LONGFELLOW BRIDGE HISTORIC REHABILITATION

Abstract

The Longfellow Bridge is a well-known Boston and Cambridge landmark. The structure, which carries both roadway traffic and rail, has recently been rehabilitated through a $305 million Design-Build Contract. Built in 1907, the bridge has become an emblem for the Commonwealth. The Rehabilitation of the Longfellow Bridge set out not only to re-establish the functionality of a critical piece of Massachusetts infrastructure, but also to preserve the original bridge aesthetic appearance. The paper below provides a brief overview of the project and a description of the steel detailing and fit up challenges which involved the installation of over 200,000 new pieces of steel.

Introduction

The historic Longfellow Bridge spans the Charles River connecting Boston and Cambridge. Stretching more than 1,900 feet, it carries Route 3 and the Massachusetts Bay Transportation Authority's (MBTA) Red Line subway over the river. Having served motorists, pedestrians, and rail travelers for more than 100 years, the bridge had widespread deterioration of its arches, columns, ornate masonry and unique metal casting features.

The rehabilitation project improved the structural integrity of the bridge while restoring its distinctive historic architectural features. MassDOT Highway Division contracted the Design-Build team of the WSC joint venture of J.F. White Contracting
.
Company/Skanska/Consigli Construction Co. (WSC) and STV, as the lead designer, for the $305 million project. STV was a sub-consultant to the WSC joint venture.

The project encompassed the complete reconstruction of the bridge's original 11 arch spans; a 12th span installed in the 1950s; the seismic retrofit of 12 masonry substructures; and the dismantling, repair and reconstruction of the four signature "salt and pepper" granite towers flanking the main span. The name stems from the 58-foot towers' resemblance to salt and pepper shakers.

The project was part of MassDOT's Accelerated Bridge Program [1], whose goal is to reduce the state's backlog of bridges in need of rehabilitation.

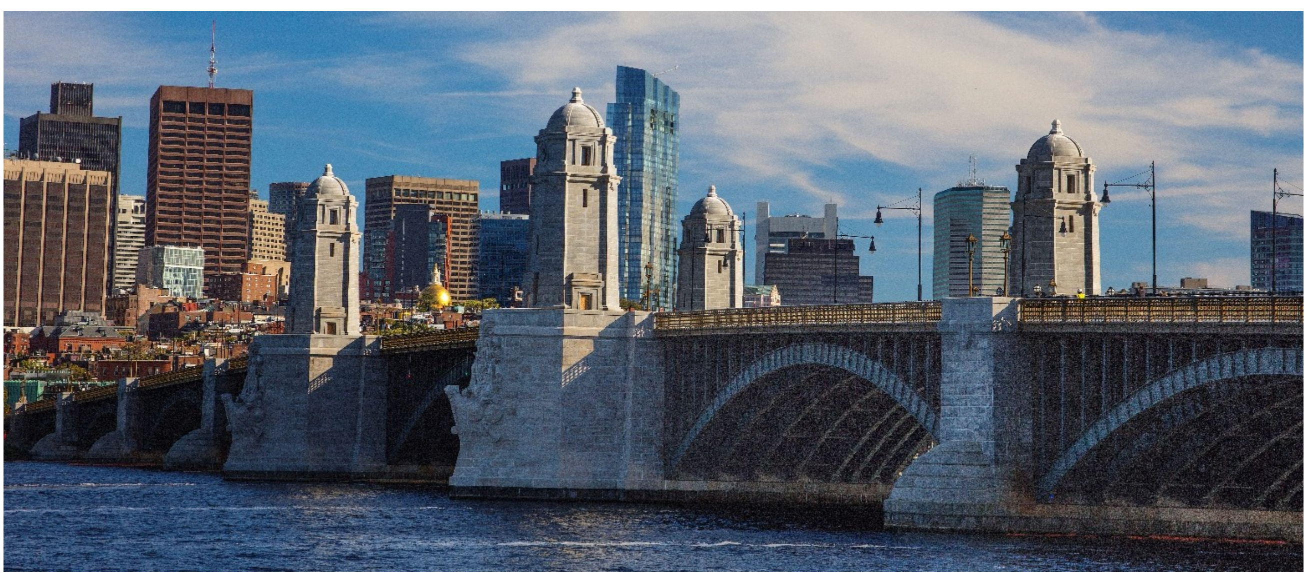

Figure 1: Longfellow Bridge after completion of rehabilitation in 2018.

