NEW ROOF, NEW ICON

The crowning achievement of the renovation of BC Place, in Vancouver, is the cable-supported retractable roof—the largest of its kind in the world—which was designed to transform the stadium into a year-round, multipurpose, open-air facility and lend spectacular new drama to the Vancouver skyline.

By David M. Campbell, P.Eng., P.E., M.ASCE, and Karen A. Lynch, P.E., M.ASCE

MICHAEL ELKAN PHOTOGRAPHY, *ALL PHOTOGRAPHS;* GEIGER GOSSEN HAMILTON CAMPBELL ENGINEERS, *ALL DRAWINGS*

SITUATED ON THE NORTH shore of False Creek in downtown Vancouver, British Columbia, the stadium BC Place opened in 1983. The original construction was undertaken on a relatively open site in what was then an industrial enclave on the fringe of Vancouver's urban center, and the stadium development was a catalyst in transforming the False Creek eastern basin into a vibrant mixed-use urban area.

This earlier success, however, presented the first of many significant challenges to the recent revitalization of the stadium, as construction access to the site had become extremely difficult. What had been a relatively open site in the early 1980s, when the stadium was constructed, is now a highly trafficked urban enclave. This prime location, however, is perhaps the facility's greatest asset today and was a key factor in the decision to revitalize the stadium rather than pursue construction of a new one.

The new, 54,000-seat stadium opened on September 30, 2011, following a $563-million revitalization that included extensive interior and exterior renovations, the most exceptional of which is the new, cable-supported retractable roof. The stadium's original air-supported roof had reached the end of its anticipated service life, but its replacement was driven by much more than the expiration of its life cycle. The stadium's owner had hoped to transform the venue into a distinctive 21st-century architectural icon of Vancouver, and the new roof became the primary means of doing so.

An initial feasibility study of the roof replacement highlighted the key challenges: site impediments and the facility's configuration all but necessitated supporting a new roof on the existing stadium superstructure. The evolution of British Columbia's building code, which is based on the *National Building Code of Canada,* was such that any new passive roof structure had to accommodate much greater snow loads and seismic demands. Given that the primary virtue of the air-supported roof structure was its extremely minimal mass and its nearly "invisible" dynamic demand on the supporting structure, it was likely that any passive structure with the capacity to carry the very significant design roof snow load of

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The roof structure is a membrane-clad radial cable truss with a retractable center. The roof membrane is supported at the bottom chord cables exposing the structure. The roof structure, *opposite,* incorporates 1,768 linear m of energy-efficient light-emitting diodes that contribute significantly to the stadium's dramatic new presence on the Vancouver skyline.

2.2 kPa would create undue demands on the existing stadium superstructure.

THE ROOF STRUCTURE—developed by a design team led by Geiger Gossen Hamilton Campbell Engineers, PC, of Suffern, New York, in consultation with Schlaich Bergermann und Partner LP, of New York City; Tensys, of Bath, United Kingdom; and RWDI, of Guelph, Ontario—is a tensioned-membrane-clad radial cable truss structure with a retractable center. The roof membrane is supported on the radial truss's bottom chord cables.

The primary structural system comprises 36 structural steel masts supporting the radial cable truss, which is post-tensioned within a steel compression ring (see the figures on page 52 and at the bottom of page 53). The primary structure is exposed to effect the transformational impact on the Vancouver skyline desired by the owner.

To minimize the demand on the supporting structure,

The new, 54,000-seat stadium is crowned by a cable-supported retractable roof—the largest of its kind in the world—which was designed so that the stadium could serve as a multipurpose open-air facility.

the new roof structure is a "closed system" (as was the air-supported roof), equilibrating the horizontal forces of the cable truss internally and relying only on the existing stadium superstructure for vertical support and to resist applied lateral loads. The tangential horizontal moment on a mast assembly resulting from the upper radial cables is resisted by the vertical separation of the tension and compression rings. The former is at the base of the roof, and the latter is nominally 12.5 m above this elevation. Since the stadium plan and the original ring geometry were developed as a superellipse to equilibrate the air-supported roof's skew-symmetric cable layout, the 36-sided polygons of the new rings would not follow this form. The geometry of the ring polygons, together with the cable truss prestress, was therefore established so as to provide a funicular equilibration of the cable forces. This resulted in the distinct architecture of the system, the exterior compression ring and interior tension ring nested in plan. The configuration concentrates structural material at the

perimeter, where it is easiest to erect, and allows the roof span to be formed solely of cables.

