I-93 Bridge Repair, Memorial Day Weekend 1999

The spirit of partnership among owner, engineering consultants and contractors — especially the cooperative efforts of two competing contractors — ensured that repairs to this bridge were done in a timely manner.

ALEX BARDOW, ABDOL HAGH & RORY NEUBAUER

On Friday, May 28, 1999, as most people were preparing for the upcoming Memorial Day weekend and the official start of summer, the Massachusetts Highway Department (MHD) was gearing up for what would become an intense, three-day emergency repair of the I-93 bridge over the Charles River in Boston. Earlier that day, MHD personnel had found settlement along a finger joint on the upper level that had been caused by the buckling of the web of one of the stringers supporting the upper deck.

This repair effort would require shutting down the entire bridge for the better part of the weekend, effectively severing the principle routes from the north and northeast into downtown Boston on one of the heaviest travel weekends of the year. Nevertheless, through a partnership effort of the MHD and private engineers and contractors, the repairs were completed and the bridge was re-opened to traffic by 2:30 P.M. Monday, just in time for the returning weekend traffic.

Anatomy of the Problem

The main I-93 crossing of the Charles River (see Figure 1), built in 1951, is a 375-foot-long single-span Warren through truss bridge with two roadway levels. The lower roadway, at the level of the lower chord, carries I-93 southbound; the upper level, located approximately at mid-height on the truss, carries I-93 northbound. The approach roadway spans consist of two girders that support the floor system and the deck. There are finger joints on both levels where the approach roadways meet the truss span.

The girders of the lower level approach spans share a common pier with the truss. The girders of the upper level frame into a transverse girder that is supported at either end by columns that frame into the truss bearings at the pier. The stringers, which support the truss span's upper level deck, also frame into this same transverse girder. In order to allow for

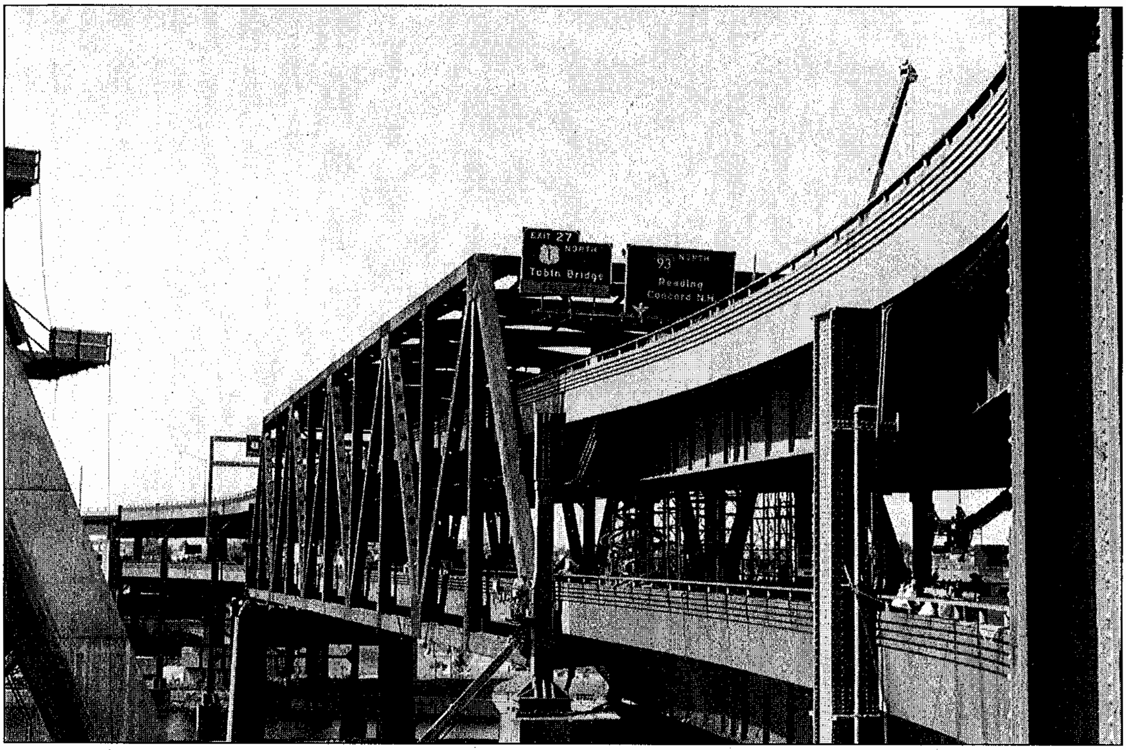

FIGURE 1. A view of the main I-93 crossing of the Charles River.

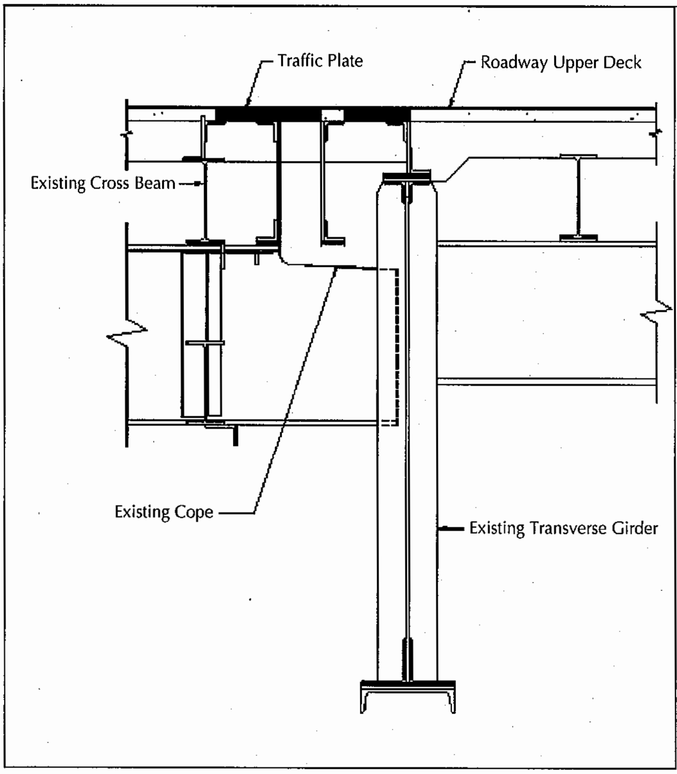

FIGURE 2. The existing W36 cope.

thermal movements between the truss and approach spans, the truss stringers sit on expansion bearings in a saddle that is attached to the transverse girder. Directly above the stringer ends is the finger joint, where one side is supported by the transverse girder and the other by the stringers.

