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Mechanical Rehabilitation of the Houghton-Hancock Vertical Lift Bridge

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Bridge Information

The Houghton-Hancock Bridge (also known as the Portage Lake Lift Bridge) is a 250 foot long double deck vertical lift bridge originally opened in 1959. The double deck bridge can have vehicular traffic on the upper or lower deck depending on whether the lift span is seated on the pier seats or intermediate seats. The movable span weighs approximately 4,600 kips. The bridge is at the same location as other movable bridges dating back to 1875. The bridge crosses over Portage Lake and connects Houghton, Michigan and Hancock, Michigan. This bridge is the only connection and a critical link between Copper Island and the lower portion of the Michigan Upper Peninsula main land. It is owned by the Michigan Department of Transportation (MDOT).

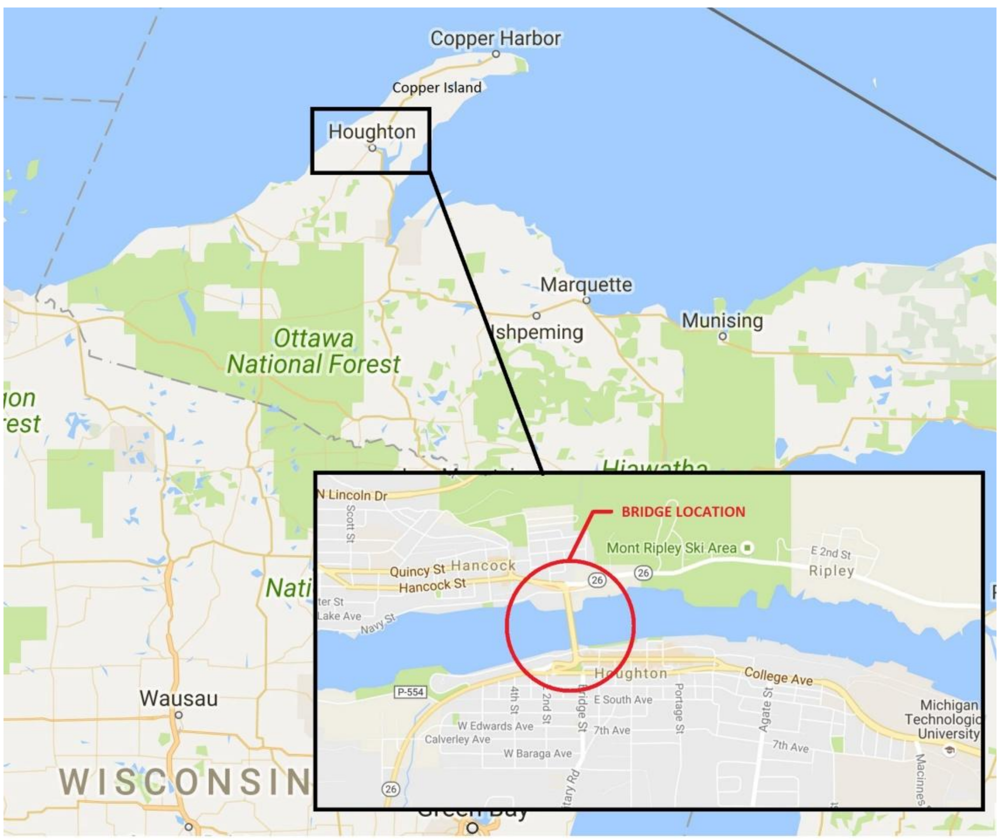

Figure 1: General Bridge Location Map

Bridge Rehabilitation Project Details

General

The scope of work included Structural, Mechanical and Electrical Rehabilitation. This paper will focus on the Mechanical aspects of the rehabilitation contract. The bi-level deck of the lift span remains on its lower seats during winter to accommodate snowmobile traffic on the lower deck and vehicular/pedestrian traffic on the upper deck. During the rest of the year, the lift span operates primarily from its intermediate seats to allow added clearance for navigation. Vehicular and pedestrian traffic utilize the lower deck of the lift span during the navigation season. This lift bridge is believed to be the world’s heaviest and widest double-decked vertical lift bridge.

Design Phase

The scope of the mechanical rehabilitation included counterweight wire rope replacement, solution for shaft indexing between final pinions, repair of bridge operating machinery damaged by bridge seating issues and other ancillary bridge machinery system rehabilitation. Careful consideration of construction sequencing, extreme winter weather and material procurement times had to be taken into account during design to ensure vehicular and marine impacts were minimized. The average low temperature during the winter shut down work period is 9 degrees Fahrenheit during January/February and 17 degrees during March with highs typically only reaching just above freezing starting in March. Material procurement times for several long lead items including the wire ropes required an advanced procurement contract to be included as part of the mechanical design in order to meet the desired construction window for the project.