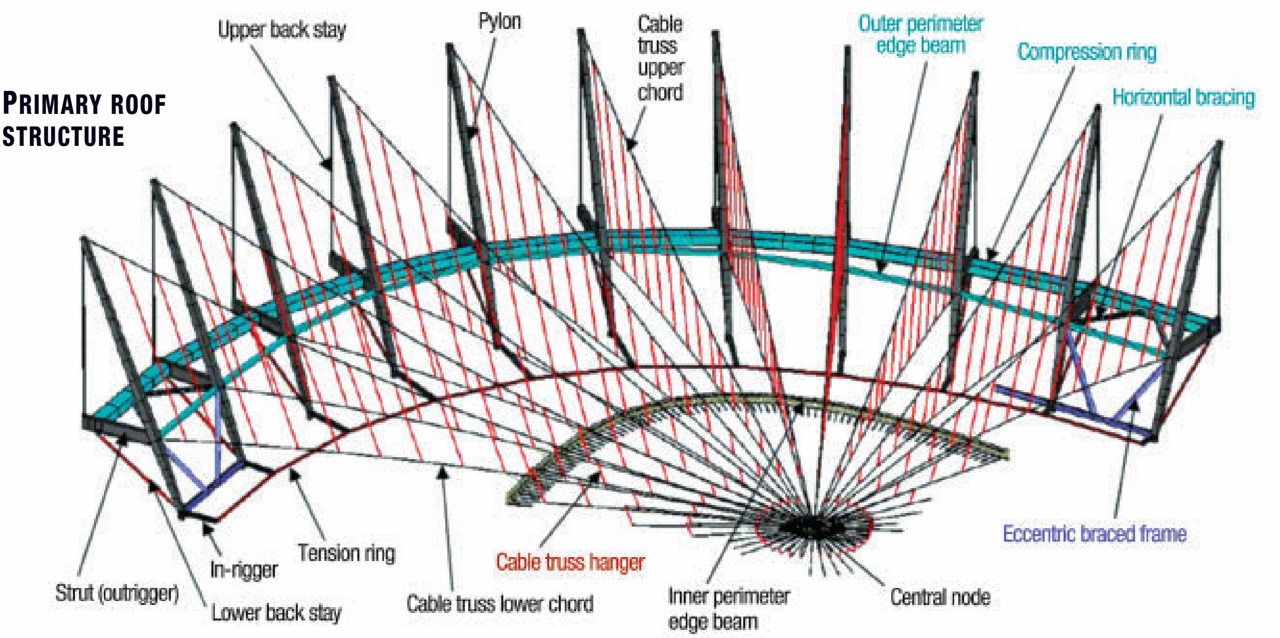
The roof cladding consists of three systems, which were chosen for their low mass, functionality, serviceability, and suitability: a retractable membrane roof composed of fluorocarbon composite fabric over the field; a fixed roof canopy, which covers the balance of the roof and is composed of a fiberglass roof membrane coated with polytetrafluoroethylene (PTFE) and supported by steel arched ribs that span between radial bottom chord cables; and a clerestory facade, which is composed of ethylene tetrafluoroethylene (ETFE) film membrane panels and louvers.

