# The North Bank Bridge

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ABSTRACT: The North Bank Bridge is a 700 ft long iconic pedestrian bridge in Boston and Cambridge, Massachusetts, USA. Ammann & Whitney designed a “sinusoidal bridge” for the highly constrained site which was conceptualized in cooperation with Buro Happold in a community oriented process. The tubular steel truss bridge features fiber reinforced polymer decking. Analysis of the bridge included a thorough investigation of lateral vibrations and global buckling. Construction was distinguished by the collegial atmosphere and Barletta Heavy Division’s efficient method of producing the irregular truss geometry. The project was initiated as a remediation measure for the Central Artery / Tunnel Project and was constructed with American Recovery and Reinvestment Act funds.

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## PROJECT HISTORY

In the early 1900’s the Charles River was dammed, removing from the city the dangerously polluted mudflats which were previously exposed with the low tide, allowing the river to become the centerpiece of America’s first regional park system. Unfortunately, the Esplanade (the newly created linear park), was cut off from the harbor by at-grade rail infrastructure connecting Greater Boston with northern New England. When the Central Artery, a six-lane elevated highway, was built through the center of the city in the 1950s, it further isolated the Esplanade from the harbor while also dividing and isolating neighborhoods throughout the city.

Less than twenty years later, engineers began discussing the demolition of the highway. If the highway were replaced by a tunnel, the city would be made whole once more. This vision was realized with the execution of Boston’s Central Artery / Tunnel Project (CA/T) under the management of the Massachusetts Turnpike Authority. Federal regulations required mitigation for the impact of this work on existing and planned parks. Further, the new highway bridges required the use of land owned by the regional parks agency. The state highway department therefore committed to construction of a network of pedestrian and bicycle paths and the construction of 80 hectares of new public spaces, including the North Bank Bridge.

The bridge design began with the derivation of multiple bridge concepts and engagement with a very active local community. The unorthodox nature of the chosen concept required a rigorous design and review process, which was complicated by the unavoidable transfer of the project between agencies (the responsible agency at any given phase is referred to generically as Owner throughout this document). Project partners faced significant hurdles related to existing infrastructure and contaminated soils in transforming the industrial site into park land.

In 2007, the Owner solicited bids for the project. The low bid was approximately 20% higher than the estimated cost and the Owner determined not to proceed with the work. When the American Recovery and Reinvestment Act (ARRA) became law in 2009, high priority was given to projects that were "shovel-ready," i.e. with completed bid documents ready for advertisement. The North Bank Bridge was chosen to receive funding. The bid process was successful and construction began in 2010.

## CONCEPTUAL DESIGN

The first phase of design was carried out as a collaboration of Ammann & Whitney, Buro Happold, and Julian Hakes. Through a series of site visits and design charrettes, several concepts were developed and sketched (see Figure 1) in an effort to create an icon worthy of the Esplanade, while addressing the multitude of geometric constraints. Taken from west to east, these are: clearance above an amphibious vehicle launch ramp (Boston Duck Tours), clearance above the railroad tracks, clearance between a historic building (Tower A) and a parallel highway ramp (Ramp CT), clearance below the Leverett Circle Connector Bridge, clearance above the Millers River, and clearance below the Zakim Bridge (see Figure 2).

Each concept was then sketched and presented to the community. The project benefitted from the active involvement of a wide range of stakeholders, organized into a standing committee. The Citizens Advisory Committee (CAC) was composed of