Construction Phase

The construction phase for this project began with an advanced material procurement contract in July of 2014 for all long lead mechanical items. The onsite construction work began in January of 2015 with an aggressive schedule that included several mechanical tests that had to be completed prior to removal of the existing wire ropes. The replacement of the existing wire ropes had to be completed during the annual winter marine closure with the bridge on the lower pier seats to eliminate the impact to the waterway traffic. The lower deck of the bridge also had to remain open to snowmobile traffic for winter, leaving the upper deck for vehicular traffic. Throughout construction, impact to the general public had to be minimized in order to keep this critical link open to traffic at all times.

Machinery Indexing

Design Considerations

At the start of the project MDOT indicated that the bridge has historically had several issues including transverse and longitudinal skew during operation and poor seating characteristics that resulted in live load pumping under traffic. During the initial site visit, strain gage balance testing was conducted and revealed poor load sharing between corners in each tower. Backlash measurements that were taken during the initial inspection revealed considerable differences in total cumulative backlash through each gear reduction between the east and west corner in each tower. As a result of this cumulative backlash difference between corners, adjustment of the indexing between the east and west shafts would only allow the machinery to share load evenly during raising or lowering. For example, if the pinions were rotated to contact their raising face in the bridge fully seated position this adjustment of the indexing with the existing machinery would only allow for equal load sharing in one direction (raising) and the pinion with less backlash would be ahead of the opposite pinion in the other direction (closing).

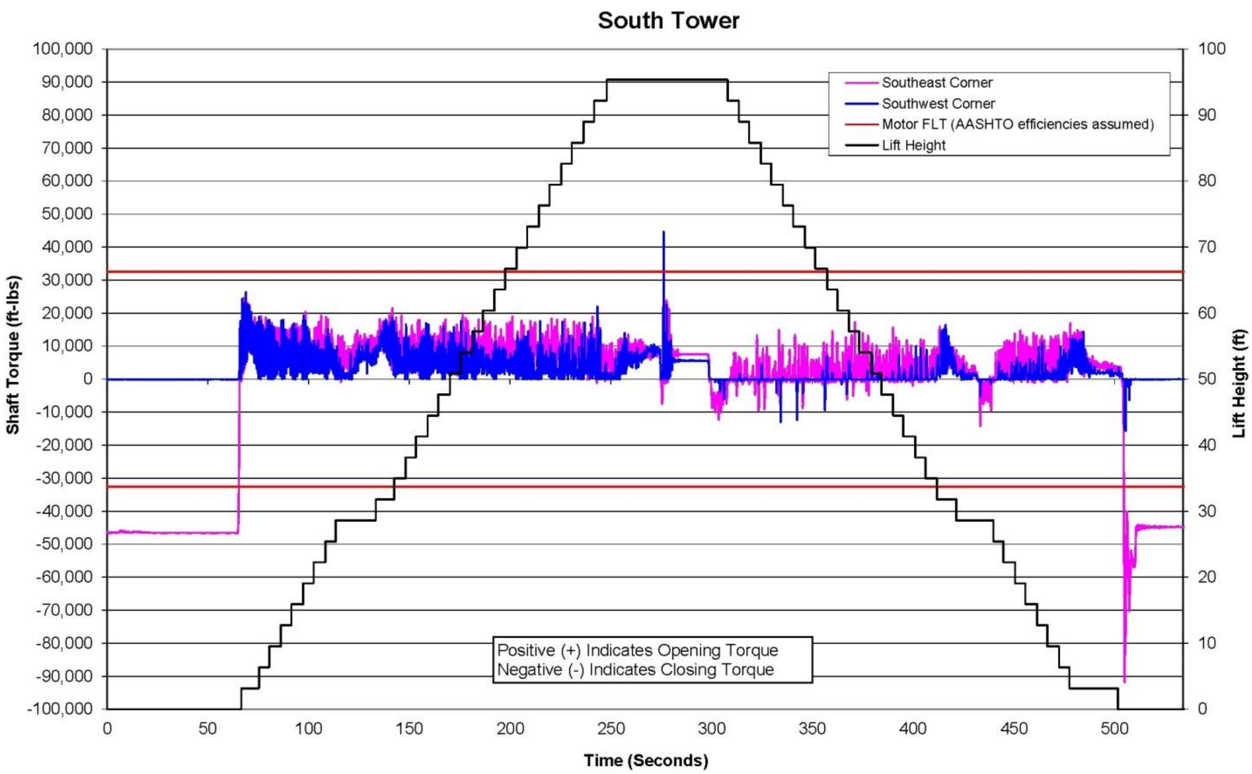

Figure 2: Initial Strain Gage Shaft Torque for South Tower (Source: Stafford Bandlow Engineering)