The detailing of the stringer ends and finger joint proved to be the culprit in the Memorial Day emergency. First, the top flange of the stringer end was coped so that it would fit under the plates and channels that made up the finger joint support assembly. This cope effectively created an inverted "T" section (see Figure 2). Although the primary stress in the web was from shear, the reaction created a second-order bending moment that the "T" section had to carry. This bending moment put the unbraced coped web into compression.

FIGURE 3. The traffic plate on the upper deck of the bridge.

The design of the inverted "T" was no doubt properly performed and its adequacy assured according to American Association of State Highway and Transportation Officials (AASHTO) code. It is only in hindsight, after years of the cumulative effects of the second-order bending stresses, that the shortcomings of these details became apparent, and by learning the lessons they present, engineers can ensure the better durability of future bridges.

Second, any water coming through the open finger joint was allowed to pour over the stringer ends since the drainage trough was located below the stringers. An attempt was made to channel the water away from the stringer ends using small channel sections that sloped towards the trough.

At the time of the original construction, the detailing of these elements was consistent with standard industry practice. Open roadway joints were a common feature in bridge design and there was little concern for the potential corrosion of structural steel from long-term contact with water. Over the years, this situation was further exacerbated by the increased use of salt in the wintertime to keep the roadways clear and passable.

A final contributing factor was the direction of traffic. Although the same detail was found at both ends of the upper level truss span, it was the south finger joint that had started to settle. This settlement is attributed to the fact that this joint receives more impact as trucks roll onto the truss span from the approach span, while the north finger joint sees less impact since trucks are rolling off the truss span.

As it happened, the coped stringer ends lost section after 40 years of corrosion, while at the same time increased traffic loads and heavier trucks produced larger compressive loads on the web from the second-order moment from the reaction. After years of pounding, the unbraced stringer end buckled on that fateful Friday. As it buckled, the stringer

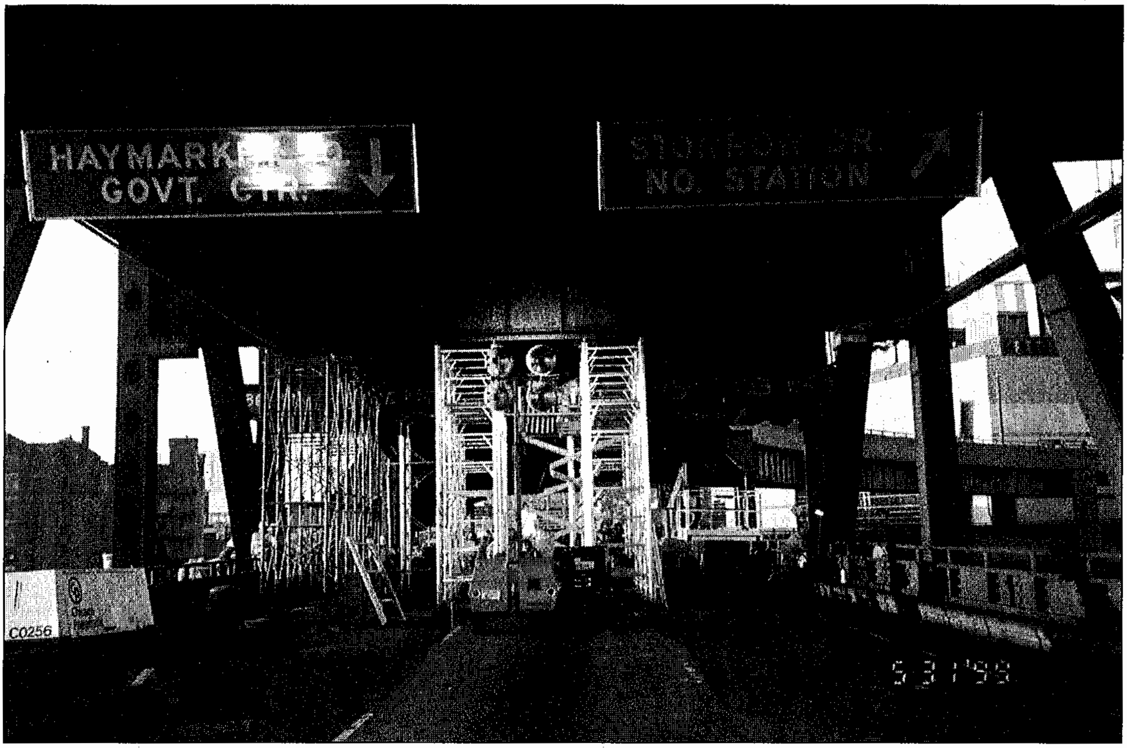

FIGURE 4. I-93 southbound at the Charles River Bridge showing the shoring towers.

end settled, pulling the finger joint down with it.