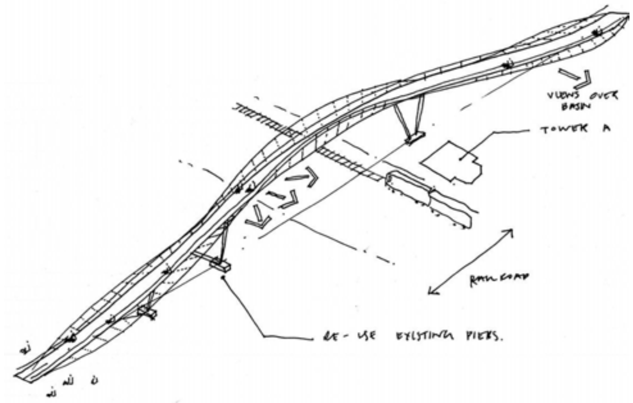


Figure 1: Concept sketch

representatives of neighborhood groups, local businesses, and advocacy organizations and possessed site and procedural knowledge gained through years of activity on the CA/T.

The initial options presented to the CAC included a "rainbow arch" design and an asymmetric beam "solid industrial" design but the preferred concept was dubbed the "sinusoidal bridge" because of its snaking, undulating form in plan and elevation. The bridge is composed of a truss structure that is positioned alternately below and above the deck level according to the site constraints.

At the west and east, approach embankments are provided to a height of approximately 10 ft at either end of the alignment. The structure commences with a minimal depth as the trusses sweep below the deck in the approach spans. They then rise above the deck over the railroad so that the necessary 18.5 ft clearance is achieved while minimizing the overall length of the structure. Through the transition, the trusses fold in close to the walkway, accommodating the narrow gap between Tower A and Ramp CT. The alignment was set to allow for the re-use of existing foundations, thereby minimizing cost, risk, and disruption.

The selection of steel pipes for the truss members was made as these sections can be readily bent to form complex curves in plan and elevation without a concern that imperfections will be noticeable. Above the railroad, a high sided protective mesh screen is required and tucked neatly within the elevated trusses.

The design is satisfying for a number of reasons. First, it is a simple form that is borne out of the site constraints. Second, the bridge's beauty comes from the expression of the structure alone. Third, the collaborative team work that occurred in evolving the design concept was an enjoyable process but one which also enabled the relevant stakeholders to give input at an appropriate stage to produce a memorable structure.

FINAL DESIGN

GENERAL - A holistic and iterative approach was used in which superstructure and substructure geometry, member cross sections, etc. were continuously updated and analyzed for clearances, global buckling, lateral vibrations, member stresses, etc. all while prioritizing preservation of the approved concept, the user experience, maintainability, and constructability.

The tubular steel trusses are made up of deck chords and sweeping outer chords connected by verticals spaced at 10'-5" and intermittently reinforced with diagonals. At each vertical, there is a floorbeam that supports the fiber reinforced polymer (FRP) deck. The deck is composite with the truss. Where required, the shear action of the deck is augmented with lateral steel braces. Throughout the length of the bridge, the sweeping outer chords of the truss remain outboard of the deck chords. The angle of