In addition, the existing machinery design did not include means to adjust corner to corner indexing of the drive machinery in the event of rope slip at the sheaves. The gear couplings at the primary reducer output shaft only provided adjustment in 5.25° increments. This adjustment is equivalent to a change in backlash at the final pinions of 0.054". This change in backlash at the final pinions is not sufficient to provide precise indexing adjustment for load sharing. Implementation of a primary differential type reducer and replacement of the subsequent open gearing was considered during the preliminary design, but the configuration of the existing motor and machinery brakes, along with the costs associated ruled out this option. The solution to allow indexing between corners utilizes a new indexing coupling on one primary reducer output shaft (per tower). This new indexing coupling was a custom double engagement gear coupling with a shrink disc on one side to allow for infinite adjustability of the corner to corner indexing of the machinery. A new shaft was also included in the design to use with the new shaft indexing coupling. The new indexing coupling was included as part of the advanced material procurement contract with pilot-bores in each coupling half. The general contractor for the main construction contract was responsible for measurement of the exiting components to provide final bore dimensions to the coupling manufacturer for final machining of the couplings.

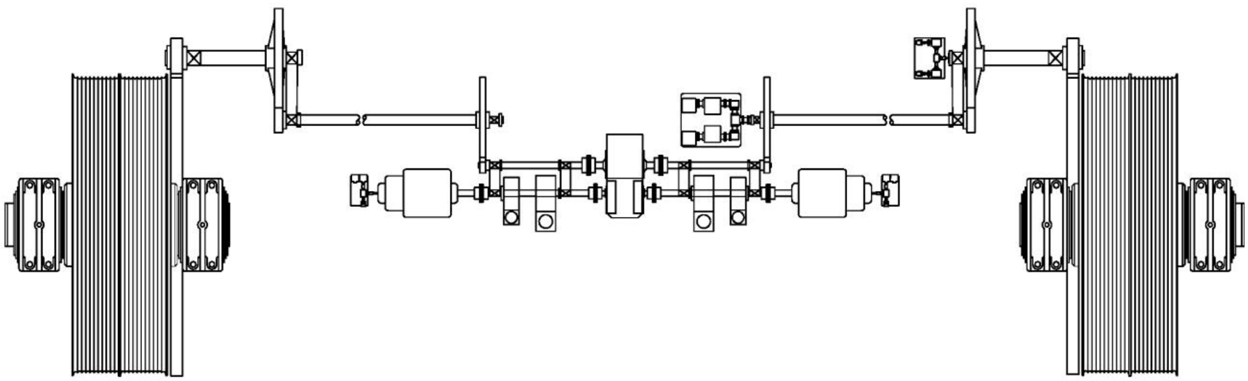

Figure 3: General Machinery Layout

To achieve good load sharing with the existing machinery configuration two possible options were explored. The first option was to alter the engagement (center distance) of the final pinion with the rack in order to increase or decrease the backlash at the final tooth mesh. Any movement of the final pinion would also affect the previous gear sets because the existing gearing is mounted in union style plain journal bearing housings. Adjustment to the engagement of the final pinions was ruled out because it would have required adjustment to all previous gear sets as well. The second option that was considered, and used for this project, was to machine new final pinions with custom tooth thicknesses to mitigate the differences in backlash between corners in each tower. Blank forgings for the new pinions were included as part of the advanced material procurement contract due to the long lead time. The general contractor for the main construction contract was responsible for all machining of the blank forgings, which included pinion bore, keyway and gear teeth.

