NATIONAL AWARD

LONG SPAN

The Leonard P. Zakim Bunker Hill Bridge is the focal point of Boston's multi-billion-dollar Central Artery/Tunnel Project. The new "Gateway to Boston" epitomizes the philosophy of form following function; a signature structural form was borne out of a multitude of functional requirements and stringent site constraints.

The bridge's first four lanes opened to northbound traffic in March 2003. Six more will open and ease the gridlock that has plagued Boston's downtown elevated highway system for decades. The bridge's two-lane cantilevered roadway carries northbound traffic from the Sumner Tunnel and North End. A series of parks and recreation areas, encompassing 44 acres, are planned for the riverbanks at the bridge base.

INNOVATION IN STEEL DESIGN

A light steel-composite main span stretches 745' over Boston's Charles River. It is arranged in a hybrid structural configuration with heavy concrete back spans, and produced the optimal layout for the bridge's site-constrained urban location. The hybrid configuration is a first-time application in the United States.

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Photo © Andy Ryan

The main span's steel framing consists of two longitudinal box edge girders of trapezoidal cross-section and transverse floor beams at 20' centers. The supporting cables attach to the outer fascia web of the box edge girders between the floor beams, allowing the floor beams to cantilever 45' to the east side of the bridge.

A longitudinal fascia girder frames into the outer ends of the cantilever floor-beam extensions. Precast concrete panels, made composite with superstructure steel framing through cast-in-place closure strips, form the deck.

STEEL COMPOSITE TOWER

The eccentrically placed dead and live loads, due to the cantilevered roadway, resulted in tensions on the eastern cables that were considerably larger than on the corresponding western cables. This difference in cable tensions under dead load created a considerable amount of torsion and lateral bending in the tower spire. It also led to complexities in bridge-erection analysis; the net transverse cable forces acting on the deck during cantilever construction were carefully considered. Use of a composite tower design with a grade 70 high-performance-steel core, which doubled as a cable anchor box, was key. This also was a first-time application.

Use of lightweight concrete for the cantilevered lanes minimized the tower-spire torsion and lateral bending. This reduced the difference in forces in the eastern and western cables to about 60 percent. Compact cable-anchorage details were used to minimize the transverse cable spacing, reducing the torsion lever arm.

Residual torsion was eliminated through a counteracting moment produced by placing the main-span cable pairs eccentric from the tower centerline. The two-stage minimization procedure reduced the required eccentric offset to just 3" with respect to the tower centerline with no significant visual effects.

COMPACT DETAILS AND CONTROLLING GEOMETRY

The bridge's cable arrangement, inverted Y-towers, and wide roadway section produce a structure with a high degree of three-dimensionality. This increases the complexity of framing and detailing of bridge elements. In particular the cable geometry required considerable engineering to enable the proper anchoring.

The slender towers and the compact tower-leg sections optimized the use of composite tower design with a steel inner core. The core controlled the complex geometry of the cables using the shop-fabricated steel box; it eliminated the need for post-tensioning in the tower walls to resist tensile forces due to cables; and it served as reinforcing steel for the tower in the vertical direction. The composite tower design also enabled a reduction in the cross-sectional dimensions of the tower spire section, improving visual quality.

GIRDER-TO-CABLE ANCHORAGE DETAIL

A similar compact detail designed with 70 HPS steel was used for the cable anchorage at the girder. This allowed an effective load-transfer mechanism between the cable and the girder, placed bolts and welds in preferred action modes (shear vs. direct tension), and provided a high degree of accessibility for inspection and maintenance. It also improved fabrication and constructability due to the single weldment. Grade 70 HPS was used for the cable anchorages and steel-composite tower spires, providing increased strength and high ductility. The steel improved fabrication of the cable-anchor pipes, reducing plate thickness by nearly one-third. It also reduced the anchor-box weight by the same percentage, minimizing the number of splices needed for construction considering the lift weights. This was a first-time application.

