New Concepts for Concrete Bridges on the Central Artery/Tunnel Project

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Summary

The massive Central Artery/Tunnel Project is nearing completion in metropolitan Boston, Massachusetts. It is a $14.8 billion project, including four-lane slurry wall tunnels under an existing elevated highway, steel and concrete immersed tube tunnels, concrete tunnels jacked under railroads, five complex interchanges, and two major bridges. Of the five interchanges, two have been constructed in segmental concrete and one of the bridges has been constructed as a steel-concrete hybrid cable-stayed bridge. During the design and construction of these structures, new concepts needed to be developed to address winter construction, to reduce hauling weights, and to provide seismic resistant fixed piers for the segmental construction. For the cable-stayed bridge, the issues addressed included asymmetry, hybrid construction, isolating foundation elements, and stay cable anchoring and tensioning systems. This paper deals with the assortment of new concepts developed for the project.

Keywords: Precast; Segments; Erection; Straddle Bent; Saw cutting; Fixed Segment; Design Charette; Drilled Shaft; Hybrid; Iso-tension

1. Introduction

The approximately $14.8 billion Central Artery/Tunnel Project (CA/T) is a major reconstruction of an urban interstate highway through downtown Boston, Massachusetts. The project is a massive urban renewal project in the heart of the city. It involves depressing the elevated Central Artery (I-93) into a tunnel and extending the Massachusetts Turnpike (I-90) from its terminus at the intersection with I-93, to Logan International Airport. All construction on the project is being performed while maintaining traffic flow with detours, temporary structures, and night time construction.

This article focuses on new concepts in concrete construction introduced on the project, specifically in the area of segmental concrete at the two interchanges at either end of I-93, and the hybrid asymmetrical, cable-stayed Leonard P. Zakim Bunker Hill Bridge (Zakim Bridge).

Fig. 1 I-93/I-90 South Bay Interchange

2. I-93/I-90 South Bay Interchange

The $650 million South Bay Interchange is a key segment of the CA/T. It will replace and expand an existing deteriorated interchange in stages to handle increased traffic volume. The new massive multi-level interchange (Fig. 1) will be all-directional and include the I-90 extension to Logan International Airport through the Fort Point Channel and Ted Williams immersed tube tunnels.

The interchange, the junction of I-93 and I-90, is located to the south of downtown Boston. The new interchange construction is a combination of precast segmental viaducts, jacked tunnels, slurry wall tunnels, and open boat sections. Presently, this interchange is about 90% complete and most of the viaducts, tunnels, and ramps are open to traffic.

3. I-93/Route 1 Interchange

The $188 million I-93/Route 1 Interchange is the northern gateway to Boston in Charlestown, and is located just north of the state-of-the-art Charles River Crossing bridges. As such, the interchange consists of numerous viaducts and ramps (Fig. 2). This interchange is now complete and open to traffic.

Fig. 2 I-93/Route 1 Interchange

The interchange construction primarily consisted of precast segmental viaducts. The main line viaducts for I-93 have a relatively tangent alignment; however because of site restrictions, the ramps connecting I-93 to Route 1 have a tight radius of curvature of less than 100 meters.

4. Precast Segments

Early in the project, it was decided that all viaducts and ramps would have dual designs, in concrete and steel, with both using box girders for reduced maintenance and improved aesthetics. To make the concrete alternative competitive, the project developed three standard segment shapes for one-, two-, and three-lane options. When necessary, a mix of these standard shapes was utilized. All segments were match cast using the short line method at distant precast plants (about 200 kilometers away) and, due to a lack of storage space, brought to the construction site the previous day or night and erected. The top slab of the segments were transversely tensioned and grouted at the precast plants prior to shipping. Segmental concrete structures account for 55,200 and 45,350 square meters at the I-93/I-90 and I-93/Route 1 interchanges, respectively. Span lengths varied from 27 to 66 meters, while roadway curvature varied from 67 to 3,200 meters. Superstructure width also varied from 6.7 to 29.3 meters.