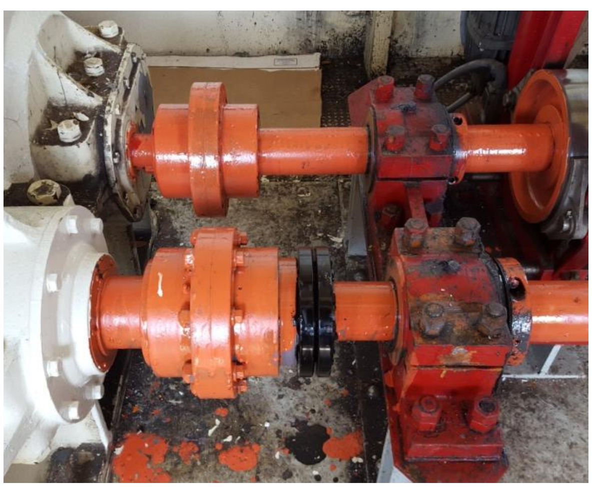

Photo 1: New Shaft Indexing Coupling Installed on Primary Reducer Output Shaft

Design Changes During Construction

Photo 2: Southwest Pinion Shaft on Lathe for TIR Measurement

The Contract for this project included taking several backlash measurements at each open gearset to determine the cumulative backlash from the primary reducer output to the final pinion in each corner of each tower. At the start of construction in January 2015 Stafford Bandlow Engineering (SBE) obtained the required measurements for Zenith Tech, Inc. (ZTI) and reported significant run-out of the southwest pinion shaft and the southwest pinion top land. The run-out measurements prompted an in-depth investigation on the southwest pinion shaft. This was not originally part of the project scope. The in-depth investigation required removal of the southwest pinion shaft from the tower top to take measurements of total shaft run-out in a machine shop. Prior to removing the southwest pinion shaft from the tower top, the remaining open gear measurements were recorded and showed measureable run-out at each final pinion. The shop measurements confirmed that the southwest pinion shaft was deformed.

The southwest pinion shaft was centered on a lathe at Calumet Machine in Hancock Michigan and measurements were taken at several locations along the pinion shaft after all paint had been removed. The total indicator reading (TIR) was recorded, and the highest documented reading for the southwest pinion shaft was 0.096” TIR. The measured TIR confirmed that the southwest pinion shaft was permanently deformed and was likely a result of an extreme event in the past. Upon confirmation that the southwest pinion shaft was deformed, the decision was made to replace all four pinion shafts during the 2015 winter bridge shutdown. The replacement of the four pinion shafts also included replacement of each final pinion, but re-used the existing gear mounted on the inboard end of each pinion shaft. The four new pinions had to be fabricated with custom tooth thicknesses to eliminate the total cumulative backlash difference between corners in each tower. While adjustment to the cumulative backlash difference between corners in each tower could have been achieved by reusing one pinion in each tower, the fabrication of four new pinions

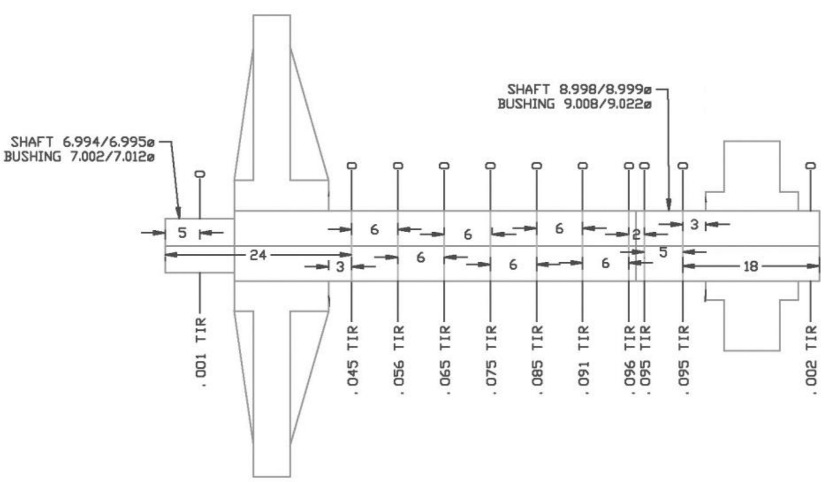

Figure 4: Southwest Pinion Shaft TIR Measurements

with custom tooth thicknesses allowed more flexibility in the final pinion tooth thickness. This flexibility in selecting new pinion tooth thickness allowed the final backlash at each pinion to be in a range close to the recommended backlash for this size of teeth.

Photo 3: Dummy Gear Measurement Jig to Measure Backlash at Final Rack

All backlash measurements that were taken at the final pinion/rack with the deformed shafts could not be used to determine the necessary tooth thickness modification for each new pinion. New measurements were taken by Modjeski and Masters (M&M) with a custom measurement jig, which was fabricated by Calumet Machine. The fabricated measurement jig included a two inch thick dummy gear with 3 precisely machined gear teeth of known chordal tooth thickness. This dummy gear was mounted on a shaft with round bearing inserts to rest in the existing pinion shaft bearing bases. Backlash measurements were directly measured along the tooth face using a dial indicator on the involute tooth profile of the dummy gear. Three measurements were taken along each tooth face with the dummy gear to directly measure for any tapered wear on the rack teeth. These measurements were repeated at several locations around the diameter of the rack for each sheave location. The new pinion/rack backlash measurements were used along with the original backlash measurements taken on the preceding gearsets by SBE to determine the required pinion tooth thickness at each location to compensate for the existing cumulative backlash differential.