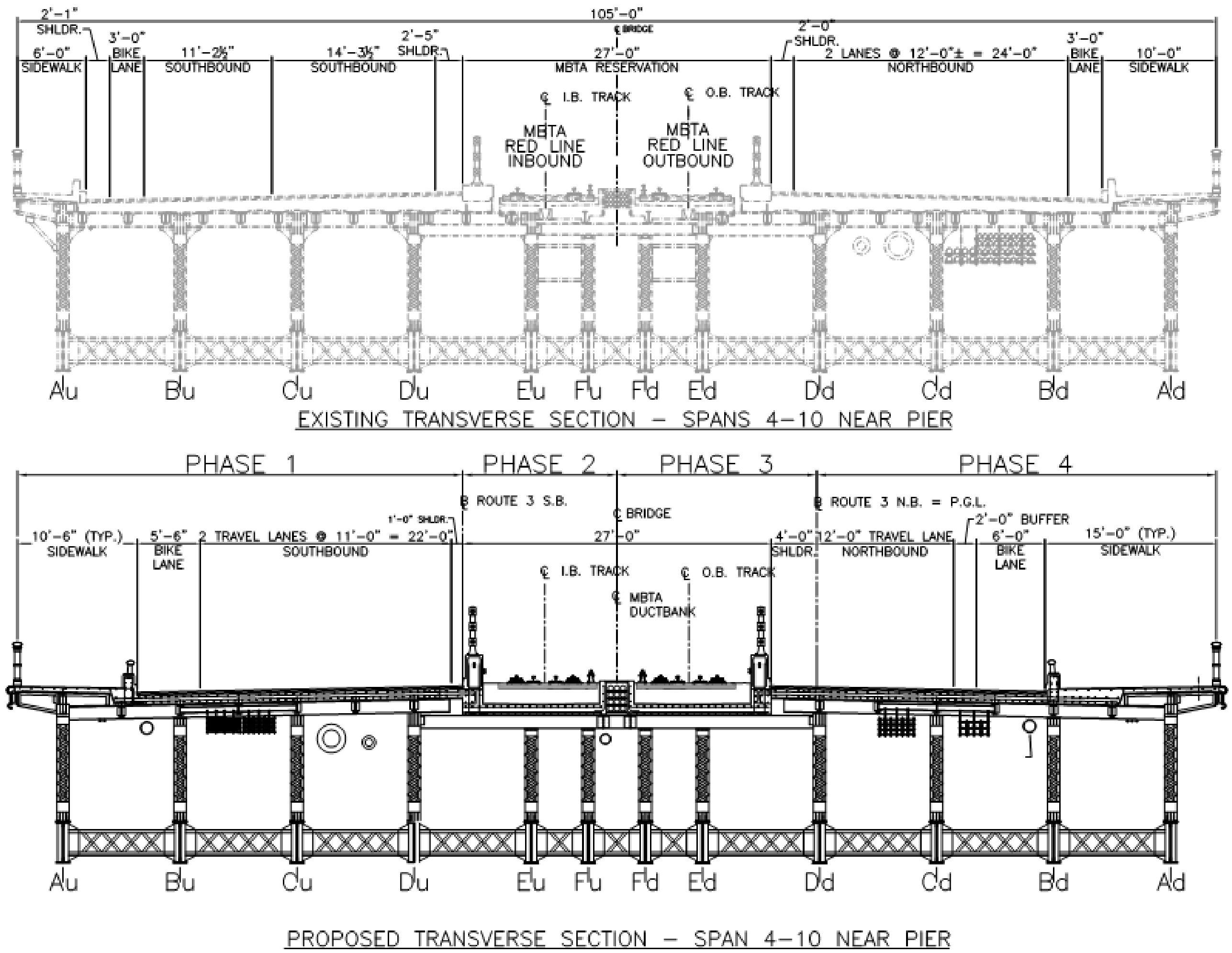

Figure 2: **Cross-sections of the existing bridge (top) and proposed rehabilitated bridge (bottom) with four construction phases.**