Initial Response

MHD's District 4 personnel first discovered the settled finger joint after investigating motorist complaints about an excessive bump at the joint. District 4 structures maintenance personnel conducted further investigation on that Friday morning, at which time it was found that the web of the east fascia stringer had buckled, causing the joint settlement (see Figure 3). At that time, the joint had settled about 3 inches at the east gutter line. MHD contacted the district's emergency repair contractor, which was prepared to repair the stringer later that evening.

The structures maintenance personnel notified the MHD Bridge Engineer and invited Bridge Section personnel to see it firsthand. The Bridge Engineer and staff from the Bridge Inspection Unit of the Bridge Section arrived at the bridge shortly after noon. During this visit, it was discovered that the web of the next beam over (the first interior on the east side) had also buckled. Although the bridge and stringers were not in any danger of failure, engineers were concerned that the continued pounding of traffic would result in the additional settlement of the joint. This settlement would potentially be a serious hazard, whereby a vehicle could loose control as it went over the joint, resulting in an accident in the middle of the heavy holiday traffic. Based on these concerns, traffic on the upper level was restricted to the west side so that it rode on the part of the joint that was still intact.

Because at the time it appeared that the problem was limited to two stringers, MHD engineers decided on a repair scheme that would splice over the buckled stringer webs with two half-inch plates. Angles would be provided at the top and bottom to provide stiffness to the plates. A bolted field splice would be provided to connect these plates with the remaining intact portion of the stringer web, located about 5 feet from the end.

Engineers from MHD's Bridge Section's In-House Design Unit prepared the design of the splice and the plates. A steel fabricator was contacted to make the plates and ship them to the bridge in time for MHD's repair contractor to install them that night.

Shoring towers were also erected below the affected stingers in order to unload the stringer ends so that the splice plates could be installed (see Figure 4). The shoring towers were located over the stringers of the lower level. A study of the original dead and live design loads for the stringers, which were given on the construction plans, showed that they had sufficient capacity to carry the dead load of the upper level stringers in addition to their own dead load.

MHD remained concerned about the condition of the remaining two stringers, which were now carrying the entire traffic load. To monitor the situation, engineers from the Bridge Section were stationed on the bridge in shifts around the clock. These concerns were, unfortunately, well founded. Late Friday evening by 11:00 P.M., the second interior stringer web had also buckled, leaving only the west fascia stringer web intact.

Faced with the growing settlement of the finger joint, MHD made the decision to close the upper level to all traffic. Although this severed a key artery from Boston to the north and northeast, most of the weekend traffic had already passed, thereby diffusing the situation somewhat.

However, MHD was now faced with an even greater problem to repair and only the weekend to do it. The bridge would have to be back in full operation by Monday afternoon so that the returning Memorial Day travelers would not find themselves faced with a complete gridlock and extensive detours.

MHD decided to repair all four stringers, since it did not want to take a chance with the west fascia stringer. Accomplishing this task would require massive resources of materials, equipment and labor. In addition, the services of a construction engineer were needed to design the contractors' means and methods for the repair.

Just as it did in 1996, when a lumber truck hit a column on the same bridge, MHD turned to the Central Artery/Third Harbor Tunnel (CA/T) Project for assistance. This call went out at about 1:00 A.M. on Saturday, May 29, to the CA/T Project's Director of Construction.

A CA/T Project team was assembled through the rest of early Saturday morning. Two CA/T Project contractors were contacted to provide the needed resources, one of which also provided the services of its consulting engineer for the necessary construction engineering.

Selecting the Repair Method

While preparing for the construction operation early Saturday morning, one of the CA/T Project contractors began to consider that, instead of repairing each stringer individually, perhaps a steel frame could be erected to support the stringers. This scheme would require fairly large-sized steel members. However, the advantage was that all of the required pieces could be pre-fabricated in a shop and then assembled on-site. Although this solution was a more radical approach, it could achieve the desired results in less construction time.

The MHD Bridge Engineer was contacted at home at about 8 A.M. on Saturday to discuss this proposal. The engineer promptly went to the bridge site to review the feasibility of this scheme with one of the CA/T Project contractors. During this meeting, it became evident that the advantages of this concept made it the more desirable repair option. As the engineer and contractor worked together, the final repair scheme emerged. A new transverse girder would be installed that would support the stringers near their ends, effectively replacing the function of the damaged stringer ends. Columns that would frame into the truss bearing assembly would support the stringer ends of the transverse girder. An engineer from the construction engineering firm also arrived later that morning on the bridge to take measurements in preparation for the design.

Shortly after that, construction engineer firm representatives were on the bridge working on the design aspects of the proposed concept. Prior to the start of the design, a thorough inspection of the upper and lower deck stringers was performed in order to ensure that stringer end problems did not exist on the lower deck girders. Two variations to the initial concept were considered. In one approach, the W14 columns would be installed in-line with the new W36 girders, which were 5 feet away from the stringer ends. In the second approach,

