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106th Street Bascule Bridge Repairs

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Abstract

The 106th 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 (CDOT). 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 1927 and currently opens for vessels about 8,000 times per year. Operational problems for the west leaf resulted in interference between the northwest pinion gear and rack teeth in July 2018. An investigation project was undertaken to identify the root cause of the interference problem and to propose cost effective and constructible options to correct the operational issues and allow the structure to return to normal service for a minimum period of five to ten years.

A detailed rack and pinion tooth inspection was performed, followed by a precision survey to locate each rack tooth and the alignment of the machinery drive shafts with respect to the bridge leaf trunnions. The inspection and survey work determined that the existing northwest pinion shaft alignment was not level or parallel to the trunnion alignment. In addition, the entire northwest machinery frame was approximately 1/2 inch closer to the trunnion axis (horizontal plane) than specified in design. Significant wear and variable runout was observed on several of the existing rack gear teeth. The design team presented several repair options, including repair of the rack teeth, bushing and machinery frame repair scenarios, pinion gear replacement geometry options, and resulting electrical system modifications.

A repair project was undertaken to restore the original profile of each of the northwest rack teeth. This work was completed by building up each of the rack teeth in place by welding and then shaping to the desired tooth geometry. The entire northwest machinery frame was replaced with a new frame. The existing shafts were reused and fit to the new frame. All open gears were reused except for the pinion gear, which was replaced utilizing a design geometry similar to the original design.

During the work on site, it was determined that the leaf balance was poor and that the existing concrete counterweight box was in need of significant repair to extend its service life. An innovative repair approach was implemented with the goal of restoring the concrete counterweight structure and improving the leaf balance and center of gravity location.

This paper will discuss the challenges associated with welded repair of existing rack tooth castings in-place, the installation of a new machinery frame within the footprint of the existing frame, rehabilitation and reuse of existing machinery frame anchor bolts, alignment of the new machinery frame to the existing rack alignment, installation of counterweight repairs, and leaf commissioning.

Introduction

The 106th Street Bascule Bridge located in Chicago, Illinois is a two-leaf Chicago-type bascule bridge that carries two lanes of traffic eastbound and westbound over the Calumet River and was constructed in the late 1920s. The bridge is owned and operated by the Chicago Department of Transportation (CDOT). The structural bridge framing for each leaf consists of two trusses connected by lower chord lateral bracing members and floor beams, some of which are also trusses. The floor beams support an open steel grid deck for the majority of the roadway length. Filled or partially filled areas of the deck are located above the counterweight pit and adjacent machinery areas. The distance across the river between trunnions is 250 feet-6 inches providing a clear river opening of 220 feet between masonry. The main trusses are spaced at 42 feet. Sidewalks are present outboard of each truss. The bridge is typically opened to 65 degrees to facilitate the movement of marine vessels and operates approximately 8,000 times per year in this busy region of the river. Figure 1 is an elevation sketch of the structure taken from the design drawings.

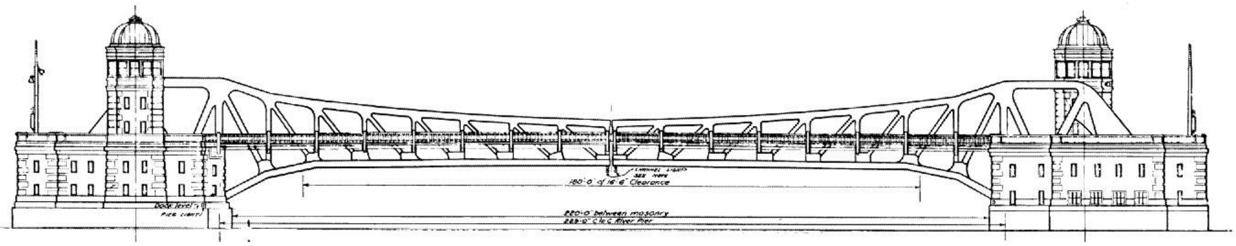

FIGURE 1. Bridge elevation sketch taken from design drawings.

Mechanically, each bascule leaf is driven by two main pinion gears that engage a circular rack mounted in each main truss behind the trunnions. The pinion gears are driven by independent drives consisting of open gears that sit in a machinery frame (Figure 2) supported by a reinforced concrete foundation outboard of the truss. The machinery frame also supports an electric motor that drives the open gearing. The weight of each span is balanced by a reinforced concrete counterweight that is located at the rear of the trusses into which steel support and truss bracing members are incorporated. When the bridge is closed each leaf rests on live load supports forward of the trunnions and mechanical center locks are driven to provide deflection continuity between the leaf toes.

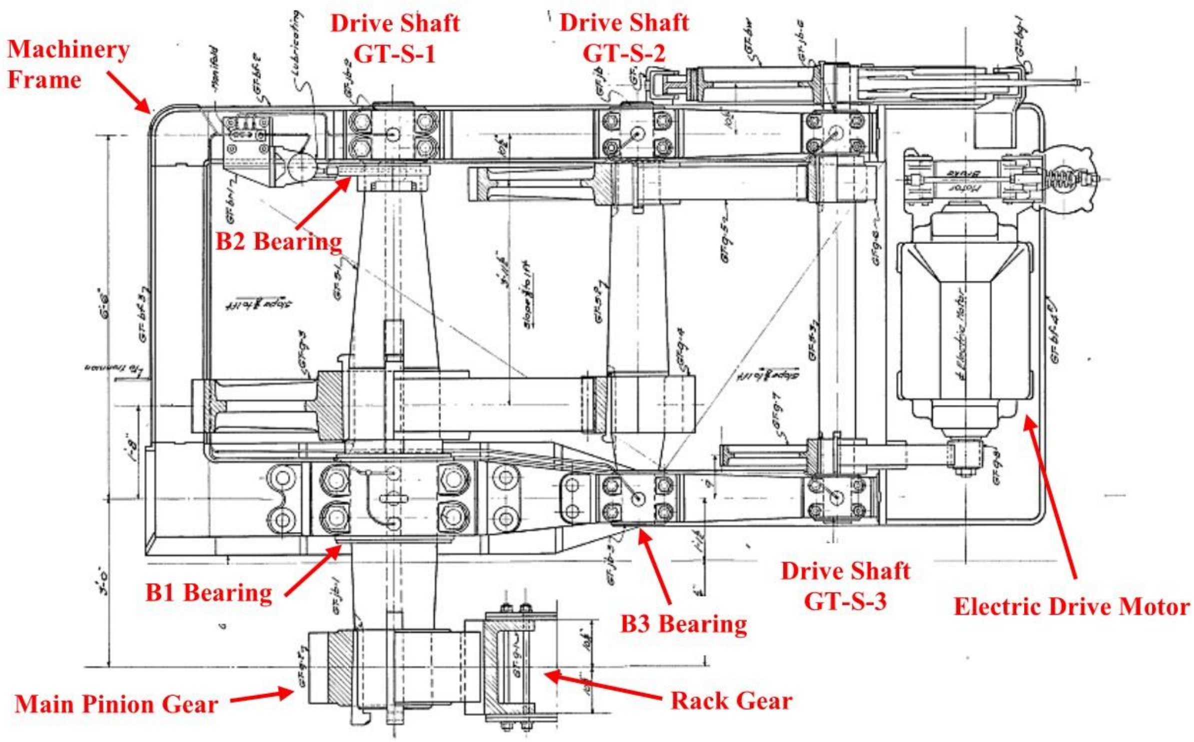

FIGURE 2. Typical machinery frame and drive train layout from original design drawings.

