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Recent Structures in North America: an Introduction

We are very proud to introduce this brief series of papers on recent North American structures, showcasing recent advances in construction technology, as well as a new approach to our built environment.

While it is undeniable that the use of high strength and "high-technology" materials has advanced the frontiers of construction, the constant evaluation of traditional materials and construction techniques is also necessary. As an example, the Carquinez Bridge featured on this issue demonstrates how the in-depth studies on the performance of orthotropic bridge decks built over the past four decades all over the world has led to improvements on detailing, which are expected to result in a much longer useful life and lower maintenance. Those newly developed details, which have been subjected to extensive full-scale laboratory testing, are currently being introduced in American bridge design codes.

A very active and vital "codes and standards" community in North America makes sure that design codes are constantly updated. As an example, the revised ASCE Standard 7-02 "Minimum Design Loads for Buildings and Other Structures", published in 2002, includes substantial changes to the wind provisions (incorporating lessons learned during major hurricanes of the last decade in the Gulf Coast area), and snow, earthquake, and ice load provisions.

Since functionality and low maintenance have always been a mainstay of North American engineering, we are particularly pleased to see, as a common denominator to all the structures here presented, three other aspects that traditionally were not as relevant:

- *growing importance and concern for aesthetics*
- *community involvement for the evaluation of the aesthetics of proposed structures, their functionality, construction methods, and respect for the natural environment*
- *sustainable development.*

The eyes of many structural engineers worldwide are now turned to New York City, where plans are in the initial design stage for the redevelopment of the World Trade Center site. Here, we are already seeing how community involvement has become ingrained in the design process, how aesthetics will drive the selection, and how revised codes – in this case with respect to progressive collapse consideration and security considerations – will govern the structural design.

The affluent 90s have left a positive impact on the built environment in North America, both because of the availability of funding for research and development of better standards, and because of the willingness to devote part of the construction budget to achieve an aesthetic result. Even as we brace for more difficult and austere times, the beauty and functionality of these structures will remain for many years to come, and will inspire us to look for better ways to build.

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Introduction

The new 100 USD million Leonard P. Zakim Bunker Hill Bridge is a 429 m long, 55,8 m wide cable-stayed structure that carries 10 traffic lanes over the Charles River. The main eight-lane roadway is cradled within two inverted Y towers. A secondary two-lane roadway is cantilevered 13,7 m to one 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/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 a two-lane roadway cantilevered outside the eastern cable plane are among the bridge's most notable features.

In March 2003 (*Fig. 1*), the four northbound lanes of the bridge's 10 lanes opened to vehicular traffic. When fully open to traffic in 2004, the bridge will provide an estimated 110 000 motorists a more expedient daily route across the Charles River to join the interstate highway I-93. Named after 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.

Design options for a new crossing of the Charles River date to the early 1990s. Public opposition to many of the schemes produced a stalemate, until a creative concept proposed by Swiss bridge engineer Christian Menn was accepted in 1994 and the engineering firm HNTB was selected in 1995 to lead the final design. This bridge is evidence that many communities increasingly demand more than just utilitarian structures in their bridges. 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 of aesthetic standards.

Fig. 1: Leonard P. Zakim Bunker Hill Bridge

Project Complexity

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 meters 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 (*Fig. 2*).

The 227,1 m main span length places the two tower foundations on land, providing a clear channel free of any piers in the water way 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 accommodates 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). The CA/T project involves depressing the I-93 interstate arterial roadway below ground as it cuts through downtown Boston. The need to tie in to this I-93 tunnel as it exits out of the ground necessitates a ground-hugging profile at the south end of the bridge. The bridge soffit is barely 6 m above the finished ground as it reaches the south bank of the river at a relatively steep 5% grade. The geometric limitations at this end result in a relatively short south back span with a span ratio of only 0,31 (*Fig. 3*).

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

The overlap of the existing bridge and new bridge at the end of the south back span 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 cable planes along the longitudinal edge girders.

This unique cable geometry necessitates the inverted Y towers. The towers are widest at the roadway level and are bent back below the deck forming a diamond shape due to constraints on the foundation footprint.