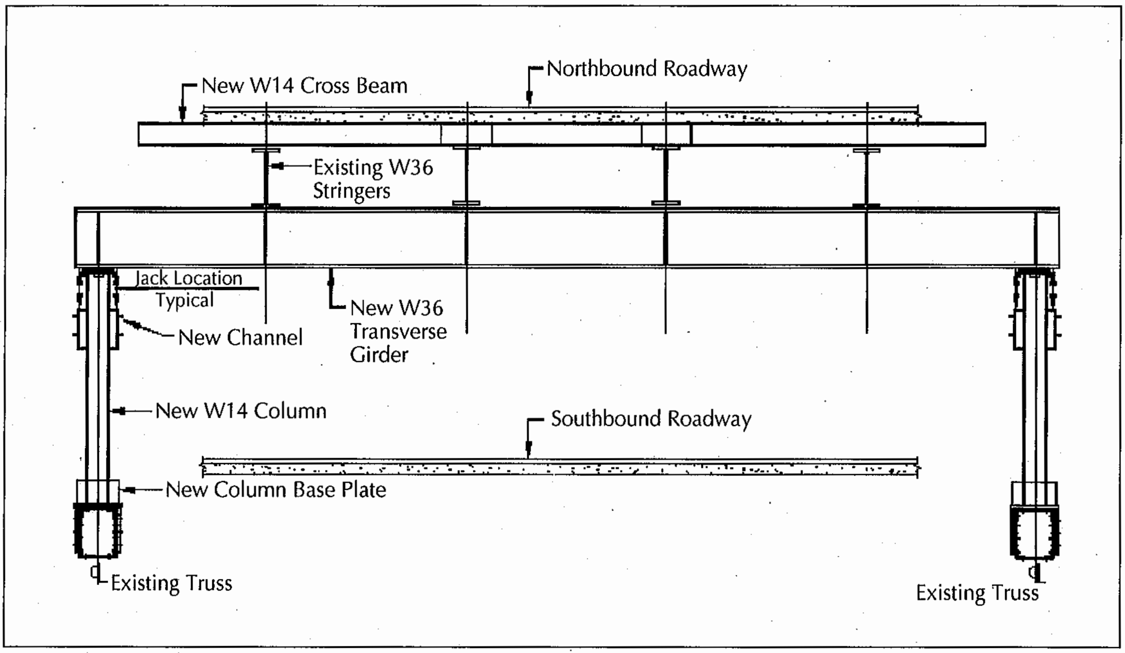

FIGURE 5. Elevation view of the new support beam and column.

the columns would be placed closer to the stringer ends and eccentric to the W36 girders (see Figure 5). After performing preliminary analyses and computations for the two approaches, it was determined that the impact of the selected concept would be minimal on the existing truss members and connections.

In order to expedite the design of this scheme, it was decided that MHD engineers would work in partnership with the CA/T Project team. MHD engineers went to a CA/T Project field office in Cambridge to work with the construction engineers on the design. The CA/T Project contractors coordinated the material and equipment needs and assisted in advising on the constructability aspects of the design.

By early afternoon, the CA/T Project construction team, as well as the construction engineers and MHD personnel, assembled at one of the CA/T Project contractors' office and commenced with the final design of the proposed concept. By 6:00 P.M. that same day, the design was completed and coordinated between all design and construction team members. Plans were finalized with the steel fabricator to perform the structural steel fabrication of all the major components, such as the transverse girder and column assemblies. The steel fabricator received working drawings of the components by 6:30 P.M. on Saturday.

Preparations for Repair

The design and the construction team worked together in preparing shop drawing sketches that would identify all member sizes and connection details as well as any preparatory work for the existing trusses. All sketches were completed by 10:00 P.M. and faxed to the steel fabricator.

Availability of material was an important issue that could have derailed the entire design and construction effort. The W36 transverse girder was provided by one CA/T Project contractor, the W14X109 columns were provided by the other, and all plates, angles and bolts were provided by the steel fabricator. Most required members were obtained by the construction team and others were substituted with alternate sizes that were available to the construction team.

Fabrication commenced at about 6:00 P.M. that night and the transverse girder was delivered to the site about 2:00 A.M. the next morning. A total of 15 shop personnel worked on fabrication issues during that period of time. The W14 columns and bearing plates were de-

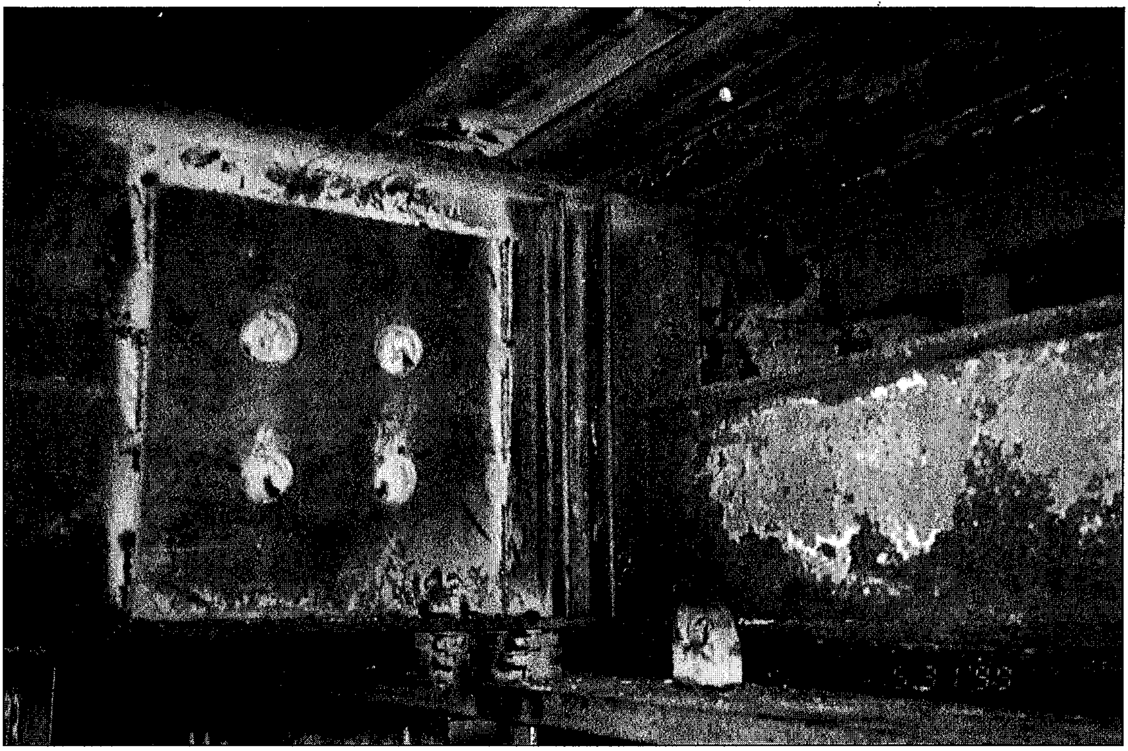

FIGURE 6. Web doubler plates.

livered to the construction site by 6:00 A.M. Sunday.