The bridge has a history of vessel allisions throughout its service life. These vessel strikes have caused various degrees of damage to the bridge structural members and mechanical equipment. One documented vessel strike and subsequent repair project that took place circa 1990 required major structural repairs to one of the main trusses, realignment of trunnion bearings and machinery components, and reinstallation of fractured anchor bolts. Another more recent vessel allision caused major damage to one of the cast steel machinery frames including several wide cracks. Due to pressure to reopen the bridge to traffic, temporary repairs included realigning the machinery in the frame to as optimal a position as possible and welding to repair the frame. A new welded steel machinery frame was ordered from a fabricator and delivered to the owner, but never installed due to funding and schedule constraints.

Over time, the suboptimal alignment between the pinion gear and bridge rack at the damaged/repaired machinery frame caused severe gear tooth wear on the pinion and rack components. This advanced wear eventually led the northwest pinion gear teeth to interfere with the mating rack gear teeth toward the bottom of the rack (leaf in the nearly seated position). Following the interference issue, the northwest pinion gear and shaft were removed from service and a contracting and engineering team were engaged to develop and implement emergency repairs.

Initial Inspection Findings

The four racks, consisting of five segments each, were evaluated over a series of three site visits. See Figure 3. Rack teeth (RT) were designated as RT1 through RT46 from the bottom of the rack to the top. Excessive pack rust and debris were typically located on the teeth toward the bottom of each rack. RT3 through RT39 are typically engaged during normal bridge operations and were inspected up close for any defects. RT40 through RT46 are located above the typical rack teeth that are engaged during normal bridge operations. These teeth were not inspected up-close, but were visually reviewed from the machinery frame.

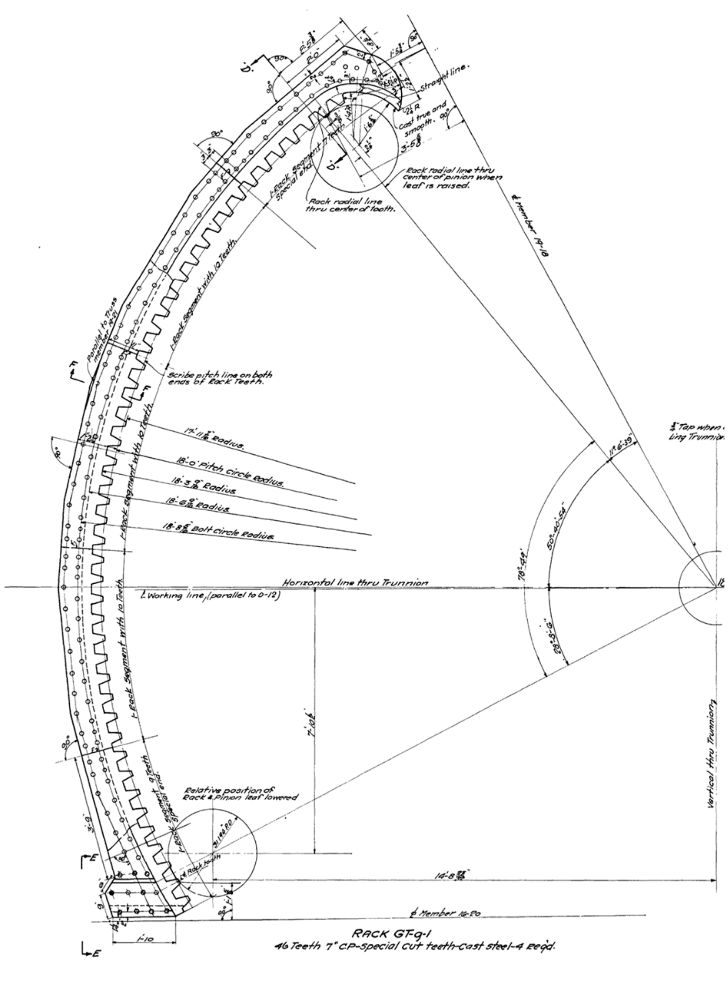

FIGURE 3. Rack orientation.

A cursory inspection of the four racks (2 per leaf), the pinion gears, and the B1 bearings was conducted on July 20, 2018. The purpose of this examination was to determine if any gross defects exist in the rack teeth, the pinion teeth, or the B1 bearing housings and fasteners following the rack tooth/pinion tooth interference that occurred at the northwest rack and pinion. The following observations and measurements were recorded during this site visit:

- No major cracks or large casting defects were observed on any of the rack segments. Typical rack tooth wear in areas other than the bottom ten teeth of northwest rack is shown in Figure 4.
- The interference between the northwest rack and pinion caused severe damage to the rack teeth toward the bottom of the rack. RT4 appeared to have suffered the worst damage. However, RT2 through RT8 showed evidence of significant recent tooth wear/damage as a result of the incident, as shown in Figure 5.

FIGURE 4. Typical rack tooth wear.

- The northwest pinion tooth that appeared to mate with RT4 also exhibited significant damage and is shown in Figure 6. Typical northwest pinion tooth wear is shown in Figure 7.
- The B1 bearing for the northwest pinion shaft exhibited a broken southeast bearing cap stud. The stud fractured at an existing fatigue crack in the threaded region at the bottom of the stud, at the interface between the square nut and the bottom of the housing assembly. The fracture surface appeared to have been recently exposed since it exhibited a limited amount of surface corrosion, as shown in Figure 8. No other B1 bearing cap studs or base bolts were observed to be broken; however, several inches of each bolt/stud length were occluded from direct view. Nondestructive testing was not performed to investigate the volumetric integrity of these items.

FIGURE 5. Severe northwest rack tooth damage.

- Basic root-to-tip measurements (pinion tooth root to rack tooth tip) were recorded from the four rack/pinion meshes with the bridge leaves raised. These measurements were taken using a ruler or steel scale, resulting in limited precision. The southwest, northwest, southeast, and northeast measurements were 1-1/4 inches, 2-3/8 inches, 9/16 inches, and 15/16 inches, respectively. Note that the specified design value for this measurement is 13/16 inches.

- The northwest machinery frame contained obvious repair welds near the support of the pinion shaft bearings that were reportedly installed several years ago.

FIGURE 6. Significant damage to northwest pinion gear tooth.

An in-depth, up-close inspection of the rack teeth for the north and south racks of the west leaf was performed on July 24, 2018. The purpose of this examination was to clean the majority of debris and pack rust off of the existing rack teeth for a more accurate determination of the existence of any large defects. Fine defects such as short cracks, if any, could not be identified readily due to surface conditions. Basic measurements of the rack tooth top land and circular pitch were collected during this examination. The following observations and measurements were recorded during this site visit:

- Rack tooth top land measurements for the southwest rack in the operating range generally varied from about 1-1/2 inches to 1-7/8 inches. Minimum top land measurements of 1-5/16 inches to 1-7/16 inches were recorded on RT3 and RT4, respectively. Circular pitch measurements for these rack teeth varied from about 6-7/8 inches to 7-1/8 inches.