STEEL ISOLATION CASINGS PREVENT IMPACT TO EXISTING TUNNEL

The Massachusetts Bay Transportation Authority's (MBTA) Orange Line subway tunnel is located in the immediate vicinity of the south tower foundation and passes directly under the north tower. A tunnel ventilation building is within 2' of the south tower and a 36" critical water main is located within the south tower foundations. The transmission of lateral bridge loads to these existing underground facilities through surrounding soil was determined to be unacceptable. This required isolation of the drilled shafts nearest to these facilities from the surrounding soil by encasing them within an outer structural steel shell. This was a first-time application.

BRIDGE LAYOUT AND AESTHETICS

Site constraints included the existing subway tunnel near the bridge foundations, the existing double-decked bridge (that had to remain until the new bridge was complete), the Charles River locks and dams, and the underground water main. The 745' main steel span placed the two tower foundations on land, providing a channel free of piers in the water immediately upstream of the Charles River locks and dam. Site constraints meant the tower width at the deck level could accommodate only eight of the bridge's 10 lanes. The two remaining lanes were cantilevered to the outside of the eastern cable plane (within the main span).

The CA/T Project involved depressing the I-93 arterial roadway below ground as it cut through downtown Boston. The need to tie in to the I-93 tunnel as it emerged required a ground-hugging profile at the south end of the bridge. The bridge soffit was barely 20' above the finished ground as it reached the south bank of the river at a relatively steep 5-percent grade. Geometric limitations at this end resulted in a relatively short south back span with a span ratio of just 0.31.

The overlap of the existing bridge and new bridge at the end of the south back span made anchorage of cables along the median of the roadway the only viable solution for the back spans. The main span is supported with two cable planes along the longitudinal edge girders.

This cable geometry necessitated the inverted Y-towers. The towers were widest at the roadway level and bent back below the deck, forming a diamond shape. The cables positioned along the median and the extremely short south back-span length made the marrying of the light steel-composite main span with the torsionally rigid and heavy concrete box-girder back spans optimal.

DESIGN CHALLENGES

Some other factors that contributed to the complexity of design:

Exceptional deck width: At 10 lanes and 183', the structure is the widest cable-stayed bridge in the world. Because of limits on the maximum tower width, two lanes had to be positioned outside of the eight-lane roadway carried within the tower legs, cantilevered to the outside of the east cable plane.

Shadow effect: As an environmental commitment, the shadow effect of the bridge's wide deck on the river needed mitigation. Bridge deck openings in the median and in the space between the eight-lane main roadway and two-lane ramp were provided to mitigate shadow effects. The force effects around these openings were carefully analyzed.

Tower strut: The change in direction of the tower legs at the roadway produced a diamond shape and required a horizontal tie member at the roadway to connect the hip points of the tower diamond. The deviation of the large gravity loads carried by the towers due to the directional change produced enormous tensile forces in this

Photo Courtesy Phil DeJoseph

tie member, or tower strut. In addition, the interaction of the tower strut with the back spans produced torsion, bi-directional bending and shear.

Geotechnical conditions: The over-burden fill material involved potential environmental contaminants. The foundations located in highly variable and relatively weak rock conditions required special design and construction considerations.

Seismic considerations: Design criteria required elastic structural response under 0.17g rock acceleration. This, combined with the presence of potentially liquefiable soil lenses in the north back-span area, posed project challenges.

Asymmetric and hybrid structural layout: The bridge is the first major asymmetric and hybrid cable-stayed bridge in the United States. Its back-span layout and two cantilevered lanes make the bridge asymmetric in both longitudinal and transverse directions. The hybrid bridge consists of a steel-composite main span over the Charles River, steel-composite towers and concrete box-girder back spans joined to the main span at the tower strut. The hybrid layout accommodated the bridge's relatively short back spans.

Cantilevered ramp: The cantilevered ramp produces a global eccentric loading on the bridge structure under both permanent dead load (DL) and transient loading. The DL eccentricity produces an imbalance of cable forces between the western and eastern cables that, in turn, produces torsional and transverse bending moments in the tower spire.

