Innovative Association of Materials in the Leonard Zakim Bunker Hill Bridge

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Summary

The new $100 million Leonard Zakim Bunker Hill Bridge is a 429 m long, 55.8 m wide cable-stayed structure crossing the Charles River in Boston, Massachusetts. It is a complex cable stayed structure serving as a critical link of the Central Artery/Tunnel Project. It is also the city's newest landmark

and was recently named for the late Lenny Zakim, a nationally recognized civil rights advocate, and the Battle of Bunker Hill, a key battle of the Revolutionary War fought in nearby Charlestown in 1775.

The bridge has solidified its stature as the city's newest symbol of civic pride and patriotism. At the same time, it is most notable for its graceful structural form and state of the art engineering achievements. The bridge is a clear example of the innovative association of materials to formulate an optimal solution within the project constraints.

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1. Introduction

The Leonard Zakim Bunker Hill Bridge (Fig. 1) is a 10-lane cable-stayed structure carrying four lanes of Interstate-93 over the Charles River in each direction and an additional two lane ramp. The main eight-lane I-93 roadway is cradled within two inverted Y towers, while the secondary two-lane roadway is cantilevered 13.7 m to the eastern side of the main roadway, making the bridge asymmetric in cross-section. The 227.1 m main span superstructure is of steel composite design. With concrete box girder back spans, the overall layout becomes hybrid. The unusually wide deck is carried by cables spaced at 6.098 m on center in the main span and 4.573 m on center in the back spans. The bridge, which forms Boston's Central Artery

Fig. 1: Leonard Zakim Bunker Hill Bridge, Boston, MA, USA

/Tunnel (CA/T) Project's critical link over the Charles River just north of downtown Boston, is unique among cable-stayed structures in several respects. Its cable arrangement, slender inverted Y towers, and cantilevered two-lane roadway are among the bridge's most notable features. The four north-bound lanes of the interstate were opened to traffic in April of 2003. The remaining six traffic lanes are scheduled to be opened in early 2004. The first phase of the bridge opening was recognized locally as the most visible evidence that Boston's monumental multi-billion-dollar CA/T Project is moving toward its completion.

Design options for a new crossing of the Charles River date to the early 1990s. Public dissatisfaction with the early schemes by the CA/T ended when the project adopted a creative concept proposed by Swiss bridge engineer Christian Menn in 1994. HNTB was selected in 1995 for the final design of the new landmark bridge. It is yet another example of the ability of the bridge engineering community to deliver efficient, economical, no-frills "form-following function" designs that meet the highest aesthetic standards and satisfy the community expectations for more than just utilitarian structures in their bridges without resorting to exotic forms or theme based designs.

2. Site Conditions Govern the Bridge Layout

The numerous constraints of the unique project site and the functional requirements govern the key aspects of the bridge. Its structural form is practically born out of the limitations of the heavily built-up project site. An existing underground subway tunnel within a few feet of the bridge foundations, the existing double-decked bridge (that must remain until the new bridge is complete), the Charles River locks and dams, a large underground water main, and other surrounding structures are among the major site constraints.

The 227.1 m main span length places the two tower foundations on land, providing a clear channel free of any piers in water immediately upstream of the Charles River locks and dam.

Constrained by the Massachusetts Bay Transportation Authority's Orange Line subway tunnel and an active ventilation building on one side and the existing bridge on the other, the tower width at the deck level can accommodate only eight of the bridge's 10 lanes. The two remaining lanes are cantilevered to the outside of the eastern cable plane (within the main span). In the back spans, the two lanes can be built only after the removal of the existing bridge.

Fig. 2: The existing bridge (left) and subway tunnel (right)

CA/T project involves depressing the I-93 interstate arterial roadway below ground as it cuts through downtown Boston. The need to tie into this I-93 tunnel as it exits out of the ground necessitates a very low profile at the south end of the bridge. The geometric limitations at this end also result in a relatively short south back span leading to a span ratio of only 0.31.

The extension of the new bridge footprint into the area underneath the existing bridge over the southeastern corner of the south back span (Fig. 1, 2) makes anchorage of cables along the median of the roadway the only viable solution for the back spans. The main span is supported with two

Fig. 3: Inverted Y Towers with Bent-back lower legs

cable planes along the longitudinal edge girders. This unique cable geometry necessitates the inverted Y towers (Fig. 3). The towers are widest at the roadway level and are bent back below the deck forming a diamond shape due to constraints on the available foundation footprint.

The bridge epitomizes the philosophy of form following function; a signature structural form is borne out of a multitude of functional requirements and stringent site constraints. With its slender towers and light superstructure, the bridge is an extremely efficient structure with few ornamental aspects. As described in the following, geometric refinements, refined analysis, application of innovative and efficient structural systems and details, and selection of optimal materials were combined to provide efficient solutions to a diverse array of technical challenges on this highly complex project. A focus on the visual effects of the technical solutions in addition to their mere technical merits persisted throughout the design.