FIGURE 7. Typical northwest pinion tooth conditions.

- Rack tooth top land measurements for the northwest rack in the operating range generally varied from about 1-3/8 inches to 1-3/4 inches. However, the top land measurements for RT3 through RT7 varied from 13/16 inches at RT3 down to 0 inches at RT4, and then up to 1/2 inch at RT5, 9/16 inches at RT6, 7/8 inches at RT7, and 1-5/16 inches at RT8. The pinion gear has 14 teeth, and while the rack tooth top land measurements for the remainder of the rack (RT9 through RT39) are in the "general" range given above, a noticeable reduction in top land tooth dimension is concentrated about each turn of the pinion gear for rack teeth that are multiples of RT4. Circular pitch measurements for these rack teeth varied from about 6-3/4 inches to 7-1/4 inches.

- No significant cracks or other defects in the rack tooth castings were observed.

Basic root-to-tip or center distance measurements were recorded for the north and south racks and pinions of the west leaf on July 26, 2018, with the bridge operated by CDOT personnel. The following observations and measurements were recorded during this site visit:

FIGURE 8. Failed B1 bearing bolt.

- Three root-to-tip measurements were recorded for the southwest rack and pinion engagement using a small flexible steel scale. These were taken with the bridge open, the bridge closed, and about half-way through the travel of bridge operation. The measurements were generally consistent and varied from about 1-5/8 inches to 1-3/4 inches. Note that this range is slightly different than the 1-1/4 inches measured on July 20, 2018, with the bridge in the raised position.
- Three basic measurements of center distance between the northwest rack and pinon were recorded. At the time of the measurements, the northwest pinion gear had been removed from service and cribbed up on its B1 bearing housing base. A steel tape measure was used to measure the distance from the edge of the pinion shaft bore hole to the face of three rack teeth for the same bridge positions noted above. The mid operational distance and bridge open measurements were consistent, while the bridge closed measurement was larger by about 7/8 inches.

The collected measurements at the north rack and pinion location indicate that the root to tip clearance in the vicinity of RT4 was 3-1/4 inches resulting in an engagement depth of 11/16 inches compared to a design engagement depth of 3-5/16 inches or 21% of the originally specified engagement. This combined with the rolling action of the gears and gear tooth wear were sufficient for the rack and pinion to disengage. Design rack and pinion geometry is shown in Figure 9.

With the northwest rack pinion cribbed up and out of the way of potential interference with the mating rack, CDOT resumed operation of the west leaf using only the southwest span drive machinery.

As part of the initial investigation, strain gage balance testing of the west bascule leaf was conducted on August 13, 2018. The testing revealed a seated imbalance of 4,893 lb measured at the toe of the bridge at an angle of -20 Degrees relative to horizontal resulting in a maximum imbalance of 5,200 lb during operation of the bridge. Recommendations were made to reduce the imbalance to a maximum of 2,000 lb in order to reduce machinery loads.

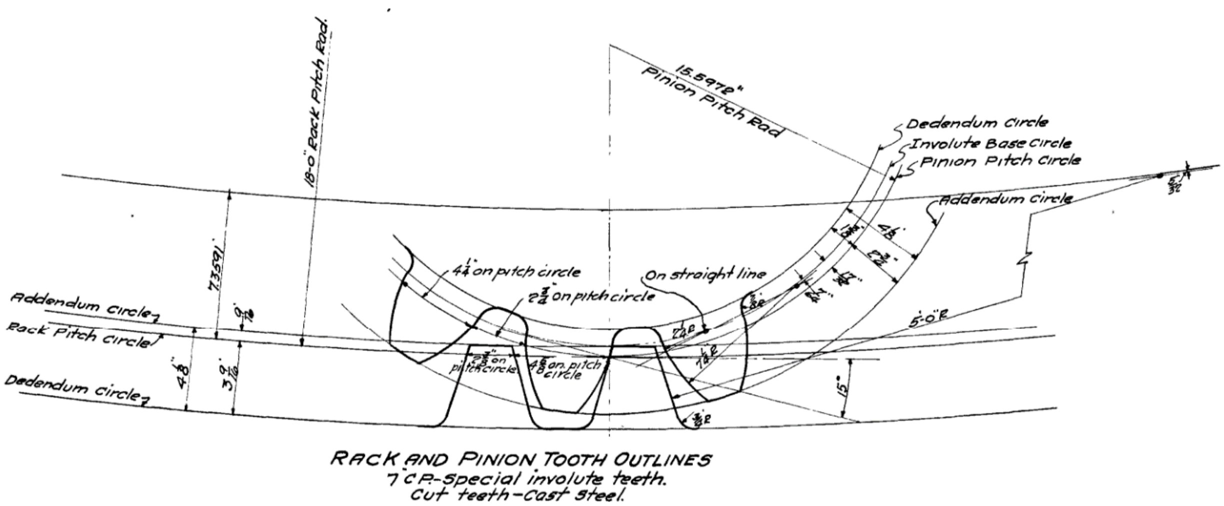

FIGURE 9. Design rack and pinion geometry.

Analysis and Development of Emergency Repair Options

Following the initial investigation, options were developed and analyzed to varying degrees for the purpose of increasing the rack tooth engagement of the northwest rack and pinion. The following options were considered and are presented in order of increasing project risk associated with cost and schedule, but also with increasing probability of extended service life.

1. Modify the geometry of the rack pinion teeth at the northwest quadrant to provide teeth with a longer addendum and greater engagement. While this solution provided for greater engagement, the gear tooth geometry required to provide satisfactory engagement was detrimental to the performance of the gears and would have likely result in accelerated gear tooth wear.

2. Increase the diameter of the northwest rack pinion by designing a new pinion with one additional tooth. This would increase the pinion diameter by 2.2 inches and increase the pinion engagement by 1.1 inches. Additional design modifications may have been required to optimize engagement but the primary increase in engagement was due to the increase in the number of teeth. This option would result in gear tooth geometry similar to the existing gear tooth geometry and therefore the gear teeth were not expected to experience accelerated wear. However, operational testing and possible electrical/mechanical adjustments would need to be investigated and implemented in order to ensure proper load sharing between the two motors that drive the leaf.

3. Replace the existing machinery frame at the northwest quadrant with a new frame that CDOT had in storage, delivered in response to the vessel allision that resulted in repair welding of the existing frame. This option, although a very good option, required the most work, the most time to implement, and the highest construction and engineering costs. CDOT chose to forego this option unless the existing frame was found to require replacement based on the results of an inspection that had yet to be performed or if no other suitable option existed.

Each of the above options required repair to the damaged rack teeth. The proposed method of repair was to build the existing rack teeth up with weld metal and profile the teeth in the field by grinding. Due to the large rack radius, the rack teeth were essentially flat sided which would make profiling easier than a tooth with a curved surface.