Fig. 3 Balanced cantilever erection using a gantry

5. Segment Erection

Four basic types of segment erection techniques were used during construction of the I-93/I-90 interchange:

1. Beam and winch.
2. Conventional crane coupled with beam and winch.
3. Specially built 130-meter self launching overhead gantry (Fig. 3).
4. Frame over railroad tracks with segments erected at one end and rolled to the other end to minimize disruptions to railroad traffic.

Fig. 4 Span-by-span erection at double-deck bents with overhead gantry

The first three methods were used for balanced cantilever construction, whereas the last two methods were used for span-by-span erection.

At the I-93/Route 1 interchange (Fig. 4), all of the fairly straight viaducts were constructed span-by-span using a specially built overhead erection gantry, whereas curved roadways were erected balanced cantilever using conventional cranes.

6. Innovative Construction Techniques

At the start of construction, the I-93/I-90 Northbound contractor proposed several innovative construction concepts to improve construction operations and to provide an improved product. These proposals were welcomed by the project, and in a coordinated partnering effort, the schemes were discussed and developed by the contractor, managing consultant, and section design consultant. A brief description of these proposals follow.

Fig. 5 Precast fixed bent segment

6.1 Precast Fixed Bent Segments

The viaduct design provided for fixed bents and a cast-in-place box girder segment monolithically connected to the bent column. During construction, a precast fixed bent segment was used in lieu of the above. The shell of the fixed bent segment was precast using the typical segment forms (Fig. 5). A hole in the bottom slab allows the column reinforcement to terminate inside the bent segment diaphragm, which was cast after erection of the precast segment. Cast-in-form inserts allow for the continuity of rebars between the precast segment and the cast-in-place diaphragm. The interface between precast concrete and cast-in-place concrete was roughened to 6-millimeter amplitude to provide for shear transfer.

A specially built frame was attached to the bent column for support and alignment of the segment during erection. The three-level frame comprised an upper level that supports the segment on hydraulic jacks and allows for vertical and rotational adjustments; a middle level that allowed for translational adjustments; and a lower level supported on brackets attached to the pier by 36-millimeter post-tensioning thread bars placed in ducts that extended through the pier.

Fig. 6 Precast fixed segment in place on support frame

During erection, the precast segment was placed on the support frame using a crane (Fig. 6). After alignment of the segment, the space between the soffit of the segment and the top of the pier cap was grouted, the diaphragm reinforcement was placed, and the diaphragm concrete was cast. After completion of the diaphragm, typical cantilever construction began. A similar technique was used for the precast expansion joint segments to reduce hauling weight.

6.2 Straddle Bent Construction Using Saw Cut Precast Segments

The viaduct design included a monolithic connection between the cast-in-place straddle bents and the precast box girders. The straddle bent design included a short length of the superstructure cross-section extending from the side face of the straddle bent. These extensions were a starter section for the superstructure with a cast-in-place closure joint between the extension and the first precast segment.

Typically , the alignment of the superstructure is not perpendicular to the straddle bent, but is at a skew angle of less than 90 degrees. To improve contructibility, the cast-in-place extensions were replaced with precast starter segments that have the skew angle built into the segment geometry. Shear keys were cast into the face of the straddle bent to provide for shear transfer.

The starter segment was produced by saw cutting a typical rectangular segment along the required line of the skew angle, using a large diameter diamond blade circular saw (Fig. 7). Guides for the saw were placed on the top slab, the interior surfaces of the webs, and bottom slab. The initial top slab cut extended down into the webs so that the secondary web and bottom slab cuts completed the operation.

Fig. 7 Saw cutting of segment

Fig. 8 Saw cut segments being erected

After saw cutting was complete, the two segment pieces were held together using post-tensioning bars and shear keys were added at the cut face using a coring machine. Typically, one rectangular segment provided two starter segments with the required skew angle.

During erection, the starter segments were hung from temporary support and alignment beams (Fig. 8). After alignment of the segments, the 150-millimeter nominal closure joint between the segments and the straddle bent was formed. A block out was provided in the top surface of the straddle beam to allow for placement and alignment of the longitudinal post-tensioning ducts after erection of the segments.