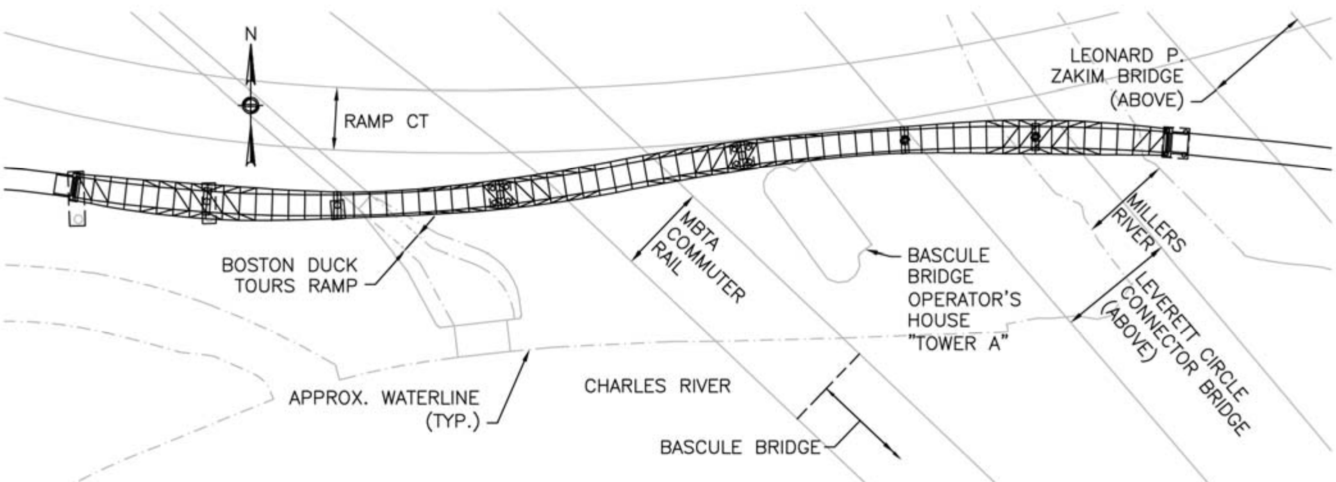


Figure 2: Plan

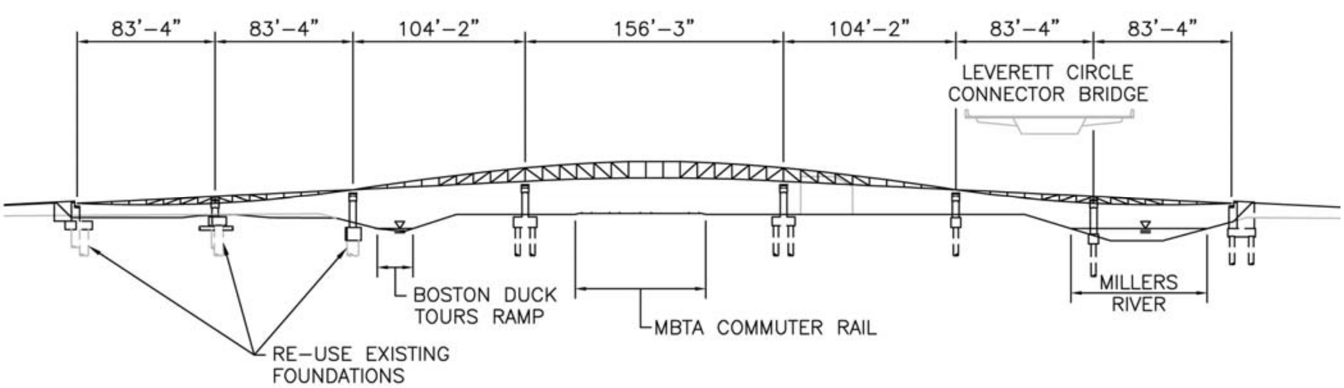


Figure 3: Elevation

the verticals to the walkway varies as the outer chord follows its sinusoidal path.

The 7 span continuous structure has a total centerline length between abutment bearings of 697′-11″ (see Figure 3). The horizontal alignment of the bridge centerline consists of a simple reverse curve, with the point of reverse curvature located at the middle of the bridge.

GEOMETRY - In determining the superstructure geometry, there were several major goals: follow the conceptual design, avoid site constraints, re-use existing foundations, and meet the accessibility requirements of the Americans with Disabilities Act. Further, the geometry is a major determinant of the structure's behavior, requiring an iterative approach.

To address the above a controllable, repeatable approach was adopted in which the geometry was determined parametrically. The centerline was set as two circular arcs in plan, set in relation to the existing foundations and major site features and constraints. Accessibility requirements largely determined the vertical geometry of the centerline. The deck chords were set to simply follow the centerline. The outer chord geometry was then determined algorithmically.