CDOT initially requested that the engineering team study Option 2 based on our assertion that this was a viable option and one that, although not the best, would likely produce acceptable results with the goal of implementing an emergency repair scheme that could return the bridge to reliable service while programming for a more substantial rehabilitation could take place.

To our knowledge no one has ever tried to operate a bascule bridge with independent drives having different gear train ratios. The addition of one more tooth on the rack pinion changes the gear train ratio by 15/14 or 7%. In other words, for the same motor speed, the north drive would be trying to drive the west bascule leaf 7% faster than the south drive. Obviously, the bridge could not rotate at two different speeds. Therefore, the electrical components would need to compensate for the two different drive train ratios.

A study conducted by our electrical engineers determined that the variation in motor loading due to the variation in rack pinion teeth would be limited to 22% assuming otherwise identical drive setups for the northwest and southwest drives. The theoretical analysis was done for varying motor speeds based on motor manufacturers furnished characteristic curves and information regarding the bridge drive system provided on the original as-built electrical drawings. A typical motor characteristic curve is shown in Figure 10. Knowing that the motors for the west leaf would be rewound as part of the work and with the opportunity to conduct testing of similar equipment on the east leaf, we remained confident that the 15 tooth pinion solution was viable.

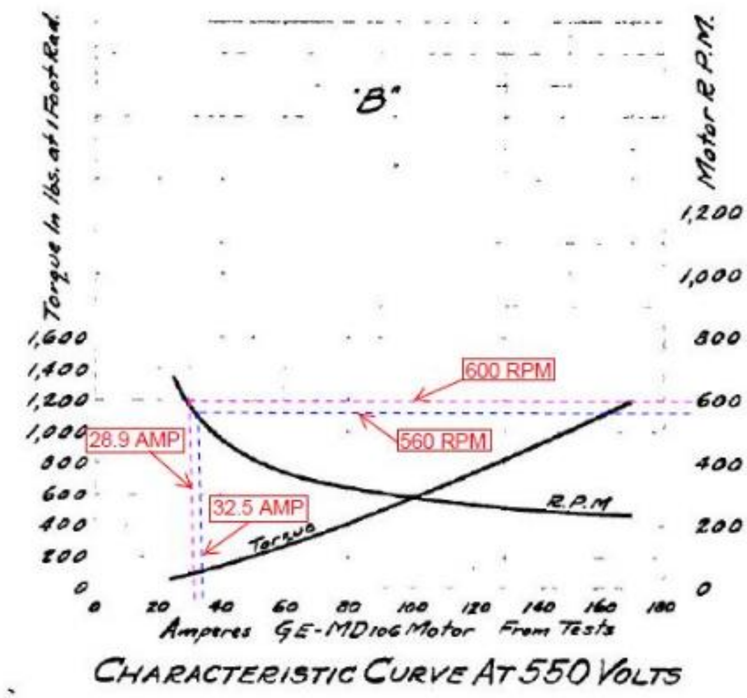

FIGURE 10. Motor characteristic curve.

Southwest Pinion Shaft Failure

With the northwest rack pinion out of service, CDOT continued to operate the west leaf of the bridge using only the southwest drive machinery. Compared to operating the machinery with both drives, the loads in the southwest drive were roughly twice as high as they would have been with both drives operating. This proved to be too much for the machinery to handle and on or about November 26, 2018, the southwest drive machinery experienced a catastrophic failure.

FIGURE 11. Southwest drive train failed shaft.

FIGURE 12. Southwest drive train failed bearing bolt.

Photos taken by WJE on November 27, 2018, show a complete fracture of one of the machinery shafts and failed bearing bolts. A large crack in a machinery shaft is shown in Figure 11 and a failed bearing mounting bolt is shown in Figure 12.

This failure left the bridge in the closed position and inoperable which was unacceptable to marine traffic. In order to keep marine traffic flowing, a decision was made to use the similar shaft from the northwest span drive machinery and relocate it to the southwest span drive machinery to restore operation of the west bascule leaf. This work was completed, and the west leaf was then operated and secured in the raised position by December 10, 2018. The bridge remained in the open position with the roadway detoured until all emergency repairs were complete. See Figure 13.

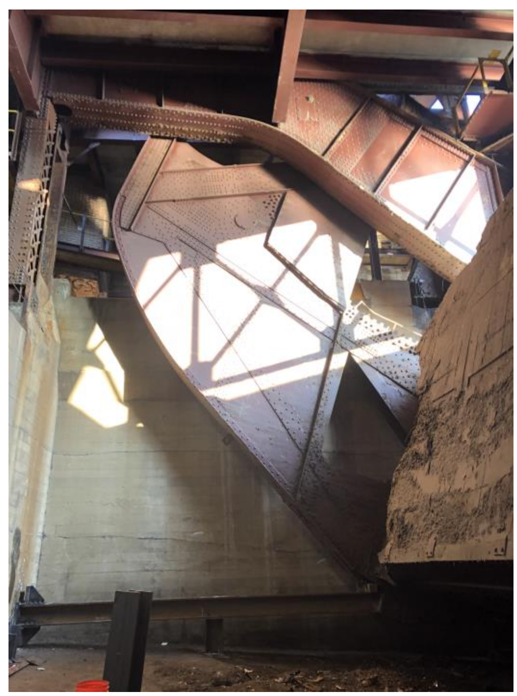

FIGURE 13. Strut holding bridge open

NW Machinery Frame Inspection

A detailed inspection of the existing northwest machinery frame was completed to assist in the assessment of its fitness for future service. The frame supports three open gear shafts, the drive motor, and brake components as shown in Figure 2. Visual and nondestructive testing of the frame were completed following cleaning by sandblasting. Visual inspections were aided by Magnetic Particle Testing (MT) to investigate any visually identified defects. In general, widespread cracking, pitting, and minor to severe section loss was observed (Figure 14). Cracks in the frame components were typically observed at the transitions in the casting between vertical stiffeners and the frame bottom and/or top flanges in the area of the B1 Bearing and along the frame segment closest and parallel to the seawall. Cracks were also observed in the casting around the base of the B1 Bearing. In addition, several repair welds observed on the frame were judged to be of poor quality. However, these repairs were found to be largely intact. The result of these findings was a recommendation to remove the existing deteriorated machinery frame from service due to its condition. However, alignment data for and within the frame was also obtained for further evaluation.

FIGURE 14. Machinery frame cracks and pitting.

Precision Survey

In order to further assess the current condition of the machinery on the west leaf a precision survey was conducted. Falk/PLI conducted the survey, with direction from WJE on December 10 and 11 2018. The survey included both the northwest and southwest machinery. The survey was conducted with the west leaf shored in the open position and survey data was referenced to a line that passes through the outboard end of the two trunnions that support the west bascule leaf.

The purpose of the precision measurement data assessment was to:

- Determine the position and alignment of the northwest machinery frame shafts/bearings.
- Determine the position of the northwest rack teeth with respect to the trunnion alignment.
- Determine the position and alignment of the southwest pinion shaft.
- Determine the position of the southwest rack teeth with respect to the trunnion alignment.
- Discuss how this measurement data affects any project-related engineering recommendations.