The surface of the block out was roughened to 6-millimeter amplitude and block out concrete was placed concurrently with the closure joint concrete to provide integration of the secondary cast-in-place concrete with the initial cast-in-place concrete. After curing of the closure, typical cantilever construction was begun. This technique was successful with very complicated geometry. The most extreme case involved a 7% profile grade, 2% cross-slope, and 11° skew.

7. Zakim Cable-Stayed Bridge

The Zakim Bridge is located in a congested area between the existing double deck I-93 bridge on the east, the existing Storrow Drive Connector ramps to the south, the Charles River Dam & Lock system to the east and a bascule bridge to the west, in addition to accommodating the Orange Line subway below the bridge and a 0.92-meter-diameter water main at the south tower. An elaborate bridge type selection process was undertaken to decide on the most appropriate bridge type to overcome these constraints, and a detailed preliminary design was prepared to address the various challenges of the selected design.

7.1 Bridge Type Selection

The Zakim Bridge had to meet the objectives of numerous state and federal regulatory agencies, including the Federal Highway Administration (FHWA). The bridge design needed to present sound engineering solutions to numerous site constraints while also meeting community expectations that the structure create a distinctive "signature" on Boston's skyline. To fulfil these goals, the project team conducted a bridge type study (design charette) for a main span of 227 meters and assembled a multidisciplinary team of experts in structural engineering, inspection and maintenance, highway design and engineering, urban planning, construction, environmental engineering, architecture, and cost and scheduling control.

The project team identified 16 bridge types, which included trusses, arches, cable supported structures and others. A short list of seven, including a two-hinged arch, a simple span truss and five cable-stayed bridges, were then chosen for further evaluation. An evaluation matrix was prepared based on priority factors, as well as a quality rating for the impacts previously mentioned. Ultimately, the concept proposed by Dr. Christian Menn was selected (Fig. 9).

Preliminary designs were then prepared for steel, concrete, and hybrid alternates for the asymmetrical cable-stayed structure. Each alternate posed unique challenges, and a peer review committee composed of international bridge experts concurred with the project team that only the hybrid alternate should be pursued. As part of the preliminary design, due to the asymmetry and extremely wide bridge deck, the preliminary design needed to address shear lag effects, constructibilty, torsional effects, and others.

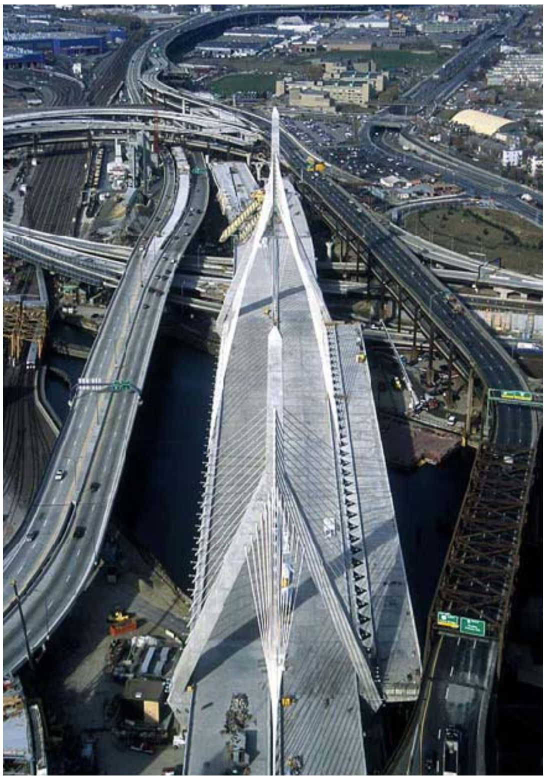
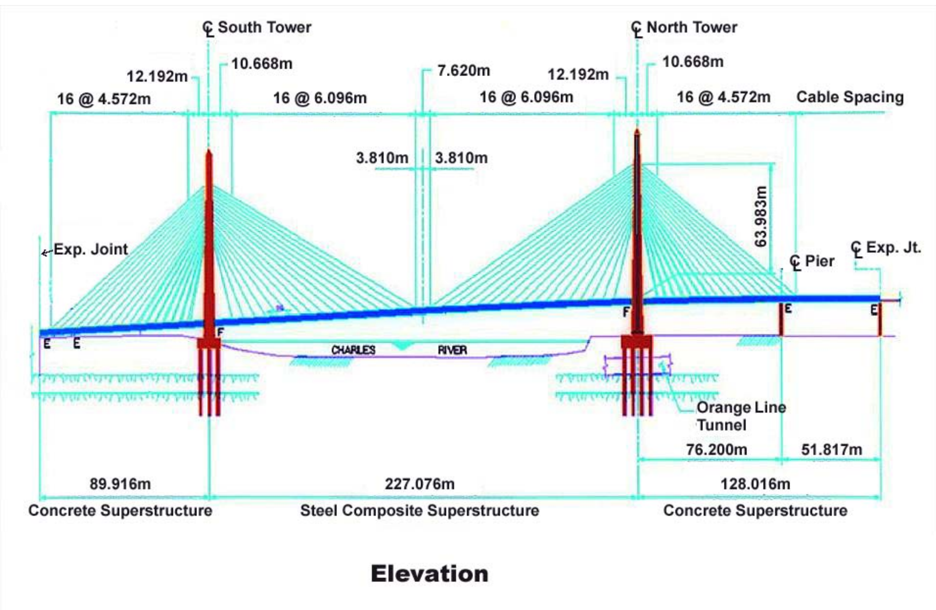