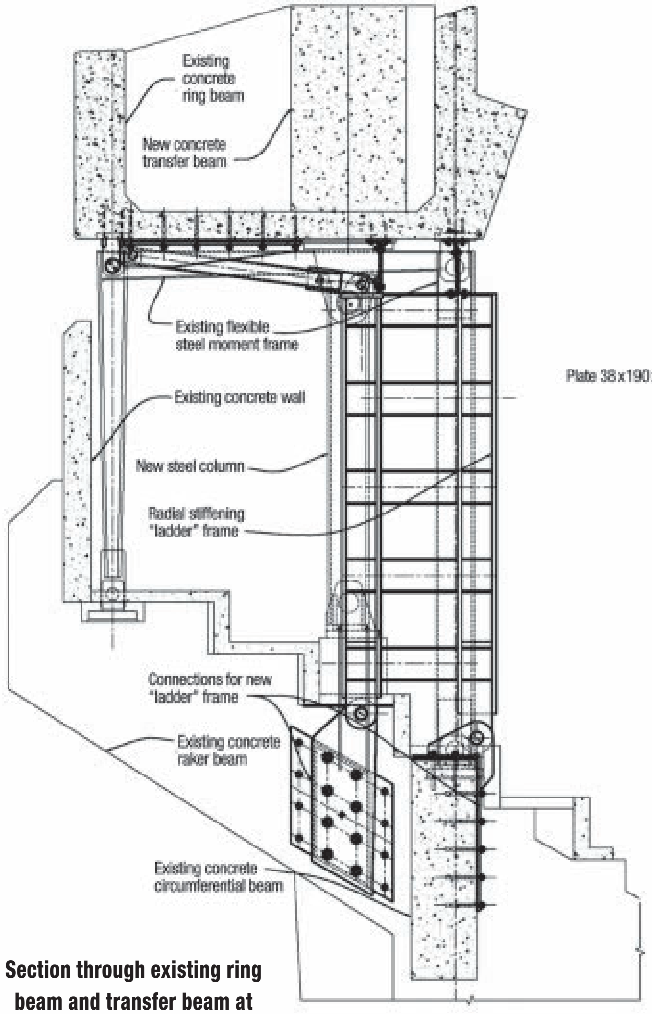
The primary structural system comprises 36 steel masts supporting the radial cable truss, which is posttensioned within a steel compression ring.

The retractable roof, covering approximately 7,500 m^2, is composed of pneumatically inflated cushions that span between radial bottom chord cables. The interior space between the top and bottom membranes of the cushions is pressurized by compressors within the roof's center node. The internal operating pressure of the cushions is 500 Pa and is increased to a maximum of 2,000 Pa when the design snow load is present. (As a point of reference, the operating pressure of the air-supported roof was 270 Pa with a maximum of 700 Pa.)

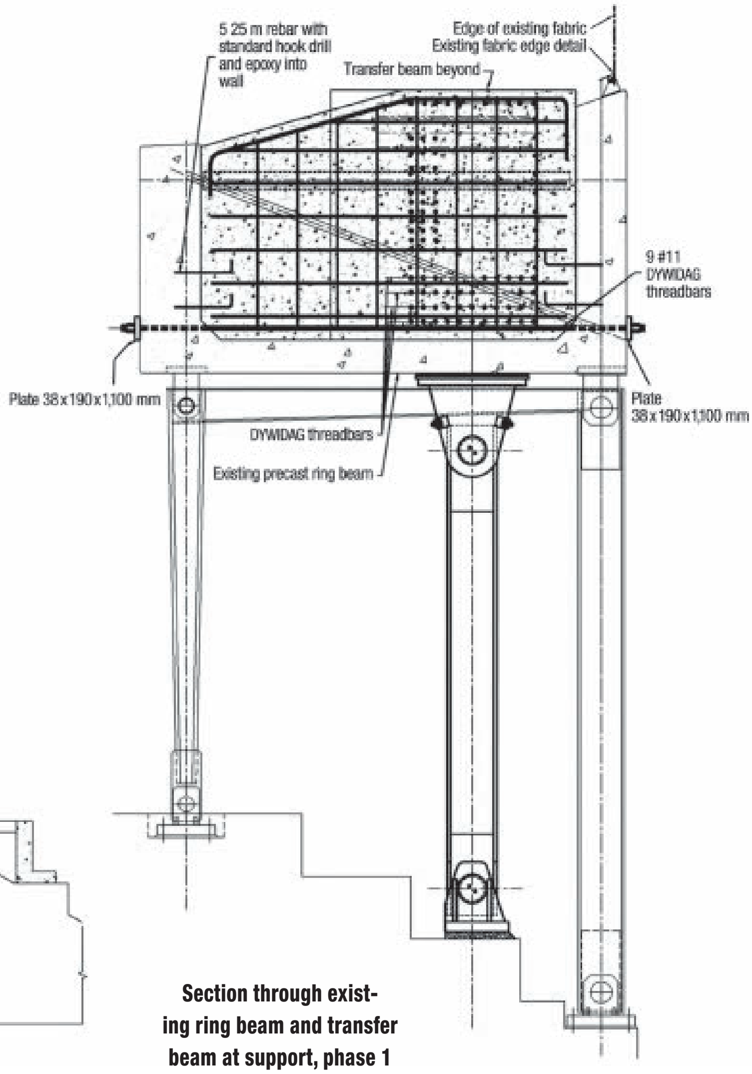
The retractable roof is a prefabricated membrane assembly supported by trolleys that ride on the radial bottom