The survey showed that the northwest machinery frame was globally both higher and closer to the river than indicated on the original design drawings. Based on the data it appears that the horizontal offset may have been about 0.5 inches and the vertical offset about 0.3 inches. This may have been due to original rack and pinion alignment considerations. The survey also shows significant variations in the frame itself which are well outside of machine shop tolerances, indicating distortion of the frame since original installation.

Figures 15 and 16 show the variations in the machinery frame. While there is some distortion evident at all shaft/bearing locations, the most obvious distortion is at the rack pinion shaft bearing B1 where the survey shows a horizontal shift of 0.853 inches and vertical shift of 0.595 inches. Both of these variations are more than 0.200 inches greater than the variation of the other bearings at this side of the frame. Additionally, the horizontal and vertical slopes of the rack pinion shaft are 0.050 inches per foot or more than twice the slope of the other shafts in the machinery frame in both directions. The distortion of the frame is consistent with the force vector that would be resisted by the frame during a major rack and pinion tooth interference event.

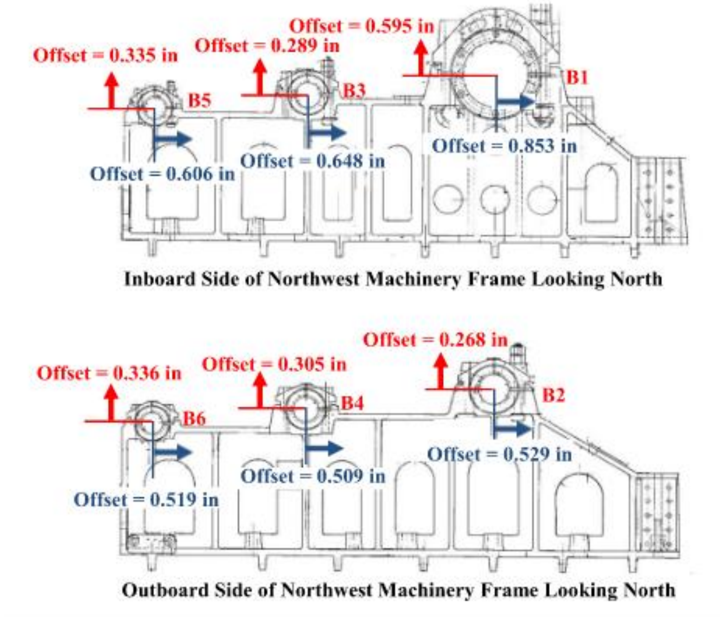

FIGURE 15. Variations in machinery frame geometry.

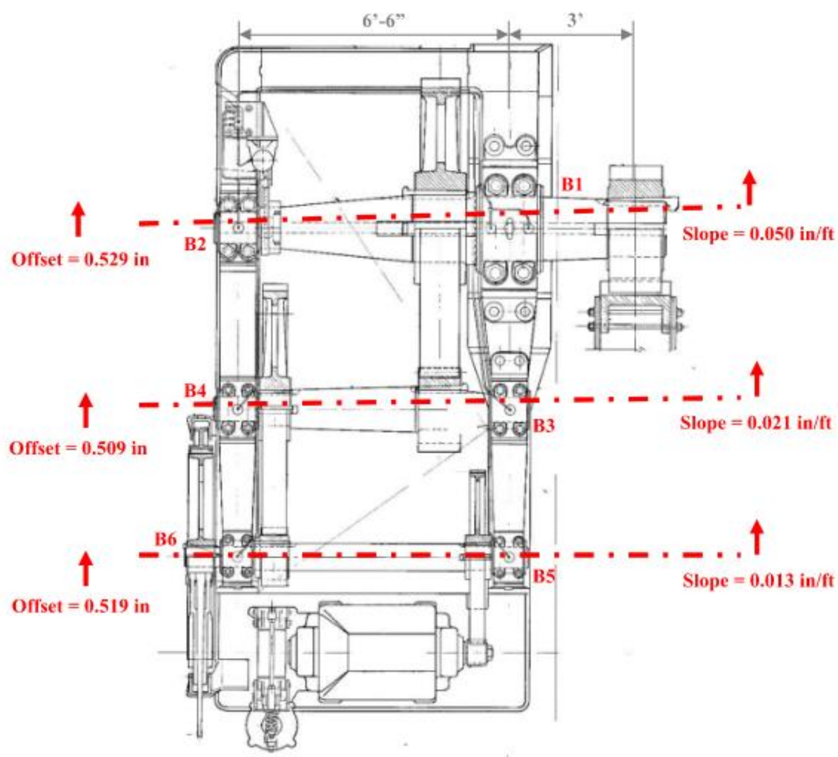

FIGURE 16. Variations in machinery frame geometry.

The survey showed that the position of the northwest rack pinion was 1.227 inches closer to the trunnion than indicated on the original design drawings. Since the pinion is internal to the rack, this results in greater separation of the rack and pinion than intended.

The survey of the northwest rack included RT 2 (near the closed position) through RT44 (near the open position) with measurements being tracked at the top land of the teeth. Where accessible measurements were taken at both ends of the teeth. Figure 17 shows the deviation of the location of the rack teeth compared to the design drawings. The teeth nearest the fully closed position were approximately 1 inch farther away from the trunnion reference line than indicated on the design drawings while the teeth near the fully open position of the rack were nearly the same as shown on the design drawings. Therefore, at the fully closed position the rack and pinion teeth were separated by about 2 inches more than shown on the original design drawings.

