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Counterweight Sheave Trunnion Rehabilitation to Correct Poor Operating Behavior

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INTRODUCTION

Norfolk Southern Bridge DH-514.47 is a through truss span drive vertical lift bridge that carries one track of rail across the Mississippi River in Hannibal, Missouri. For the purposes of this paper, the bridge is oriented east-west with Hannibal to the west and Springfield, Illinois to the east in accordance with the established direction of the railroad. The lift span truss is 406'-0" long (center to center of end truss points) and 20'-6" wide (center to center of trusses) and weighs 3 million pounds. The bridge was erected circa 1959 in Florence, Alabama, but was relocated to its present location in 1992. At its present location, the lift span raises 41'-4" to allow passage of primarily commercial marine traffic on the Mississippi River.

Limited rehabilitation of the mechanical components was performed as part of the relocation in 1992. The electrical drive and controls were replaced in 2011. Following the electrical rehabilitation, operations personnel reported an unusual operational behavior of the bridge, which can be best described as a see-saw or oscillatory end to end rocking behavior which the lift span exhibited throughout its full operational range. The reported behavior resulted in intermittent seating problems and also induced undesirable shock loading in the machinery and structure. This paper shall present the investigation undertaken to identify the source of the problem, the rehabilitation design and construction effort to correct the problem, and the concluding testing to assess the efficacy of the rehabilitation work.

FIELD INVESTIGATION

In September 2011, Norfolk Southern engaged Stafford Bandlow Engineering, Inc. to investigate the reported behavior. The field investigation was conducted on September 11 through 15, 2011 and encompassed the following tasks in an attempt to identify the source of the noted behavior:

- Perform operational testing to witness the reported problem
- Perform an assessment of the main counterweight rope and operating rope tensions
- Perform strain gage testing of the bridge to quantify the balance condition of the lift span and to determine if any friction problems exist
- Perform a visual and internal (as necessary) inspection of the counterweight sheaves and support bearings

The investigation was conducted in general accordance with, and the machinery was evaluated against, the relevant sections of the AREMA Manual for Railway Engineering which govern movable railway bridges. Significant findings of the investigation are discussed below.

Operational Behavior
The lift span was operated through multiple lifts over the course of the inspection and the behavior of the bridge was observed. The general 'see-saw' rocking behavior of the bridge was apparent throughout all operations conducted during the investigation. This behavior is documented in the chart recording of the mechanical operating loads presented below in Figure 1.