The existing W36 stringers were ground smooth using metal grinders and all rust and loose material was removed. This preparation was necessary for the installation of the web doubler plates (see Figure 6). At the truss connection, all plates were ground using a metal grinder in order to prepare the surfaces to receive the column base plates.

Installation of New Elements

A 6-ton carry deck cherry picker was used to move miscellaneous material within the site area. Due to the low headroom conditions, a front end-loader with a boom was used to position and raise the W36 transverse girder in place. Two chain falls attached to the upper deck were used to snug the W36 transverse girder in place prior to the setting of the columns. The W14 columns were installed using a 35-ton cherry picker from the upper deck of the bridge and drifted into place below the W36 transverse girder and the truss diagonal.

During the 60 hours of field work, a total of 30 to 50 field personnel were on the site at any given time, erecting the temporary shoring and installing the structural steel. Even though it was a holiday weekend, a sufficient labor force was held over or called in to facilitate the necessary repairs. One CA/T Project contractor on the team supplied support services, equipment, small tools, welding machines and materials to supplement other contractor workforce efforts.

First, purlin beams were installed between the deck and the existing W36 stringers. These purlin beams were located directly over where the new transverse girder would be installed. This way, the deck and finger joint loads would not have to be supported by the buckled stringer web. The next task was to install the new columns.

After the columns and the transverse girder were installed and secured in place, base plate side elements were installed and welded to the cap plate (see Figure 7). All spaces between stringers and the W36 transverse girder were shimmed with steel plates. After completing

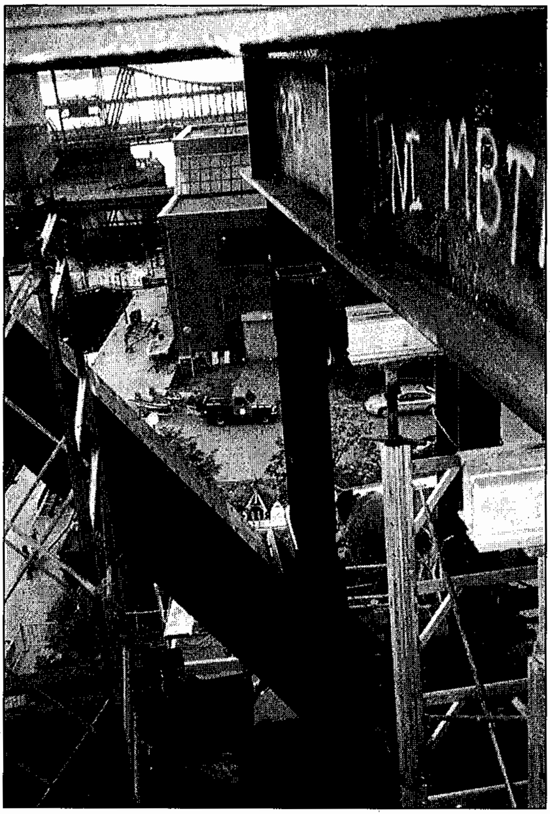

FIGURE 7. The new W14 columns and the W36 traverse girder.

the installation, the transverse girder was jacked up against the existing stringers using two 50-ton hydraulic jacks.

After the jacking operation was completed, the upper deck roadway surface was still uneven across the expansion joint. A steel plate was used to create a transition between the two sections of the bridge deck that were uneven. Most of the unessential equipment and material were removed from the site by 12:00 P.M. on Monday. Soon after jacking the transverse girder, the temporary shoring of the upper deck was sequentially removed from the site. The upper deck was opened to traffic at 2:00 P.M. on Monday, a half-hour earlier than the lower deck in order to assess the impact of the traffic on this retrofit.

Post-Memorial Day Work

In order to assure the long-term integrity of the retrofit frame, the designers always intended to install additional braces and to replace some of the welds with high-strength bolts to eliminate the potential for fatigue cracking. This additional work would also include the strengthening of the stringer ends so that they could better support the finger joints. However, all of this additional work, which was not critical to the re-opening of the bridge to traffic, could not be completed by the Monday on Memorial Day weekend. As a result, MHD decided to do this work after Memorial Day using its normal emergency repair contractor.

First, bolts were installed for the connection between the transverse girder and the support columns. Also, bolts were used to secure the fascia stringers to the transverse girder in place of the welded keeper plate connection.

Second, bracing struts were installed between the truss end posts and the top flange of the transverse girder to provide additional restraint against flange buckling at the ends of the transverse girder. Lacing plates were installed between the stringers and the transverse girder to secure them laterally. The top flange of the transverse girder itself was restrained by angles bolted onto the bottom flange of the interior stringers.

In order to minimize the impact that this work would have on traffic, MHD decided to perform this work at night, primarily during the early morning hours, using partial lane closures. These two tasks were accomplished during weekday nights between June 1 and June 11, 1999. No work was performed during the weekend nights (from Friday night to Saturday and from Saturday night to Sunday).

The other task that remained was to retrofit the stringer ends so that they could better support the load of the finger joint. The design consisted of bolting plates and angles on each side of the stringer web to act as a strut between the finger joint's connection with the stringer and the stringer's bottom flange, where the web was solid. This work was begun on June 14 just after the completion of the first two tasks outlined above and continued through June 22.

Repair of the North Finger Joint

Since the same stringer end details were used for the finger joint at the northern end of the upper level that were used at the southern end, MHD felt that those stringer webs could also potentially buckle at any time. Thus, even before the repairs were completed on the southern end, MHD decided to perform similar repairs at that end as well. However, this time MHD would be able to schedule and plan the construction effort in advance.