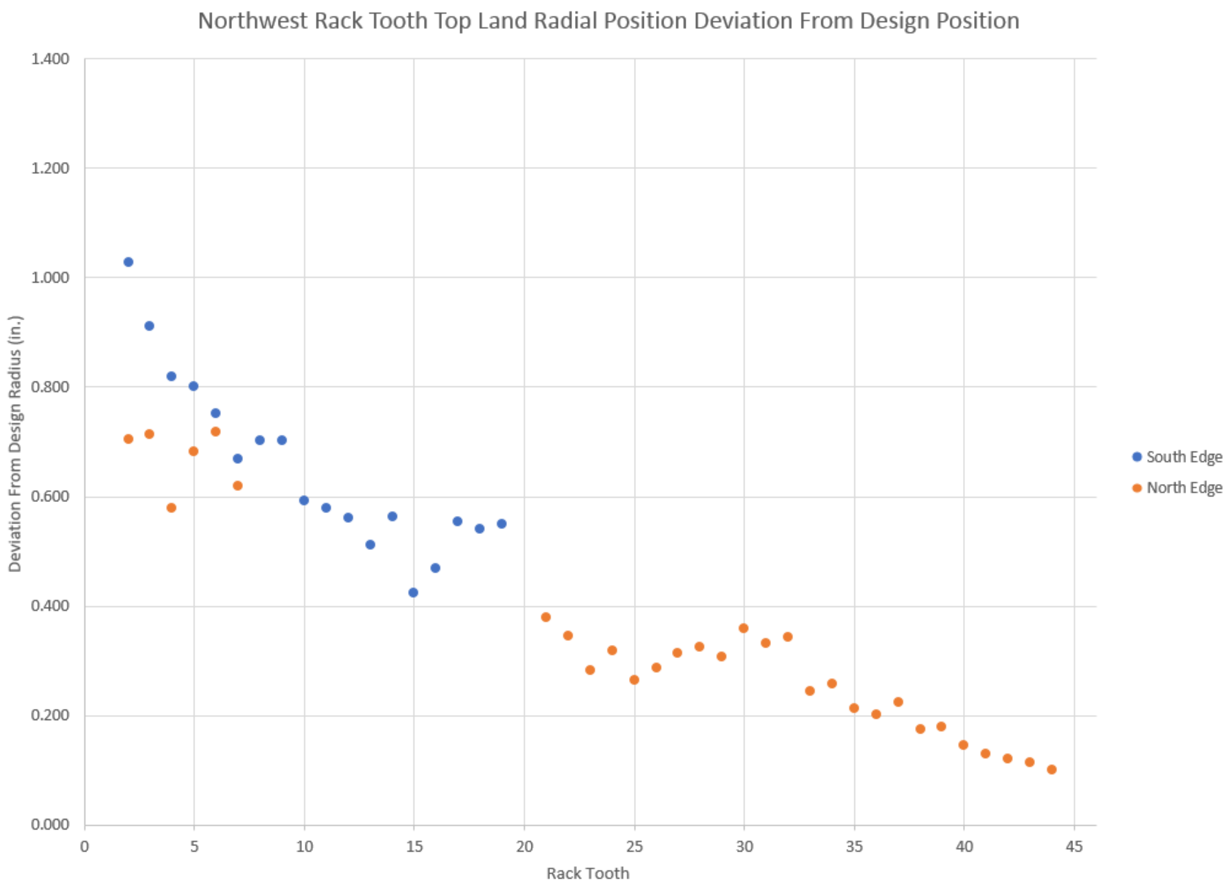

FIGURE 17. Northwest rack tooth radial position deviation from design.

The survey showed that the position of the southwest rack pinion was 0.049 inches farther from the trunnion than indicated on the original design drawings. Since the pinion is internal to the rack, this results in less separation of the rack and pinion than intended.

The survey of the southwest rack included RT2 (near the closed position) through RT39 (near the open position) with measurements being tack at the top land of the teeth. Measurements were taken at outboard ends of the teeth. Figure 18 shows the deviation of the location of the rack teeth compared to the design drawings. The teeth nearest the fully closed position were approximately 1.3 inches farther away from the trunnion reference line than indicated on the design drawings while the teeth near the fully open position of the rack were about 0.4 inches farther away than shown of the design drawings. Therefore, at the fully closed position the rack and pinion teeth were separated by about 1-1/4 inches more than shown on the original design drawings. This resulted in the southwest rack pinion having 3/4 inches more engagement than the northwest rack pinion.

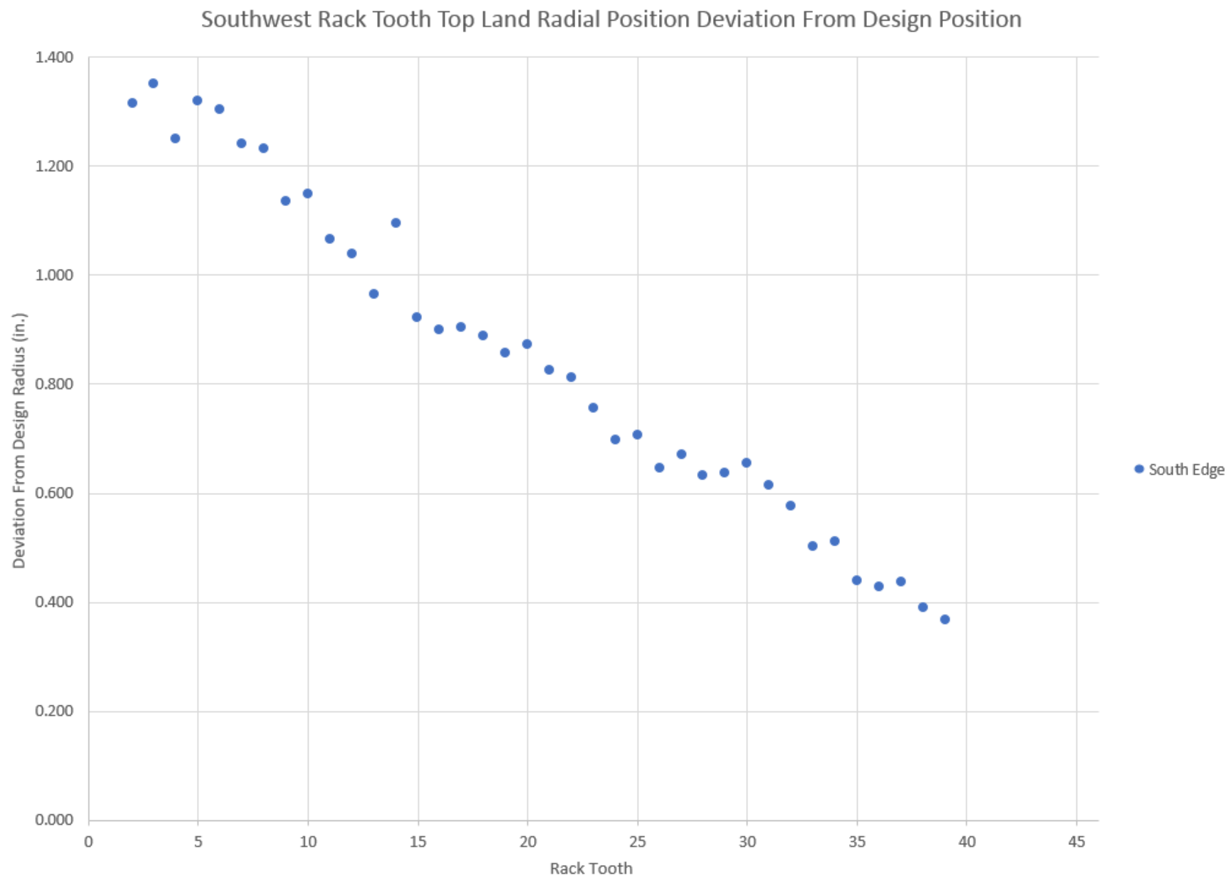

FIGURE 18. Southwest rack tooth radial position deviation from design

Based on the results of the survey an analysis of the worst possible northwest rack and pinion mesh was undertaken. The root to tip clearance was modeled as 2.715 inches as shown in Figure 19. This allowed for enough tooth engagement that with the pinion driving the rack, interference at the top land was not an issue however under a back driving scenario (rack driving the pinion) interference was likely. This was not acceptable.

Modifying the pinion tooth form had been previously explored and was not considered viable due to the potential for accelerated wear.

Given the poor condition of the northwest machinery frame documented through physical inspection as well as a precision survey, WJE strongly recommended that the northwest machinery frame be replaced with the frame that CDOT had available. Based on CDOT's desire to leave the racks in place, the frame replacement would be combined with weld repairs to the northwest rack segments to restore the rack teeth to their original profile.