The cables positioned along the median and the extremely short south back span length made the torsionally rigid and heavy concrete box girder back spans optimal leading to the hybrid superstructure layout.

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

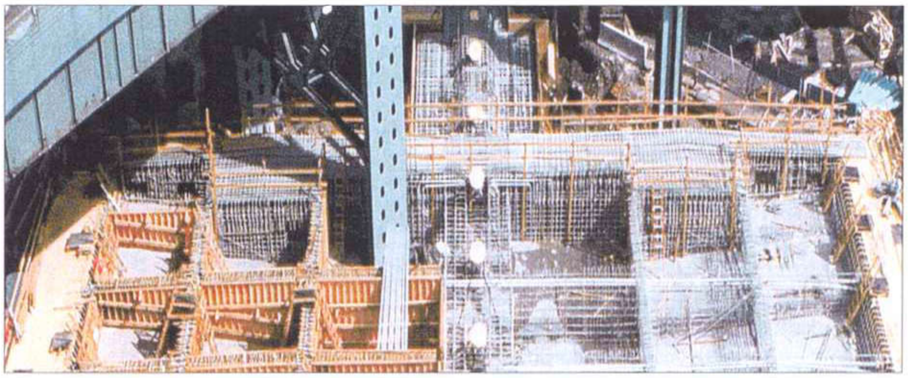


Fig. 3: South end of south back span during cast-in-place construction of cellular box girders. The last three back span cables were anchored to a spline extension (shown) as the bridge superstructure was terminated prematurely to avoid conflict with a CA/T ramp tunnel (not shown).

a diverse array of technical challenges on this highly complex project. A focus on the visual effects of the different solutions in addition to their technical merits persisted throughout the design (*Fig. 4*).

Fig. 4: Construction of north tower

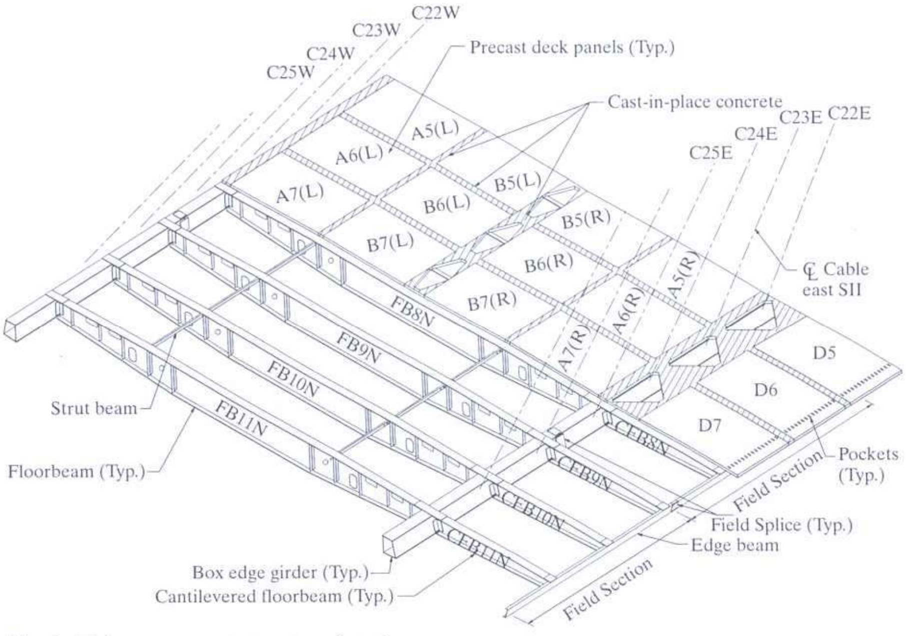


Fig. 5: Main-span superstructure framing

Key Technical Challenges

The main span steel framing consists of two longitudinal box edge girders of trapezoidal cross section and transverse floor beams at 6,1 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. 5*).

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.

