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92nd Street Bascule Bridge Repairs

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Abstract

The 92nd Street Bridge located in Chicago, Illinois is a two leaf bascule bridge carrying one lane of traffic in each direction over the Calumet River and is owned and operated by the Chicago Department of Transportation. The structure for each bascule leaf is comprised of two built-up riveted steel trusses that support a floor system and bridge deck. Bridge operation is facilitated by a rack and pinion drive system, with circumferential rack segments installed within each truss. The bridge was originally constructed in 1913 and currently opens for vessels about 8,000 times per year. Operational problems at the mesh of the rack and pinion for both trusses of the West Leaf led to two major repair projects over the last seven years. Prior to each repair project, a precision survey was completed to determine the rack segment locations, the trunnion alignment, and the position of the pinion and shaft with respect to available as-designed and as-built records. The findings of the precision survey and the resulting structural and mechanical engineering recommendations for repair options are presented. For each project, the repair objective was to reestablish proper meshing of the rack and pinion gear teeth while maintaining the existing pinion and shaft alignment. Repair implementation challenges throughout both repair projects, including a vessel strike during the second project, and final operational outcomes are given.

Introduction

The 92nd Street Bascule Bridge is a two leaf bascule bridge carrying one lane of traffic in each direction across the Calumet River and is located in Chicago, Illinois at the intersection of South Ewing Avenue, South Harbor Avenue, South Mackinaw Avenue, and the alignment of 92nd Street. This bascule structure is the first operable highway bridge along the Calumet River after entering from Lake Michigan. This bridge is normally closed to allow passage of vehicular traffic but operates often for marine traffic. The bridge was constructed in 1913 and currently operates about 8,000 times per year. Figure 1 is a location map of the structure.

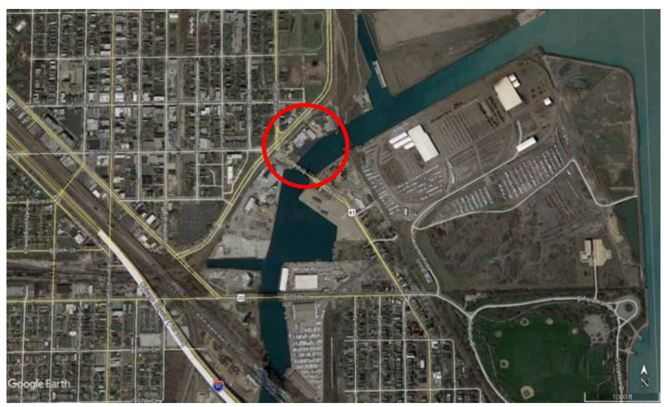


FIGURE 1. Location map of bridge structure (from Google Earth Pro).

Structure Description and Project Background

The bridge provides a clear span between river piers of about 200 feet and a vertical clearance when closed of about 16 feet at normal pool elevation. The span between trunnion centerlines is 228 feet. The two main bascule trusses for each leaf are spaced laterally at 39 feet-6 inches, providing for a roadway width of 36 feet. Sidewalks are cantilevered from the roadway floor framing and bascule trusses on both sides of the roadway. Figure 2 is a truss diagram for one leaf indicating the truss node naming convention.

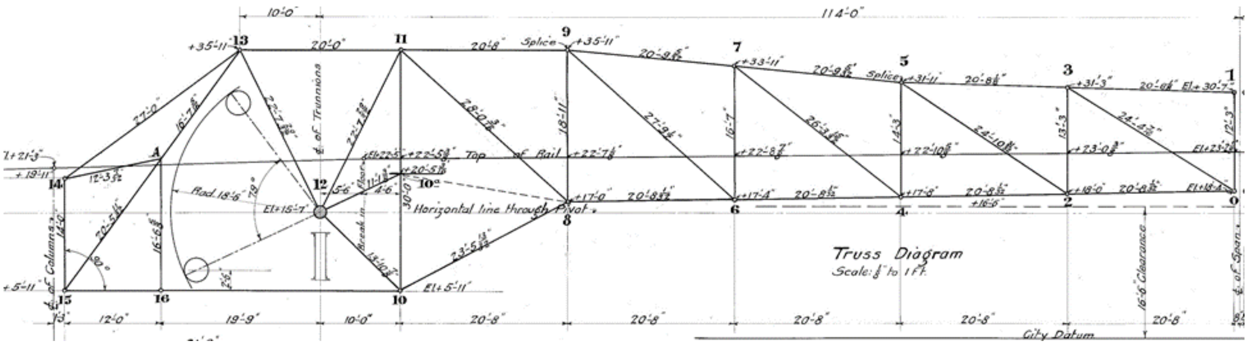


FIGURE 2. Truss diagram for one leaf taken from the original design drawings.

The bascule trusses are each driven about their trunnion pivot points using a motor and drivetrain comprised of four open gear sets beginning at the DC electric motors and ending at a rack and pinion. A plan view of the existing south drive train for the West Leaf is shown in Figure 3. Each bascule truss contains a circumferential rack made up of five rack segments. Each interior rack segment has nine teeth. The bottom rack segment (engaged while the bridge is closed) has nine teeth and a special bottom end configuration while the top rack segment (engaged while the bridge is open) has seven teeth and a special end configuration. An overall view of the rack segment layout is shown in Figure 4.

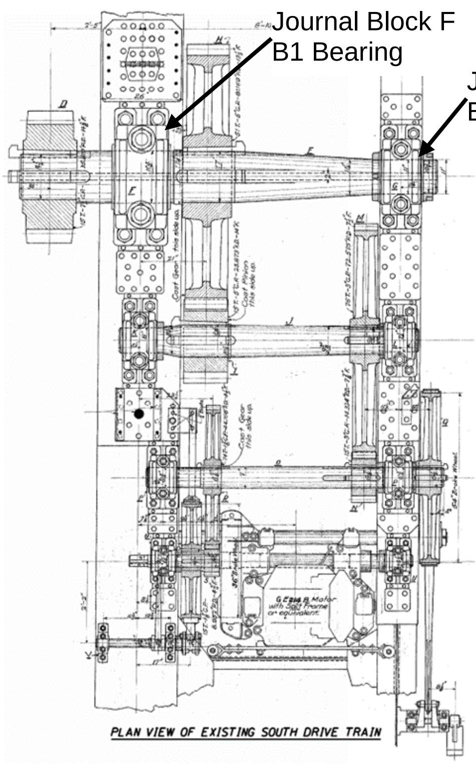


FIGURE 3. Plan view of existing south drivetrain for the West Leaf taken from the original design drawings.

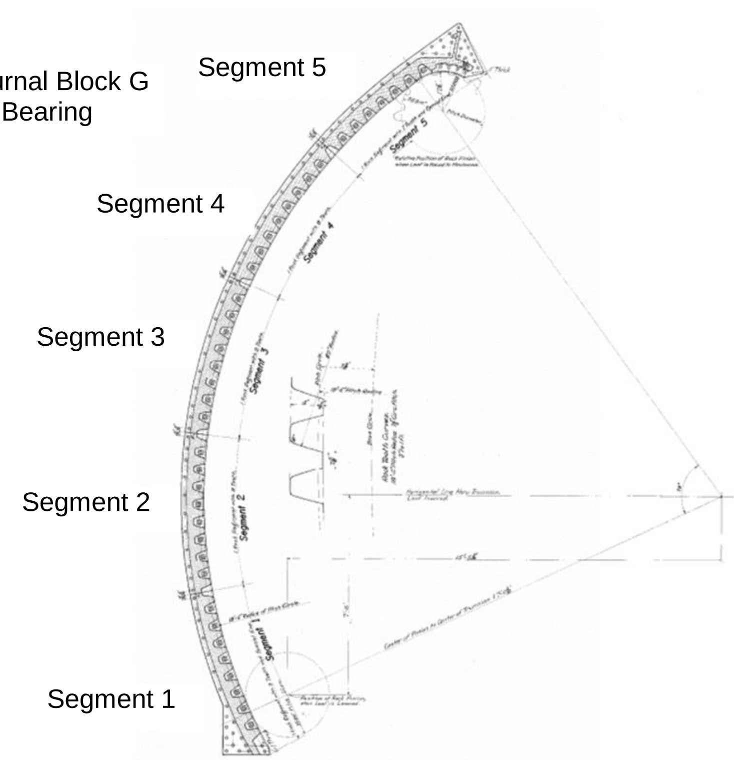


FIGURE 4. Typical rack segment layout and naming convention taken from the original design drawings.

This structure is located at a bend in the river alignment where the Calumet River turns about 45 degrees left when looking downstream. This turn and the relatively narrow waterway provided by the bridge have resulted in vessel contact with the west leaf on several occasions. Vessel contacts over the service life of the structure reportedly caused misalignment between the southwest rack and pinion drive machinery that resulted in the pinion coming out of mesh with the rack in mid-2010. In order to operate the bascule leaf, the shaft attached to the southwest pinion was temporarily disengaged. Therefore, the west leaf was driven only by the northwest rack and pinion. The balance of the west leaf was reportedly fine-tuned by Chicago Department of Transportation (CDOT) forces to allow operation of the leaf in this manner. Subsequently, the base bolts connecting the rack pinion shaft journal block to the machinery frame worked loose and caused unacceptable vibrations during span operations. In response to this development, CDOT operated the bascule leaf to the full open position, and took the bridge out of service in October, 2010.

