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Waterfront Winner

By James O'Callaghan

The David L. Lawrence Convention Center in Pittsburgh used a cable-stayed design to create the largest clear-span convention space in the U.S.

A new addition to Pittsburgh's Allegheny riverfront, the David L. Lawrence Convention Center combines contemporary design with cable-stayed engineering technology to create a distinctive structure and a landmark exhibition space.

The building's architecture relates to the urban topography and its industrial history. The site's proximity to the 6th, 7th and 9th street suspension bridges inspired a cable-stayed structure. The design team brainstormed methods of achieving a clear-span roof over the main exhibition space in a manner similar to suspension-bridge technology. The result was a roof structure of primary suspension cables over central masts anchored at the end by the building main structure. The use of structural steel contributed towards the center's U.S. Green Building Council LEED™ (Leadership in Energy and Environmental Design) gold rating for achievement in sustainable design—the largest LEED-certified structure in the United States.

Going the Distance

The facility also features the largest column-free space in the United States. In order to create this space, the design team investigated long-span structures, and chose to integrate suspension-bridge design principles to create the clear span. The structural design of the building was developed to minimize the requirement of concrete anchorages typically used in suspension bridges to resolve the massive tension forces in the supporting cables. The building structure evolved to accommodate both the program needs and the major internal loads developed by the tension-cable roof structure.

The anchorages at the ends of the cable are major steel frames that transfer roof-tension loads and form the floor and roof support of the building structure. A key principle of structural design is the resolution of these height-tension forces within the building framework, eliminating the need to resolve the forces through costly foundation works. This was efficiently achieved using the steel trusses, convention-floor supporting beams and a tension grade beam.

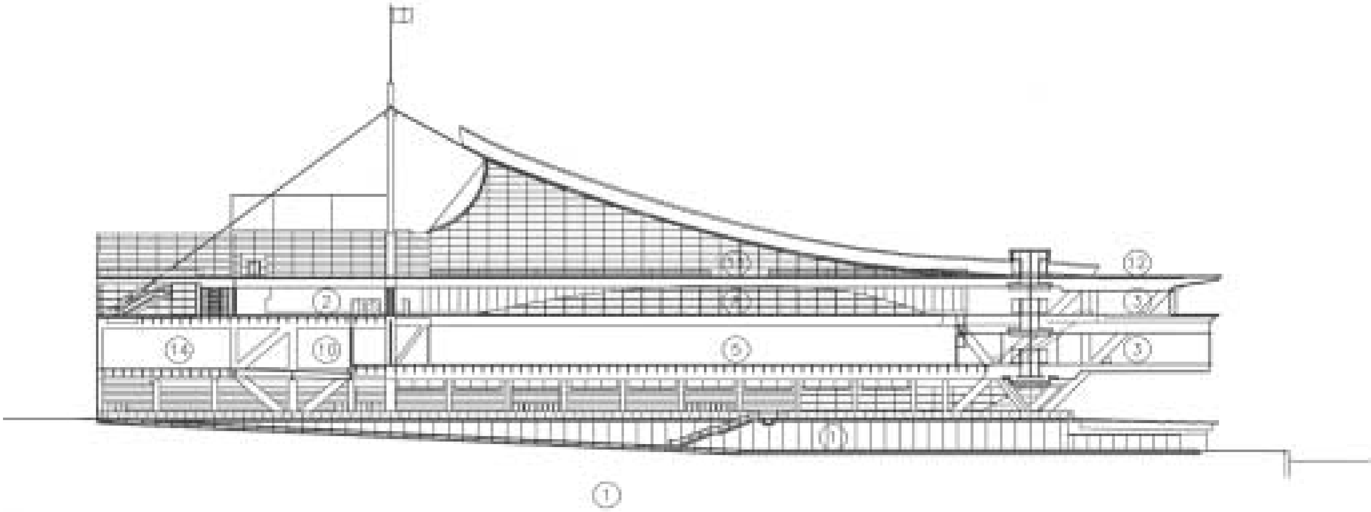
The lateral stability of the building structure is achieved using the main vertical-circulation concrete cores located on either side of the main exhibition floor. Lateral loads imposed on the building are transferred through the floor plates via diaphragm action to the main concrete cores.

The vertical load-bearing structure supporting the floors and roof vary in material choice and technique, depending on efficiency, economy, and application.

Firm Foundation

The underlying soil conditions beneath the building are generally a mix of gravel and marl with fill in areas to a depth of 60′. The site is close to the river, and historically was used as docks and railroads. Many hidden obstructions required removal, such as concrete foundations of the old elevated railroad.

The ground investigation survey detailed the depth of rock strata between 50′ and 70′, depending on location. The



Key

1. Water feature
2. Entrance lobby
3. Prefunction area
4. Lower exhibition halls
5. Main exhibition halls
6. Meeting rooms
7. Lecture rooms
8. Pedestrian bridge
9. Service bridge
10. Service corridor
11. Promenade
12. Riverfront terrace
13. City terrace
14. Loading dock
15. Parking garage
16. Administration
17. Kitchen
18. Main ballroom
19. Junior ballroom (for future hotel)

NORTH–SOUTH SECTION

strata were suitable for piles or caissons. A deep-foundation system was used for the convention center as a result of these recommendations, the frequency of the required foundations, and the required high column loads. An analysis of piles versus caissons revealed the most suitable solution to be caissons due to the large pile groups requiring a prohibitive pile-cap cost.