The Bridge

The Longfellow Bridge was a product of the City Beautiful Movement, a reform philosophy of North American architecture and urban planning that flourished during the 1890s and 1900s with the intent of introducing beautification and monumental grandeur in cities. Prior to designing the Longfellow, the original designers of the bridge, William Jackson, chief engineer, and Edmund M. Wheelwright, consulting architect, travelled to several European cities where they inspected notable bridges, such as the Pont du Midi in Lyons, France and the bridge over the Moskva River in Moscow[2]. Their design for the Longfellow consisted of 11 steel arch spans supported on ten granite block masonry piers and two massive abutments. Two piers have sculptures that represent the prows of Viking ships. The two central piers carry the neoclassically inspired granite towers. The arch spans increase in length successively from each bank out to the main span at the center of the Charles River. The end spans measure 100 feet in length whereas the main span measures 188 feet.

Historic Review

The Longfellow Bridge is considered Massachusetts' most historically significant bridge, making it subject to federal preservation standards and reviews. To head off potential scheduling snags, the project team implemented a consultation process at the outset of the project to expedite issues regarding historical aspects of the bridge rehabilitation with the six federal, state and local stakeholders involved under Section 106 of the National Historic Preservation Act (NHPA).

NHPA gives consulting parties the authority to review all aspects of the design that may affect the bridge's historic character. As designs developed, the design-build team met regularly with preservation officials to outline constraints, describe possible options and provide recommendations. The team used 3-D software to show the project's visual impacts to the preservation officials.

STV ultimately obtained design approval from MassDOT, the Federal Highway Administration, Massachusetts Bay Transportation Authority, Massachusetts Department of Conservation and Recreation, U.S. Coast Guard, the City of Boston, the City of Cambridge, the Massachusetts Department of Environmental Protection and the Historic Review Board (Section 106).

Structural Analysis

The original MassDOT contract called for the re-use of the 122 steel arch ribs that support the original 11 spans of the bridge. However, due to capacity concerns, the contract allowed for up to 12 of the arches to be replaced. The design team set a goal of preserving all of the arch ribs. National Bridge Inspection Standards-trained inspectors conducted a series of hands-on inspections and nondestructive testing of the steel arch ribs. They recorded section loss and any other signs of structural distress and delivered the data to the design team.

A full 3-D analysis model was developed for each span, and several thousand live load cases were investigated, which combined roadway, pedestrian and rail traffic. Through this process of using actual and exact measured arch properties and extensive modelling, the team demonstrated that all of the arches had adequate capacity to meet current code requirements.

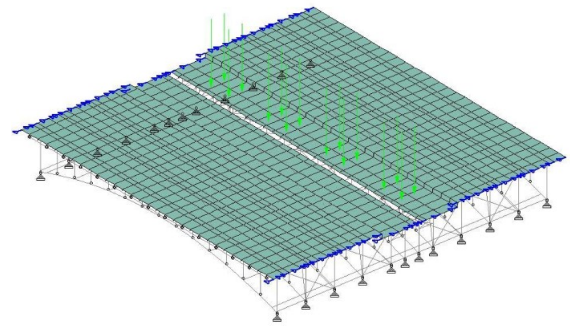

Figure 3: 3-D Model used to analyze arches for various live load cases, including pedestrian, roadway and train loads.

Construction Phasing

A crucial transportation link between Boston and Cambridge, the Longfellow Bridge carries 90,000 Red Line train passengers, 28,000 cars and trucks and well over 1,000 bicyclists and pedestrians daily between the cities[3]. Since it is such a key thoroughfare, it was essential to maintain the Red Line service and minimize impacts to the traveling public, local businesses and the boating community during construction.

When WSC and STV reviewed the proposed construction staging approach in the contract documents, the team identified several safety and feasibility concerns. The design-build team developed a staging plan that allowed for a sequencing of work that progressed systematically from the upstream side of the bridge to the downstream side, and which simplified the steel fit-up. More importantly, the construction stage bounded by active rail traffic on both sides was eliminated, which increased worker safety and productivity and reduced the number of activities requiring weekend closures.

The phasing schemes developed by the team were instrumental in keeping the Red Line open and traffic moving. There were four construction phases, but it took six traffic stages to perform the four construction phases. The STV team developed plans to maintain access for all users as well as emergency vehicles. The MBTA Red Line, sidewalks, bike lanes and one inbound (toward Boston) vehicle travel lane were kept open on the bridge at all times. Extensive detour plans allowed for traffic movement around the Charles River Basin between Boston and Kendall Square for vehicular outbound traffic (towards Cambridge). During 25 approved Red Line shutdown weekends, MBTA customers used bus service. The team worked closely with the Cities of Boston and Cambridge as well as numerous stakeholder groups to reduce impacts to bridge users.