2010 Investigation and Repair Project

Initial Field Measurements and Observations

WJE was engaged by CDOT to investigate the conditions of the racks and pinions for the west leaf of the 92nd Street Bridge following its removal from service. WJE performed initial documentation of the condition of the rack teeth for both the north and south racks. Figure 5 is a sketch of an as-designed rack tooth taken from the original mechanical shop drawings. Each rack has 43 teeth with a circular tooth pitch of 7 1/2 inches and a pitch radius of 222 inches. Each tooth is 4 5/8 inches tall and has a thickness of 2 5/8 inches at the pitch radius, where load is transferred between the rack teeth and the pinion teeth. It should also be noted that the pitch radius of the rack is positioned 5/8 inches from the top land of each rack tooth.

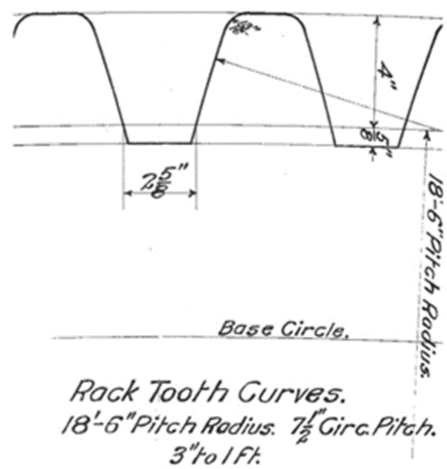


FIGURE 5. As-designed rack tooth taken from the original mechanical design drawings.

At the time of the documentation work, the west leaf was in the full open position. Therefore, rack documentation took place beginning with the bottom rack tooth, called Rack Tooth 0, and proceeded “up” the rack to the pinion position. Two important dimensions were recorded during documentation of each rack. The first was the thickness of the top land for each rack tooth. This is the dimension across the flat surface of the top of the tooth. As designed, this thickness should be equal to approximately 2 5/16 inches. However, actual measurements indicated that the top land tooth thickness ranged from 1 1/4 inches to 2 1/8 inches for each tooth measured. The purpose of this measurement was to quantify the rack tooth wear locations and severity.

The second measurement taken was the center-to-center dimension of the top lands for adjacent rack teeth. The purpose of this measurement was to determine if the rack tooth wear had resulted in an improper pitch between the rack teeth. This problem can cause the pinion teeth to interfere with the rack teeth, or can cause accelerated tooth wear. Measurements indicated that the pitch of the rack teeth ranged from 7 3/8 inches to 7 13/16 inches.

In addition to the basic measurements recorded, photographic documentation of typical tooth wear was obtained. Figures 6, 7, and 8 demonstrate typical rack tooth wear on Rack Teeth 5, 4, and 1 of the north rack, respectively. For comparison, the cardboard template shown in each photograph outlines a full scale cut-out of the as-designed rack tooth geometry. Significant plastic metal flow and geometric change was evident on most rack teeth.

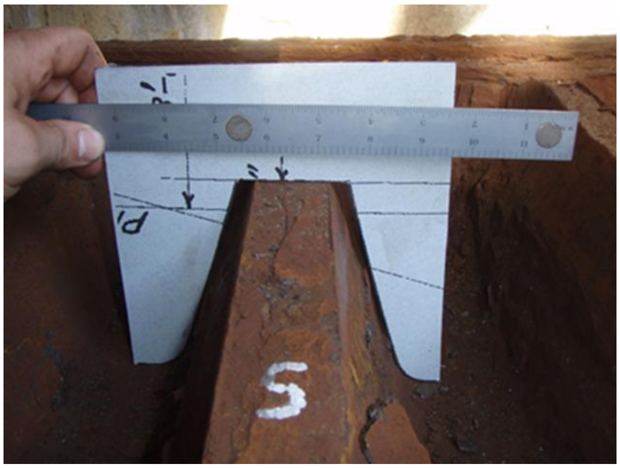


FIGURE 6. Rack tooth wear shown on Tooth 5 of the north rack.

FIGURE 7. Rack tooth wear shown on Tooth 4 of the north rack.

Each pinion gear has a total of 15 teeth with a 7 1/2 inch circular pitch and a pitch radius of 17.905 inches. Each tooth is 4 5/8 inches tall and has a thickness of 4 1/2 inches at the pitch radius. This results in a design backlash of 3/8 inches in the rack and pinion system. Figure 9 is a detail of a typical pinion tooth and rack tooth mesh taken from the original mechanical shop drawings.

FIGURE 8. Rack tooth wear shown on Tooth 1 of the north rack.

A full scale cardboard cut-out was used to compare the pinion tooth geometry to the as-designed geometry. Figure 10 demonstrates the typical pinion tooth wear on the north pinion. The typical tooth wear exhibited on each tooth includes plastic metal flow from the tip toward the root of each tooth. In addition to wear it was reported by CDOT that there had been at least one incident of a pinion tooth breaking and being repaired by welding it back on.

An additional measurement of the distance between the top land of the north rack tooth and the root of the engaged north pinion was recorded with the leaf in the closed position, as shown in Figure 11. The measurement indicated that the distance between the top land of the rack and the root of the pinion was

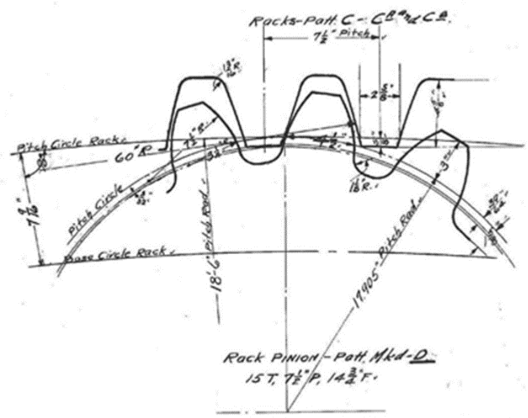


FIGURE 9. As-designed pinion tooth and rack tooth mesh detail taken from original drawings.

FIGURE 10. Pinion tooth wear shown on a representative north pinion tooth.

approximately 2 1/2 inches. The design distance for this measurement was 1 inch. Therefore, the pinion was approximately 1 1/2 inches out of position.

The journal bearing block for the north pinion (Journal Block F, or the B1 bearing) was also investigated. This bearing includes a phosphorous bronze bushing sleeve that was designed to be bored to fit the shaft journal and provide "good bearing" according to the mechanical shop drawings. A detail of this bearing taken from the mechanical shop drawings is given in Figure 12. The bearing block is bolted through a steel casting using four 3 inch diameter turned base bolts.

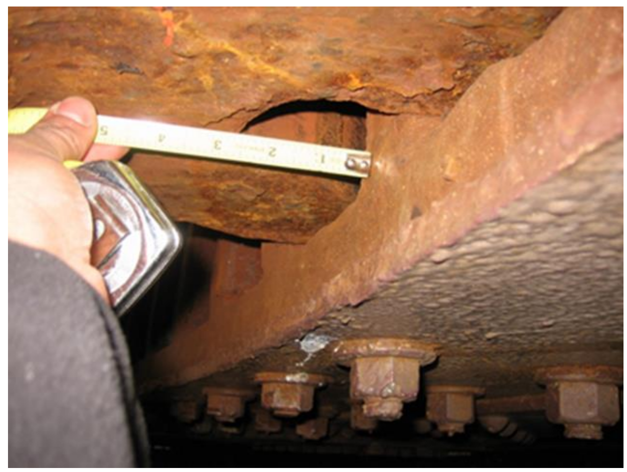


FIGURE 11. Root-to-tip measurement for the north pinion with the leaf seated.

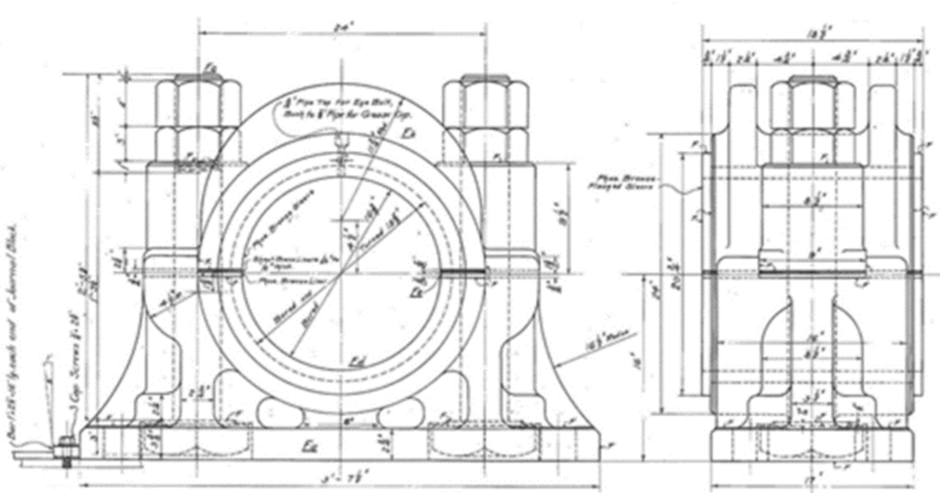


FIGURE 12. As-designed pinion shaft bearing Journal Block F, also known as the B1 bearing. Detail taken from the original bridge design drawings.