The caissons primarily take vertical gravitational loads generated from the structure above. The large tension loads developed in the cable roof structure are resolved within the steel frame and therefore do not require resolution through the foundation system. The caissons vary in diameter from 1′-6″ to 7′, with the larger caissons carrying up to 4,000 tons. Concrete grade beams spanning between the caissons were used to pick-up external envelope conditions and elevator pits.

Steel Frame

On each of 15 framing lines, there are major frames to the north and south of the building known as the bow and stern frames—a nod to their resemblance to parts of a ship. Their configuration supports the main floors, and they are the anchorage mechanisms for the main cable roof. As a result of the loads induced by the roof structure, the members within these frames frequently are beyond the capacity of domestically available rolled steel sections. This led to the need to detail plated W sections often in excess of 500 lb/ft. The method of plating sections was preferred so steel could be sourced domestically as opposed to using jumbo sections mostly available overseas. The total weight of steel in the building structure exceeds 18,000 tons. The bow frames are approximately 120 tons and the stern frames 200 tons each.

The tension generated in the roof cables and then transferred through the bow and stern frames results in a net force pulling these two frames toward one and other. This force is resisted by a strut used between the bow and the stern at the second-floor level. This compression strut also is used to support the exhibition floor system. The strut is a fabricated phase box girder and weighs 800 lb/ft.

The framing between the bow and stern frames forming the floors is generally deep-rolled W sections, which, in turn, support concrete double-tees on the stern and concrete/metal deck in the bow.

Above the main stern frame, the structure changes to a steel beam-and-post system, more traditionally formed in building structures. The floors at the 4th and

Above: Schematic section through the convention center.

Below: The upper cable spans from an anchorage weldment, over the central mast, and across the exhibition hall ceiling.

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5th levels are metal deck on steel beams, and concrete cast to a thickness of 6¼″.

As a result of the large-scale displacements experienced by the structure during the erection and tensioning of the cable structure, it was necessary to develop a sophisticated articulating joint in the steel frame between the bow and the second-floor compression strut. The function of the articulating joint was to allow transfer of the compression forces while facilitating the rotation of the bow frame during erection.

Floor Structure

The frequency of the main structural frames at 60′ on center resulted in the need for a floor structure that could efficiently span these distances. In addition, the requirement for the 2nd-floor exhibition space is particularly demanding in terms of the 350 psf live-load criteria. The adopted solution to meet this demand and others relating to cost, schedule and ease of construction was the use of pre-cast double-tee sections. The double-tees were designed specifically for the high loadings at 36″ deep. The tees are supported on the steel structure at every frame line.

The large displacements of the structure during roof tensioning had to be incorporated into the detailing of the precise double-tees. Each tee had to effectively transfer shear between it and the adjacent tee while simultaneously facilitating the axial shortening of the supporting beam. A simple folded-plate shear connector was developed by the team that offered a very cost-effective solution to a complex problem. The tees are topped with 3″ concrete to provide the required diaphragm action across the floor place and to provide the finished surface. (For information on where to purchase concrete plank and double-tees, please see the concrete plank product listing on page 63 of this issue.)

In order to maximize the economics of using pre-cast for the main 2nd-floor exhibition space, it was decided to adopt pre-cast columns and structure to form the floors between the stern frames.

Cable Roof Structure

In order to achieve the clear spans over the 2nd-floor exhibition space, the cable structure proved a more efficient solution than that of a steel-truss long-span structure. The economics of this suggest that 300′ to 350′ cable roofs are very competitive mechanisms for achieving long spans.

A main cable spans on every frame line between the bow and stern frames of the structure, to which they are anchored using large plate weldments. The main span of the roof varies between 330′ and 420′ along the length of the building.

The cable roof consists of an upper cable spanning from the anchorage weldment on the bow frame over a central mast (increasing in height between frames 1 to 15) and down to an anchorage weldment at the 3rd floor of the stern frame. The upper main cable supports lightweight steel trusses that span perpendicularly to the adjacent cable. These trusses are at 10′ on center down the slope of the roof.

A standing-seam stainless-steel roof spans between the steel roof trusses to form the roof surface. The upper cable is prevented from uplift by the action of the lower dampening cable. The lower cable is a reflected arch of the upper cable. Each cable induces tension on one another via vertical hanger cables that are the mechanism by which the main upper and lower cables initially are tensioned. The resulting tensioned cable truss has stiffness and limits the overall vertical deflections of the roof.