Fig. 9 Leonard P. Zakim Bunker Hill Bridge looking north, replacing the structure to its east

7.2 Bridge Configuration

The bridge features a 56.4-meter-wide, five-span hybrid superstructure with a main span of 227 meters; two south back spans of 34.2 and 39.6 meters; and two north back spans of 51.8 and 76.2 meters (Fig. 10). The tower piers are inverted Y shapes. The pinnacles of the south and north towers are 89.9 and 98.5 meters, respectively, from the tops of their foundations. The back spans consist of multi-cell cast-in-place concrete box girders, 3 meters deep and 38.4 meters wide. Main structural elements include a 3-meter-wide central spline beam with internal floor beam diaphragms at 4.6 meters on center, framed with four secondary webs. The spline beam in turn is supported by a single plane of cables spaced at 4.6 meters.

The main span consists of longitudinally post-tensioned precast concrete deck panels, acting compositely with longitudinal steel box edge girders and transverse steel floor beams (at 6.1-meter centers) by means of cast-in-place closure strips. The box edge girders are supported by cables anchored on the outside web at 6.1-meter intervals. On the main span side, a two-lane ramp is carried on floor beam extensions cantilevered on the east side of the main line deck. Lightweight precast concrete deck panels are used for the ramp to minimize eccentric dead loads.



On the back spans, the ramp is a single cell concrete box girder supported independently on concrete piers. Open-grid fiberglass closure panels partially cover the underside of the main span superstructure to enclose utilities, creating a more aesthetic underbelly while also providing access for inspection and maintenance.

Fig. 10 Elevation of the bridge

7.3 Foundation and Drilled Shaft Design

Measures were taken to ensure that the Orange Line tunnel below the bridge was not adversely impacted by foundation construction activities. The 2.44-meter-diameter drilled shafts closest to the tunnel were placed outside a 1.5-meter buffer zone, in addition to being installed within 2.74-meter-diameter isolation casings—thereby eliminating transfer of any seismic forces to the tunnel. The gap between the casings and the drilled shaft is unfilled.

7.4 Tension Strut at Tower Piers

The change in direction of the tower legs at the deck level produces large tension forces in the connecting beam, called a "tension strut," between the tower legs. On this bridge, the tension strut also serves as the transition from the main span composite steel superstructure to the post-tensioned concrete box girder back spans. Additionally, compressive forces from the cables, which are carried in the spline beam of the back spans, need to be transferred to the edge box girders of the main span and vice versa. The edge girders, in turn, are then attached to the main-span cables. As a result, special attention was focused on tension strut design, while shear lag effects and tension stresses in the concrete were also carefully evaluated.