Two conditions of concern were observed. When struck with a 3 lb. hammer, some of the four turned bolts were able to be rotated. Therefore, the bolts were clearly not tight. In addition, it was possible to insert a putty knife horizontally into the bearing sleeve between the shaft and the phosphorous bronze bushing to a depth of about 2 inches. This is shown in Figure 13, and is indicative of advanced wear.


FIGURE 13. Painter's tool inserted between the pinion shaft journal and bearing bushing.

Precision Survey

A precision survey of the locations of the north and south trunnions and racks and of the north pinion was conducted by In-Place Machining Company (IPM) at the direction of WJE. During this work, both static (bridge in one position) and dynamic (bridge operating) measurements were recorded. IPM used a precision laser measuring instrument to perform all measurements. IPM installed survey reference points throughout the bridge machinery area to establish the part frame.

Static measurements were conducted in two planes on each trunnion representing the trunnion end surfaces. The part coordinate system was then defined with the "Z" axis running through the centers of the circles defined by the north end of the north trunnion and the south end of the south trunnion. This line is referred to as the trunnion axis. The "Z" origin was defined originating at the center of the north trunnion north end, with positive "Z" toward the south trunnion. The "X" axis was defined as a line running longitudinally along the bascule span originating at the center of the north trunnion north end, with positive "X" toward the river. The "Y" axis was defined as a vertical line originating at the center of the north trunnion north end, with positive "Y" up.

Using the established part coordinate system as a reference, the center of the north trunnion south end was determined to be located below (negative "Y") the north end by 0.049 inches and in front of (positive "X") the north end by 0.049 inches. The center of the south trunnion north end was determined to be located below and in front of the south end by 0.094 inches and 0.032 inches, respectively. These measurements suggest reasonable trunnion alignment.

Additional static measurements were taken to define the curvature and position of each rack. Two lines of measurements were taken on the north rack and one line of measurements was taken on the south rack. On each line of measurements, the precision laser measuring instrument was used to measure the position of the top land surface of every other rack tooth over the length of the rack. Prior to recording measurements, each measurement position was chipped using a hammer and cold chisel to remove heavy rust and foreign material. Even with this effort, the surfaces measured were very irregular. Using the established part coordinate system, the radius center of the north rack was determined to be approximately 0.683 inches below and 0.665 inches in front of the trunnion axis. The radius center of the south rack was determined to be approximately 0.273 inches below and 0.780 inches in front of the trunnion axis.

Static measurements were also taken on the position of the north pinion and shaft in three planes along the shaft. The radius from the trunnion axis to the center of the north pinion shaft was found to be 203.445 inches. Adding the pitch radius of the pinion (17.905 inches) the total distance to the pinion pitch radius from the trunnion axis was found to be 221.35 inches, which is considerably less than the design dimension of 222 inches.

Dynamic measurements were conducted on the north and south racks to determine the alignment of the racks with respect to the established part coordinate system during bridge operations. One location on each rack was monitored during multiple bridge operations. The dynamic rack data indicated that the data recorded from the rotation of the observed location about the trunnion axis did not deviate significantly along the axis or radius of the “best-fit” circle. However, the monitored location on the north rack was found to move away from the north trunnion while the monitored location on the south rack was found to move toward the south trunnion. The magnitude of displacement was within 0.080 inches, indicating that this observed phenomena was most likely attributable to twisting of the structure as it was operated using only one pinion.

Dynamic measurements were also recorded from a monitored location on the end of the north pinion. The rotation of the pinion shaft/gear did not deviate significantly along the axis of the “best-fit” circle. However, the slight misalignment of the pinion with respect to the established part coordinate system was evident. In addition, significant deviation along the radius of the “best-fit” circle was observed. The maximum recorded deviation range was approximately 1/4 inch while the pinion was operating. This indicated that the pinion displaced approximately 1/4 inch out of position during operation of the bascule leaf. Movement was confirmed during leaf operations by use of dial gauges, shown in Figure 14.

FIGURE 14. Dial gauges installed on north pinion shaft and Journal Block F.

After completion of the investigation related to Journal Block F the loose base bolts connecting the north rack pinion shaft journal block to the machinery frame were tightened by CDOT and leaf operation was restored driving the leaf with a single pinion.

Rack and Pinion Refurbishment

The initial WJE investigation and report concluded that mechanical repairs were required and recommended that a mechanical engineer be engaged to assist in the development of those repairs. To that end, Stafford Bandlow Engineering (SBE) was engaged in December 2010 to review the documentation of the investigation performed by WJE, to prepare calculations to determine the capacity of the rack and rack pinion both in the original and as worn condition, and to compare the AASHTO required loading with the capacity of the rack and pinion gear. Ultimately, the goal was to evaluate the effect of the existing rack and pinion misalignment and wear on bridge leaf operational performance.

In order to perform this work, SBE completed field measurements of the rack and pinion as required for preparation of shop drawings to replace the severely worn and damaged pinions. SBE evaluated a few options for the new pinions including replacement in-kind with the original geometry, increasing the number of pinion teeth, and designing a special rack pinion geometry to improve the rack and pinion mesh using the existing poor radial alignment. Figure 15 depicts the engagement of the original pinion geometry with the worst case existing radial misalignment at the south rack.

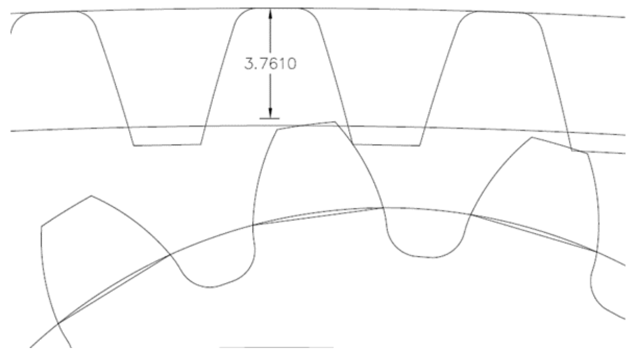


FIGURE 15. Engagement of the original pinion tooth geometry with the worst case existing radial misalignment at the south rack.

It was concluded that there were several major issues with re-using the original pinion tooth geometry at the worst case existing radial misalignment for both racks:

1) There was a risk of the tips of the teeth interfering when back driving (which had been previously reported and was an impetus for this repair project).
2) The pinion teeth experience single tooth loading close to the tip which created concerns about the bending strength of the teeth and the risk of tooth breakage (which had been previously reported and was an impetus for this repair project).
3) The rack teeth were loaded at the tip. While this did not create a bending strength issue due to the design of the internal rack teeth, the contact between the face of the pinion tooth and the corner of the rack tooth would accelerate wear of the teeth.
4) The operating pitch diameter of the pinion was so far from the original pitch diameter that there was a large discrepancy in the pressure angles of the tooth faces where they were in contact. It was expected that this would accelerate wear.

SBE investigated numerous alternatives for modifications to the pinion tooth geometry to mitigate each of the issues caused by the radial misalignment. The geometry proposed in Figure 16 provided the greatest possible benefits, but did not remove the risk of accelerated wear.

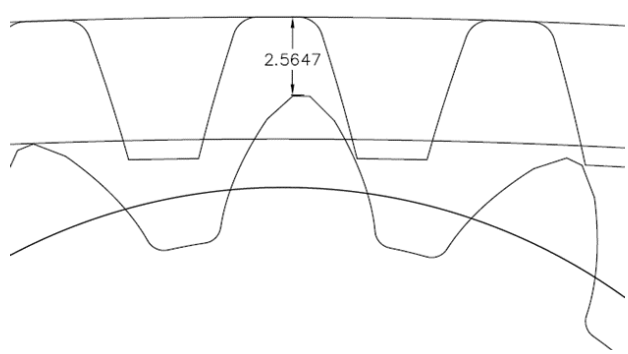


FIGURE 16. Engagement of the proposed special pinion tooth geometry with the worst case existing radial misalignment at the south rack.

The proposed geometry increased the outside diameter of the pinion but maintained the whole depth of the tooth. This would result in a substantially thicker tooth at the base which was much stronger and also move the contact on the pinion teeth further from the tip. Both of these effects would mitigate the risk of tooth breakage. A substantial tip relief was added to mitigate the risk of the tips of the teeth interfering when back driving. Despite these improvements it was not possible to eliminate the contact with the tip of the rack tooth and the large discrepancy in the pressure angles of the tooth faces where they were in contact. The only way to eliminate these issues would be to reduce the radial misalignment.