Effects of 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 these effects by reducing the DL eccentricity. This reduced the difference between the forces in the eastern and western cables to about 60%. Use of compact cable anchorage details were then used to minimize the transverse cable spacing 's' thereby reducing the torsion leverarm 'd' (*Fig. 6*). Finally, producing a counteracting moment by placing the main span cable pairs eccentricity from the tower centerline eliminated the residual torsion. The previous two-stage minimization procedure reduced the eccentric offset required to just 76,2 mm with respect to the tower centerline, making the visual effects of this geometric adjustment insignificant.

Geometry Issues

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 cable anchorages.

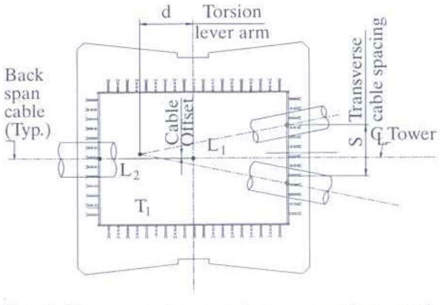


Fig. 6: Tower spire torsion – section and forces

Need for Compact Details

The slender towers and the compact tower leg sections made the use of composite tower design with a steel inner core optimal. The steel inner core also served as a cable anchor box serving multiple functions. It provided a convenient way for controlling the complex geometry of the cables with precision using the shop fabricated steel box, eliminated post-tensioning

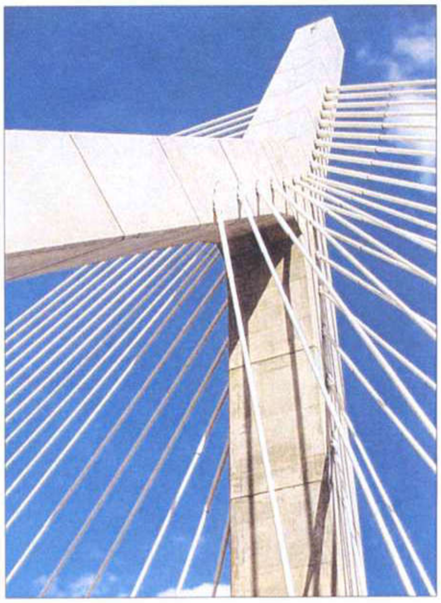
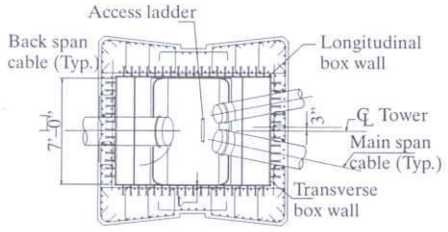
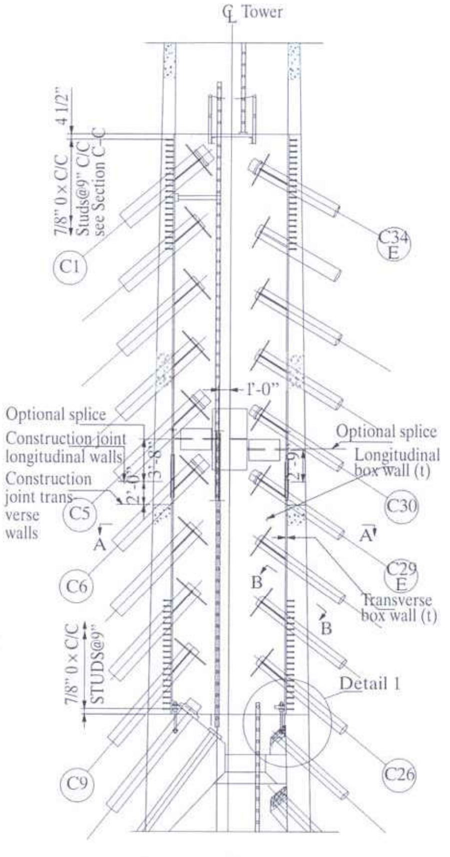