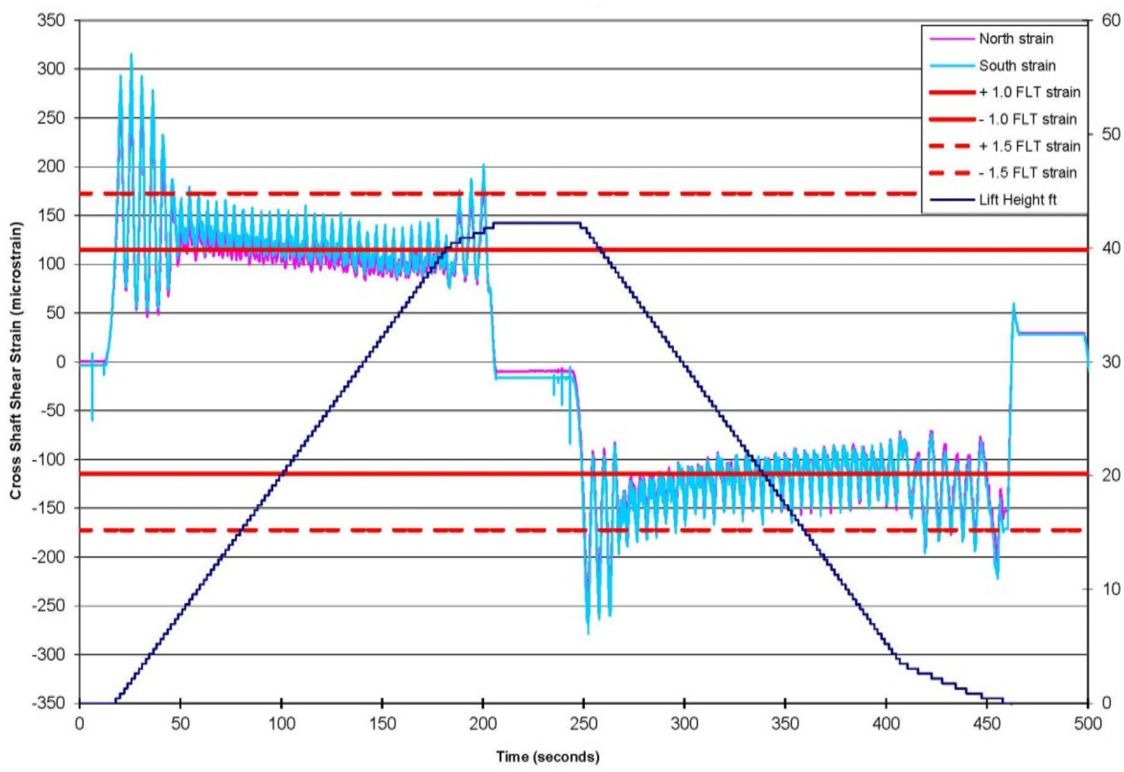

Figure 1. Chart recording of machinery operating loads at outset of work in September 2011.

Review of the chart recording shows that the shaft strains exhibit a saw tooth pattern due to the oscillating loads in the machinery resultant from the stick-slip behavior of the bridge during operation. The loads are greatest at the initiation of movement when raising the span from seated or lowering it from fully raised. It is notable that the peak loads are over twice the nominal operating loads.

Full load output of the 60 HP main motor produces approximately 115 microstrain in each instrumented cross shaft, assuming an equal load split through the primary reducer. Solid bar lines are provided on the chart recording to denote the full load motor output. The peak strains due to the fluctuating loads are as much as 2.78 times greater than that produced under full load motor output, and the nominal operating loads approach or exceed full load motor output for the duration of span operation in both the raising and lowering directions of span travel.

Machinery is typically designed for 150% full load motor torque. Dashed bar lines are provided on the chart recording to denote the machinery design load. The load fluctuations when accelerating the span from rest and decelerating the span from full speed exceed this threshold on greater than an intermittent basis. Loads in excess of the machinery design loading can result in accelerated wear and/or outright failure of machinery components.

Rope Evaluation
While some slack was evident in the operating rope system, no significant disparity in rope tensions was noted between the rope pairs which could generate the observed oscillatory loads. Additionally, assessment of the rope tensions via the measuring method provided on the 1992 rehabilitation plans found the tensions to be acceptable.

While the assessment of the nominal rope tensions did not generate any concern, the assessment of the varying rope tensions during operation was a concern. The operating rope assemblies at several corners of the bridge made loud creaking noises in the vicinity of the deflector sheaves during the load/unload cycle. Investigation of the noises found that during the load cycle, the uphaul sheaves rotated relative to the downhaul sheaves as load was induced in the uphaul ropes prior to the span moving (this is the portion of the cycle when the ropes creak), and then when the span moved incrementally the load in the uphauls was relieved and the downhaul deflectors rotated to catch up with the uphaul deflectors. Normal behavior is for both deflectors at a given corner to move simultaneously since the uphaul and downhaul ropes should pay-in and pay-out at the same time. The observed behavior is indicative of a significant alternating load imbalance between the ropes at opposite ends of the span during operation. A cursory visual inspection of the operating ropes revealed that the load imbalance had resulted in substantial wear of the operating ropes as evidenced by the extensive wear flats across the majority of the exposed wire crowns attesting to the substantial load under which the ropes were operating.

Figure 2. View of wear flats on crowns of operating ropes.

Strain Gage Operational Testing
Strain gage testing was conducted to establish the balance condition of the bridge as well as to identify any significant friction or operating loads which warranted consideration.

The dynamic strain gage test method measures the strain in the drive shafting and relates it to the operating load through fundamental mechanics. The test method is predicated on the fact that the only load in the machinery during operation is due to span imbalance and system friction. For a given span position, the imbalance assists the machinery in one direction (raise or lower) and resists the machinery in the opposite direction of bridge balancing. Friction always opposes the machinery. Therefore, the summation of the raising and lowering force at a given lift height divided by two is equal to the span imbalance force, and the difference is equal to the system friction. This assumes that the system friction is equal in both directions.