Seeking a temporary repair (approximate life span of 10 years), CDOT elected to remove and refurbish the existing rack segments and then reinstall the rack segments using the existing alignment with the new special pinions. This approach required no major structural modifications to the bascule trusses, but required removal of all ten rack segments from the west leaf, shipping to a machine shop, addition of weld material to build-up the worn rack teeth, and finish-machining to return the teeth back to their as-designed profile. New turned bolt fasteners were fabricated and used by a contractor to reinstall the refurbished rack segments using the existing holes in the rack segments and rack gusset plates. Lastly, CDOT directed the contractor to properly torque the bearing cap and base bolts for both pinion shafts and partially refurbish the B1 bearings.

The work proceeded first at the south rack and pinion while the leaf was operated using the north rack and pinion. Once the south rack and pinion was reinstalled and operational, the rehabilitation work was performed for the north rack and pinion. A photograph showing the unique tooth profile and tooth tip relief required at the new south pinion is given in Figure 17. Work was completed in late 2012 and bridge was returned to normal operational service, driven by both racks and pinions. A precision survey was not performed to document the as-built condition of the rehabilitated rack and pinion alignment. In addition, no bascule span balance adjustments were made in an effort to minimize pinion tooth loads during leaf operations.

FIGURE 17. Special pinion tooth profile used for the new south pinion.

2017 Investigation and Repair Project

Initial Field Measurements and Observations

Following approximately 5 years of normal operation, wear of the new south pinion teeth began to cause operational issues. When the pinion was back driven at the locations of the worst radial misalignment, the top land of the pinion tooth rolling into engagement with the rack began to contact the top land of the mating rack tooth resulting in abnormal noises and vibrations. CDOT decided to remove the south pinion from service in June 2017 and continued to operate the leaf with the north rack and pinion. Adjustments to the bridge balance were made by CDOT forces at that time in an attempt reduce the operating tooth loads for the north pinion. This adjustment caused the north pinion to experience similar noises and vibrations. In response, CDOT carefully operated the leaf to the fully open position and locked the leaf in place. The WJE and SBE team were again engaged to review the operational difficulties and provide recommended solutions.

A preliminary visual review of the amount of tooth wear was performed. This evaluation concluded that rack tooth wear was only apparent for a limited number of rack teeth, and was generally confined to the tip of the rack tooth above the as-designed rack pitch circle. There was uneven wear visually evident on the pinion teeth. An example of tooth wear for the south pinion is given in Figure 18. Based on this information a measurement plan was developed:

- Pinion and rack teeth were numbered.
- Pinion tooth thickness measurements were taken to document the variations in pinion tooth wear
- Radial runout measurements and gear root/tip clearance measurements were recorded.

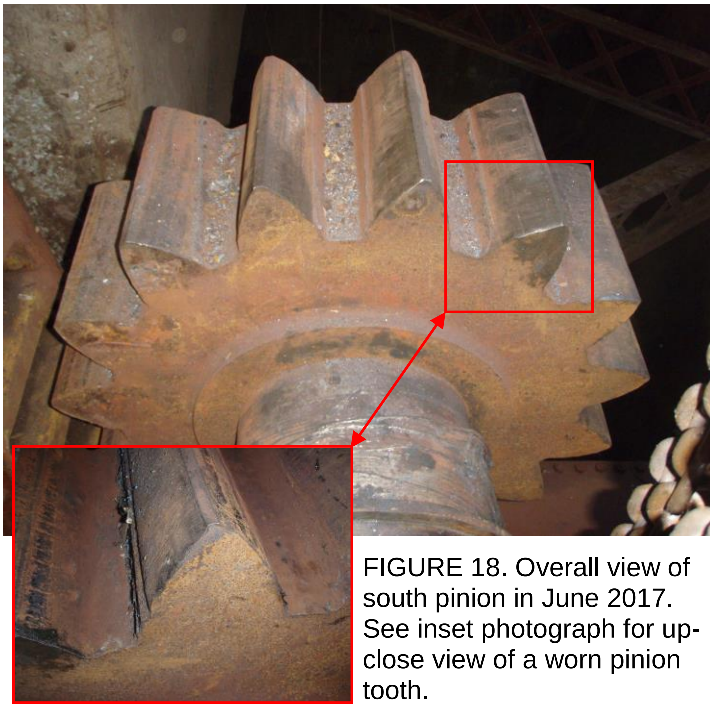


FIGURE 18. Overall view of south pinion in June 2017. See inset photograph for up-close view of a worn pinion tooth.

It was found that there was significant wear for the pinion teeth that meshed with the rack teeth which exhibited the wear at the tips of the teeth and that these teeth were at the most extreme limits of radial runout (maximum root/tip clearance). Based on a geometry layout of the teeth and these field observations it was concluded that the high rate of wear was directly related to the radial misalignment and that in order to achieve satisfactory performance for this bridge, which operates extremely often, the radial misalignment should be improved.

The previous work had identified that the south rack segments had 1.2 inches to 2.45 inches of radial misalignment and the north rack segments had 0.75 inches to 2 inches of radial misalignment. The table below shows the change in runout over the length of the rack using the radial position at Segment 5 (open position) as the zero reference and the deviation from the ideal radial location to establish the correct center distance to the pinion:

Rack Run-Out Measurements 6/29/2017					
North Rack			South Rack		
Segment	Change Run-Out Over Length (in.)	Ideal Location (in.)	Segment	Change Run-Out Over Length (in.)	Ideal Location (in.)
5	0	0.75	5	0	1.2
4	0	0.75	4	0	1.2
4	0.25	1	4	0	1.2
3	0.125	0.875	3	0	1.2
3	0.625	1.375	3	0.25	1.45
2	0.625	1.375	2	0.625	1.825
2	0.875	1.625	2	1.125	2.325
1	0.875	1.625	1	1.125	2.325
1	1.25	2	1	1.25	2.45

A measurement was recorded at the first and last tooth for each segment except for Segment 5 which was engaged near the end of the segment with the leaf open. The cells highlighted in red reflect the areas that correlated to the high rates of wear on the pinion teeth.

The mechanical inspection also identified a recurrence of the severe wear of the B1 bearings which was attributed to failure of the lubrication piping and lack of lubrication.

Precision Surveys and Vessel Allision

IPM was again engaged to perform a precision survey of the rack and pinion alignment for the north and south racks to confirm that the measurements taken during the first investigation were generally still valid and to rule out the possibility of major misalignment as a result of anecdotal reports of further vessel contact with the structure. The IPM survey took place on July 20, 2017 and while the results of the survey work were being compiled into a report, the west leaf suffered a significant vessel impact with the leaf locked out in the fully open position.

FIGURE 19. Bottom of the south truss connection where the live load shoe was previously attached. Note severely bent steel gusset plates and stiffening angles.

The vessel strike resulted in significant damage to the south truss live load shoe connection that removed the shoe from the truss. Views of the bottom of the truss connection showing where the live load shoe was once attached, and the inside of the truss connection are given as Figures 19 and 20, respectively. Damage was also evident at several truss lateral bracing members and their connections. A follow-up precision survey was performed by IPM on August 2, 2017 to determine if the overall bridge alignment had been affected by the vessel strike.

Fortunately, the results of the three precision surveys generally agreed (within the possible repeatability tolerances). Therefore, it was found that the alignment of the racks and pinions with respect to the trunnion axis for the west leaf had not changed substantially over the course of the seven years since the first survey work was performed.

FIGURE 20. View of the inside of the south truss connection where the live load shoe was previously attached. Note bent connection angles.

Repair Recommendations

With this information, the engineering team recommended the following options to improve the mesh of the north and south rack and pinion systems in increasing level of complexity and cost (time with the structure out of service to vehicular traffic and dollars spent) but with decreasing risk of further major repair projects in the near future:

1) Remanufacture the south pinion to restore the “special” gear tooth profile and provide minor modifications to the north pinion teeth in-place that would allow leaf operation to continue with no changes to the racks.
2) Remanufacture the south pinion to restore the “special” gear tooth profile. Remove the bottom two rack segments for the south rack and the bottom one rack segment at the north rack and reinstall them to improve the radial alignment to be no worse than the other segments. This would substantially reduce the range of misalignment over the length of the rack but would not eliminate the radial misalignment entirely.
3) Remanufacture the south pinion to restore the original gear tooth profile. Remove all rack segments for the south rack and the bottom two rack segments at the north rack and reinstall them to improve the radial alignment to be no worse than the other segments.
4) Remanufacture both pinions to restore the original gear tooth profile. Remove all rack segments for both racks and totally reposition the entire rack to restore an optimal radial alignment.

Initially, the engineering team was authorized to proceed with development of repair documents and project specifications that would direct a contractor in execution of Option 3, above. Conditions of the existing rack gusset plates required that new side plates be added to provide additional stiffness in some areas, to act as splice plates over corroded or deteriorated areas of the existing rack gusset plates, and to establish new turned bolt holes through adequate material thickness that would properly support the rack segments on their new alignment. Note that the existing rack gusset plates contained existing turned bolt holes that in several cases overlapped with the bolt holes required for the adjusted rack segment positions.