Span Balance

At the start of the construction contract the lift span was approximately 11,500 pounds span heavy per tower with a significant transverse imbalance biased towards the east side of the lift span. The bridge has had a history of trouble seating on both the pier seats and intermediate seats. This construction contract included work to address the balance condition of the lift span, machinery indexing, live load shimming and poor seating characteristics of the bridge. The contract required the final balance condition of the bridge to be between 4,000 and 6,000 pounds span heavy per tower. Additionally the machinery indexing adjustments required a final maximum torque split of 60 percent to 40 percent at the final balance condition.

The initial live load shimming was completed to achieve good roadway alignment for on-coming and off-going traffic in both directions at both the pier seat and intermediate seat. The machinery indexing and balance adjustments were performed at the same time and were an iterative process. A small adjustment to the machinery indexing in one tower would affect the measured transverse imbalance of the lift span in that tower. Once good load sharing was achieved through indexing adjustments in each tower, small adjustments to the transverse imbalance in the counterweights were made to achieve as close to equal corner to corner imbalance as possible. The final changes to the transverse imbalance also resulted in better load sharing of the machinery. The final imbalance condition of the bridge at the completion of construction was 5,466 pounds span heavy in the north tower and 5,345 pounds span heavy in the south tower. The final transverse imbalance is presented in the table below.

Final Bridge Balance Condition (Fully Seated at Lower Seats)				
	East Corner	**West Corner**	**Split**	**Total Imbalance**
North Tower	2,317 lbs	3,149 lbs	42%/58%	5,466 lbs
South Tower	2,357 lbs	2,989 lbs	44%/56%	5,345 lbs

Final live load shim adjustments at the pier seats and intermediate seats were completed after final machinery indexing and transverse balance adjustments were complete. The final adjustments to the pier seat live load supports had no effect on the load sharing during operation and only influenced the machinery loads at seating. After shimming was completed on the pier seat live load bearings, the same process was repeated at the intermediate seat live load bearings.

While shimming the southwest intermediate live load bearing there was an issue achieving proper roadway alignment. Even with all of the shims removed, the span was too high relative to the approach roadway elevation. In an effort to find out if this condition predated the construction contract, M&M discussed the issue with MDOT personnel. The bridge operators were able to confirm that there have been persistent problems for years when operating the southwest span locks with the bridge on the intermediate seats. This new information led to an investigation of the southwest span locks. Adjustments to the span lock elevation are made from inside the tower leg, and after inspecting the southwest span lock it was clear that it had been adjusted up as high as possible and was still rubbing when actuated. All parties involved came to agreement on the solution to mill down the bottom of the southwest live load bearing ½ inch, which solved the issues relating to seating loads, roadway elevation, and span locks. Equalization of the seating loads through shimming of the live load supports virtually eliminated any seating problems that were evident in the past.