PRIMARY ROOF STRUCTURE





Section through existing ring beam and transfer beam at support with ladder frames



Section through existing ring beam and transfer beam at support, phase 1

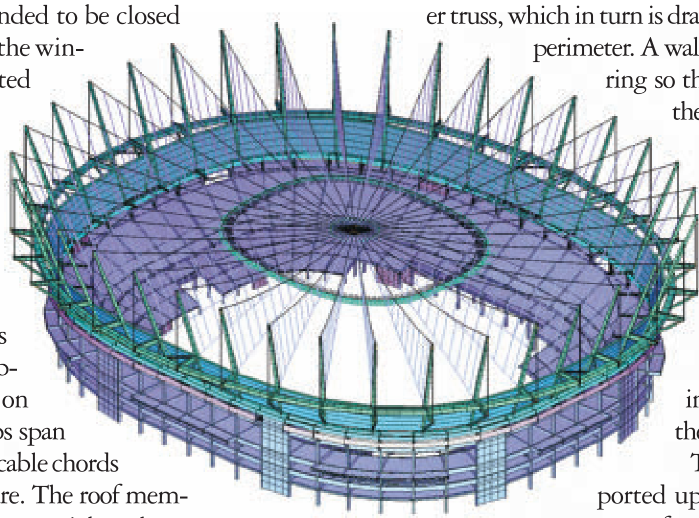
chord cables. When retracted, the membrane cushions are deflated and collected to the center node, where they are stowed in a 20 m diameter receptacle for protection from the elements. The roof is intended to be closed (fabric deployed) through the winter season and to be retracted when weather permits in the summer season. The deployed roof laps over a "shelf" at the perimeter of the fixed canopy roof, a pneumatic cushion providing the seal.

The fixed roof canopy is a PTFE-coated fiberglass fabric membrane supported on tied steel arch ribs. The ribs span between the radial bottom cable chords of the primary roof structure. The roof membrane is the same generic material as that used for the air-supported roof. An acoustic liner covering approximately 50 percent of the roof area is provided.

At the inside edge of the fixed roof canopy is a glazed ring cantilevered from the inner ring girder truss and providing a "shelf" for retractable roof overlap. The glazed shelf is pitched to drain to a continuous gutter around the edge girder truss, which in turn is drained via radial pipes to the roof perimeter. A walkway is provided on top of the ring so that service personnel can reach the retractable roof winches, seals, gutters, and drains.

The outer roof perimeter is supported by built-up hollow steel members of trapezoidal cross section spanning between masts. A continuous steel perimeter gutter is attached to the inside of the edge beam below the fabric panel clamp line.

The primary structure is supported upon a new, cast-in-place concrete transfer girder built within the original air-supported roof's precast compression ring. Additional steel columns were added parallel to the upper deck's outer column line to support the transfer structure and the new



Stadium Superstructure with Primary Roof Structure

roof loads (see the upper right figure on page 53). This work was completed in 2009 during the first phase of the project while the facility remained in use. As the existing ring beam was used as the air-supported roof's air distribution plenum for melting snow, additional air ducts were required for this purpose for the winter of 2009–10, when the facility was the host venue for the opening and closing ceremonies of the 2010 Winter Olympics.

The roof system is supported on 36 radially guided slide and rotation bearings and is laterally supported in the tangent direction at four braced bays at the cardinal points in plan. This uncoupling of the roof from the supporting structure allows for the relatively large deformations of the rings necessary to resist various load conditions without transferring lateral loads to the existing supporting superstructure. However these large deformations—as much as 450 mm—created challenges in supporting the mast bearings throughout their range of motion and in detailing the secondary facade clerestory structure.

The facade clerestory is composed of five horizontal panels; the panel immediately above the original precast ring beam takes the form of a series of operable louvers for ventilation. The primary elements of the facade are hollow structural steel girts spanning nominally 20 m between masts and the panelized single-skin ETFE foil membrane with vertical aluminum ribs. The connection of the girts to the masts must accommodate tangential expansion and contraction from zero at the head to the maximum at the foot of the facade. This was achieved by pinning one end of each girt and allowing a cuff at the other to slide on a horizontal 80 or 120 mm spigot. This enables the foot of the facade to "float" with the masts.