Bridge DH-514.47 is a span drive vertical lift bridge with the drive machinery located in a machinery house above track level at mid-span. Typically, centrally located span drive machinery arrangments are symmetric so that it is only possible to determine the loads at each side of the lift span as well as the overall load for the entire span. However, the drive machinery arrangment for this bridge is asymmetric about the central cross shaft with the west end of the operating drum gear frames having an additional idler gearset. This idler gearset opened the possiblity for directly measuring the loads to each operating drum.

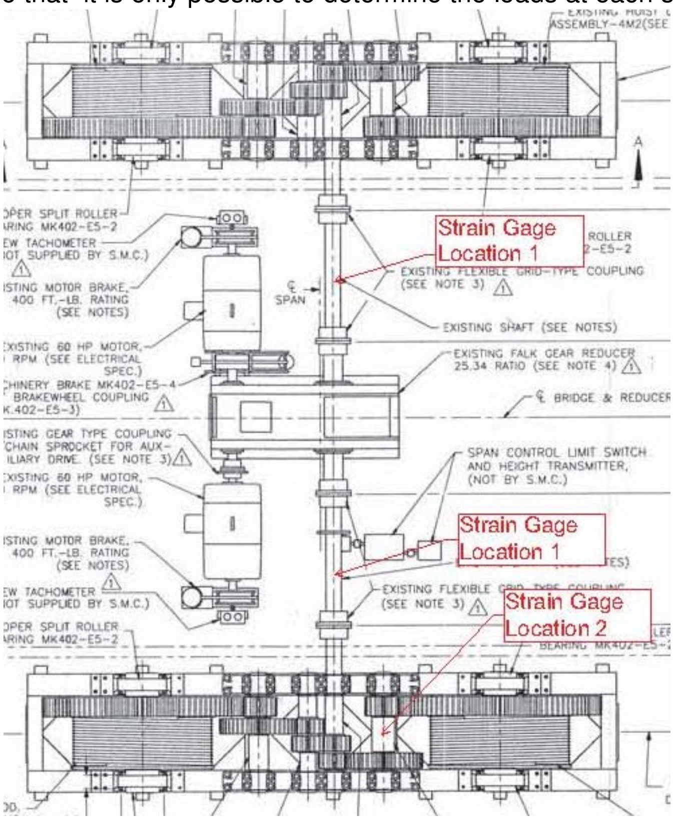

Figure 3. Span Drive Machinery Arrangement. View of strain gage installation locations.

Based on the available access, strain gages were installed at the following locations:

Location 1 – Gages installed on the cross shafts between the primary reducer and each gear frame. This installation is typical for a span drive vertical lift bridge and provides an assessment of the side to side balance as well as the overall balance of the lift span.

Location 2 -An additional gage was installed on the intermediate shaft in the south gear frame in an attempt to separate the loading to each of the two corners at that side of the span. Note that a corresponding gage could not be installed in the north gear frame without substantial disassembly of the machinery enclosure, which was not done.

The testing yielded the following results:

- The overall imbalance of the lift span was appropriate.

  The balance for this bridge is a function of the main counterweight ropes passing over the sheaves during operation which results in a linear change in imbalance. Based on the 48 wire ropes having a unit mass of 8.48 lbs./ft and a 41 foot lift height, the total change in imbalance throughout operation is nominally 33, 400 lbs. Standard practice would set the initial imbalnace at 16,700 lb. span heavy so that the bridge is as span heavy when seated as it is counterwight heavy when raised. This imbalance would be equally divided among the four corners of the lift span so that each corner would have an imbalance of 4,175 lbs.

  The measured imbalance of 13,653 lbs. was reasonably close to the target balance of 16,700 lbs.

- The system friction measured through the testing was excessive.

  The theoretical system friction for this bridge was based on an assumed structure weight of 3,000,000 lbs and a coeficcient for motion of 0.09 as specified in section 6.3.7 of the AREMA Manual for Railway Engineering which governs movable bridge work. Based on these inputs, the calculated friction value for the lift span was 58,500 lbs. (presented as an equivalent force at the operating ropes for direct comparison to the imbalance values).

  The measured system friction of 73,283 lbs was 25% greater than the theoretical value, which is typically regarded as being conservative for design purposes. The following table has been compiled from Stafford Bandlow Engineering's prior strain gage test experience to provide a comparison of measured friction values versus bridge weights for a wide selection of lift bridges to reinforce the excessively high magnitude of the measured friction.