Because of restrictions related to emergency repair work, repairs to the southwest rack and pinion could not be justified and WJE recommended no repairs at the southwest rack and pinion at the time but indicated it would be prudent to address the problem in a future capital project.

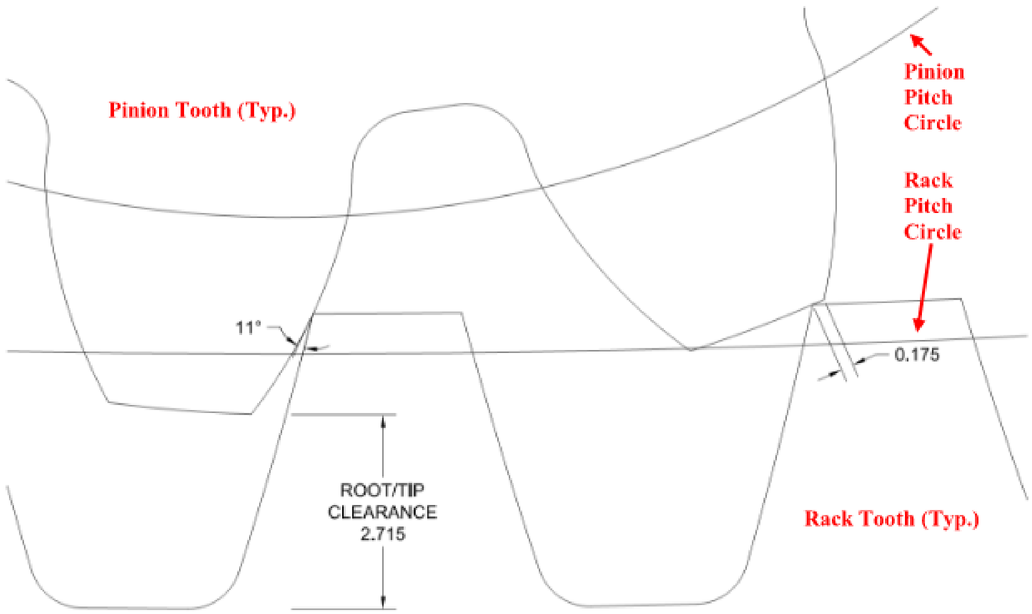

FIGURE 19. Rack and pinion mesh model.

CDOT accepted WJE recommendations and work began to implement the required repairs which included the following:

- Replace failed shaft and bearing mounting bolts at the southwest quadrant.
- Replace the northwest machinery frame with the machinery frame owned by CDOT. This frame was procured years ago as a replacement for the northwest machinery frame and was never installed.
- Weld repair the northwest rack teeth.
- Counterweight modifications to reduce machinery loading.

NW Machinery Frame and Component Inspection and Repairs

FIGURE 20. Frame at storage location.

Many years ago, CDOT procured a replacement machinery frame for the northwest quadrant and this frame was never installed. The frame was essentially the same as the existing frame but was of welded steel construction instead of the original cast steel construction. The frame was sitting in a CDOT yard and was initially inspected in August of 2018. At the time of the initial inspection, the frame appeared to be in serviceable condition despite having been stored outside for many years. See Figure 20.

The frame was manufactured by Steward Machinery Company (SMC) and fortunately the shop drawings for the newer frame were available to the engineering team.

The drawings were checked versus the original design drawings for the existing frame and found to be dimensionally compatible. The bearings in the frame were undersized so that clean up to the dimensions of the existing shafts was required prior to shaft installation.

The frame was shipped to SMC in Birmingham, Alabama along with other components required to return the bridge to service. The following components were inspected by both SMC and WJE:

- New span drive machinery frame for the north side of the west leaf.
- Low speed (rack pinion) shaft for the machinery frame.
- Intermediate shaft for the machinery frame.
- High speed (brake wheel) shaft for the machinery frame.
- Gear and pinion for the intermediate shaft for the span drive machinery at the south side of the west leaf.

All of the machinery was found to be in serviceable condition and WJE provided a report for recommended repairs and testing. All of the work went according to plan with the exception that the brake wheel was replaced after finding numerous cracks in the existing brake wheel casting. A summary of the work performed at SMC is as follows:

- Rehabilitate machinery frame.
- Provide new rack pinion.
- Rehabilitate existing northwest rack pinion shaft and mount new pinion on shaft.
- Provide replacement shaft for failed southwest span drive machinery shaft and mount existing gears on new shaft.
- Provide new machinery brake wheel for northwest span drive machinery and mount on existing shaft.
- Hand polish all machinery shaft journals.
- Assemble northwest machinery frame and confirm proper alignment and test for free rotation by hand.
- Mount and align rewound span drive motor to the frame.
- Clean and paint all machinery.

All work was complete by SMC in early June of 2019. Figure 21 shows the northwest machinery frame in the final stages of assembly in the shop.

FIGURE 21. Machinery frame during shop assembly.

Rack Weld Repairs

Existing wear on the northwest rack teeth was repaired by depositing weld metal on the faces of each tooth to build up the section past the original geometric profile, and then hand grinding back down to the desired original tooth design profile. The process of welding on existing cast steel teeth originally construction in the late 1920s required a review of the material chemistry, which was performed using shavings obtained from representative areas of the casting segments in the field. A welding procedure was developed using this information and best practices learned from experience on past similar projects. The welding procedure required that shielded metal arc welding (SMAW) or “stick” welding was utilized due to the ability of the process to create good penetration and the tolerance of embedded impurities. An elevated preheat and interpass temperature of 300 Degrees Fahrenheit was required, with a maximum interpass temperature of 400 Degrees Fahrenheit. A 2 hour bake-out at the preheat temperature was also required to encourage migration of any hydrogen trapped in the new welds. A series of templates cut to the original tooth profile of several consecutive teeth were used to ensure that the welding process did not affect the pitch of the teeth along the length of the rack.

Once the teeth were built up using the welding process, they were ground back down by hand to the desired profile. This process used electric power driven grinders with stone wheels to achieve rough results, followed by sanding disks that were used to finish the tooth profile and result in acceptable surface finish. Finishing templates were used to ensure that the correct tooth profile and pitch were achieved as the finished product (Figure 22).

FIGURE 22. Rack tooth template.

Counterweight Repairs

The west leaf counterweight consists of a concrete counterweight with embedded plate girders and truss members that form the overall counterweight frame. According to the original design drawings, the rear portion of the counterweight was to be filled using a 290 lb./cu. ft. composition concrete mixture (steel punchings mixed with normal weight concrete) while the remainder of the volume was to be filled using 170 lb./cu. ft. lead slag concrete. Lower and upper pockets in which removable cast iron counterweight blocks could be stored were also included in the original design. A section view of the original design is shown in Figure 23.