Figure 4: **Construction Stage 2 with train on shoo-fly during work under MBTA reservation.**

For the first phase of construction, the Boston-bound (inbound) roadway was closed, inbound traffic was diverted to the outbound roadway on the downstream side and outbound traffic was detoured to the river crossing at the Museum of Science. During the second phase, both the inbound side roadway and inbound Red Line track were closed. Inbound MBTA trains shifted to the outbound track and outbound trains were displaced to a temporary "shoo-fly" bypass track placed on the outbound roadway. Stages 3 and 4 mirrored Stages 1 and 2 for the outbound side of the bridge. Through all phases, the bridge was kept open to Red Line trains, pedestrians, cyclists and inbound vehicular traffic.

On the bridge's Boston side, the rail-supported structure in the MBTA reservation (the area between the fences with the MBTA's tracks) on Spans 2 and 3 could not be accessed, even with the use of the shoo-fly track. This length of structure had to be replaced through accelerated construction during weekend closures of MBTA Red Line service. STV produced a design scheme for the accelerated construction that limited the closures to just six weekends for 500 linear feet of track-supported structure replacement.

Detailing and Fit Up Challenges

The historic nature of the bridge drove many of the design challenges. In addition to the project being compliant with modern engineering practices and codes, the historic restoration and preservation of certain elements was of vital importance.

Based on the Section 106 "Conditional No Adverse Effect" finding for the project, the structure was broken into three categories, namely:

- Critical Elements to be Restored
- Elements to be Sensitively Rehabilitated
- Elements of Little/No Historic Value.

Figure 5: **Arch span including historically critical railing and fascia and sensitively rehabilitated arch ribs and spandrel columns.**

Critical Elements included existing ornamental cast iron fascia castings and cover plates, and the existing ornamental pedestrian railing.

Elements to be Sensitively Rehabilitated were generally the most visible members on the bridge, including all the arches, the A-line columns along all spans, and most of the columns and buckle plates on Spans 1, 2, and 11, which span over roadways as opposed to the river.

In order to rehabilitate these members with historic sensitivity, original design detailing was considered and replicated as necessary, but not without challenges.

Rivets

The Longfellow Bridge utilized hot riveting during the original construction, which was a popular technique used in bridge construction at the time. Since then, however, rivets have become essentially obsolete in the construction industry due to developments within the bolt industry. Rivets, although cheaper to manufacture, are more labor intensive and require more specialized skills and tools than bolts. And bolts have come a long way throughout history, from becoming standardized across the world to gaining strength and consistency between bolts as knowledge and materials develop.

Around the 1960s and 1970s, bolts took the place of rivets as the standard fastener type and construction technique across the bridge industry. By today, the practice of fabrication of steel bridges through the use of riveting has essentially disappeared in the USA.

It proved challenging for the design-build team to find a steel fabricator with the skilled labor and tools, or the desire to obtain training and tools, to work on riveted members for the Longfellow Bridge rehabilitation. Since the original construction used rivets, the members designated to be historically accurate replica members required riveted construction to match the original fastener type. These members include all A-line spandrel columns, sidewalk stringers and sidewalk beams across all spans. Additionally, any columns or buckle plates that could not be rehabilitated, knee braces, and arch rib girder and column diaphragms on Spans 1, 2 and 11 required historically accurate replica members fabricated using rivets.

Members that were designated to have modified historically accurate replacement members as opposed to replica members were fabricated using button-head tension control bolts. These include the less visible members on Spans 3-10, such as all column lines except the A-line.

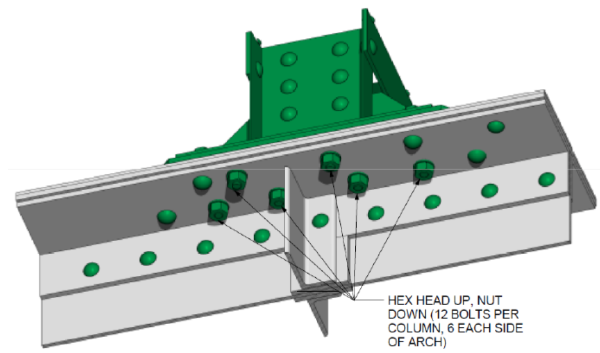

Figure 6: 3-D Model used to show button-head TC bolts vs hex-head bolts in column installation.