3. Globally Optimized Hybrid Asymmetric Structural System

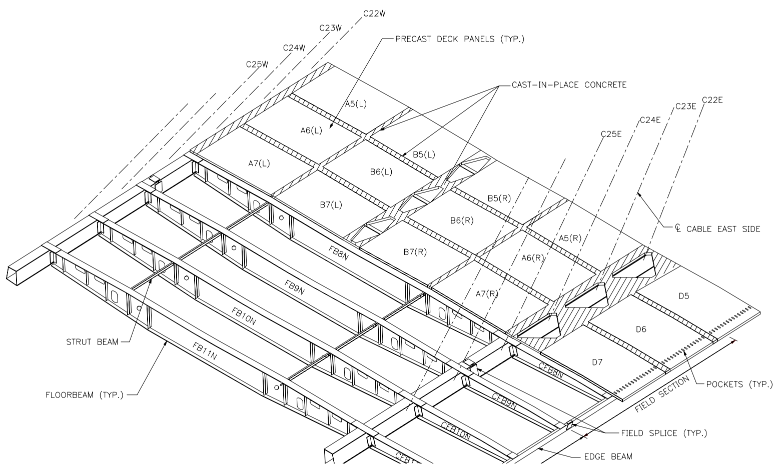

Fig. 4: Main-Span superstructure framing

The 55.8 m wide main span is of steel composite design. The steel framing consists of two longitudinal box edge girders of trapezoidal cross section and transverse floor beams at 6.098 m 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 13.7 m to the eastern side of the bridge (Fig. 4).

A longitudinal fascia girder frames into the outer ends of these cantilever floor-beam extensions. Pre-cast concrete panels, made composite with superstructure steel framing through cast-in-place closure strips, form the deck. The bridge is dually asymmetric; first in cross section due to the cantilevered ramp, and, second in the longitudinal direction due to span layout dictated by the site constraints. The bridge is also hybrid with the lighter steel-concrete composite main span transforming into a concrete multi-cell box girder back spans.

The hybrid design with torsionally rigid, heavy concrete box girder back spans was optimal due to cables positioned along the median as well as the extremely short south back span length.

4. Use of Light Weight Concrete to Minimize Eccentric Loading

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 was sufficient to create a considerable amount of torsion and lateral bending in the tower spire. In addition, this also led to complexities in bridge erection analysis as the net transverse cable forces acting on the deck during the cantilever construction required careful consideration.

Using all lightweight concrete for the cantilevered lanes first minimized the tower spire torsion and lateral bending. This reduced the difference between the forces in the eastern and western cables to about 60%.

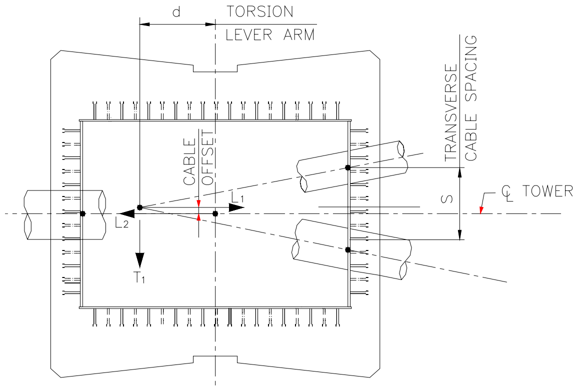

Fig. 5: Tower spire torsion - section and forces (above) and the view from roadway (below)

5. Geometric Solutions

Use of compact cable anchorage details were then used to minimize the transverse cable spacing 's' thereby reducing the torsion leverarm 'd' (Fig. 5). Finally, a counteracting moment produced by placing the main span cable pairs eccentrically from the tower centerline eliminated the residual torsion.

The previous two-stage minimization procedure reduced the eccentric offset required to just 3 inches with respect to the tower centerline, making the visual effects of this geometric adjustment insignificant. The unique cable arrangement, inverted Y towers and wide roadway section produce a structure with a very high degree of three-dimensionality. This increases the complexity of framing and detailing of bridge elements, particularly affecting cable anchoring in the towers. The cable geometry required considerable engineering to enable the anchoring of the lowest cables in the tower core without external type anchorages.

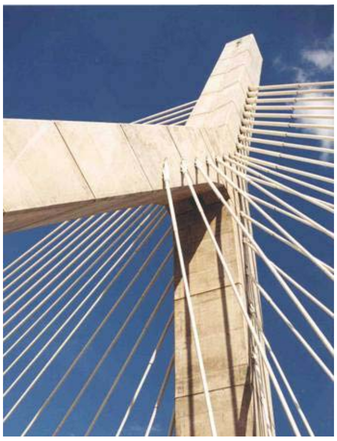

Fig. 6: Complex tower and cable geometry

6. High Strength High Performance Steel

The slender towers and the need for compact cable anchorages made the use of composite tower design with a steel inner core optimal (Fig. 7). The steel inner core served as the cable anchor box and multiple additional functions. It provided a convenient way for