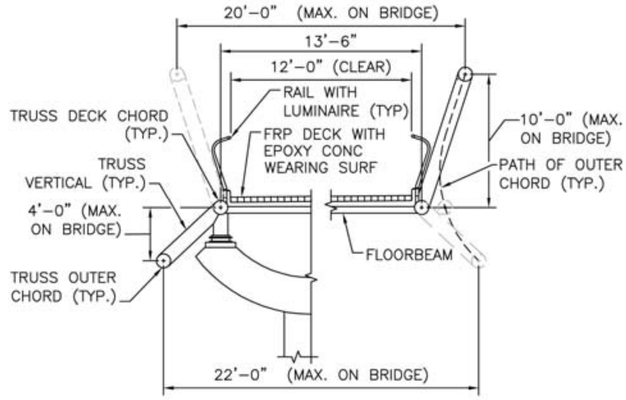


Figure 4: Typical section

First, a series of "sinusoidal" arcs were set in elevation relative to centerline. Next, a set of lines joined by an arc were defined in cross section (see Figure 4). Given a longitudinal position along the centerline, the vertical location of the outer chord was determined from the sinusoidal arcs. Given this vertical location, the horizontal location was determined from the lines and arc in cross section. These cross sectional locations were then radially applied to the three dimensional centerline to get a set of three dimensional working points. All of these calculations were performed with a simple spreadsheet.

This data was used to automatically draw a solid model of the bridge. This model was then inserted into a model of the site which included laser survey at the point of

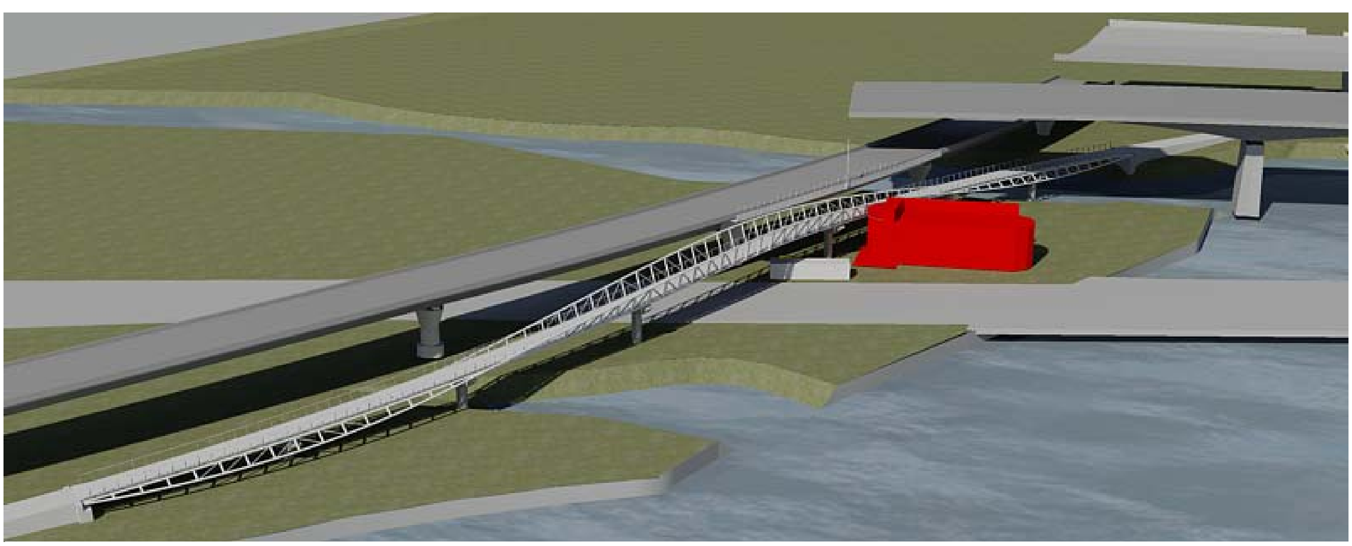

Figure 5: Rendering of bridge and site (looking northeast)

minimum clearance at the control tower (see Figure 5). With this model, the aesthetics and clearances were examined. The data was also used to rapidly generate an analysis model. Any issues with the geometry found in the site model or the analysis model were easily addressed by adjusting the parameters of the algorithm in the spreadsheet and performing another iteration. The finalized working points were presented as a table in the Contract Drawings.