Due to the dangerous nature of hot riveting, all riveting was confined to the shop for built-up members. All field connections between members were made using bolts. Where possible, button-head tension control (TC) bolts were used for connections with the button-head facing towards the most visible direction of the connection to maintain a similar aesthetic to the original rivets. In some instances, such as the inner row of column connections to the arches, hex-head bolts needed to be used for installation purposes. Based on the entering and tightening clearances available with the column design and the existing rivet holes being reused for bolts, the torque gun used to tension the TC bolts did not fit, and hex head bolts were used instead.

Buckle Plates

Included on the list of historically significant elements on the bridge to preserve were the buckle plates. When the bridge was originally constructed in 1907, steel buckle plates were installed across the bridge, spanning between stringers and floorbeams to support the concrete deck and sidewalk. Two convex “buckles” per panel provided two-way action to support the unreinforced concrete slab above. [4]

Figure 7: Existing buckle plates from below before demolition.

In 1959, during a major rehabilitation of the bridge, portions of the deck were removed, along with the supporting buckle plates, and replaced with sections of reinforced concrete. For the 2018 rehabilitation, the entire deck and sidewalk was replaced. With a new reinforced concrete, the buckle plates become obsolete structurally, but remain important from a historic perspective.

A goal during reconstruction was to salvage and reuse any of the original buckle plates that were in good condition, installing the original buckle plates and any additional replica buckle plates needed to fill in the three spans over the roadways, Spans 1, 2 and 11. These spans were so designated because there is pedestrian access below the spans.

Based on the construction phasing, the Design-Build team proposed, and the Section 106 Consulting Parties agreed, that it was not feasible with the schedule to extract, refurbish and reinstall any of the original buckle plates on the upstream roadway of Span 11. Replica buckle plates were fabricated and installed during the early phase work, with the intent to use all salvaged plates on Spans 1, 2 and the downstream portion of Span 11.

Upon the continuation of demolition however, all the existing buckle plates were found to have advanced deterioration, and none of the original buckle plates were deemed to be in good condition or able to be refurbished and reinstalled.

In the end, the roadway decks and sidewalks on Spans 1, 2 and 11 utilized replica buckle plates as stay-in-place forms. Spans 3-10 over the river did not have the same requirements, so instead of using replica buckle plates as stay-in-place forms, removable formwork was used to cast both roadway decks and sidewalks.

Columns

The Longfellow Bridge has over 2,600 spandrel columns evenly spaced along the arches every 7’-3” to hold up the deck framing. Each built-up column consists of two C10 channels, inner web plates at the top and bottom and lattice bars on all columns greater than approximately 4 feet tall. The columns make up an important piece of the aesthetic of the bridge and are considered historically important. Many of the columns are categorized as Elements to be Sensitively Rehabilitated.

Some of the columns were always intended to be replaced. Some had considerable deterioration, especially the D-line columns under the joint between roadway deck and MBTA reservation. Others had less deterioration but were in areas that did not require preservation or sensitive rehabilitation. These columns were replaced with new steel.

On Spans 1, 2 and 11, which kept the original framing plan, all roadway columns were deemed elements to be preserved. All columns that required replacement within these spans were designated to be exact replicas, and consequently required riveted construction.

On Spans 3-10, all columns other than the A-line were not held to the same preservation requirements as Spans 1, 2 and 11. The new framing on Spans 3-10 was modified slightly from the original framing, and as such, the new columns along the D-line on these spans are modified replica columns, maintaining most of the detailing from the original columns, but modifying the tops of the columns to work with the new continuous floorbeams above. Since these columns are towards the middle of the bridge and located on the spans that are less visible from land, modified replication was allowed instead of historically accurate replication, and the requirements for construction method were relaxed on these columns. Instead of riveted construction, the interior columns on Spans 3-10 were built up using button-head tension control bolts.