Bridge	Span Weight (lbs.)	Friction (lbs.)
DH-514.47	3,000,000	73,000
B-184.50	3,144,000	18,884
CD-182.30	3,441,000	31,294
CD-509.6	1,950,000	35,646
Burlington Bristol	2,530,000	28,867
Jacksonville V.L.	2,440,000	27,178
Carlton	2,964,000	15,281
Marine Parkway	4,588,400	20,279
RFK Triboro Bridge	4,401,000	31,678

Figure 4. Comparison Table of Friction Values and Bridge Weights.

As noted from the above table, the measured friction at this structure is the highest friction level for the reference cases independent of bridge size.

- Testing conducted using the gages at Location 1 as identified in Figure 3 did not determine any appreciable difference in the loading at either side of the lift span (i.e. the transverse loading). In contrast, testing conducted using the gages at Location 1 and Location 2 did indicate a disparity in the end to end loading of the lift span. In particular, the data from the Location 2 gage was used to determine that there was a significant disparity in the measured friction between ends of the span with the friction at the west end being almost twice as high as at the east end. This disparity is consistent with the condition of the trunnion bearings which are discussed below .

Trunnion Bearing Evaluation

The lift span is equipped with eight trunnion bearings. The bearings are arranged in pairs and are located at the top of the towers at each end of the lift span. Each pair of trunnion bearings supports one of the main counterweight sheaves which carry the wire ropes that connect the lift span to the counterweight. The sheaves turn in the trunnion bearings to accommodate travel of the wire ropes when the lift span raises or lowers. As the full dead weight of the lift span is transferred to the trunnion bearings through the sheaves, the resultant bearing friction during operation is the largest contributor to system friction. Based on the excessive friction determined through the strain gage testing, the scope of inspection was expanded to include internal inspection of a representative number of the trunnion bearings, with a focus on the west end of the bridge which yielded the higher friction values.

Figure 5. View of trunnion bearing with end plate removed.

The trunnion bearings are plain bearing assemblies which consist of bronze bushings mounted in a pillow block housings. Each bearing assembly has a bronze bushing in the base, but no bushing in the cap. An end plate is provided to seal the housing and act as a grease reservoir. All bearing end plates were removed as part of the inspection to evaluate the state of lubrication and allow an assessment of bearing clearance as well as a limited assessment of the journal surface.

All bearings were found to have substantial lubrication on all exposed surfaces of the trunnion and in the end plate reservoirs.

Bearing clearances ranged from 0.365” to 0.420” and were well in excess of the anticipated plan value of 0.090”. The large clearances indicate the bearings were either assembled with greater clearance than indicated on the original plan or that the bearings exhibit substantial wear.

A probe wire was inserted into the gap between the bearing cap and the trunnion journal at the top of the bearing and run across the top of each journal surface to provide an assessment of the journal condition. The probe wire detected significant abrasive scoring at all West Tower bearings as well as one bearing in the East Tower. While all bearings exhibited substantial clearances, it was notable that the nominal clearances at all bearings with significiant abrasive scoring were 0.060” to 0.090” greater than at the bearings which were not noted to have significant scoring.

As part of the inspection, the probe wire was also inserted in the grease grooves at the bottom of the bushings to determine if the grease passages were clear. At multiple locations, the grease grooves were clogged with metal shavings from the abrasive wear which had the appearance of steel wool. The metal shavings were also found mixed in the lubricant at the top of the journals. The presence and location of the metal shavings indicated that the abrasive wear was an active, on-going process, and that the condition of the journals was steadily deteriorating.

Figure 6. Metal Shavings pulled from Trunnion Bearing Grease Groove.

Figure 7. Trunnion Bearing Cap Raised. Journal exhibits severe abrasive scoring along entire length.

On the basis of these findings, a decision was made to remove several bearing caps to establish the extent of the scoring. Removal of two bearing caps at the West Tower exposed severe abrasive scoring that extended across the entire width of the journals The fillet regions exhibited corrosive pitting, metal rip-out and light abrasive wear. Removal of one bearing cap at the East Tower exposed similar, albeit lesser, wear.

Investigation Conclusions

The inspection findings provided the basis that excessive friction at the trunnion bearings is resulting in a stick slip rotation of the journals, which in turn is causing the see-saw behavior of the lift span during operation. The net effect of the trunnion bearing friction is not only that it contributes to increase nominal loading of the machinery, but also that it induces pulsating loads into the machinery throughout the stick-slip behavior. The presence of the wear particles in the bearing load region indicates that this is an active, on-going problem that will generate continued deterioration of the bearings, which in turn will increase friction levels and result in increased loading of the machinery. To avoid machinery failure, the recommendation was made to initiate rehabilitation of the trunnion bearings in the near term.