Once the geometry was set, the bridge was again presented to the community to confirm that the bridge was as they expected. The solid model was used to produce renderings and a fly through video which were used as presentation materials. The CAC enthusiastically approved of the geometry and final design work commenced.

GLOBAL ANALYSIS - The bridge was modeled with finite elements using Lusas software. Foundations, substructure, and steelwork were modeled as beam elements and the deck was modeled with shell elements (see Figure 6). The deck acts compositely with the truss, and the model includes the effects of staged erection of the deck. The model was used to determine member forces and to examine the structure's lateral vibration characteristics and stability. Further details on the model can be found in the relevant sections below.

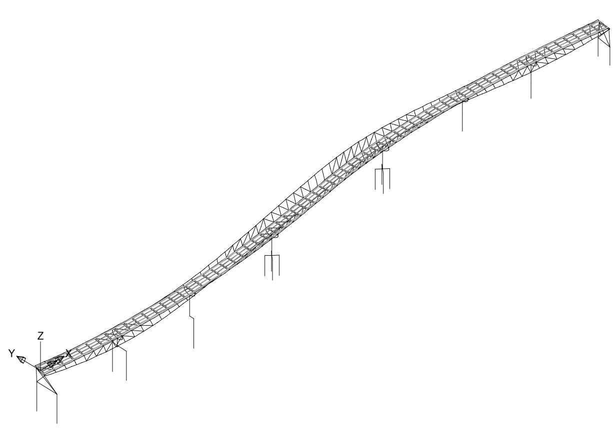

Figure 6: Lusas model

DECK - The bridge incorporates an FRP deck for reasons discussed in the Vibrations section below. Unlike most structures with FRP decking, the FRP deck is made composite with the truss with a high strength bolted detail. As discussed in the Construction section, the bolts are tensioned after the bridge is erected. The deck is therefore not composite for dead load. The analysis model reflects this staging.

VIBRATIONS - Conscientious of the ongoing interest within the engineering community in pedestrian induced vibrations, the Owner stressed this issue at the earliest stages of design. After a thorough discussion, the Owner specified a minimum frequency of 3 Hz for the first vertical mode per the American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications for Design of Pedestrian Bridges. Since the frequency of the horizontal cyclical load due to walking is half that of the vertical, the Owner specified a minimum frequency of 1.5 Hz for the first horizontal mode (see Figure 7).

Meeting these specifications required several iterations of truss geometry, truss member sizes, arrangement of truss diagonals, bearing layout, and substructure and foundation design. It was also found beneficial to substitute an FRP deck for the previously assumed concrete deck. Due to FRP's high stiffness to weight ratio, this had a dramatic effect on the vibration behavior of the bridge.

At the end of this process, the bridge met the above criteria, but it was deemed prudent to perform a more thorough analysis. As is now widely known, on a bridge with a low lateral frequency and the correct distribution of pedestrian lateral loading, unacceptably large movements can result. If a small group within a large crowd of pedestrians happens to be walking in phase, this group can set up

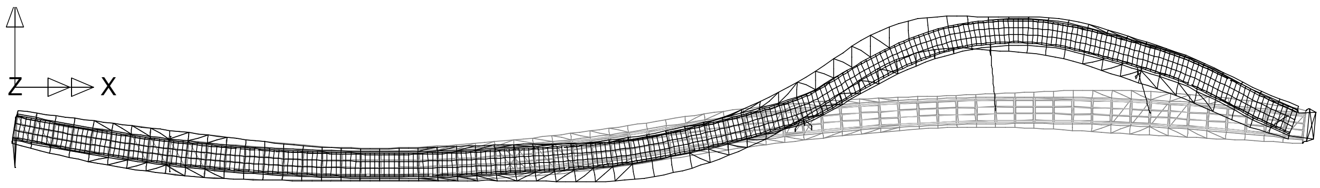


Figure 7: Plan showing first lateral mode of vibration, f = 1.6 Hz

a resonant response, which will encourage others to synchronize with them. Eventually, this feedback will produce motions that can become disturbingly large.