Through vetting of the constructability of this work, it was determined that the top north rack segments would need to be removed to allow installation of the new side plates for the existing north rack gusset plates. At that point, the engineering team was directed to proceed with the more comprehensive repair plan described above as Option 4 and final design was completed as the contractor mobilized and began work at the site. The contractor was directed to shore the west leaf in the fully open position by pinning the structure between the counterweight pit walls. Following completion the shoring system, work to repair the south truss in the area of the live load shoe began. In addition, the contractor started work required to remove the five rack segments from the south and north racks.

Structural Design and Implementation

The structural focus of the work in accordance with Option 4 was to design appropriate rack side plates that could meet the project requirements. This included the classical structural design process, fabrication and shipping requirements, consideration for how the rack side plates would be installed, and consideration for how the desired rack segment alignment would be achieved. The new rack side plates had to cover an area with major dimensions of about 27 feet by 11 feet, and needed to accommodate the curvature of the rack while avoiding several existing geometric interferences on the existing trusses. In addition, the new rack side plates had to be lifted into position by threading them between the truss arms and the existing roadway. The side plate installation process also required removal of several existing structural fasteners that were eventually replaced to tie the plates back into the truss members. Lastly, the installation process required removal of several existing cover or splice plates in the area being cover plated.

Given the normal construction tolerances associated with adding new steel to existing structures, the decision was made to fabricate the new side plates with a minimum number of fastener holes. The only drilled holes in the new plates during fabrication were those that would be match drilled through the existing gusset plates where fastener holes did not previously exist using the new plates as a drilling template. Each existing bolt hole in the truss was match drilled through the existing hole to create the best possible fit between the new and existing steel. Turned bolt holes for the rack segments were left undrilled until final rack segment installation operations described below.

The side plates were designed in two plies. The interior ply installed against the existing truss gusset plate was specified as 3/4 inch thick and was fabricated in three pieces. This plate thickness matched the thickness of the counterweight box support angle and provided a smooth surface against which to install the outer ply, which was specified as 1/2 inch thick. The outer ply was fabricated in two pieces, with the seam between the two pieces positioned away from the seams of the inner ply. This plate arrangement allowed for handling of the materials, removal of existing rack gusset cover plates, and removal and replacement of existing fasteners in the assembly that, when reinstalled, tied the new plates back into the truss members directly.

Shop drawings were created for the new side plates and engineers used the shop drawing information to lay the geometries of the new side plates out on the structure. Minor adjustments required by existing field obstructions and actual fastener layout on the existing trusses were made to the drawings, and the shop drawings were released for fabrication. Figure 21 shows an example of the layout marks on the inboard side of the south truss at the top of the rack.

During removal of the existing rack segments, cracks were observed in both truss members that were hidden from view behind the rack segment castings. Figure 22 shows an example of the cracks discovered in the north truss member. Repairs to remove the crack tips and cover plate over the existing cracks were designed and installed. The south truss repair included installation of a 2 inch diameter drilled hole to remove the crack tip and installation of a fill and splice plate on both sides of the truss member web plate. Cracks in the north truss member were more extensive and required installation of four specially

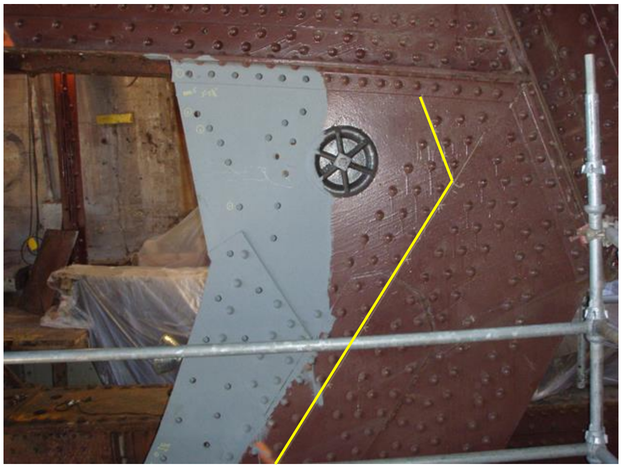


FIGURE 21. Yellow paint stick layout marks shown on the existing structure during development of final shop drawings for the new rack side plates.

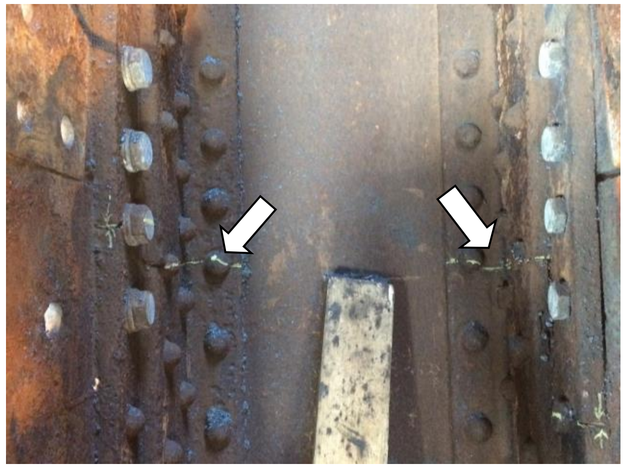


FIGURE 22. Cracks in the north truss member observed after rack segment removal.

fabricated steel angle shapes, two fill plates, and two splice plates over the area containing the cracks. Figure 23 is an excerpt from the repair design drawings showing a section view of the repair specified for the north truss member.

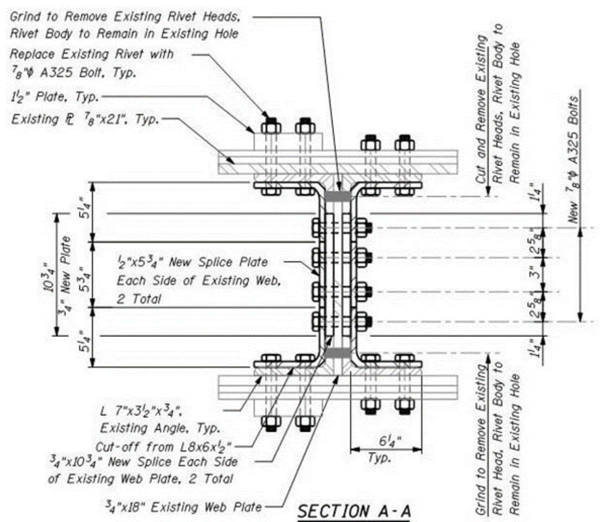


FIGURE 23. North truss member repair detail taken from the design drawings.

Mechanical Design and Implementation

The mechanical scope included:

- Determination of the proper circular pitch radius at which the rack segments would be reset in both trusses to best mesh with the existing pinion shaft alignment and position
- Development of details for:
  - Remanufactured pinions using existing forgings
  - Rehabilitation of the existing B1 bearing assemblies (Journal Block F)
  - Design of the turned rack bolts
- Oversight of the construction methods that would achieve the proper placement of the rack segments

The precision survey data was used to determine the proper rack radial location for both racks. It was determined that the new design inner surface radius of the north and south racks would be 220.725 inches and 220.466 inches, respectively. These inner radius dimensions would allow the overall rack assemblies to mesh with the newly cut pinion teeth.

The fasteners connecting the rack segments to the new rack side plates consisted of two varieties. Short turned bolts with a square head, shoulder, and threaded end were used along the inner radius bolt circle where they are installed in the tooth pockets. These were designed for an LC6 fit with the rack and the new rack side plates. The other type of bolt was a rod-type through bolt with two threaded ends. These bolts were designed to pass from the outboard side of the truss, through the two outboard side plates, the outboard rack gusset plate, the outboard side of the rack segment, the inboard side of the rack segment, the inboard rack gusset plate, and the two inboard rack side plates. These bolts were not designed to require a body fit. An axial section through a typical rack section showing the original bolt arrangement is given as Figure 24.

The pinion gear teeth were designed to closely resemble those of the original 1913 design specifications, with minor adjustments as needed to provide an acceptable mesh. An advantage of this design choice was that the existing pinions (fabricated under the previous construction project) were machined down to the new tooth profile. It was therefore not necessary to source new forgings and cut completely new gears for this project, saving the cost of the forgings and project schedule time required to acquire them. Figure 25 is an excerpt from the design drawings showing the new pinion tooth geometry inside the extents of the existing pinion forgings.

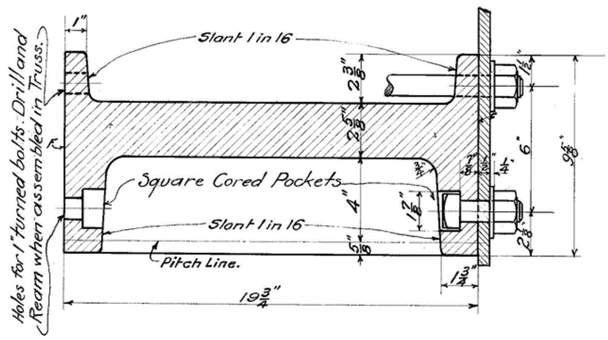


FIGURE 24. Typical section through rack segment taken from the original design drawings showing fastener arrangement.

