Emergency Repair of the I-695 Drawbridge over Curtis Creek

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EMERGENCY

Mid-day on June 29, 2009 the northwest leaf of the parallel double leaf bascule bridges on I-695 in Baltimore, MD malfunctioned resulting in the leaf stopping during closing operations at an angle of approximately 15 degrees from the seated position.

Diagnosis

Under a pre-existing agreement with the Maryland Transportation Authority (MDTA), Hardesty & Hanover, LLP (H&H) had an engineering team on site to observe each scheduled operation of the bascule bridges to assist the operators in diagnosing and addressing any concerns that may develop. Consequently, an H&H engineer was on-site, and coincidentally on the northwest leaf, at the time the malfunction occurred. It was immediately evident that a failure had occurred within the primary reduction gearing. Due to limited access to the interior of the differential gear box, it was not possible to assess the specific component(s) beyond identifying that the differential mechanism itself was not functioning properly as evidenced by the input shaft and both first and second intermediate shafts rotating, while the output shafts remained stationary.

Response

The MDTA Bridge Engineering department was notified within minutes of the failure occurring and provided with an immediate recommendation to close the interstate highway thereby diverting traffic away from the drawbridge while a contractor was mobilized to assist with closing the span by alternative means. The H&H engineering team was joined by personnel from a local movable bridge contractor, Covington Machine & Welding (CM&W), within one hour of the failure occurring. CM&W mobilized portable rigging equipment and a 35ton crane. The crane was positioned on the northeast leaf and a block was rigged to a deck stringer at the end of the northeast leaf and a cable run around the block and up to the northwest leaf where it was connected to a strap secured to a deck stringer. The crane was then connected to the free end of the cable and hoisted in an attempt to pull the northwest leaf downward. Despite maximizing the crane’s capability the northwest leaf failed to move. CM&W personnel then rigged straps around the spokes of the large gears within the secondary reduction gear sets and connected them to chain-falls which were in tern secured to the front pier wall to provide additional lowering torque. Once the chain-falls were rigged and tensioned, the crane was again loaded. Once both chain-falls and the crane were loaded to capacity, the span was moved very slightly. After a lengthy series of incremental movements, the span was brought to within a few degrees of the seated position, but could not be fully closed. A full size loaded work truck was then driven out onto the end of the partially raised northwest leaf to provide additional closing torque. The combination of the crane, the chain-falls, and the weight of the truck were finally successful in seating the leaf at approximately 7PM on the evening of the 29th. Traffic was then restored after a total duration of highway closure of approximately 8 hours.

DIFFERENTIALS

Through emergency procurement, MDTA secured the services of H&H and CM&W to perform an investigation and repair to the failed gear box on the northwest leaf. MDTA also informed the USCG of the failure and a Notice to Mariners was issued advising that the navigation channel would be closed during bridge repairs. It is significant to note that the navigation clearance of this bridge is nearly 60FT, and therefore only requires approximately 100 openings per year. However, it is also important to note that the USCG and US Army have facilities located immediately upstream of the bridge and therefore any disruption to the navigation channel significantly impacts operations for both of these federal installations. Therefore, immediate restoration of operability to the failed bascule bridge was essential.

Investigation

The morning of 30 June 2009, H&H and CM&W mobilized teams at the northwest leaf to begin an in-depth investigation of the differential gear box.

The gear box cover was removed and floating shafts were uncoupled from the output shafts to allow for the differential assembly to be removed and disassembled. It was discovered that the interference fit and key securing the bevel gear to the output shaft had failed resulting in the bevel gear spinning on the output shaft.

Recommendation

Having identified where the failure occurred, the team then presented options for the owner to move forward. Recognizing the urgency of restoring operability to the leaf, and considering the lead times required for fabricating new bevel gears and output shafts to replace the damaged parts, a short term temporary solution was required. The temporary repair would be implemented concurrently with an order being placed to Steward Machine to begin fabrication of the necessary replacement parts. A collaboration of H&H and Steward Engineers determined that the new parts would be slightly modified from the existing to achieve greater capacity from the connection of the bevel gear to the output shaft for improved future service life.

Interim Repair

CM&W was able to recondition the bore of the existing bevel gear, refinish the journal of the existing output shaft, recondition the differential bushing, re-machine the keyway and fabricate a new key, and reassemble the box by the 10th of July.