Armed with this knowledge, we applied a distributed cyclic load roughly equivalent to a dense crowd walking with 100% synchronization. The load was applied at a range of frequencies. As expected, the maximum response was found at the natural frequency of 1.6 Hz. Scaling the response to 20% was taken to represent a random synchronization of 20% of the dense crowd. The scaled reaction was very small. Unable to find published guidelines, we judged that at these very small levels of movement no feedback would occur. A search of the literature yielded the serviceability limits for horizontal vibration given in ISO 2631 (1980). In order to produce an unacceptable structural response per these guidelines, a synchronization rate of 75% of the dense crowd would have to occur.

BUCKLING - At several locations along the bridge (most notably at the main span), the outer chord is in compression and bracing against buckling is provided only by the truss verticals acting as cantilevers. The degree of lateral restraint provided by the verticals is dependent on their cross sectional properties, length, and distance from a support. Since these factors vary along the bridge, the bracing they provide to the compression chords also varies. Further, the compression chords follow a non-planar path. The buckling behavior of the bridge is therefore of concern and is very difficult to determine. A full nonlinear buckling analysis was therefore carried out.

The nonlinear analysis used a distributed load approximating the self weight of the bridge (approximately equivalent to live load) applied in a variety of patterns. The load was incrementally increased. At each increment, the deformed geometry for the previous increment was used as the basis of the stiffness matrix. For the purposes of this analysis, materials were assumed to be elastic. The deformations at each increment were examined and the structure was found to behave linearly up to approximately fifteen times the starting load. This demonstrated that linear behavior of the structure is bound by the material limits. Therefore a linear analysis was used for the general analysis and stresses were limited to the elastic range. To verify constructability, similar analyses were carried out on assumed crane picks.

USER EXPERIENCE - Because the users of the bridge will be in close contact with the structure and traveling relatively slowly, the details were treated with great care (see Figure 8). For example, all butt welds are ground smooth and the multi-piece curb was carefully detailed to allow access for the various trades during construction and to present a pleasing appearance to pedestrians once the bridge is in service.