REHABILITATION DESIGN

The findings of the investigation provided a compelling basis for rehabilitation of the trunnion bearings and replacement of the main operating ropes.

Of the two items, the integrity of the main operating ropes were regarded as being more time sensitive in maintaining the reliability of the bridge. In addition the replacement of the operating ropes did not require any special engineering support. Therefore, Norfolk Southern opted to perform the main operating rope replacement as a stand-alone work item in 2012.

Due to budgeting constraints, the sheave rehabilitation work was scheduled for 2014. The logistics of rehabilitating the trunnions dictated that the sheaves would need to be unloaded, and the bridge taken out of operational service, in order to perform this work. Norfolk Southern coordinated with the Coast Guard and obtained an extended navigation closure from January 7, 2014 through February 14, 2014 during which the work could be performed. The length of closure was aided by work occurring at the locks downstream from the bridge. Based on preliminary discussions with contractors and machine shops, and based on prior projects, this length of closure was regarded as providing adequate time for the rehabilitation work to be performed at both ends of the bridge.

The full scope of the rehabilitation work encompassed unloading of the sheaves, re-machining of the trunnion journals to eliminate the severe abrasive scoring, outright replacement of the bearing bushings, limited re-machining of the bearing housings to accommodate the new bushings, and replacement of the main counterweight ropes which was performed as a supplementary item given the effort required to support the counterweights. Specific areas of the rehabilitation design that were necessary to make the work viable and achieve an acceptable end product are discussed below.

Support for Main Counterweights

In order to unload the sheaves, the counterweights needed to be supported. The framing in each tower was equipped with a hanger arrangement dedicated for this purpose. However, the hangers were rigidly framed into the structure. Therefore, it was necessary to jack the lift span and lower the counterweights to make the pinned connection to the hanger plates. After the counterweights were pinned, the ropes could be disconnected at the lift girder (which completely unloaded the sheaves), and the lift span could then be lowered back down to the pier to support rail traffic.

The available plans did not identify specific jacking points on the lift girder. An analysis of the end floor beam was performed and identified that the existing air buffers could be removed and the underlying mounting surfaces used as the primary jacking points. However, the end floor beams would need to be stiffened at any other location where load was applied. Therefore, it was advantageous to ensure that the selected jacks had sufficient stroke to eliminate the need to jump the jacks as part of a stepped jacking process.

Figure 8. Existing Counterweight Hanger Link in Stowed Position. Lower link is notably longer than distance to clevis connection on counterweight.

The necessary jacking stroke is dependent upon the elastic stretch of the ropes, the constructional stretch/shrinkage of the ropes, and the height which the span had to be raised in order to make the pinned connection of the hanger links with the counterweights. The length of the existing lower hanger link was substantially longer than required to pin the counterweight in its existing position and would have required the lift span to be raised 25” solely to make the pin connection, not considering rope stretch. The largest available commercial jack in the required size (600T) had an 11” stroke. Therefore, over 2 full strokes of the jack would have been required to lower the lift span once the counterweight was pinned. To eliminate this unnecessary work, the design incorporated a new lower hanger link that was shorter than existing and reduced the required jack stroke to 1.5” to make the connection. In consideration of this new reduced pin height, and the anticipated constructional and elastic stretch, it was regarded that the counterweight could be unloaded in one stroke of the available commercial jacks.

Grease Grooves

Lubrication of bearings is critical to their proper function. The available 1960 design plan for the trunnion bearing identified two grease ports in the cap, which were called out as being serviced with grease cups. No information was provided on the lubrication of the lower bushings. The available 1992 rehabilitation drawing identified four axial grooves in the lower bushing; the grooves were close ended at their inner (thrust face) end and open ended at their outboard ends. The rehabilitation drawing identified a tapped hole through the outer surface of the bushing at its inner end but was not specific as to location. As found in the field, the two grease ports in the cap were equipped with button-head grease fittings, and two additional button-head fittings extended from the inner (thrust face) side of the bearing to presumably service the grease grooves in the lower bushing.