The control system was then modified to allow a maximum of 25% of normal operating speed and a 10mph wind restriction was proposed to and accepted by the USCG as a temporary limitation pending permanent repairs. The leaf was successfully tested and put back into service for passage of a USCG vessel on the 17th of July.

Permanent Repair

MDTA was then able to coordinate with the USCG to utilize a six week navigation closure that had been previously arranged for work on the adjacent bascule spans on Pennington Avenue in the City of Baltimore.

The six week period was to be used to complete fabrication and replacement of the temporarily repaired parts in the differential on the northwest leaf while simultaneously investigating the differentials on the other three leafs.

The parts identified to be replaced included both bevel gears, bevel gear keys, output shafts, differential bronze bushing and all reducer shaft bearings. The new bevel gears were identified to have two areas of improvement to increase the torque capacity required for operations. The first modification was to increase the interference fit between the bevel gear hub and shaft. The second modification was to extend the bevel gear hub to provide a larger bearing area for the new key.

Based upon the results found within the other three differentials it was determined to order replacement parts for them as well. Unfortunately, lead time for the manufacture and installation of all four sets of replacement parts could not be completed within the six week navigation closure window, so it was necessary to prioritize which boxes would be repaired with the two sets of parts that would be completed.

Based on the successful performance of the temporary repairs within the northwest leaf, it was determined to install the new parts in the differentials on the northeast and southwest leafs, and to perform a temporary repair on the southeast leaf. This work was completed within the scheduled six week closure and reduced speed operation of all leafs was restored.

A second navigation closure of one week duration was then scheduled for 17th of September to complete the permanent repair on the southeast leaf differential.

A third navigation closure of one week duration was then scheduled for the 5th of October to complete the final differential repair on the northwest leaf.

TRUNNION SHAFTS

Prior inspections, including span balance measurements, had indicated poor lubrication and an advanced state of corrosion to the bridge mechanical systems. Recognizing the contributing effect of the elevated friction on the operating load experienced by the differential, an effort was undertaken concurrent with the gear box rehabilitation, to investigate and remedy the poor condition of the open gearing and more significantly, the trunnion shafts and bearings.

Investigation

During the six week navigation closure that began in late July 2009, the trunnion bearing caps were removed to allow observation of the top half of the trunnion shafts. Extensive corrosion with pitting approaching ¼” in depth and circumferential scoring of the trunnion shafts was observed at all eight locations. Minimal lubrication was evident and it was found that clogged grease grooves were preventing the introduction of new lubricant.

Recommendation

At a minimum, a means of lubricating the trunnion shafts needed to be re-established. In addition, based on the calculated stress levels in the trunnion assemblies and the measured friction values, a recommendation was made to recondition the surface of the shafts to remove all pitting and scoring. Due to the depth of the pitting, it was anticipated that the existing grease grooves would be concurrently removed during the reconditioning effort. Also, as a result of eliminating of existing grease grooves and the substantial reduction in outside diameter of the trunnion shafts, new trunnion bearing bushings were required. MDTA determined to immediately proceed toward the full rehabilitation of all eight trunnion assemblies.

Interim Repair

With the bearing caps removed, the exposed portions of each trunnion shaft and bushing were cleaned with hand tools, emery cloth, and solvent. Each leaf was then operated to expose the two forward grease grooves for manual cleaning. Lubricant was then applied over the entire surface of the shafts and the bearing caps were reinstalled. This work was all completed before the end of the six week navigation closure in August 2009.

Permanent Repairs
To accomplish the proposed work in a minimal amount of time, MDTA created a Design/Build type arrangement between H&H and Covington. This allowed for identification of long lead items which could be prioritized for design and purchase orders issued. The critical items identified as controlling the schedule included the bronze bushings for the trunnion bearings and the structural system for jacking the leaf to remove the existing trunnion bearings.