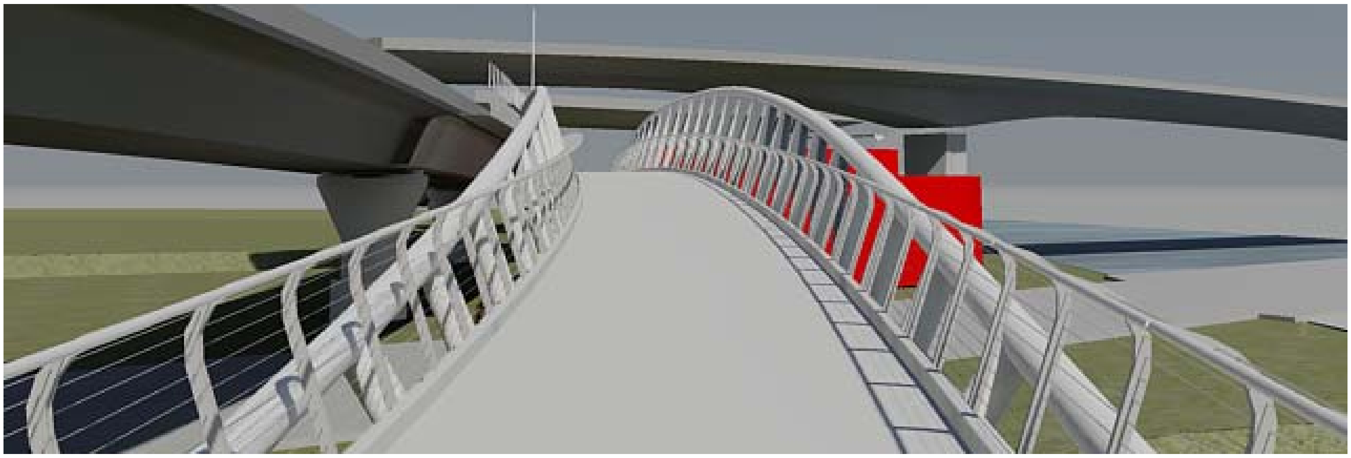

Figure 8: Rendering of bridge and site from bridge user's perspective (looking east)

Ammann & Whitney's railing concept is bridge specific. To minimize visual clutter, the posts are layed out with the truss bays, leaning away from the user at the ultimate slope of truss. A horizontal infill of tensioned wires maximizes transparency to the users, but creates a "ladder" effect which can be dangerous for children. A return at the top of the railing post simultaneously eliminates this ladder effect and presents the handrail back to the user. Lighting is unobtrusively provided by an LED light strip integrated into the handrail.

A full height safety infill is provided in each truss bay at the railroad span. A tensioned stainless steel mesh infill is used, eliminating additional cross frames required by rigid infill.

Before final detailing, the railing and safety infill concepts were presented to the community for approval.

CONSTRUCTION

The specific capabilities of the Contractor (Barletta Heavy Division) suggested a series of small, but important, modifications to the plans. The Contractor, Ammann & Whitney, and the Owner worked closely to resolve each issue with either no reduction in quality or an improvement. This spirit of cooperation carried over to more mundane aspects of construction, such as dealing with unforeseen buried conditions. The Owner deserves a large share of the credit for this success for fostering an environment of open communication.

SUBSTRUCTURE - The Contractor scheduled all foundation work to take place before starting steel fabrication. This was done to preserve the opportunity to modify the superstructure geometry in the case of a major obstruction and subsequent relocation of a footing.

Fortunately, this was not necessary. Monoshafts were designed with an oversized "can" at the interface of the shaft and column, which allowed for drift of the shafts within the specified tolerance. Multiple shaft footings were designed with a generous edge distance. Drilled shaft installation went smoothly with only one shaft encountering an obstruction. The Contractor and Ammann & Whitney worked closely to quickly relocate the shaft and redesign the footing within the limits of the previously installed support of excavation.

STEELWORK - The Contractor proposed a simple and effective method for fabricating the complex geometry of the truss chords. First, a non-uniform rational basis (NURB) spline was defined using the working points provided on the drawings. This spline was used as the reference geometry. The spline was then broken down into a series of segments, the lengths of which matched the length of pipe which could be easily procured. Each segment was then approximated by a planar element, consisting of discrete bends and tangents. Each planar element is connected to its neighbor with the ends "timed" together such that the overall reference geometry is approximated with these planar elements to within 1/8". Prior to approval of this method, a three dimensional solid model of the proposed finished geometry was provided to the Owner by the Contractor and examined by Ammann & Whitney for aesthetic integrity.

For ease of handling and welding, the trusses are fabricated on their sides at a comfortable working height (see Figure 9). The working point coordinates supplied in the contract documents are therefore converted into relative shop coordinates. Each pipe segment is cold bent using a hydraulic ram mounted in a jig built for this project. Pipe supports are precisely located on the shop floor using a target and total station. Once the supports are in place, the bent pipe is laid in. Each chord segment is set in a minimum of three supports. Bending operations take place in the same facility as fabrication so that any segment found to not fit properly into the surveyed supports can be easily returned to the bending process. Once the north and south trusses for a given length of bridge are formed, they are brought into an upright position, truss welding is completed, and floorbeams and other members are added (see Figure 10).