Upon disassembly for rehabilitation, the grease arrangement was evaluated. Each of the four grease grooves in the lower bushing was equipped with a dedicated button head grease fitting. The two grooves closest to the split line were equipped with short piping runs so that the fittings were accessible from the sides of the bearing; these are the fittings which were commented above. The two grooves closest to bottom dead center of the bushing had their fittings located in a cored cavity in the bearing housing that was essentially inaccessible once the sheave was installed. The two grease grooves serviced by these grease fittings were found packed with old hardened lubricant that had to be forcibly removed. As a result, whereas the overall amount of lubrication found on the bearings upon disassembly appeared adequate, the lack of lubrication to the bottom of the bushing, which is the most heavily loaded region, was a likely contributor to the observed deterioration of the contact surfaces.

Figure 9. View of hardened grease that has been forcibly removed from the grease port at bottom dead center of the bushing.

Rehabilitation of the bearings as part of this work had originally included replacement of the worn bushings and re-use of the existing housings. The bushings had been detailed with four axial grease grooves with a note to match whatever lube holes existed in the housings. Based on the field findings, the rehabilitation of the bearing housings was expanded to include extension of lube lines so that all grease grooves could be directly lubricated. For the two grease ports at bottom dead center, this required drilling holes through the bottom web of the housing to allow the grease lines to be piped out to the face of the bearing.

Trunnion Alignment

Proper alignment of the counterweight sheave trunnions with the supporting bearings and with each other is critical to their serviceability. Therefore, establishing the existing trunnion alignment and planning for corrective action was essential to a successful rehabilitation. Trunnion alignment was measured at four crucial stages:

1. Existing Trunnions, Loaded Condition, (initial condition)
2. Existing Trunnions, Unloaded Condition (after transfer of counterweight load to towers)
3. Rehabilitated Trunnions, Unloaded Condition (initial install)
4. Rehabilitated Trunnions, Loaded Condition (final condition).

Trunnion alignment was measured via a tensioned piano wire. In this method of measurement, a piano wire is strung through the trunnion bore holes for the pair of trunnions at each tower. The piano wire is located relative to the center of the outboard bores in the two trunnions and measurements are then taken to determine the deviation of the inboard bores of each trunnion relative to the wire. These measurements establish the collinearity of the two trunnions.

In review of the available drawings, it was noted that the 1992 rehabilitation drawings had provided a part detail for a trunnion alignment plug, which is a device that can be inserted into the outboard end of each trunnion to positively establish the center of the bore. Use of alignment plugs simplifies the measurements and increases their accuracy. After discussion with bridge personnel established that the detailed plug was not available, new alignment plugs were fabricated based on the available plan detail. The new plugs needed slight modification of the original diametral dimensions to achieve acceptable fit-up but were otherwise satisfactory.

The trunnion alignment requirements for this project required that misalignment be held within 1/32”, which is consistent with, if not on the loose side of, industry practice. The alignment measurements for the existing loaded condition established that misalignment approaching 1/4” existed at the East Tower and misalignment approaching 1/2” existed at the West Tower. This existing misalignment far exceeded the project requirements and provided a strong basis for being a contributing factor to the observed trunnion wear.

The magnitude of the misalignment measured under the initial condition was large enough that when the trunnion bases were repositioned to meet the project requirements, the mounting bolt holes in the bases would be offset from the existing holes in the structural support and would not clean-up for the specified turned bolt size. Therefore, the decision was made to plug weld the affected holes. A detailed sketch was provided based on the existing measurements indicating the required housing correction and the affected holes at each bearing location. Upon installation and preliminary alignment of the rehabilitated bearings, the need for the plug welding was validated as the overlap of the existing steel and fresh plug weld were visible when looking down through the mounting bolt hole in the bearing base.

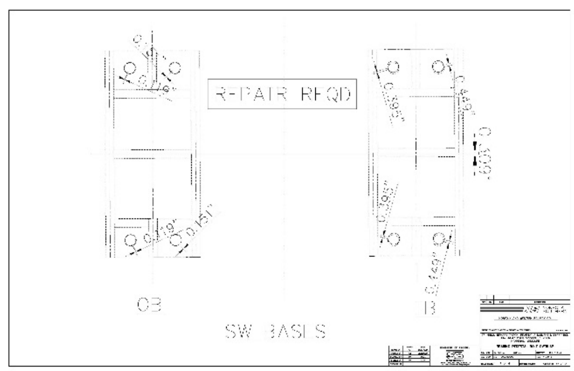

Figure 10. Plug Weld Repair Sketch for SW Trunnion Supports.