Additionally, the geometry of the roof system is such that the masts are not oriented radially; thus, the behavior of the girts is not symmetric about the mast and is unique in each location. The drainage system from the main roof, which is mounted on the masts, also must accommodate this same range of movement. A flexible membrane connects the vertical edge members of the facade to the masts, thereby sealing the entire system.

The existing stadium superstructure consists of eight nominally independent reinforced-concrete structures with lateral-force-resisting systems composed of shear walls in the circumferential direction and moment-resisting frames in the radial direction. The new roof, like the original one, is a single integrated structure supported on these eight structures. The dynamic characteristics of the roof system are intentionally quite different from those of the supporting stadium superstructure. A response spectrum analysis was performed modeling the existing stadium superstructure with the new roof. In the final design, seismic demand governed some of the roof members, the roof's eccentrically braced frames, and the travel of the mast bearings and necessitated stiffening of the story between the top of the reinforced-concrete structure and the transfer girder at the original ring beam level.

Since the original roof's ring was supported on intentionally flexible moment-resisting frames, radial lateral stiffening frames were added to control drift (see the upper left figure on page 53). The response spectrum analysis indicated that the

new roof and transfer structure contributed approximately 10 percent of the overall base shear of the stadium. Evaluation of the existing stadium by GENIVAR, of Vancouver, the structural engineer for the base structure, indicated the necessity of reinforcing the upper stadium columns supporting the roof. It also suggested the need for a general upgrade to the stadium's seismic-force-resisting systems, mostly because of code changes since the time of original construction.

The transfer of lateral load from the four braced bays to the existing shear walls presented some challenges, as the roof's braced bays do not coincide with the shear wall locations. In plan, the two systems are more than two bays (28.6 m) apart, and the vertical distance from the new bearings—on top of the ring beam—to the shear wall is 3.5 m. During the first phase, a built-up steel section was cast into the new concrete transfer beam and rigidly connected at the existing column lines. In order to allow movement of the mast and simultaneously transfer lateral load, a pivot strut was connected from the base of the mast at the braced bay to the embed created during the first phase. Below the ring beam, another beam was welded to the underside of the embed and bolted to the shear wall

The deployable overhead fabric panels are soccer screens that provide a visual screening canopy over the lower bowl, visually reducing the size of the stadium as the upper deck is blocked from view. The soccer screens consist of 54 fabric panels that are deployed from rollers mounted behind the ribbon board of light-emitting diodes at the front of the upper deck's balcony. The panels span from the rollers to four catenary ropes at the leading edge—one at each sideline, one at each end zone—which clear span the stadium interior. The system is tensioned via the rollers, and the screens are designed for use when the retractable roof is open or closed.

system. This series of beams, which in addition to the elevation change has two changes in plan orientation, resists the lateral load from half of the roof.

The retractable roof opens to reveal more than 7,500 m^2 of sky, making the stadium an attractive venue for a variety of activities, including sporting events, summer festivals, concerts, and exhibitions. The dramatic roof facade—which is known as the Northern Lights Display—employs 1,700 ETFE panels and incorporates 1,768 linear m of energy-efficient light-emitting diodes that lend themselves to customized displays. The lighting, in fact, contributes significantly to the iconic new presence that BC Place has become. The stadium is illuminated from 5:30 AM until sunrise on most mornings and from sunset until 10 PM on most evenings. **CE**

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PROJECT CREDITS **Owner:** BC Pavilion Corporation (PavCo), Vancouver, British Columbia **Revitalization project architect:** Stantec, Vancouver, British Columbia **Roof design and engineering:** Geiger Gossen Hamilton Campbell Engineers, PC, Suffern, New York, in consultation with Schlaich Bergermann und Partner LP, New York City; Tensys, Bath, United Kingdom; and RWDI, of Guelph, Ontario **Principal in charge and engineer of record for the roof:** David M. Campbell, P.Eng., P.E., M.ASCE **Project engineer for the roof:** Karen A. Lynch, P.E., M.ASCE **Structural engineer for the stadium superstructure:** GENIVAR, Vancouver, British Columbia **Architectural lighting design consultant:** C.M. Kling & Associates, Inc., Alexandria, Virginia