Photo 4: North End of Span Roadway Alignment

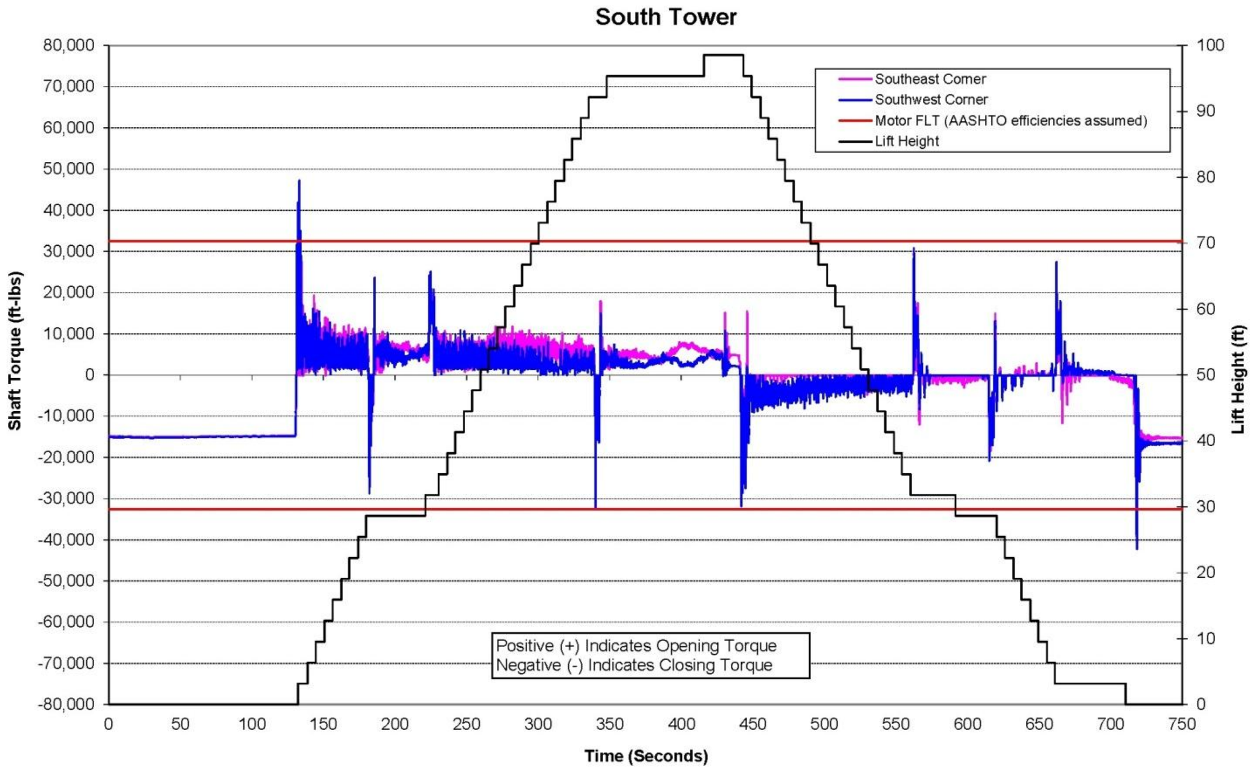

Figure 5: Final Strain Gage Shaft Torque for South Tower (Source: Stafford Bandlow Engineering)

Balance Chain Rehabilitation

Design Considerations

The balance chains had been rehabilitated in 1996. After approximately fifteen years of service, several of the balance chain links on the Houghton-Hancock Bridge became seized. The purpose of a properly functioning balance chain is to provide appropriate counterweight for the lift span in all positions of lift by compensating for counterweight rope weight transfer as the bridge is raised and lowered. With the links seized, the counterweight system loses its ability to adjust incrementally, as designed, and puts unnecessary stress on mechanical components.

Photo 5: Balance Chain Bushing from 1996 Rehabilitation

A review of the 1957 shop drawings and the 1996 rehab drawings showed that self-lubricating bushings were specified for the balance chain links. The design intent was to provide a relatively maintenance-free low friction bearing surface between the link pin and the clevis bore. The approved rehab drawings from Calumet Machine; however, called for a “Oil-Lite” bushing made of, “CA911 with double loop inside diameter groove, graphite filled.”

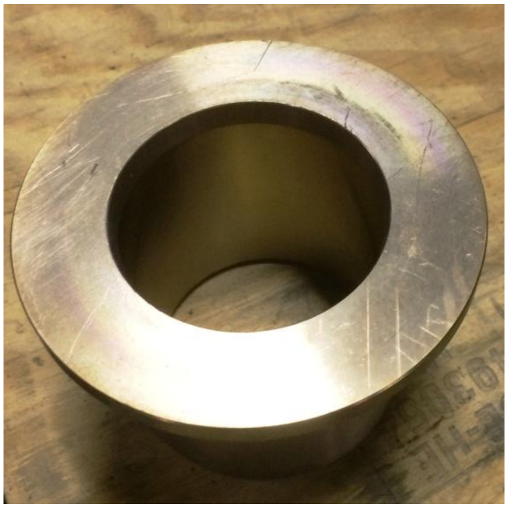

Photo 6: New Deva Metal 101 Balance Chain Bushing

The bushings manufactured for the 1996 rehab failed to meet the design intent. Although the cast bronze used has a high yield strength it has no self-lubricating properties. Bronze bushing manufacturers also do not recommend double loop style grooves for graphite filled lubrication, especially with limited shaft rotation like in this application. This style groove is much better suited for grease lubrication only. Over time the graphite had likely worn and was no longer providing the intended “self lubricating” properties to the bushing. Moisture and debris had likely also penetrated the voids in the harsh environment. In an attempt to combat debris build up and corrosion, the rehab designer included lubrication ports and passages on both sides of the link pins to provide fresh lubrication for the bushings. However, the balance chains are nearly inaccessible for hands-on inspection and maintenance. Because of this, the passages were plugged at initial installation and fresh lubricant had never been added, thus further accelerating the propagation of contamination and link seizure.