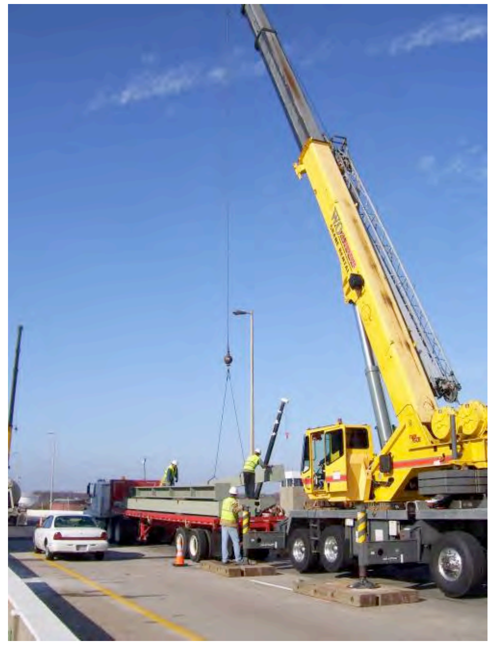
Jacking System Design

Concept development

Of primary importance to both the MDTA and the USCG was to minimize any disruption to the highway and waterway users. Through close coordination with both agencies and the contractor, two closure periods of four week duration each were agreed to for performing the work. Dates were established for the first closures to occur in January/February 2010 and the second to occur in March 2010. Working backward from these dates established a five month timeline to complete design, fabrication, and mobilization. Due to the extensive coordination required by MDTA to arrange for the detours that would be required, and for the USCG to arrange shipping schedules, these dates were considered absolute.

One technique that was adopted to help minimize fabrication time and to control costs was to design the jacking frames so they would be re-usable between the two bridges. This was accomplished through extensive field measurement to verify the pieces could be made interchangeable and through detailing of connections to allow for varying field conditions.

Considerable effort was invested in developing the specific mechanism for raising the bridge off of the trunnion bearings. Experiences with similar projects had typically utilized the jacking frame to support hydraulic jacks for pushing the bridge into the air. The dimensions of the jacks that would be required to accomplish lifting the 2.6M LB of each leaf would not have been easily accommodated within the framework of a small interchangeable jacking frame assembly such as was required for this application. Therefore, a method to lift the bridge up, rather than pushing the bridge up, was determined to be more easily constructed and less costly to fabricate and erect.With the selection of CM&W to perform the machinery work, an added benefit was their ability to fabricate structural steel for the jacking system. This allowed for collaboration with the fabricator during design and detailing of the structural steel to ensure materials, welds, piece dimensions and weights were well within the capabilities of the shop and would require minimum lead times for fabrication. One example of this was that the original design concept required the use of 70ksi structural steel to achieve weight savings and to better accommodate the physical space constraints. CM&W contacted regional suppliers and determined that the required quantity of material was not readily available and several additional weeks for procurement would be needed. This would have jeopardized the work schedule, therefore, the final design of the jacking system utilized the more readily available 50 ksi steel.

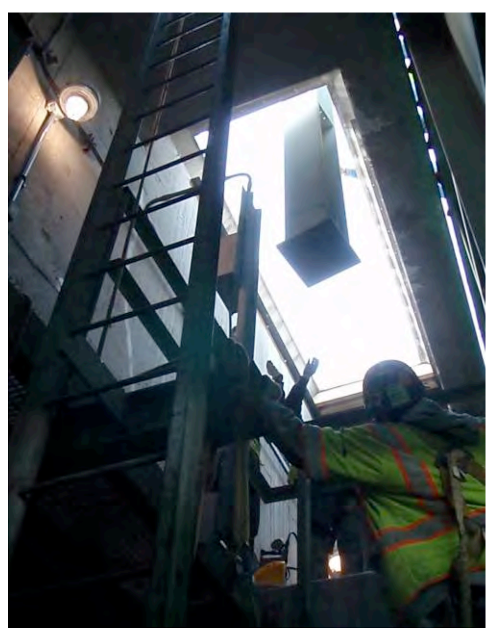


The size and weight of the crane that would be required to install and remove the jacking frame, trunnion bearings, and machine lathes was also a critical aspect of the design. The crane would not be permitted on the movable span, and would therefore require a long radius lift for all picks. The crane was required to be mobilized and demobilized during daytime single lane closures leading up the full shutdown period. This meant that the width of the crane with outriggers extended was limited to approximately 15 ft. The existing bridge deck and supporting members were all checked to ensure safe lifting operations. It was determined that a maximum pick weight of about 12 kips would be allowed for each component.

Analysis and Detailing

Allowing highway users to continue using the bridge while in the jacked position was considered for the design of the jacking frame. From a design standpoint, using 70 ksi or even 100ksi steel for the jacking frame members would have been required. However, this option was eventually ruled out for several reasons: a) Milling work would be affected due to vibration of the bridge from live load. Chattering and bouncing of the lathe would compromise the final surface of the bearing. b) The entire bridge would need to be closed down for final jacking frame installation and jacking of the bridge anyway. The added complexity and cost of MOT operations and possible confusion to motorists were considered to be sufficient to conclude that the bridge would remain closed to traffic while jacked.