The columns that received the designation from the Section 106 Consulting Parties as Elements to be Sensitively Rehabilitated include the A-line columns across all spans and all the other roadway columns on Spans 1, 2 and 11. Aside from any columns that had severe deterioration, which needed historically accurate replication, all of these columns were intended to be refurbished and reused.

During the first phase of demolition, the A-line columns were carefully removed and brought off-site for repair and cleaning. The A-line columns were generally in good condition with little to no deterioration and needed only minor repairs. Once cleaned, the columns were hot-dipped galvanized and painted. However, within weeks of galvanizing, it became clear that hot-dipped galvanizing the steelwork was proving to be problematic. The columns started bleeding rust at the rivet locations from in between the plies of steel at the top and bottom web connection plates.

Figure 8: Riveted steel members on Span 1.

After discussions with the Section 106 Consulting Parties and the owner about the historic importance of reusing the original materials compared to replicating the columns with new steel to ensure a better service life of the members, the decision was ultimately made to throw away all the existing steel and replicate all the columns using new steel. Each piece of the new column was hot-dipped galvanized individually before being used in the built-up member. For the historically important columns along the A-lines and on Spans 1, 2 and 11, the columns were fabricated using riveted construction. The field connections to the arches below and to the framing above the columns were made using button-head TC bolts or hex-head bolts.

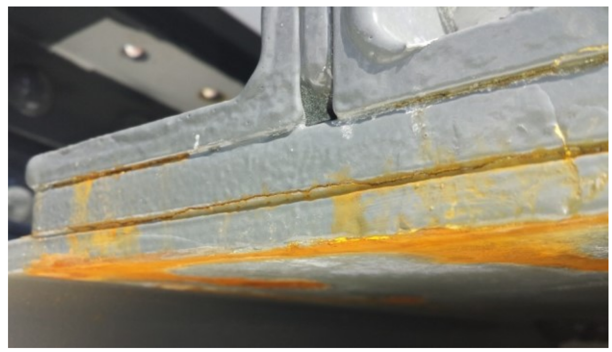

Figure 9: Rust bleed on existing column after hot-dipped galvanization of built-up member.

Steel Fit Up

Aside from the challenges of demonstrating adequate capacity to allow for the reuse of all of the arches described previously, a major challenge of reusing the existing arches, especially through multiple construction stages, was fit up between the new and existing steel.

During the rehabilitation of the Longfellow Bridge, the existing arches remained in place, and the new columns and deck framing were installed from the bottom up, attaching new steel piece by piece to the existing arches. Although the tolerances of the members of the new framing can be controlled to great accuracy with modern fabrication techniques, the tolerance of the field fit up of those new members to the existing arches was not as accurate. The supporting arches were not always at the theoretical design location from the original construction.

By design, the arches are evenly spaced at 10’-3” on center beneath the roadways and 5’-0” on center beneath the MBTA reservation, and the columns are evenly spaced at 7’-3” on center along the centerline of the arches.

In reality, the arches are not perfectly straight and evenly spaced across the spans. Some of the arches have overall sweeping curves horizontally, with the entire arch bowing into or away from the centerline of the bridge. Some arches were slightly tilted or had slightly skewed webs or top flanges. As rivets and columns were removed from the arch flanges, it became clear that the rivet holes at the column base connection plates did not fully align with the holes in the existing top arch flanges. Because rivets are installed in a molten state, the holes they fit into did not need to fully align since the molten metal would deform into the space available. Additionally, the holes did not always line with the center of the existing rivet heads.

Figure 10: Gantry used during construction to place steel roadway framing into best-fit location based on existing arch misalignments.

All these misalignments, as well as the steel arches moving up and down with temperature changes, created a large challenge to obtain accurate and precise field measurements and to achieve proper steel fit up during installation.

After interaction with MassDOT, it was agreed that the primary tool used to build tolerance into the erection of the steel framework was slotted holes in slip-critical connections. A connection could utilize slotted holes as long as at each faying surface, the slot abutted a standard hole.

The existing rivet holes in the arches were reused for bolts. Holes were reamed as necessary to be able to fit a bolt through, and this reamed hole was considered a slot, even if the dimensions were outside the standard definitions of slots. This means that the base plates on top of the arches at each column location needed standard holes. After the rivets were removed, field measurements confirmed the locations of the holes, and new base plates were drilled to match the field conditions. Even though the arch ribs were slotted, an additional slot was used in the same connection at the column base angles. With the base plates between the two slotted components, each faying surface only had one slot. The column base angles were slotted to give adjustment to the columns in the longitudinal direction of the bridge. The columns were installed as close to the theoretical 7’-3” spacing as possible.