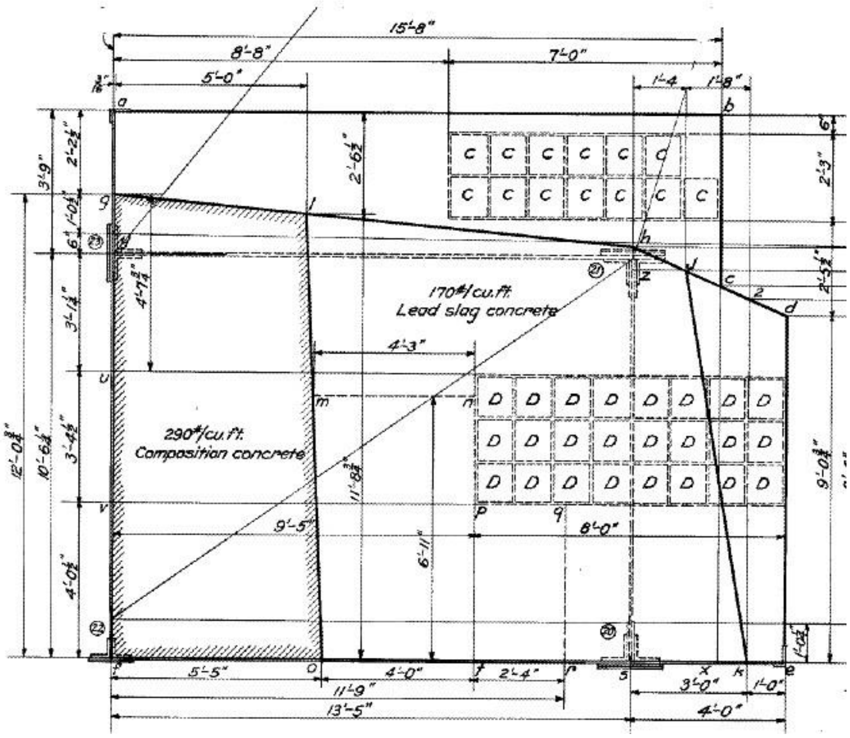

FIGURE 23. Counterweight section from original bridge design drawings.

A thorough visual inspection was completed to determine the extent of concrete deterioration. In addition, materials samples were removed by coring to examine and characterize the depth and extent of concrete cracking, delaminations, and freeze/thaw damage. Representative concrete conditions are shown in Figure 24. In general, the composition concrete mixture was typically loose, and exhibited deterioration consistent with freeze/thaw damage, as well as possible poor proportioning of the original mixture, whereby the density of the steel punchings was too great, and the cement paste was not able to adequately fill the voids between the punchings. The lead slag concrete mixture was found to be in comparatively better condition at the surface with less evidence of freeze/thaw damage, but exhibited large concrete spalls, delaminations, wide cracking, and poor consolidation. Due to the nature and extent of the existing deterioration, it was recommended that selective demolition to remove loose and damaged areas of the concrete counterweight be completed and that an innovative approach to both encapsulating vulnerable concrete and raising the counterweight center of gravity be developed.

FIGURE 24. Typical counterweight concrete conditions.

Following removal operations, formwork was installed, and the upper forward portion of the counterweight box was restored to its approximate original dimensions. Following this work, a series of steel topping plates were installed, and field welded together to result in a solid steel “roof” for the concrete counterweight box. These plates served to encapsulate the remaining exposed original concrete on the top surface of the counterweight box and also to raise the counterweight center of gravity which was advantageous for the leaf balance. Once the steel topping plates were installed, a cementitious grout material was pumped to fill any voids between the new topping plates and the concrete surface below. To allow effective further future weight adjustment, a series of stiffened angles were welded to the top of the counterweight roof plates. This allowed attachment of cast iron counterweight blocks at the most advantageous position.

Northwest Machinery Frame Installation

The existing damaged northwest machinery frame was removed from the site and scrapped. Once the cast frame was out of the way, partial demolition of the supporting concrete was undertaken. One goal of the partial demolition was to remove enough concrete to allow installation of the new frame at a lower elevation to promote better engagement of the new pinion gear with the existing rack teeth. Another goal was to expose the existing machinery frame anchor bolts to a depth that would allow them to be cut off and threaded. A coupler nut and anchor bolt stub were later installed to accept the new machinery frame. This allowed reuse of the embedded portions of the anchorage within the existing foundation and eliminated the corroded portions of the existing anchor at its attachment to the old frame. Each anchor bolt and coupling nut were tested in situ by proof loading the anchors using a center-hole hydraulic ram (Figure 25). Load and displacement were monitored during each test.

FIGURE 25. Machinery frame anchor bolt proof testing using center-hole hydraulic ram, load cell, and displacement measuring device.

Once the anchor bolts were repaired, the new machinery frame with all gearing components installed was lowered into position and temporarily supported at the prescribed elevation. The mesh of the pinion gear with the corresponding rack teeth was evaluated and minor adjustments to the vertical position and cant of the machinery frame were made using a series of hydraulic rams and shim stacks. The bridge leaf was operated using the southwest drive train to ensure the best possible mesh between the pinion gear and repaired rack teeth along the length of the rack. Gear tooth contact was verified using bluing.

FIGURE 26. Finished grouted machinery frame support and floor.

The new machinery room floor and frame support in the areas affected by the demolition were restored using an innovative approach to achieve the desired result. First, the portion of the machinery room floor interior to the new machinery frame was formed and poured. Materials consisted of normal weight concrete and the final floor finish was sloped to a drain that will allow future water to exit the area rather than building up and potentially causing anchor bolt and frame deterioration. Once this section of the floor was allowed to cure and experience initial shrinkage, the remainder of the floor area and machinery frame support was achieved by grouting.

Grouting took place in two lifts due to the depth of the pour. The material selected was intended to provide extended working time to allow installation of the grout over a large area prior to set-up. This high-precision mineral-aggregate grout also provided a non-shrink solution that achieved a minimum of 8,000 psi strength in 28 days. A product representative was consulted at the site to determine the proper grouting lift height and curing parameters to achieve the desired result. A representative photograph of the finished floor product is shown in Figure 26.

Leaf Commissioning

The next step in the commissioning process included additional bluing of the northwest pinion gear and rack teeth to verify good contact after grouting and prior to putting the bridge in regular service. The bluing process identified several teeth that required minor profile grinding to result in acceptable contact. This work was performed using the hand-driven operations used to profile the teeth after welding.

Once the engineering team was satisfied that acceptable tooth contact was achieved, the leaf balance was determined using the dynamic strain gage method. Adjustments in position for counterweight blocks were made and additional leaf balance measurements were obtained. Following all work, the leaf was placed back into service with an equivalent toe reaction of 2,000 lb in the seated position.

Summary

This emergency repair project was undertaken in response to an interference between the northwest pinion gear and rack that occurred due to advanced tooth wear. This wear was determined to most likely be the result of a combination of original installation position for the machinery frame and rack segments and the effects of several vessel allisions that have taken place throughout the service life of the structure. Several options for emergency repair were developed with the goal of working within the guidelines of a CDOT emergency repair project while providing the best possible scheme with an optimal service life. Replacement of the existing damaged machinery frame along with rehabilitation or replacement of existing machinery components was the best option for this project. Repairs to the existing rack teeth and machinery frame foundation were undertaken to support that work. Required leaf balance adjustments and the existing condition of the concrete counterweight were also addressed. The bridge was subsequently returned to normal service. A major rehabilitation project for the overall structure is scheduled for the near future.