Interface of bridge construction with surrounding contracts: Numerous ramps phasing in and out under the north back span left little room for falsework for the cast-in-place box girder construction. As a result, the north back span was designed to provide the contractor with the option for incremental launching, starting from the tower. The congested site provided minimal space for contractor laydown.

ENGINEERING SOLUTIONS

Innovative design solutions were developed to address the multiple project complexities.

Geometric refinements: Stay-cable geometric refinements eliminated the tower-spire torsion and minimized lateral bending caused by the two-lane cantilevered ramp. They also eliminated the need for external cable anchorages at the tower. The bridge marked the first such application of the process.

Analysis refinements: Included were significant three-dimensionality and the cantilevered ramp's impact on static, dynamic and stage-by-stage construction. The difference in DL cable forces on the bridge's eastern and western cables produced a net transverse force that tended to steer the bridge superstructure to one side during cantilever construction; this situation required refined construction staging. In addition, the hybrid span layout required careful consideration of force transfer between the main-span and the back-span structural systems.

Use of optimal materials: High-performance steel was used for the cable anchorages and steel-composite tower spires, providing increased strength and high ductility in these critical components. The main span used painted, grade 50 structural-steel framing. The bridge marks the first use of such diverse materials on a single structure. Heavyweight concrete ballast was used in the south back span to counter the effect of the span's shorter length. Lightweight concrete was used for the roadway of the two-lane cantilever ramp to minimize the eccentric dead load.

Effective mitigation of impacts to adjoining facilities: Through use of 9'-diameter structural steel isolation casings, bridge foundations were isolated from existing facilities so as not to transfer construction and bridge-loading effects. The 8'-diameter drilled shafts located within the effective zone of influence from the Orange Line tunnel were designed with 9'-diameter steel isolation casings. This allowed the 8' shaft to displace within the casing, preventing soil-structure effects on the tunnel. In addition, detailing of the south tower foundation and construction staging eliminated impacts to the 36" water main.

Steel-composite tower: The upper towers were designed with a steel box core for anchoring of cables. The steel core eliminated the need for post-tensioning in the tower walls and reinforces the concrete outer shell. The core facilitated construction by enabling shop-fabrication of the complex cable-anchor geometry.

Isolated extension of spline girder: HNTB shortened the south back span by an additional 45' to avoid interface with a tunnel at the bridge' s south end. The length reduction was made feasible with an isolated superstructure spline extension to anchor the first three cables of the south back span, the first application of this technique.

Shaping of deck slab openings: Bridge deck openings minimized shadow effects on the river. Finite-element analysis optimized the shaping of the openings to minimize stress concentrations while maximizing open area.

Tower strut post-tensioning: The tensile stresses in the concrete tower strut were negated through extensive post-tensioning. Space and detailing limitations restricted the post-tensioning. Tendon geometries were optimized to give drape (vertical) and sweep (horizontal) profiles to each tendon to match the external force effects. The 22 tendons (55x0.6" giving a 60,000-kip pre-compression force) were the maximum that could practically fit within the strut. Post-tensioning was applied in stages with advancing construction to avoid overstressing the other tower elements. This was the first such application in the United States.

Application of latest cable technologies: The design team provided detailed evaluation of the potential for rain/wind vibration of stay cables and included methods for effective mitigation. The mitigation measures, applied for the first time on a U.S. bridge, consist of cable cross ties, cable-pipe surface modifications and external dampers.

Also marking the first application on a U.S. bridge, the design specified ungrouted stay cables. The elimination of grout increases the efficiency of stay cables by reducing their self weight, cutting costs and allowing for potential future replacement. The first application of cable tensioning one-strand-at-a-time eliminated the need for large stressing jacks.

With its slender towers and light superstructure, the bridge is an example of how geometry, analysis, structural innovation and careful material selection can meet technical challenges on a complex project. The Zakim Bunker Hill Bridge destroys the myth that structural efficiency can be achieved only by sacrificing aesthetic impact.★