During design, M&M recommended replacing all balance chain link bushings with self lubricating bronze bushings homogenously impregnated with solid graphite lubricant (Deva Metal 101). The original Ø2.50” RC6 fit between the bushing and the pin was increased to 1/16” total clearance between the bushing and pin. The intent of this design change from the original design was threefold: first it provided a larger gap for corrosion to span, second it allowed the pin to move radially and dislodge any deposits, and third it enabled remote maintenance by means of a pressure washer to flush out any debris that may have accumulated. The press fit between the bushing outside diameter and balance chain link inside diameter was coordinated with the bushing manufacturer and an LN3 fit was selected. The existing stainless steel clevis pins are ideally suited for this application and environment, and were reused with the new balance chain bushings during the winter shutdown.

Photo 7: Balance Chain Link with Pin Removed (Note Corrosion at Interface with Mating Link)

Due to the long lead time for the 560 new balance chain bushings required, the bushings were part of the advanced material procurement contract. The inside diameter of the existing balance chain links was not known at the time of design therefore it was critical that the new bushings could be provided with oversized outside diameters to be machined after measuring the inside diameter of the balance chain links.

Construction

The removal of the balance chains required taking down each of the eight chain assemblies individually and shipping them by flat bed truck to Calumet Machine for disassembly and reassembly. During disassembly Calumet Machine discovered that the existing balance chain links did not match the details shown in the 1996 rehabilitation plans that were used to develop the current plans. A boss was present with a counterbore for the existing bushings on each link at the female end. Upon disassembly this boss showed signs of significant corrosion on each link and was likely part of the cause for the seized links. Without modifications, the new balance chain bushings could not be installed in the existing balance chain links. The Contractor was directed to re-machine each balance chain link to accept the new balance chain bushing details as shown in the contract plans. A total of 264 balance chain links were machined to accept the new balance chain bushings.


Photo 8: Balance Chain Link (Left Side: Boss not Removed, Right Side: Boss Removed

Wire Rope Replacement

Design Considerations

The Ø2-5/8” 6x19 IPS Fiber Core Wire Ropes that were installed on the bridge prior to this construction contract were original to the bridge and date back to 1959. There are a total of 84 counterweight ropes. The 159’7” long existing ropes had stretched 5-1/2” over the 56 year service life from their original rope length. The new wire ropes were included as part of the advanced material procurement contract due to the long lead time for fabrication. Special consideration for storage of the wire ropes was included in the Contract Special Provisions to provide directive to the advanced procurement contractor where and how to store the wire ropes. In general, all items that were provided as part of the advanced procurement contract were required to be stored by the advanced procurement contractor until the items were requested by the installation contractor.


Photo 9: Hydraulic Jacks Supporting Lift Span During Rope Unloading

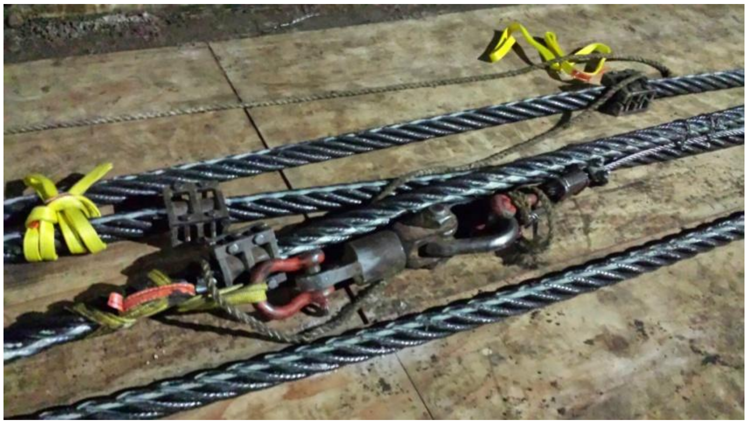

Photo 10: Tugger Connection to New Wire Ropes for Rope

The replacement of the wire ropes required careful consideration of the sequencing to minimize bridge closures and also allow the ropes to be removed and installed during short nighttime lane closures. Additionally, emergency vehicles had to be able to cross the bridge at all times throughout construction. A recommended procedure was provided in the Contract plans that required two overnight bridge shutdowns. One for unloading of the existing wire ropes, and one for reloading of the new wire ropes after making the lift span side connection. The recommended procedure also included a single lane closure for removal of the existing wire ropes one at a time after cutting the rope above the counterweight side block socket. A temporary tugger line connected to an air tugger was to be used to lower each existing counterweight rope down to the roadway level. A similar procedure was recommended for hoisting the new counterweight ropes over the sheave to make the counterweight side connection. The recommended procedure only required the bridge to be closed to vehicular and snowmobile traffic for two overnight periods and allowed the remaining rope removal and installation work to be completed with only short vehicular traffic interruptions.