The rehabilitation of the B1 bearing assemblies (Journal Block F) required design of new bushings within the journal block, and design of new keeper chocks installed at either end of the bearing base. Bronze bushings fabricated from Alloy C93700 were specified. The bearing block housings and caps were shipped to a machine shop where the new bushings were fabricated and installed. The inner diameter of the bronze bushings were finish-machined to an LC6 fit with the existing pinion shaft after the pinion shaft was cleaned with emery cloth to remove foreign materials and any raised score marks.

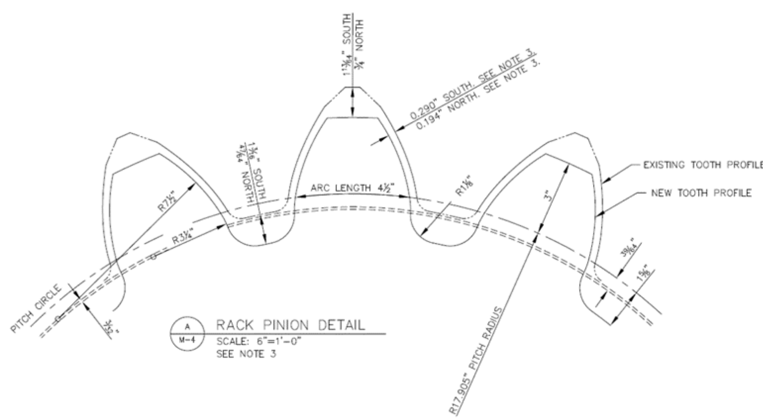


FIGURE 25. Design drawing excerpt showing new pinion tooth profile inside extents of existing pinion forgings.

The journal block was completely restored including providing new liners, new turned cap bolts, machining the inside bore to provide an LC1 fit with the new bushing and machining the bottom to provide a flat faying surface. The side faces of the base were also machined flat to bear upon the side chocks.

The mating surface for the journal block on the machinery girders was field machined to clean up and restore a flat faying surface and flat surfaces at the side chock plates. New turned stud bolts were designed to reconnect the bearing housings to the machinery girders. The holes in the bearing bases and the fit area within the machinery girder were line bored after final alignment to produce an LC6 fit with the new turned bolts. The tapered chocks were custom machined to fit.

Preparation and Installation of Rack Segments

The existing rack segments were removed from the bridge and shipped to a fabrication shop where they were sandblasted to remove corrosion product. Several of the existing turned bolt holes in the rack segments were observed to not be round, as shown in Figure 26. In addition, the holes varied in size from about 1 1/16 inches up to 1 3/16 inches. Each existing hole on the inner radius bolt circle (bolt holes located in the tooth pockets) was therefore drilled out to 1 1/4 inch diameter to accommodate the majority of these imperfections. Outer radius bolt circle holes where the bolt/hole fit was less critical were increased in size as needed to provide a round 1 1/16 inch diameter bolt hole at each location. Specially fabricated centering plugs were used to guide annular cutters to drill the new hole while maintaining the position of the original hole center, since the interior surface of the rack in each tooth pocket contains a square shaped pocket sized just large enough to accommodate the square turned bolt head. In addition, the bolt holes on the outer radius bolt circle were required to accommodate the through bolt alignment.

FIGURE 26. Turned bolt hole in existing rack segment.

To facilitate reinstallation within the bridge, it was determined that the best accuracy could be achieved on the shortest schedule by fabricating templates of the rack segments that could be used to match drill the new rack side plates. Templates were fabricated using 1/2 inch thick steel plates by computer controlled plasma cutting one-piece templates that encompassed the full size rack geometry (five segments butted end to end). A total of four templates were fabricated, one for each side of each rack. The inner radius of each template was set to match the desired inner radius of the completed rack assembly.

FIGURE 27. Typical rack assembly laid out on the floor plate during the templating process.

The rack segments were then laid on a flat steel plate scribed with the desired inner radius of the new rack alignment. The rack segments were tack welded to the floor plate and a cut template was laid across and secured to the top surface of the five rack segments. The existing holes in the rack segments were then match drilled through the 1/2 inch thick template. Temporary bolts were installed through several of the holes and the tack welds fixing the opposite side of each rack segment to the floor plate were removed. The entire rack was then flipped over, shimmed true and flat, and the process was repeated for the second template and then for the second rack. Figure 27 shows one full rack (five segments) laid out on the floor plate during the templating process. A representative photograph showing a template in position for match drilling is given as Figure 28.

The rack segments and templates were then shipped back to the bridge and prepared for installation. The inboard and outboard template for the south rack were temporarily hung near the desired position within the existing rack gusset plates. The inboard template was indexed along the existing rack gusset plates to the desired position and then a precision laser measuring instrument was used to adjust the inner radius of the template until data along the curve closely matched the design inner radius for the completed rack assembly. Measurement operations in progress are shown in Figure 29.

FIGURE 28. Template clamped to the rack during the templating process.

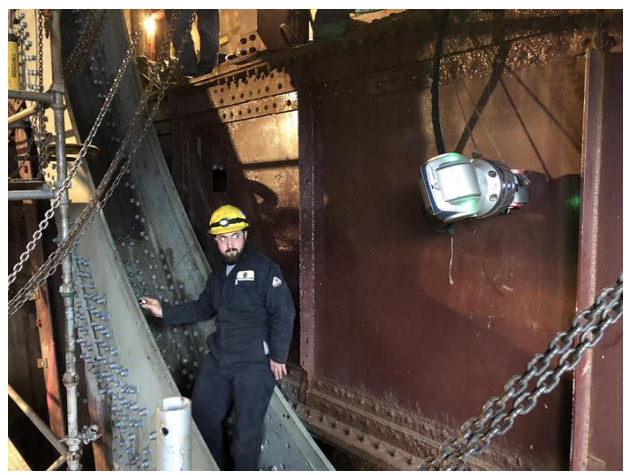


FIGURE 29. IPM Personnel utilizing laser tracker to verify template alignment.

Several turned bolt holes in the template were then match drilled through the existing rack gusset plate and the new rack side plates. The inboard template was then removed and Segment 2 and Segment 4 for the south rack were lowered into position and pinned into place using specially machined body-fit steel pins through the inboard plate assembly. Temporary bolts were installed to ensure a tight fit.

The precision laser measuring instrument was then used to record data as the two installed segments were adjusted until they were level across the top land of the rack teeth. Once level was achieved, three inner radius turned bolt holes including the upper and lower end hole of each of the installed segments were match punched to the existing outboard rack gusset plate. The two segments were removed and the punch marks were used to drill the six indicated holes through the existing outboard rack gusset plate and the two side plates. At this point, the outboard template was installed using the six newly drilled holes and the overall alignment of the template was verified with the precision laser measuring instrument. The inboard template was reinstalled using the holes drilled previously as a guide and all template holes were match drilled through the structure using the templates as a guide.

Once the drilling was complete, the south rack templates were removed and the five rack segments were installed using steel alignment pins. Temporary bolts and clamps were used to compact the gusset and side plates against the rack segments and the outer radius through bolts were installed by sliding them through the assembly. Nuts for the through bolts were made snug tight on both ends.

Reaming operations to ensure the best possible turned bolt fit for the inner radius bolt circle then began. The nominal turned bolt shoulder was specified for fabrication as 1 5/32 inches in diameter. Most match drilled bolt holes provided good alignment among the four plies (rack, gusset plate, and two side plates). However, some bolt holes did not provide close enough alignment ply-to-ply to allow the hole in every ply to clean up to the desired LC6 fit tolerance when only enlarging the nominal bolt hole diameter by 1/32 inch. This is attributed to the inability of the two separate templates to hold the rack gusset plates in perfect vertical alignment along the entire length of the template, as the solid cast rack segment would when installed.

The installation procedure was modified slightly in order to achieve the best possible fit for all inner radius turned bolt holes for the north rack. The process was generally the same and used the help of the precision laser measuring instrument to properly position the templates. Segments 2 and 4 for the north rack were also installed to ensure proper indexing of the two templates between the inboard and outboard rack gusset plates. All outer radius turned bolt holes were match drilled through the two templates. However, only the top end and bottom end hole in each rack segment was match drilled through the existing rack gusset plate and two side plates using the templates as a guide.

The templates were removed and the five segments were pinned in position. Temporary bolts and clamps were used to compact the gusset and side plates against the rack segments and the outer radius through bolts were installed by sliding them through the assembly. Nuts for the through bolts were made snug tight on both ends. The north rack segments are shown pinned in position in Figure 30.

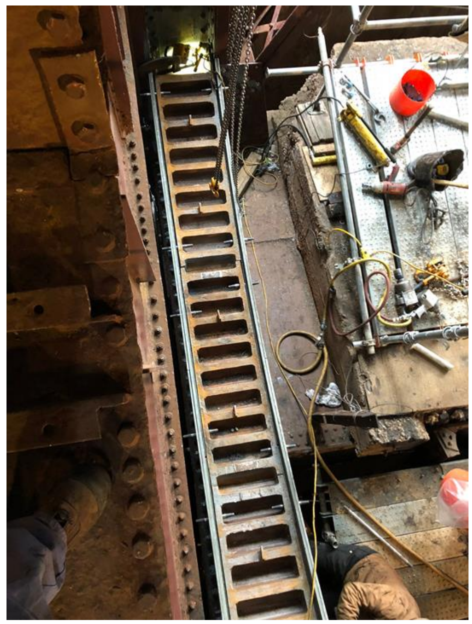


FIGURE 30. Rack segments installed with alignment pins, ready for final drilling and reaming.