MHD's repair contractor would perform all of this work. As much of the preparatory work as possible would be done during nighttime lane closures. The only time when the bridge would have to be closed to traffic would be when the transverse girder was being installed and jacked into place. However, the public would be notified of this closure well in advance.

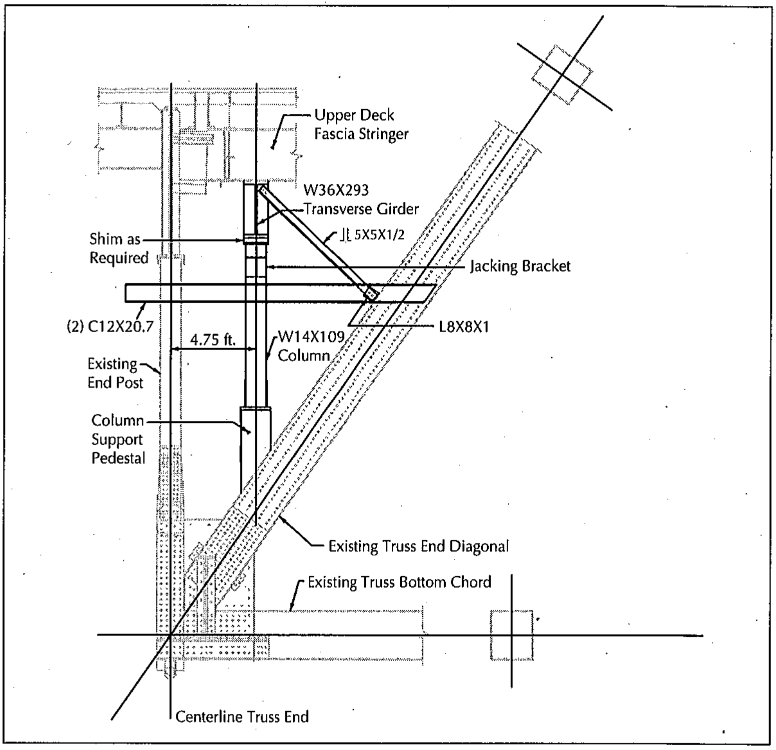

FIGURE 8. Repair bent at the north finger joint.

Furthermore, MHD engineers took this opportunity to apply the experience gained from doing the work at the southern end to improve the constructability of the repair at the northern end.

The most significant change made was in the design of the support columns and their attachment to the truss end posts. On the southern end, because the column bases were cut at an angle and shop-welded to the base plate, there was no way to adjust the location of the column to line it up with the transverse girder.

For the northern end, MHD engineers decided to place the column base plate horizontally. The saddle side plates were fabricated with five sides so that, when installed, the top edges were level (see Figure 8). The column with its base plate would be placed on top of these plates and welded in place. This way, the column could be moved somewhat, if needed, so that it would line up with the transverse girder.

The second decision involved the use of a template to pre-drill the bolt holes for the saddle side plates in the truss end post. The location of the rivets as well as the geometry of the end post itself were first accurately transferred to the template. Then, after the saddle plate bolt hole locations were shop-drilled in the template, the template was re-installed on the truss and the bolt holes drilled in the truss end post. Using this method, the column saddle plates were installed without any problems and the top edges of the saddle plates were essentially level.

The work on the northern end finger joint began June 9. The first tasks consisted of installing the additional purlin beams between the deck and truss stringers and reinforcing the stringer ends. This work was done concurrently with the work being performed at the southern end in order to utilize the same lane closures, thereby minimizing the impact on traffic. The stringer end reinforcement was completed on July 1.

Next, on June 21, field measurements for the templates for the saddle plates were taken and the templates themselves were prepared over the next two days. The drilling of the holes for the saddle plates began on June 23 and contin-

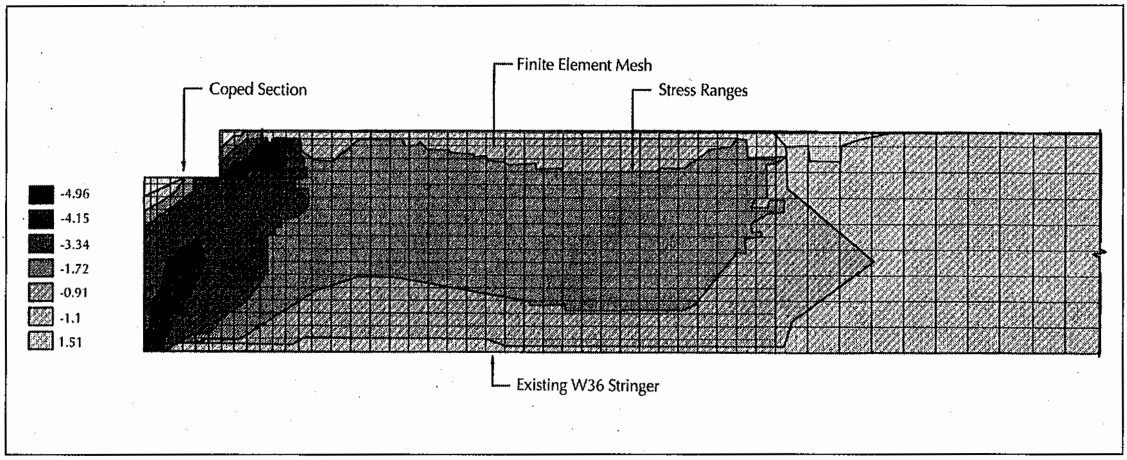

FIGURE 9. Finite element mesh of the existing W36 stringer with coped top flange.

ued through June 29. The northeast column was completed first and then the northwest column.