The tension developed in the roof cables exceeds 2,000 tons. This force is resolved through the steel bow and stern frames and is resisted by a couple generated between these two steel frames. This couple is the compression induced on the exhibition floor and a steel tension grade beam buried below the grade slab. The exhibition floor resists the compression via a large plate girder, which carries the pre-cast double-tees forming the 2nd-level exhibition floor, and resists the equivalent of 2,500 tons of permanent compression induced by the couple action.

Cable Wall Façades

The gable ends of the building required a glass façade that not only could accommodate the large deflections experienced by the roof, but also could deal with the curving geometry between the building and the roof structure. The first of these challenges was addressed by combining the mullions of the façade with the roof structure. By dropping vertical cables at every proposed mullion position and by tensioning them between the flexible roof structure and the rigid building structure, the live-load deflections of the roof structure were reduced from 3′ to less than 6″. This made the head gasket detailing significantly less complex. The tensioned vertical hangers could then be used as the wind-load support for the façade glass panels. The façade panels used are unitized and therefore the detailing between each adjacent panel had to be such that the large out-of-plane deflections could be accommodated without compromising the weather seal. This flexible cable wall, using insulated glass panels, is a world first that provides a mullion-free, large-spanning glass wall.

Construction

Joint-venture construction management of Turner and PJ Dick, Pittsburgh offices, managed the construction of the project. The Sports and Exhibition Authority of Pittsburgh had agreed to a fast-track procurement process with the CM and the design team was asked to accommodate this in the production of staged bid packages. For the building structure, these packages were for deep foundations, foundation concrete (caisson caps), structural steel work, pre-cast concrete, cast-in-place concrete and the cable roof. The first of these packages was bid prior to the completion of the design development phase. Bidding of the structural steelwork and roof structure was conducted prior to completion and co-ordination of the structural documents.

The complexity of the cable roof and its interaction with the steel frame to which it is anchored created a major challenge in erection engineering. Phil Khalil, project engineer for DMP/GEPC, set up a time-history computer analysis of the roof-tensioning procedure, including the deflections of the anchorage frames. This sophisticated analysis tool allowed DMP/GEPC to model each stage of the roof tensioning and the associated frame deflections. In comparing the predicted deflections of the anchorage frames at various points during the tensioning, it was possible to make adjustments. This ability to make the required re-alignment adjustments was built into the frame design. This innovative approach developed with ADF International and the steel contractors placed an adjustable shim mechanism between the main 2nd-floor strut and the rotating ‘bow’ frame. By increasing or decreasing the shim distance, an amount evaluated from the comparison between real and predicted

Big, Green and Gold

The David L. Lawrence Convention Center is the largest LEED™ (Leadership in Energy and Environmental Design) certified building in the United States and the first Gold LEED-certified convention center in the United States. The building's steel-framed structure facilitated many high-performance features such as natural daylighting and ventilation, and the use of recycled products.

The shape of the roof encourages natural cross-ventilation of the main space, taking advantage of the convection currents that draw fresh air from the river. Environmental concerns are also considered in every detail of the building. Materials used include locally available industrial products like steel, glass and pre-cast concrete, recycled and recyclable materials and those with low VOC emissions. Recycled materials were used for at least 25% of the building, including over 95% of the demolition system (by weight) from the original convention center.

Structural steel has nearly 100% recycled content, and can be re-used repeatedly without losing its quality. Also, the use of locally fabricated, recycled structural steel can earn points toward a LEED rating in the recycled and locally manufactured materials categories.

Longitudinal skylights, with operable shading that includes both translucent and black-out capabilities, provide natural light and reduce the energy consumption of the building. Surrounding pre-function spaces also utilize natural lighting.

The building also has a water reclamation system and uses the underground aquifer for cooling and make-up water for the water feature. Condenser water is sprayed on the roof surface, cooled by evaporation over the large area and re-circulated through a channel that separates the roof from the Terrace. The cascading water on the metal roof also produces a highly reflective surface that minimizes heat gain from solar radiation.

For more information on the use of structural steel in sustainable design, please visit **www.aisc.org/sustainability** or view the article "Structural Steel Contributions Toward Obtaining a LEED™ rating" in the May 2003 issue of *Modern Steel Construction*, available online at **www.modernsteel.com**. Also check out the September 2003 and June 2004 "Sustainability" issues of *Modern Steel Construction*. ★

displacements, it was possible to guide the cable attachment point to exactly the required position and therefore the roof structure. The analysis, review and implementation of this process proved extremely effective and accurate, particularly given the size of the roof structure and the loads being generated through it.

Despite the immense complexity of the structural erection, the project schedule was managed on time and on budget. The result for Pittsburgh is a landmark building that actively involves the people of Pittsburgh and provides a boost for the economy through the conventions it attracts to the city.

The project was the national award winner in the $100 million or greater category of the 2004 IDEAS awards.★

James O'Callaghan was the project design principal for Dewhurst Macfarlane and Partners PC.

For more on cable-stayed steel-framed structures please see the article "Design Considerations in Cable-Stayed Roof Structures" in the March 2004 issue of *Modern Steel Construction*, available online at **www.modernsteel.com**.

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