At this point, the five rack segments were used as a guide and the remaining inner bolt circle turned bolt holes were match drilled through the installed rack segment tooth pockets. Reaming operations followed, and a more consistent LC6 fit between the turned bolts and bolt holes was achieved. The precision laser measuring instrument was used to collect as-built rack segment position data, which agreed very well with the design position for both racks, deviating by a maximum of about 1/4 inch on radius at any position along the rack.

Pinion Shaft and B1 Bearing Assembly Rehabilitation

The following photos (Figures 31 through 34) depict the work to rehabilitation the pinion shaft assemblies including the B1 bearing (Journal Block F) assembly:

FIGURE 31. The B1 bearing assemblies were refurbished in the shop.

FIGURE 32. The machinery girder was field machined to restore a flat faying surface for the B1 bearing housing.

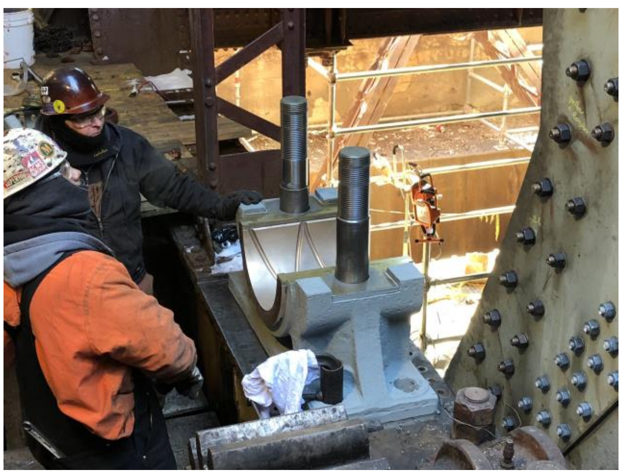


FIGURE 33. The refurbished B1 bearing housing reinstalled on the machinery girder.

FIGURE 34. The pinion shaft assembly, which had been refurbished in the shop, was re-installed.

At this point in the process temporary shims were set under the B1 bearing. The B1 bearing and the shims were adjusted to achieve satisfactory alignment of the rack/pinion and G2/P2 gear sets. Once the alignment of the B1 bearing was finalized a permanent tapered shim was machined and installed under the B1 bearing and the anchor stud holes were reamed to fit the new studs, as shown in Figure 35. Figure 36 shows the reaming fixture. Following shim and stud installation, the bearing base bolts and cap bolts were properly tightened to the specified torque using hydraulic equipment. Figure 37 shows the south pinion gear and rack assembly in their final positions.

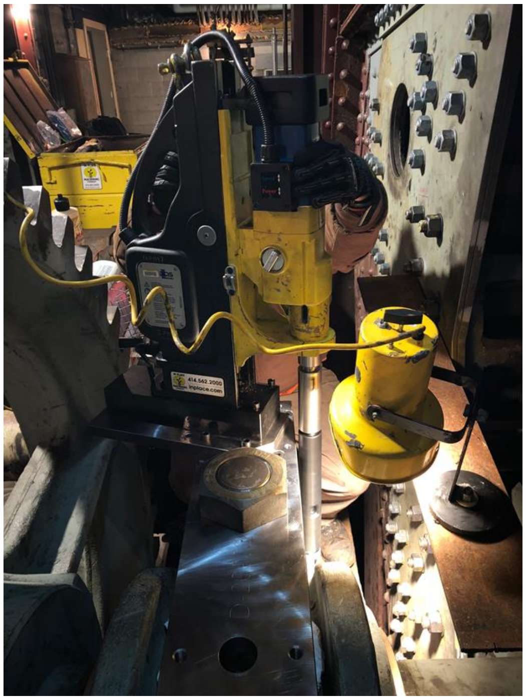


FIGURE 35. Field machining setup for reaming B1 bearing base stud holes.

FIGURE 36. Detail of fixture for reaming B1 bearing base stud holes.

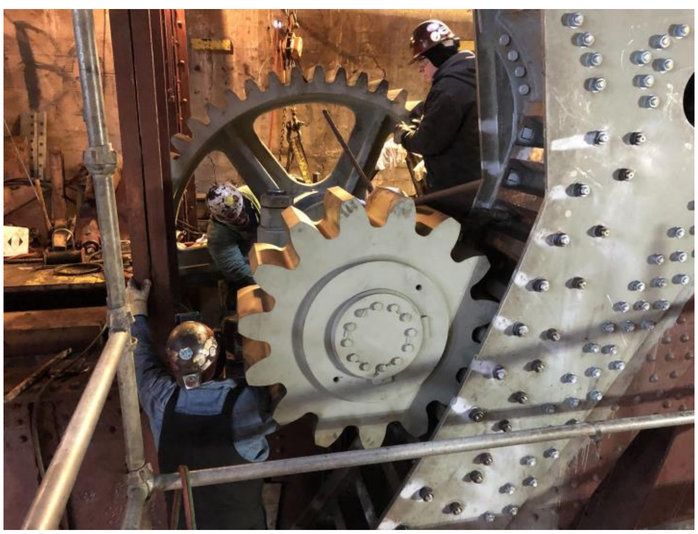


FIGURE 37. Completed repair with proper radial alignment. South assembly shown.

Bridge Balance Testing

Balance testing was performed via the dynamic strain gage method at the outset of the work in June 2017. Results are tabulated below.

Test Date: June 29, 2017						
Run	WR	Phi	Imbalance Seated		Average Friction	
	ft-lb	deg.	Moment (ft-lb)	Toe Reaction (lb)	Moment (ft-lb)	Toe Reaction (lb)
1	+683,171	-70.1	+232,652	2,041	+164,221	+1,441
2	+660,307	-66.1	+267,570	2,347	+187,223	+1,642
3	+634,373	-65.5	+263,144	2,308	+189,474	+1,662
AVERAGE	**+659,283**	**-67.2**	**+254,455**	**+2,232**	**+180,306**	**+1,582**

Notes:

1. Positive (+) imbalance indicates span heavy balance condition.
2. Positive (+) Phi is measured from horizontal on the channel side of the trunnion in the opening direction of leaf rotation.
3. Toe reactions are based on a perpendicular distance of 114 feet centerline of rotation to toe of the leaf

The leaf center of gravity was low resulting in a situation where there was a fairly typical imbalance moment when seated but a relatively high imbalance moment with the span open. The imbalance with the bridge open was greater than the imbalance with the bridge closed by a factor of 2.6. There is no benefit to having the imbalance increase to this extent and as such it was recommended to make ballast adjustments. The objective of ballast changes to the leaf was to bring the leaf center of gravity up, without much change to the toe reaction when seated. To accomplish this it was necessary to remove weight were practical from below the trunnions and add weight where possible above the trunnions. There were five different locations considered for adding or removing ballast as identified in Figure 38.

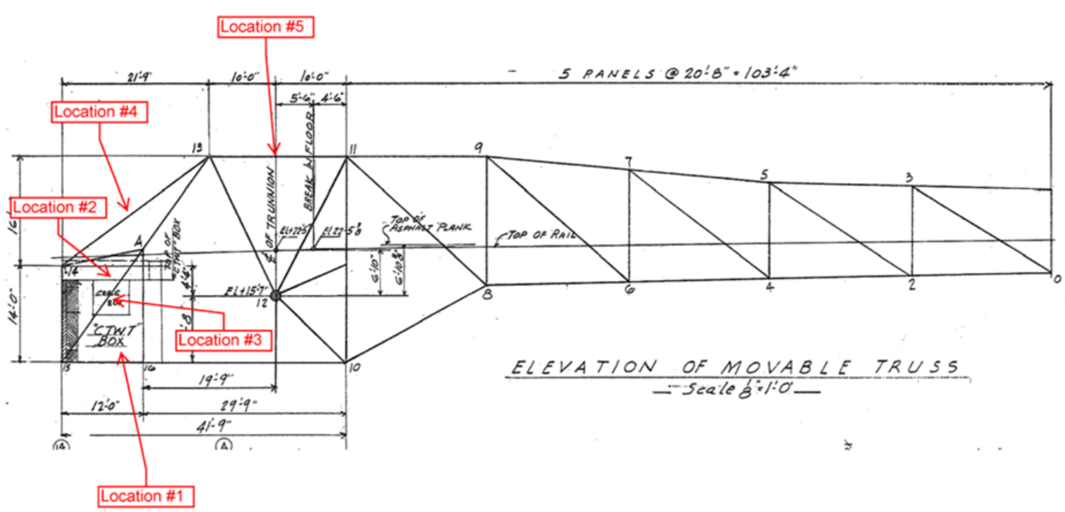


FIGURE 38. Possible ballast locations.