Figure 9: Truss fabrication

Figure 10: Typical node

In this manner, the entire steel superstructure is fabricated in a series of nine assemblies. Assembly lengths range from 31'-3" to 93'-9" with most in the range of 70 ft to 90 ft. Adjacent assemblies are pre-assembled at the fabrication plant to verify geometry prior to shipping (see Figure 11).

The bridge was designed such that the full 22'-0" cross section could fit through all local marine obstructions, but the Contractor chose to ship the panels over the road. To make this possible, the design included an optional floorbeam splice. Each floorbeam is split along the centerline of the bridge. Once on site, the floorbeams are spliced bringing each assembly to its full width. These full penetration welds are made with the use of a sliding backing ring (see Figures 12 & 13).

Figure 11: Partial pre-assembly in fabricator's yard

Once the assemblies are erected, the full penetration butt welds between assemblies are made using a similar sliding backing ring detail.

DECKING - As mentioned above, the decking is made composite with the superstructure by a high strength bolted connection. Steel angles are welded to the floorbeams, and the bottom skin of the decking is bolted to the horizontal leg of the angle (see Figure 14).

A nominal shim thickness is provided on the contract drawings to allow for any adjustments required due to tolerance in the steelwork camber. The Contractor is required to first install the decking without tightening the bolts. The walking surface must then be surveyed and the shims adjusted. Only then can the bolts be tightened. This ensures a smooth vertical curvature for all bridge users and that the ADA requirements are met.

The bridge was detailed for a pultruded deck product, but was ultimately built with a vacuumed product. The vacuum process allows for significant flexibility in panel

Figure 12: Splice detail, open

Figure 13: Splice detail, closed

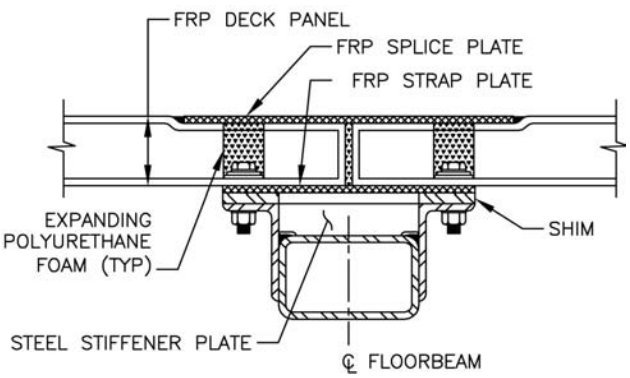


Figure 14: Deck support detail

design, so it was a simple matter to match the properties to those of the pultruded product assumed in the design.

Pultruded shapes were also assumed for use in the curbs. The Contractor chose to fabricate these pieces with a vacuum process as well. The flexibility in this process presented an opportunity to improve the aesthetics of the curb detail. Ammann & Whitney and the Contractor worked closely together to quickly determine the new design.

ACKNOWLEDGEMENTS

This project could not have been completed without the diligent work of the people at the Central Artery / Tunnel Project, Massachusetts Turnpike Authority, MassDOT, and the Department of Conservation and Recreation; nor without the support of Governor Deval Patrick and the MassDOT Board; nor without the dedication of the community, including the Citizens Advisory Committee for the New Charles River Basin, the Charles River Watershed Association, MassBike, the Charles River Conservancy, WalkBoston, and the Conservation Law Foundation; nor without Ammann & Whitney's design partners: Carol R. Johnson Associates, Stantec, and Greenman-Pedersen Incorporated.

CONCLUSION

The Central Artery / Tunnel Project removed a cleft in the city and allowed it to become whole again. As one of the Project's mitigation commitments, the North Bank Bridge removes a similar cleft between the riverfront parks and the harbor. It is our sincere hope that the bridge is found to be useful and enjoyable to the public.

Figure 15: Rendering of bridge and site