An accurate weight of the span was crucial for the jacking frame design. An overly conservative estimate of dead load would lead to jacking frame members to large to install and handle or require a very high grade steel, which was found to be unavailable on our schedule. Detailed design and shop drawings were used to prepare dead load calculations. These calculations were compared to the stress sheets provided in the plans to determine the final estimated dead load of the span. Each span was estimated to be approximately 2,600 kips.



The jacking frame was designed to be installed in two stages. Stage one included all components that could be installed prior to the navigation closure, such as replacing the original trunnion anchor bolts, and installing the columns to support the proposed jacking frame. This stage also included pre-drilling and installing all anchors into the pier that were required for the jacking frame. Templates were used extensively to accurately locate the anchor bolt locations. Stage two included all components that would require the span remain closed to navigation once installed.

The jacking frame utilized specialized hanger rods in lieu of traditional jacks. Superbolt, located in Pittsburg PA, was contacted about their proprietary bolt tensioning devices. They were able to supply the hanger rods, and multi-jack bolt tension nuts. These components when used together allowed for simple hand tools or small impact guns to jack the bridge. Four hanger rods at each trunnion bearing were utilized. Only two rods were required for lifting the bridge, the remaining two were used as spares for redundancy. The rods were each 3.5" in diameter, and constructed of 125ksi yield steel. They each had a working design capacity of about 700 kips, but were capable of supporting loads of up to 900kips each safely. Twelve weeks of lead time was required for this material and as a result was not completed until the week prior to the detour being put in place for the January 2010 closure period.

The entire concept of lifting the bridge from above rested on the feasibility of design and manufacturing a trunnion saddle. This component of the system needed to be compact enough to fit under the trunnion shaft and between the trunnion bearing and the bascule girder web, but large enough to accommodate the hanger rods and support nuts. The shape of the saddle was also critical since it had to fit tightly and uniformly around the bottom half of the trunnion shaft. The trunnion shafts were thoroughly cleaned and their diameters measured. All eight trunnion shafts were found to have similar enough diameters that custom saddle designs were not necessary. One saddle radius was specified that could be used at any trunnion shaft. The saddles were analyzed using a simplified hand calculation and verified with a detailed 3D finite element computer model. While the hand calculation was valid for basic stress design, the computer model was used to investigate problems that may arise due to poor fit between the saddle and the shaft. It was determined that a smaller saddle radius was more beneficial then a larger one. This finding was used to develop a single saddle design that could be used at each trunnion. This refined analysis and detailing allowed for only four saddles to be fabricated instead of 8, saving fabrication cost and lead time. The saddles were manufactured by Camforge of West Virginia as forgings from ASTM A668 Class M material, with a 125ksi yield strength. Numerous tests were required to verify the material and final forging including MT, UT, tensile strength, and macro-etch test. The final dimensions of the saddle were achieved by milling the inside diameter and boring the holes for the hanger rods.

Lateral Supports were required to brace the structure against wind while suspended from the jacking frame. Four brace points were chosen for each leaf utilizing the forward live load bearings and the tail of the bascule girders. The live load bearing shoes were modified to essentially lock them down after the bridge was lifted. Horizontal channels were installed at the rear of the leaf between the bascule girder and the pier walls. These two brace points provided an effect couple to resist wind forces. Consideration for temperature expansion was also a factor in locating and detailing the bracing.

Various types and sizes of anchor bolts were required for this project. They included standard expansion type anchors as well as high strength epoxy anchoring systems. Sizes ranges from 5/8" diameters for secondary members such as bracing, to 1.5" diameters for main load carrying members. A representative from Hilti was included at all phases of design and construction to ensure that the proper anchors were being utilized, and properly installed. The large diameter epoxy anchors used for the cantilever girder were the most critical anchors and were specified based on the contractor's preference, installation temperature (25 to 40 degrees F) and operational temperature (0 to 25 degrees F).