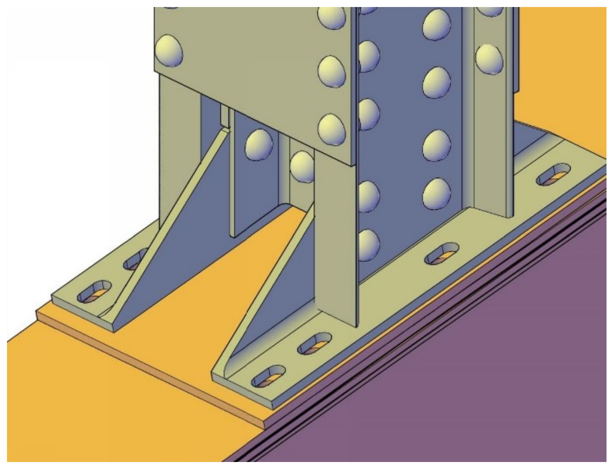

Figure 11: 3-D Model used to show slotting in column base angles for connection to arch rib to add longitudinal adjustability.

Adjustments in the transverse direction were achieved at the deck framing level. Slots were added to floorbeams at each of the column connections to account for any translation necessary to correct the misalignments of the arches and columns below. In a few instances, floorbeams were lengthened or shortened in addition to slotting the connections.

Figure 12: The final configuration of the bridge is used by pedestrians, bicycles, automobiles and trains.

Vertical adjustment in the bridge was also a challenge based on the existing arches. Survey data was collected on the vertical location of the arches at the pins and crown as well as numerous intermediate points along the A-line arches, and a best-fit parabola was found for each arch. After adjusting for dead load and temperature effects, column heights were calculated to place the deck framing at the proper height for the design profile. Theoretical modeling of temperature effects on a large arch structure depends on slightly unrealistic assumptions, such as the entire arch changing temperature at the same rate across the entire arch and each arch being installed as a perfect parabola, so some imprecision is inherent to modeling. To account for this, vertical adjustments needed to be included in the design. Nominal half inch shim packs were included in the column design height, and once the columns were installed in the field, the shims could be removed, or additional shims could be added to reach the desired height to fit up the framing. Additional height adjustments were accounted for with the deck haunches.

A Code Compliant Bridge

The bridge is now AASHTO-compliant [5] and Americans with Disabilities Act (ADA)-compliant [6]. In its final configuration, one outbound travel lane was eliminated, and bicycle lanes were added on both the inbound and outbound sides. The bridge has two inbound travel lanes (the same as before), one outbound lane, two rebuilt MBTA Red Line tracks, two bicycle lanes and two widened sidewalks.

Acknowledgements

The authors would like to thank all participants involved in the Longfellow Bridge Historic Rehabilitation, especially the following organizations.

Owner: Massachusetts Department of Transportation (MassDOT) and Massachusetts Bay Transportation Authority (MBTA)

Contractor: J.F. White Contracting Company/ Skanska/Consigli Construction Co. (WSC)

Engineer of Record: STV Incorporated

References

1. *MassDOT Accelerated Bridge Program (ABP)*. Commonwealth of Massachusetts 2018. https://www.mass.gov/accelerated-bridge-program-abp.
2. Architectural Iron & Steel in the 21st Century: Design and Preservation of Contemporary & Historic Architecture – Conference, April 4, 2016, MIT, Cambridge, MA. Longfellow Bridge Preservation Presentation – Presenters: Stacey Donahue, Robert Collari, Wendall Kalsow, Mark Ennis.
3. Commonwealth of Massachusetts Department of Transportation, *Technical Provisions, Bridge Rehabilitation Br. No. B-16-009=C-01-002 (Longfellow Bridge)*, 2012.
4. City of Boston Printing Department. *Report of the Cambridge Bridge Commission and the Report of the Chief Engineer Upon the Construction of Cambridge Bridge*, 1909.
5. American Association of State Highway and Transportation Officials, *Standard Specifications for Highway Bridges*, 17th Edition, 2002.
6. Americans with Disabilities Act, *Standards for Accessible Design*, 2010.