phase as much as 6 in. The vertical glass walls were detailed in a similar manner; thus only one tower resists the lateral load in the direction parallel to the truss span. Stop blocks and uplift preventers were added to the end connections to control the action of the atrium structure should the movement at the slide bearings exceed the anticipated ranges.

Rather than using a large truss at the lower atrium roof for the support of the upper wall, which would have hindered the openness of the atrium, the upper wall is designed as a catenary hung from the top of the U-shaped 19-story central tower, similar to a dog flap. Double 2.5-in.-diameter rods with standard clevises in an approximate parabola form a deep catenary truss with a rectangular HSS top chord. Lateral loads acting perpendicular to the plane of the wall are resisted by vertical Vierendeel trusses that span from the upper to the lower atrium roof. Due to the expansions joint locations in the hotel towers, the connection of the vertical trusses to the lower atrium roof is designed to allow movement in the north-south direction, as well as to allow vertical movement and rotation while resisting movement in the east-west direction.

In order to reduce erection time and cost, the HSS purlins forming the diaphragm of the upper and lower roofs were fabricated into modules, and all connections were designed to be field bolted. Careful consideration of ease and speed of erection, erection tolerances and adjustability, and glass system deflection limitations drove the connection design of the HSS purlin frames to the tops of the bow-string trusses.

Clevises were used to connect the rod bottom chord of the trusses to the gusset plates at each connection point. Standard and heat-treated cast #8 clevises were used for trusses with 3-in. rod bottom chords, and machined custom clevises, designed and fabricated by fastener manufacturer Wecall, were used for the 4-in. rod bottom chords; machined clevises were required at two heavily loaded trusses.

Material strengths for the clevises included ASTM A668 Class A, F_u = 47 ksi for the standard clevises; ASTM A668 Class F, F_u = 90 ksi for the heat treated clevises; and ASTM A322 Grade 4140, F_u = 98 ksi for the machined clevises. Both machined and heat treated clevises were full scale tested, to failure, at Lehigh University to determine their ultimate capacity. Based on the test results, the clevis capacities for the heat-treated and machined clevises were approximately 850 kips and 1,400 kips, respectively. Due to their small size, their clevises provided aesthetic and construction advantages over connections of other types. The use of the clevises allowed truss erection to be expedited, thanks to reduced field welding and reduced quantities of bolts.

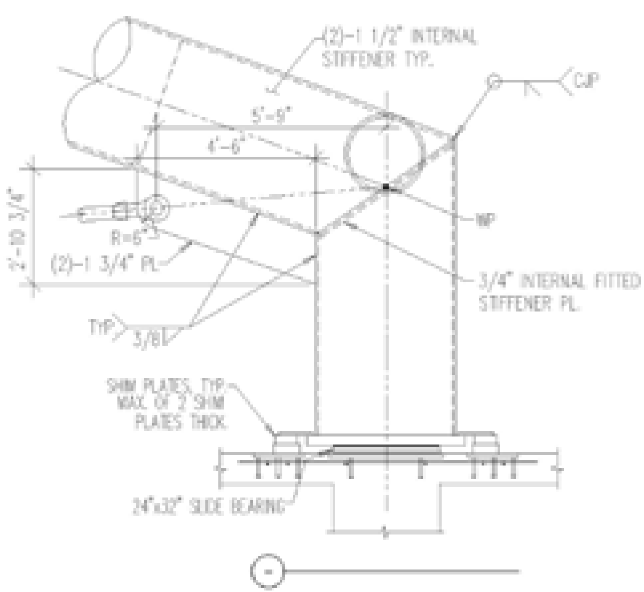
Erection Logistics

Each truss was fully shop assembled to insure proper fit-up of the field welded joints and to confirm all dimensions of each truss. Once delivered to the field in pieces, the trusses were fully assembled in a vertical position on precisely located rig platforms. The pipe top chord was shipped in three pieces for most trusses and five pieces for the two heavily loaded trusses, and full-penetration welded back together on the ground. The overall dimensions were checked again, as were the elevations of the purlin seated connections. In regards to the vertical wall, the trusses were again shop and field assembled into position following the approved erection procedure. With all of the complexities involved in this project, there were only minor fit-up issues in the steel-to-steel connections.

The exposed steel is coated with a Sherwin-Williams direct-to-metal (DTM) urethane.

Photo by The Harman Group

Erection of one of the bow-string trusses; the trusses used for the atrium were either 195 or 220 ft long.



A detail drawing of the truss end bearing. The Harman Group

The layout of the hotel wings greatly impacted erection logistics. To gain access to install the bow-string trusses of the upper atrium roof, the lower roof could not be placed. This required holding the start of erection until the center hotel tower had topped out, which further dictated the sequencing of construction of the hotel towers. Since the largest bow-string truss weighed 77 tons and also due to the tight site constrictions, a Liebherr LR 1400/2 crane—assembled in a wheeled ringer configuration and with a 450-ton capacity—was used for erection. Trusses were picked up from the atrium floor and rotated in the air, then the crane advanced into the center of the U-shaped center hotel tower to place the trusses on the roof of the hotel.

Erection of the bow-string trusses proceeded westward until the upper atrium roof was installed and the first two 220-ft-long lower atrium bow-string trusses and purlin frames were installed. Construction outriggers were fitted to the lower roof to temporarily support the vertical Vierendeel trusses of the upper wall. The temporary supports remained in place until the catenary rods and girts of the upper wall were fully installed. When the temporary supports were removed, putting the catenary into tension and hanging the upper atrium wall from the center hotel tower roof, the wall deflected down approximately 3/8 in., within 10% of what was estimated. Once the upper Atrium wall structure was completed, erection of the remaining lower Atrium roof trusses and purlin frames and lower wall Vierendeel trusses continued to the west. MSC

Malcolm Bland is a vice president with the Harman Group and principal in charge of the structural engineering of the entire hotel and convention center complex, and can be reached at ***mbland@harmangroup.com****. Christopher Conn is an associate with the Harman group and directed the design of the atrium roof structure. He can be reached at* ***cconn@harmangroup.com****. Both are AISC Professional Members.*

Owner
Gaylord Entertainment, Nashville, Tenn.

Architect
Gensler, Washington, D.C.

Structural Engineer
The Harman Group, King of Prussia, Pa.

Steel Fabricator
Banker Steel Company, Lynchburg, Va. (AISC Member)

Steel Erector
MEMCO, Culpepper, Va. (SEAA Member)

Construction Manager
Perini/Tompkins Joint Venture, Oxon Hill, Md.