Mechanical Component Design

Trunnion Shaft

The trunnion shaft rehabilitation design focused on the bearing area required to meet the allowable AASHTO dynamic bearing stress. The total amount of material removal from the shaft was determined by the depth of the pits measured on the shaft as well as review of the original as-built drawings of the trunnion shaft grease grooves. The final shaft diameter was chosen to be 27.5" which would have removed ½" of material from the diameter. The bearing stress was calculated using this new diameter and was found to be within AASHTO allowable limits.

An additional check was performed for the fatigue limit of the trunnion shafts to determine what size transition radius would be required in the shoulder adjacent to the bearing to achieve an infinite fatigue life. It was determined to increase the transition radius to ⅜", from the original ¼", to reduce the stress concentration factor.

Steward Machine was brought in to assist with planning and ultimately performing the on site machining work to turn down the trunnion shafts. Access requirements for this work were dictated by the machine dimensions provided by Steward. These access requirements then dictated limitations on the configuration of the structural system that could be utilized for jacking and holding the leaf during the machining operations.

The in-place machining operation required initial set up of the machine which took about half a day, approximately three to four days to rough cut the shaft, approximately one day to polish the shaft, and approximately half a day to machine the transition radius. Two trunnion shafts were machined at a time with continuous shifts working 24 hours a day. Each shaft averaged between 5 and 6 days to complete all machining efforts.

Trunnion Bushings

The new trunnion bushing material was specified to match the existing as-built drawings (ASTM B22 Alloy 911) with a hardness not to exceed 140 BHN.

Sand casting and centrifugal casting options were discussed prior to ordering the new bronze bushings. The Contractor chose the sand casting option and proceeded with ordering the first set of bushings. The bushing manufacturer experienced significant challenges in their efforts to eliminate porosity during the sand casting process so the second set of bushings were produced utilizing the centrifugal casting technique to achieve better quality and to maintain the project schedule. Hardness values for the sand castings were 130 BHN and for the centrifugal castings were 160 BHN. The shaft hardness was measured to be approximately at 200 BHN so the difference between the shaft and bushing was considered adequate to permit casting with either technique.

One detail changed from the original trunnion bearings was the lubrication ports and grease grooves located in the trunnion shafts. Machining the trunnion shafts removed the pitting and original grease grooves from the shaft. The rehabilitated trunnion bearings were designed to have lubrication ports located on the bearing housing and the grease grooves in the bronze bushings. The design change occurred due to the difficulty in re-machining grooves into the shaft in the field as well as the preference for eliminating stress risers on the fracture critical shafts.

Another detail changed from the original was the bearing housing cap to bushing connection. The bushing was originally secured to the housing cap through two keys 90 degrees apart. The rehabilitation design eliminated the two keys and replaced them with countersunk cap screws. The old keyways in the cap were filled with a metal epoxy filler to eliminate any voids.

The final bushing bores were rough machined pending final measurements of the shaft diameters after the field machining was completed. Once the shafts were complete, the shafts were measured in nine locations along the length and around the circumference of the journal and sent to the machine shop to start the final bore machining. An ANSI RC6 fit was specified for the new trunnion bearings.

Trunnion Shaft Alignment

Prior to the construction work to rehabilitate the trunnions, the initial trunnion alignment was measured. Accurate trunnion alignment measurements were important to allow the contractor to place the span back in its original position following the jacking operation.

A piano wire was set up using brackets mounted to the wall with a pulley and weight on one end and a fixed pin on the other. The brackets were left in place throughout the rehabilitation effort to verify the alignment at the end of construction.

The piano wire was aligned with the outboard shaft bore to within 0.005" of the center of the bore. Measurements were recorded at both inboard and outboard bore locations before and after jacking the span using an inside micrometer. Once the new bearings were in place and the span lowered, the piano wire was checked for the proper location of the span. As required, shimming was then performed to adjust the alignment. This shimming effort was accomplished through iterations of jacking and re-measuring to achieve the correct trunnion shaft and bearing alignment.

Thrust Collar & Thrust Plate

Due to the original trunnion thrust plates having extensive corrosion, a new split collar was designed. The new design was split for future removal for inspection of the trunnion shaft fillet. Additionally, grease grooves were supplied to provide grease to the thrust surfaces of the collars to prevent possible binding with the bearing.

The thrust plates located on the front face of the trunnion shaft were modified to have grease ports and fittings at the thrust surfaces to provide grease to prevent possible binding of the thrust plates as well.

CONCLUSION

All scheduled work was successfully completed within budget during the navigation and roadway closure periods that occurred in January thru March 2010.