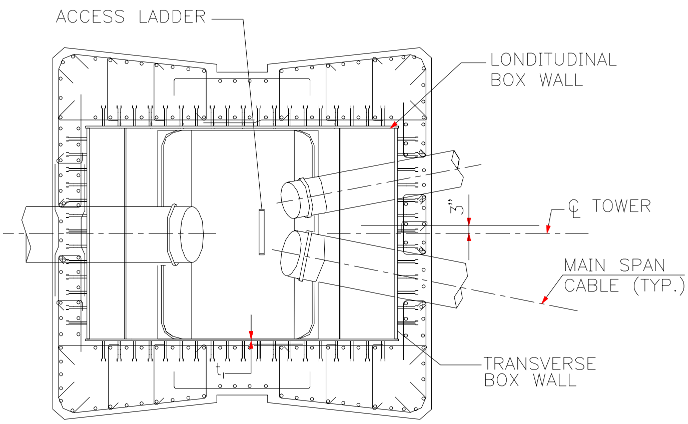

Fig. 7: HPS Steel Composite Tower

controlling the complex geometry of the cables with precision using the shop fabricated steel box, eliminated post-tensioning needed in the tower walls to resist tensile forces due to cables, and served as the inner form and the reinforcing steel for the tower in the vertical direction. The composite tower design also enabled a considerable reduction in the cross sectional dimensions of the tower spire section, thus improving the overall visual quality.

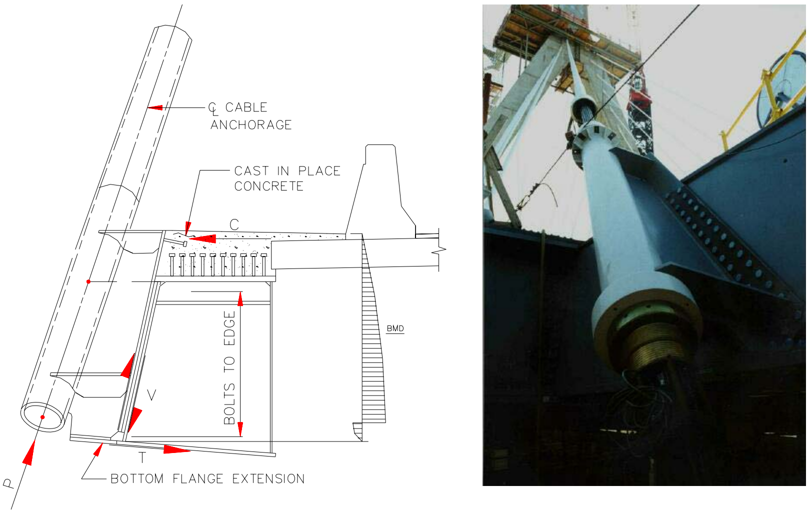

Fig. 8: HPS Steel Cable Anchorages at the Girder

The use of Grade 70 high-performance steel (HPS) provided increased strength and high ductility in these critical components. Also its use improved fabrication of the cable anchor pipes by reducing plate thickness by nearly 1/3. This also reduced the weight of the anchor box by the same proportions, thus minimizing the number of splices needed for construction considering the lift weights.

A similar compact detail fabricated using HPS steel was used for the cable anchorage at the girder (Fig. 8) . This allowed an effective, simple 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 aspects and constructability due to the single weldment without complex multi-piece connection details that require shop assembly, disassembly for shipping and reassembly at the project site.

7. Heavy Weight Concrete

At the south end of the bridge, the superstructure had to be pre-maturely terminated by about 15 m to avoid a conflict with another underground ramp tunnel in this area. The last three back span cables were anchored to a spline extension housed in an underground vault. The global effect of this loss of superstructure weight was compensated by filling several of the back span cells in the vicinity with heavy weight concrete.

Fig. 9: South back span termination and the spline extension

8. Other Noteworthy Design Challenges

The transmission of lateral bridge loads to several of the 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 steel shell. Special construction steps had to be developed to ensure proper installation of these isolation elements.

At 10 lanes and 55.8m, the structure is the widest cable-stayed bridge constructed at the present time. To alleviate concerns of shadow effects on the river due to the width of the bridge and its proximity to the water surface, deck openings in the median and in the space between the eight-lane main roadway and two-lane ramp were provided (Fig. 10).

Fig. 10: Daylight openings (above)

A finite element analysis was used to investigate the effect of these deck openings on the concrete slab stress distribution and was used in optimizing the shape of the deck openings.

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 north tower.

9. Boston's New Landmark

The Bridge has provided Boston with a new icon on the city. Complete with aesthetic lighting, the bridge is visible from key sections of the city, and is a part of the city's night skyline (Fig. 11). Going forward, the bridge's eight interstate lanes will ease gridlock that has plagued Boston's elevated highway system for decades. Even those who are not driving across it will benefit from the bridge project because a series of parks and recreation areas, encompassing 18 hectares, are planned for the riverbanks at its base. The bridge is owned by Massachusetts Turnpike Authority, and Bechtel / Parsons Brinkerhoff is the project management consultant.

Fig. 11: Accent Lighting