Fig. 7: Complex tower and cable geometry



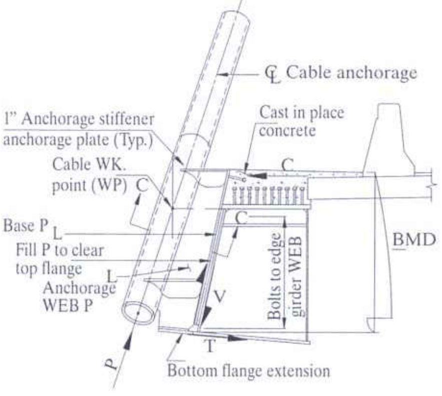
Section A–A



Tower cabel anchor box

Fig. 8: Composite tower spire details

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*). A similar compact detail was used for the cable anchorage at the girder (*Fig. 9*). 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. Grade 70 high-performance steel was used for the cable anchorages and steel-composite tower spires, providing increased strength and improved ductility in these critical components. Also this 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.



Section A–A

Fig. 9: Girder to cable anchorage

Site Constraints

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 0,6 m of the south tower and a 914 mm 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 steel shell. Special construction steps had to be developed to ensure proper installation of these isolation elements (*Fig. 10*).

Exceptional Width

At 10 lanes and 55,8 m, the structure is the widest cable-stayed bridge constructed at the present time. Due to limits on the maximum tower width, two lanes are positioned outside of the cables using cantilevered floor beams. 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. 11*).

A finite element analysis was used to investigate the effect of these openings and the cantilevered floor beams on the stress distribution in the concrete deck and in optimizing the shape of the deck openings to reduce the level of stress around the openings.

Interface Coordination

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. Also, the south back span was curtailed by an additional 13,7 m to avoid interface with a tunnel at the south end of the bridge. The length reduction was made feasible by providing an isolated superstructure spline extension to anchor the first three cables of the south back span

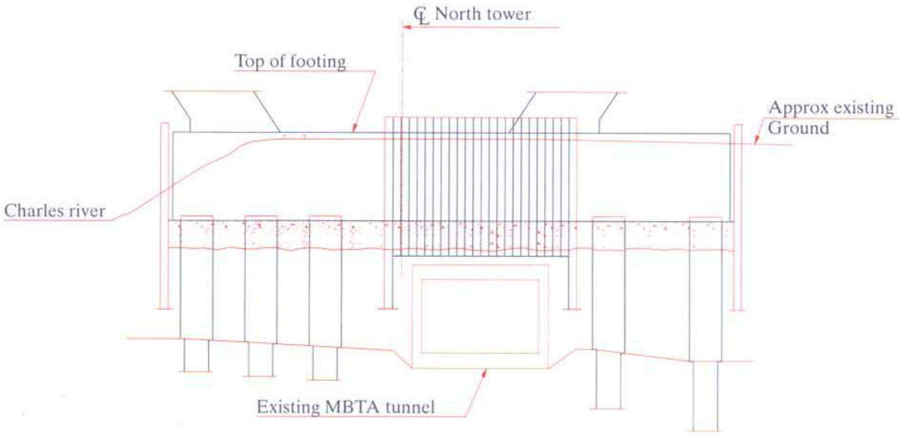


Fig. 10: Orange Line tunnel under north tower

Fig. 11: Daylight openings

(*Fig. 3*). Heavyweight concrete ballast was used in select cells of the south back span to counter the effect of the corresponding loss of weight of superstructure.

Boston's New Landmark

The bridge has provided Boston with a new icon. Complete with aesthetic lighting, the bridge is visible from key sections of the city, and is part of the night skyline. An estimated 250 000 turned out on a rainy Mother's Day 2002 to participate in the first public bridge walk and hundreds of thousands more came five months later for the second.

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 as a series of parks and recreation areas, encompassing 178 068 m^2, are planned for the riverbanks.

SEI Data Block

Owner:
Massachusetts Turnpike Authority, MA, USA

Design:
HNTB, Boston, MA, USA

Project management consultant:
Bechtel/Parsons Brinkerhoff, USA

Contractor:
Atkinson-Kewit Joint Venture, Boston, MA, USA

Steel (t): (structural, re-bar, post-tensioning and cables)	7975
Concrete (m^3):	27 000
Total cost (USD millions):	100
Service date:	March 2003