The final task that remained was to install the new W36X393 transverse girder. This installation would require a complete shutdown of I-93 for a weekend. This work was postponed until August for two reasons. First, Boston was the host city for the Major League Baseball All-Star game held on July 14. Closing I-93 in early July would have an adverse effect on the increased traffic associated with this event.

Second, a new interchange was being constructed over I-93 in Woburn, a few miles north of Boston. The erection of the beams for this project was scheduled for the weekend of July 17 and 18, an operation that would also require the complete shut down of I-93 in the Woburn area. MHD was concerned about the combined effect that the two shutdowns of I-93 would have on traffic, so the decision was made to finish the Woburn project as scheduled first, and then proceed with the I-93 bridge over the Charles River.

The installation of the transverse girder was done over the weekend of August 7 and 8. This work consisted of installing the girder itself, jacking it into place and attaching it to the support columns. The remaining work of attaching the bracing struts was performed during nighttime partial lane closures on August 10 and 11. With this work, the repairs to the Charles River bridge, which began on the Friday before the Memorial Day weekend, were finally complete.

Validation of the Retrofit Design

Bridge Design Criteria (1954). The original bridge structure was designed in 1950 according to AASHTO design requirements of 1949. That design complied with AASHTO H20-S16 loading, which is equivalent to the current designation of HS20-44.

The bridge was designed as a Warren truss with the north end pinned and a roller at the south end. Each of the two side trusses were 53.5 feet deep and 375 feet long and spanned between the concrete piers. The upper roadway framing consisted of W36 stringers at 10-foot, 8-inch on center supported by girders every 37.5 feet. The roadway slab was supported by W16 purlins spanning between the W36 stringers. All structural steel members were A36 carbon steel with the exception of the truss elements, which were made of high-strength silicon steel.

The original design drawings included the exact design dead and live loads for the bridge. In addition, truss member forces, along with the actual stresses, were provided. (It was very fortunate that this information was included since time to effect repairs was very limited. It would have taken more valuable time to assemble that information from the field.) An independent design check of one of the W36 stingers indicated that the original design complied with AASHTO requirements in 1954.

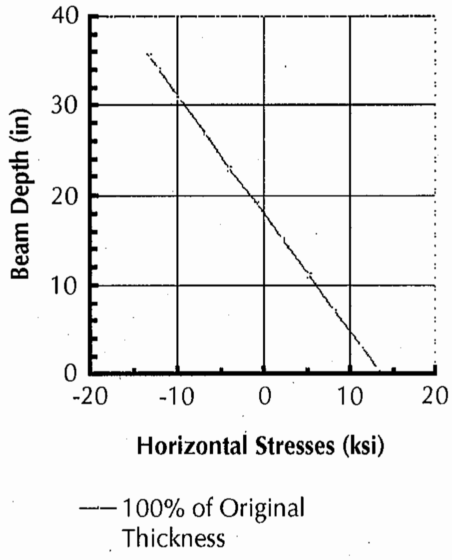

FIGURE 10. Horizontal stresses at mid-span.

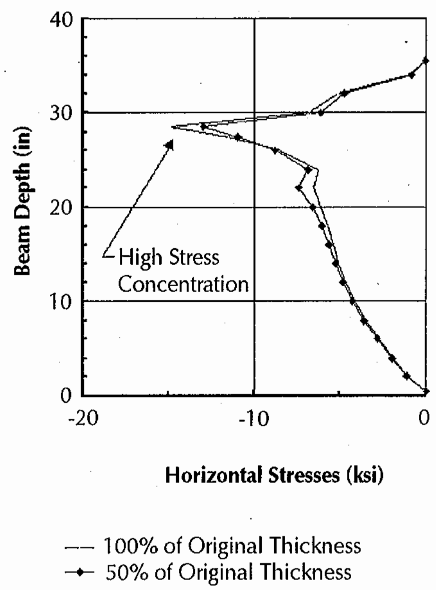

FIGURE 11. Horizontal stresses at the cope area.

Complete connection details were not provided on the original drawings. However, a review of the as-built shop drawings, combined with field observations, indicated that the connection design also followed 1954 AASHTO criteria.

Stringer End Detail — Finite Element Model. A finite element model of the W36 stringer was developed to better understand the behavior of this beam under the loading condition it had encountered over the past 40 years (see Figure 9). The computer model considered the as-built geometry of the W36 beam, particularly the end cope details as it exists on the bridge today.

Analysis results of this finite element model provided stress ranges and identified a region of high stress concentration in the web of the W36 stringer (see Figure 9). Next, a model was produced with the beam web weakened, as was the case with the corroded end conditions. Shown in Figure 10 are the stress ranges in the beam at the mid-span and the end condition where the W36 bean has a top flange cope.

Based on the results shown, it is clear that the beam was designed properly for maximum loading at mid-span and maximum shear at end condition. However, when the coped section is examined more closely, high horizontal stress concentrations near the corner of the cope can be observed. This high stress concentration coupled with corrosion and loss of section in the web were the two main factors in the buckling of the web (demonstrated by the stress range shown in Figure 11).

Truss Analysis. The truss was modeled and analyzed using STAAD computer software. The gravity loads (dead and live) from lower deck level and upper deck beams were imposed on the truss at the appropriate locations. Additionally, the new loads from the W14 columns were placed at the exact locations on the respective diagonals (see Figure 12). Large end plates, near the support point of the trusses, provided additional stiffeners for the diagonal members. This effect was also modeled in this analysis. The member stresses derived from the results were studied in order to validate the initial assumption that the repair concept minimally affected the capacity of the truss members.