Construction

Prior to removal of the existing counterweight ropes the tension in the ropes had to be unloaded. This work required the bridge to be shutdown and included provisions for an emergency ramp in the event that emergency vehicles needed to cross the bridge after the jacking. Hydraulic jacks were used to raise the lift span approximately 2’-10” to hang the counterweight from the existing counterweight hangers and completely relieve the load from the counterweight ropes. The hydraulic jacks had a total lifting capacity of 8,000 kips with a 6 inch stroke. After the load was relieved from the ropes, the rope block sockets were pulled out from under the lifting girder rope connection and restrained to prevent interference with the remaining work to lower the bridge back to the pier seats. The entire bridge jacking procedure and releasing of the lift span socket connections was completed in an overnight shutdown that began at 9:00PM and was completed at 5:30AM. The low temperature during this work was 17 degrees Fahrenheit with snow.

ZTI elected to use a procedure for wire rope removal and installation similar to the recommended procedure provided in the Contract Plans, but did not cut each counterweight rope on the counterweight side. An air tugger mounted to a truck was used to lower the existing ropes and hoist the new ropes from the top of the lift span deck. An auxiliary air tugger was mounted in the machinery room to assist with control of the rope over the sheave on the counterweight side of the sheave. Each existing counterweight rope was attached to the tugger line with a double choked nylon strap. Fabricated “cable stop clamps” were attached to each counterweight rope to prevent the nylon strap from slipping up the rope. After each rope was connected to the tugger line it was lowered to the top of the lift span deck and stretched out in the closed lane.

Installation of the new wire ropes was similar to removal of the existing ropes. The new wire ropes were uncoiled from the shipping reel and laid out on sheets of plywood along the length of the lift span prior to attaching each rope to the main tugger line. Care was taken to ensure that the surface of the plywood was free from moisture and debris. A second air tugger was added to assist with handling of the new counterweight ropes when re-rigging of the assembly was required in order to get the new counterweight rope over the sheave. Each new rope was individually hoisted over the sheave and attached to the counterweight side connection. Several new ropes were able to be installed in one night with limited interruptions to vehicular traffic using this procedure. After all of the new counterweight ropes were in place, the lift span was again jacked, but this time to reconnect the lift span side rope sockets to the lift span. The entire bridge jacking procedure and releasing of the lift span socket connections was completed in an overnight shutdown that began at 9:00PM and was completed around 6:00AM. The low temperature during this work was 10 degrees Fahrenheit.

Cold Weather Considerations and Issues

The extreme winter weather conditions in Houghton, Michigan were a concern that was considered by the design team for all work that was to be completed during the winter shutdown on the bridge. These concerns included the man hours required to perform any outdoor tasks in below freezing weather and if it was possible to complete the work in the winter conditions. During the wire rope replacement ZTI discovered that connection pieces that were intended to be used to attach the new counterweight rope below the tugger line attachment to help guide the rope as it was hoisted became brittle in the cold temperatures and broke easily. Additionally, duct tape would not stick to itself at these temperatures because the adhesive was frozen. Another concern during construction was the use of hydraulic jacks in sub-freezing temperatures with the HPU's pumping cold hydraulic fluid, but to combat this issue ZTI provided HPU's with integral heaters to keep the fluid warm during the initial span jacking to remove the ropes. ZTI elected to use HPU's without heaters during the final span jacking for reconnecting the wire ropes. Without the HPU tank heaters, the fluid was very thick and could not be pumped without tripping the breaker on the generator for the HPU pump. After two hours of heating the HPU tanks with open flame propane torches the HPU's were able to pump the fluid and jack the span.

Conclusion

The overall construction cost at the time of bid for the rehabilitation project was $7.35 million. This cost included all mechanical rehabilitation work, electrical control system upgrades, warning and barrier gate replacement, and various structural repairs. Careful consideration during design was critical to completing the required mechanical work during the 2015 winter closure. Without consideration for long lead time materials during design that were included as part of the advanced procurement contract that began in

July 2014, it would not have been possible to procure the materials in time to begin the contract work in January 2015. The shrink disc indexing coupling provided simple adjustment to the indexing of the drive machinery during testing and will allow for any future adjustments necessary to re-index the machinery. Bridge seating issues have been resolved with the adjustments to the live load bearings, balance condition and custom tooth thickness pinions to provide good corner to corner load sharing during operation.