The engineering team determined the optimal position to add ballast weight to the span was within the truss upper chord members above the trunnion (Location #5 in the sketch). This ballast position causes the most effective change in vertical center of gravity position with the bridge seated because it is the highest point of the span. It also causes the least change in toe reaction with the bridge seated since it is located directly over the trunnion axis, and serves to counteract the problem of increasing imbalance as the bridge opens because the top chord member rotates from above to behind the trunnion as the bridge operates.

Ballast Design and Installation

With the location for the most effective ballast position identified, the engineering team evaluated the truss top chord members for modifications that were required to support the needed ballast. The original Truss Top Chord Member 13-11 is 20 feet long between gusset plate work points. This built-up riveted steel truss member is comprised of two built-up channel shapes (flanges pointing outboard), with a 20 inch tall by 3/4 inch thick plate acting as the vertical base of the shape. A 6x4x3/4 steel angle was added for the channel flanges at the top and bottom, and an 8 inch tall by 3/4 inch thick fill plate was installed between vertical toes of the steel angles to complete one half of the overall member. These built-up back-to-back channels were spaced at about 21 inches and were braced to each other near their gusseted end connections using batten plates and within the field of the member using lacing bars.

The ballast design concept was required to include future modularity of the system. In other words, CDOT required that portions of the ballast weight could be easily removed if the balance condition of the leaf required it due to future projects. The engineering team responded by providing a design with the following features:

- Bottom batten plates and lacing bars were removed and replaced with a 1 inch thick plate, full width and length of the member.
- A "keeper" system of steel angles was bolted to the interior surface of the new bottom plate that allows easy addition and removal of 1 foot cube steel counterweight blocks. These blocks are the typical weight adjustment medium used by CDOT forces, and were on hand for use. A total of eleven blocks could be installed in each truss member. This system is shown in Figure 39.
- Top batten plates and lacing bars were removed and replaced with segments of 1 inch thick plate, full width of the member. Each plate segment was just over 2 feet long. The plate segments, when butted tight together, ran the full length of the member.
- The 1 inch thick top plate segments were drilled to receive 4 inch thick and 2 foot wide steel ballast plates. These 4 inch thick top plates were drilled and tapped to receive an eye bolt for easy handling.
- All of the new materials were mechanically fastened to the existing truss member using high strength bolts.

FIGURE 39. Ballast arrangement shown within South Truss Member 13-11.

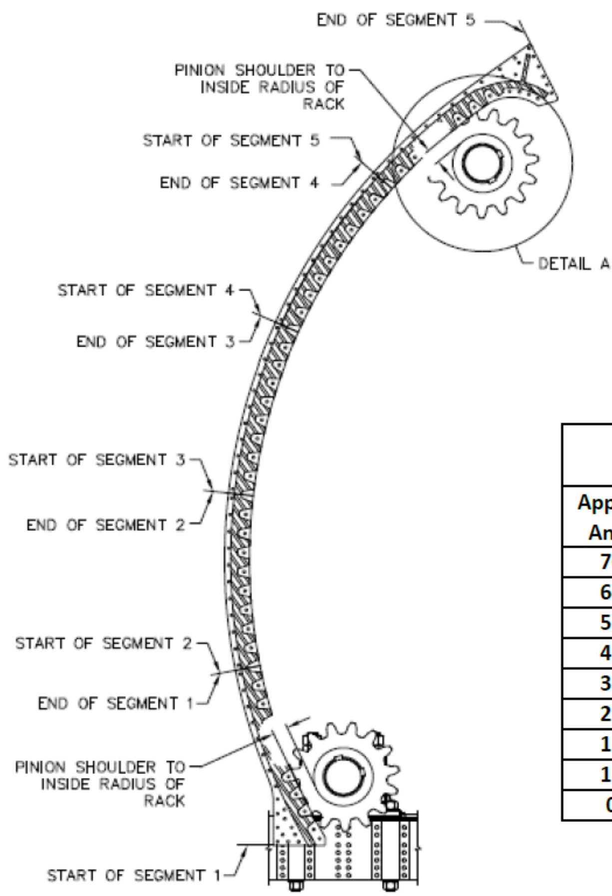
The total possible weight added using the above arrangement, in conjunction with the repair materials (new rack side plates, etc.) added to the bascule leaf, resulted in a calculated net increase in span weight of about 38,500 lbs. This net weight had a center of gravity positioned at an angle of about 107 degrees (above and behind the trunnion axis) at a distance of about 17 feet. The calculated superposition of this net weight change upon the performance curve from pre-construction testing indicated a new center of gravity location at about 1 degree above the horizontal with a toe reaction similar to the pre-construction condition. It should be noted that for any project, major changes in ballast such as those for this leaf, when installed, can produce unexpected results if the ballast weight is not accurate due to variations in material thickness, etc., or if the ballast center of gravity position is not as-designed.

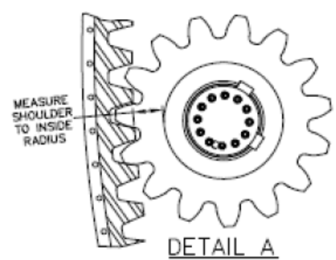
Commissioning of Repaired Bascule Leaf

An unusual feature of this repair was the fact that all of the machinery alignment work and a portion of the ballast adjustment work was undertaken with the leaf secured in the raised position due to the limited available marine channel closures. The first opportunity to see the results of the alignment and ballast adjustment work would occur during commissioning the week of January 22, 2018.

The results of the alignment checks performed during commissioning were considered a success:

- The maximum radial misalignment of the racks noted was 0.22 inches, a significant improvement versus the previous condition. See tabulated measurements below.





West Leaf Pinion Engagement Shoulder to Rack Inside Radius Measurements					
Approx. Angle	Location	south		north	
		shoulder	tip clr.	shoulder	tip clr.
70°	start of 5	5.75"	0.97"	5.75"	0.97"
64°	end of 4	6.00"	1.22"	5.81"	1.03"
51°	start of 4	5.75"	0.97"	5.81"	1.03"
47°	end of 3	5.91"	1.13"	5.84"	1.06"
33°	start of 3	5.97"	1.19"	5.78"	1.00"
29°	end of 2	5.97"	1.19"	5.78"	1.00"
15°	start of 2	6.00"	1.22"	5.63"	0.85"
11°	end of 1	5.94"	1.16"	5.84"	1.06"
0°	closed	5.84"	1.06"	5.78"	1.00"

min	0.97"	0.85"
max	1.22"	1.06"
	south	**north**

- Good alignment of the B1 and B2 bearings (Journal Blocks F and G in Figure 3) was restored.
- Good contact was achieved at both G2/P2 gear sets (See Figure 40).

Balance tests and live load shim adjustments were performed in conjunction with commissioning. Regular maintenance tasks such as greasing of the bridge center locks, trunnions, and open gear sets were also completed along with electrical systems maintenance.

The results of this work were successful in raising the angle to the center of gravity from -67 degrees to approximately 0 degrees so that the maximum span heavy condition was at the seated position and there was negligible imbalance in the raised position. The seated toe reaction was maintained at about 2,000 lbs. A photograph of the completed north truss is provided as Figure 41.

FIGURE 40. G2 Gear Contact Pattern.

FIGURE 41. View of completed north truss.

Summary and Conclusions

The West Leaf of the 92nd Street Bascule Bridge in Chicago, Illinois underwent two repair projects over the last seven years to improve the mesh of the operating pinion gears and their mating racks. Precision survey data collected in 2010 indicated that the center of the circle defined by the circumference on which the rack segments were set for both racks was in front of and below the trunnion axis. In addition, the radius of the circle and the position of the pinion shaft axes were not close to the original design drawings. These problems caused an unacceptable radial misalignment of the rack and pinion, causing accelerated tooth wear that eventually led to an inability to reliably operate the leaf.

Under the first project, which began in 2010 and was completed in 2012, the rack segments from both bascule trusses were removed, rehabilitated, and reinstalled. The existing pinion gears were removed from their shafts and replaced with new pinion gears. The new pinion gears for this project were fabricated with a special tooth form that was designed to best accommodate the observed variation in center distance and circular runout. This project was completed one rack/pinion gear at a time to minimize operational outages for both vehicular and marine traffic. The purpose of this project was to provide a temporary repair pending a major structure rehabilitation. Unfortunately, excessive wear of the new pinion gears again became a problem in 2017.

Under the 2017 rehabilitation project, the rack segments were removed and reinstalled at the proper center distance to address the root cause of the wear and reliability issues. The existing pinion gears were machined down to a tooth profile resembling that of the original bridge design. Other structural and mechanical engineering design and component installation challenges were overcome, and the bridge was successfully returned to service. This project was completed with the leaf restrained in the open position working both racks/pinions at the same time to minimize the duration of the work and operational outages for marine traffic. The total duration of marine outages for the project was a single 12 hour outage and a week of operation with a 2-hour notice. The success of the alignment work demonstrates the feasibility of utilizing precision alignments via precision laser measuring instrument to align machinery without requiring bridge movements for validation purposes. The use of full size steel templates for rack installation operations was also one of the keys to project success. Feedback from CDOT personnel is that 3 months post-repair the bridge is operating with no conditions of concern.