New Girder & Column Design. The new girder and the two W14 columns were originally chosen based on steel availability and then checked for design criteria against AASHTO

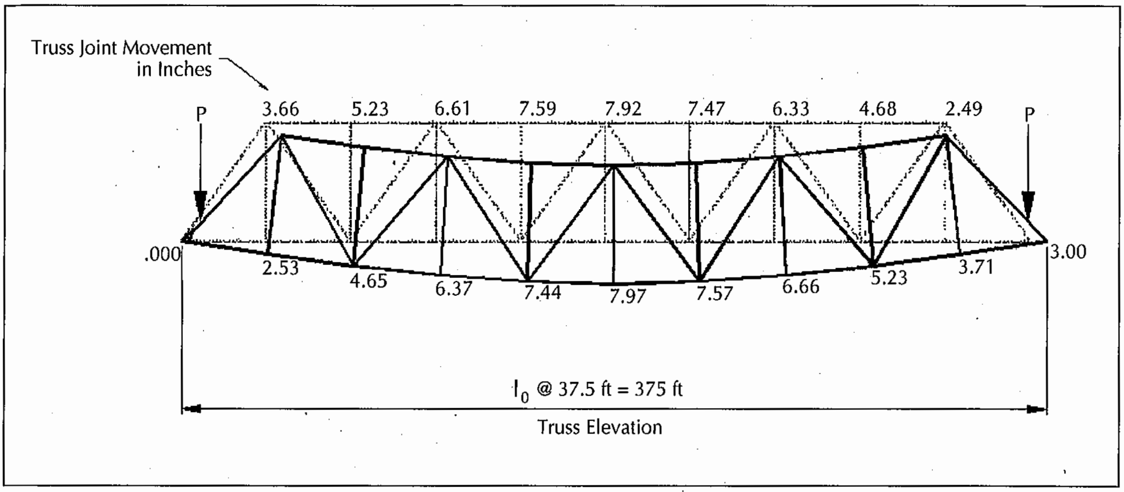

FIGURE 12. Truss deflected shape resulting from the dead and live loads.

requirements. The W36X393 transverse girder was analyzed for three lanes of AASHTO loading along with the as-built dead load of the structure (which was estimated in the field). The analysis indicated that the member was stressed to about 60 percent of its maximum bending capacity and to approximately 20 percent of its shear capacity. The steel column was also reviewed for the same criteria and was found to have 50 percent reserve capacity. The main concern with the column design was to provide a proper bearing assembly at the interface with the top plate of the existing truss diagonals. The intent was to avoid overstressing the existing diagonal top plate in local bending.

An additional concern was to design the new column for the jacking stage so that the new W36 transverse girder could come to full contact with the existing W36 stringers supporting the upper roadway. Doing so would ensure that additional downward movement of the upper deck does not occur and that the new girder dead load deflection is taken out via the jacking operation. This task was accomplished by the addition of the two jacking brackets as shown on Figure 5 and 7. Jacking loads were estimated taking into account the existing stringer reaction and the anticipated dead load deflection of the new girder at each contact area.

Web buckling criteria for the existing stringer were considered at the existing stringer support end connection. As a result of this review, along with the assessment of the existing web condition, new web doubler plates were installed and secured with plug weld at mid-depth, along with continuous welds at the fillets between the web and the flange.

Conclusion

Whenever a major transportation artery is closed by an emergency, the public expects that the responsible authorities will do whatever it takes to re-establish the levels of service to which it has become accustomed. As a result, the actions of a governing body, through its transportation agencies, come under intense scrutiny by the media to see if they are indeed living up to those expectations.

When viewed in this light, MHD's repair of the I-93 bridge over the 1999 Memorial Day weekend is an obvious success story. However, several ingredients helped ensure the outcome of that weekend. First, it was fortunate that this event occurred over a long holiday weekend that minimized the impact of this event on traffic flow. Second, with the CA/T Project already underway, Boston had a number of engineering and construction firms and material suppliers available that had the resources to devote to such an endeavor on short notice.

However, the key ingredient was the partnering spirit between MHD, contractors and engineering consultants and their willingness to work together and "think outside the box" in order to come up with an engineering solution that would be constructible in a limited period of time. The best example of this partnership effort were the two CA/T Project contractors, typically fierce competitors at the bid table, which worked side by side in a cooperative spirit to achieve a common goal. Without this partnering spirit, all of the individual strengths, experience and equipment that were deployed could not have succeeded in reopening I-93 in less than three days.

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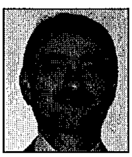

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ACKNOWLEDGMENTS — *The many individuals and organizations involved in the 1999 Memorial Day weekend I-93 bridge repair were: NEL Corp., MHD District 4's emergency repair contractor; Alex Bardow served as MHD's Bridge Engineer; Daniel Corvo supervised the engineers from MHD's Bridge Section's In-House Design Unit; Tuckerman Welding of East Boston performed the structural steel fabrication of all of the major components, such as the transverse girder and column assemblies; Joseph Allegro was the CA/T Project's Director of Construction; Perini Corp. (supplying labor and the construction foreman) and Modern Continental Construction Company (MCC) were the two CA/T Project contractors who were contacted to provide the needed resources (MCC also provided the services of their consulting engineer, Weidlinger Associates of Cambridge, for the necessary construction engineering); Rory Neubauer, Senior Vice President from MCC, coordinated the material and equipment needs; Abdol Hagh, a principal from Weidlinger Associates, took measurements in preparation for the design; MHD engineers Daniel Corvo and Savas Kiriakidis went to MCC's CA/T Project field office to work with Abdol Hagh and Mehrdad Mirzakashani, also of Weidlinger, on the design; Elie Homsi, Project Manager for Perini, assisted in advising on the constructability aspects of the design; and Joe McIlhenney and Frank Knee of Perini directed the workforce in the erection of the temporary shoring and the installation of the structural steel. The W36 transverse girder was provided by Perini, the W14X109 columns were provided by MCC, and all plates, angles, and bolts were provided by Tuckerman Welding. Charles Maguire at Fay, Spofford, and Thorndike designed the original bridge structure in 1950.*