Fig. 11 Tower anchorage unit on its side

Fig. 12 Stay cable stressing, using "Iso-tension" method, in operation

Additionally, the imbalance of bending, shear, and axial load forces in the main span and back spans under different loading combinations produce torsion, bi-axial bending, and bi-axial shear stresses in the tension strut. Due to its critical structural nature, the tension strut was post-tensioned in stages to a total jacking force of 25,130 tonnes. Limiting principal tensile stresses to pre-determined values under the working loads was an important design consideration for this element.

7.5 Cable Anchorages

The vertical leg at the tower top varies from 4.9 meters at the base to 3.2 meters square just beneath the peak. Because of the limited room to anchor cables, a prefabricated steel anchor box was built into the tower, acting compositely with the exterior concrete by means of shear connectors. The cables were anchored by bearing at the inner end of structural pipe sections built into an anchorage stiffener (Fig. 11).

Torsion in the tower leg due to the cantilevered ramp on one side posed a challenge. The dead load torsion was overcome by rearranging the location of the main span cables as they entered the tower. The back span cables were kept at the centreline of the tower.

The cable anchorages on the main span box edge girders were mounted on the outside webs and were detailed as a pipe assembly bolted to the side of the girder. The cables then pass through the anchor pipe, with the cable anchor bearing against the lower end of the pipe. The pipe is connected to a base plate with a single web plate. This detail was selected due to its visual appeal over typical box-type cable anchorages.

7.6 Stay Cables

The stay cables consist of greased and sheathed strands (14 to 73 15.7-millimeter-diameter strands/cable) inside a high density co-extruded polyethylene pipe (HDPE). For the first time in the US, the stay cables are un-grouted and the Freyssinet "Iso-tension" stressing method was used (Fig. 12). Potential cable vibrations were suppressed by use of visco-elastic dampers for all cables at the girder level, spiral beads on the HDPE pipe, and cross-ties for selected cables.

7.7 Aerodynamic Evaluation

Wind tunnel tests of both the sectional and aeroelastic models were performed for the final structure as well as for intermediate construction stages. Vortex excitation occurred at about 128 kph, within criteria, while flutter speed was measured at 715 kph, well above the requirement of 210 kph. Smoke flow visualization tests also indicated that wind flows were not significantly altered by changes to the deck section, such as deck openings and open mesh closure panels on the underside.

7.8 Construction

The cast-in-place back spans were constructed on falsework concurrent to tower construction. The tension strut at the tower piers was post-tensioned in stages. Afterwards, the superstructure of the main span was erected in a cantilever fashion.

8. Conclusion

The massive CA/T project is the largest infrastructure project of its type ever undertaken in a major US metropolis. Posing significant challenges to bridge engineers, it necessitated many unique solutions to be originally developed or borrowed from others. As of this writing, the overall project is about 90% complete.

9. Credits

Owner: Massachusetts Turnpike Authority

Management Consultant: Bechtel/Parsons Brinckerhoff (B/PB, joint venture)

Bridge Concept: Dr. Christian Menn

Type Study and Preliminary Engineering: Parsons Brinckerhoff (of B/PB)

Final Design:	BLSW (I-93/I-90 Interchange—Southbound)
	McGuire/Harris (I-93/I-90 Interchange—Northbound)
	GPVAW (I-93/Route 1 Interchange)
	HNTB, Inc. (Zakim Bridge)
Construction Management:	Bechtel/Parsons Brinckerhoff
Contractors:	Modern Continental Co. (I-93/I-90—Southbound)
	SIWP (I-93/I-90—Northbound)
	Atkinson/Kiewit (Zakim Bridge)
Post-Tensioning & Cable Stay:	DSI (I-93/I-90 Interchange)
	Freyssinet (Zakim Bridge)