The alignment measurements taken after transfer of the counterweight load to the towers were primarily intended to document deflection of the towers under the load transfer so that it could be compensated for upon reassembly of the bearing bases. The measurements corroborated information provided on one original drawing which indicated slightly greater deflection at the inboard trunnions than at the outboard trunnions. The original drawing had called for this deflection to be compensated for through installation of a 1/16” shim under the inboard bearings; this same compensation was made as part of the present work.

A dedicated sheave jacking frame was detailed in the design plans to cover the eventuality that the sheaves might need to be individually jacked to achieve acceptable alignment. However, the shim compensation made on the basis of the load/unloaded measurements as well as the alignment achieved as part of the new install were successful in meeting the project requirements so that no secondary jacking operation was required.

CONSTRUCTION

The rehabilitation work was awarded to Fenton Rigging and Contracting, Inc. of Cincinnati Ohio. The work was performed as planned in January and February 2014. Field crews were challenged with adverse weather conditions throughout the project including snow, ice and sub-zero temperatures. In addition, the shop rehabilitation of the sheave components proved more time consuming than originally estimated. The initial operation of the bridge at the completion of the rehabilitation work occurred on February 26, 2014. The bridge was returned to functional service the first week of March 2014. Due to the previously discussed concurrent repair to the locks downstream from the bridge and due to the river being effectively frozen for the majority of the work, there was no impact on marine traffic.

POST REHABILITATION ASSESSMENT

At the completion of the rehabilitation, strain gage testing was conducted to document the operating loads when the bridge was returned to service. The following table provides a comparison of the results prior to and following the rehabilitation.

STRAIN GAGE BALANCE TEST RESULTS Comparison of Results Pre and Post Rehab				
Test Period		**North Side**	**South Side**	**Total for Lift Span**
Post Rehab February 2014	**Initial Imbalance (b) lb.**	+11,020	+13,192	+24,212
	Average Friction lb.	+14,876	+15,660	+30,536
Pre Rehab September 2011	**Initial Imbalance (b) lb.**	+6,008	+7,644	+13,653
	Average Friction lb.	+35,369	+37,914	+73,283

Figure 11. Summary table of strain gage test results at outset and conclusion of project.

The tabulated results illustrate that the rehabilitation work was successful in reducing the system friction. The post rehabilitation friction value of 30,536 lbs. has been reduced to 41% of the pre rehabilitation value of 73,283 lbs, and corresponds to a friction coefficient of 0.046, which is approximately half of the friction coefficient for motion specified in the AREMA design guideline.

The chart recording of the loading from the post rehabilitation test also provides a striking comparison to the pre rehabilitation test depicted in Figure 1. The reduction in friction eliminated the 'see-saw' oscillatory nature of the span operation that was present prior to the rehabilitation and was the primary factor in initiating the initial investigation in 2011. This behavior is apparent in the sawtooth appearance of the strain traces on the strip charts for the test runs prior to the rehabilitation and is notably absent from the test run following the rehabilitation. The significant reduction in friction has also resulted in a corresponding significant reduction in load required to operate the bridge. The nominal operating loads have generally been reduced by half, and the accelerating spikes have been largely eliminated. All operating loads remain within full load torque of the drive motor.

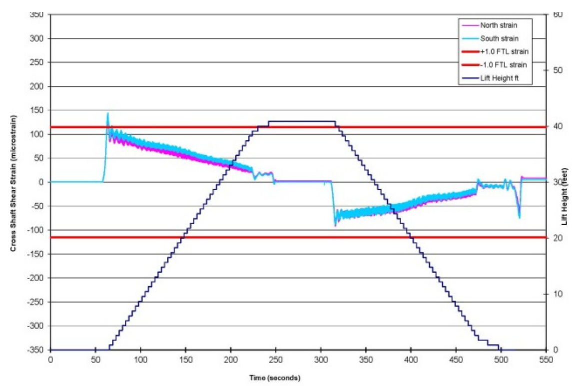

Figure 12. Chart recording of machinery operating loads at completion of work in February 2014.

In conclusion, the rehabilitation work has successfully remediated the excessive friction on this structure and improved the operational behavior. This work should be indicative of the benefit that can be obtained through rehabilitation of severely abraded trunnion journals or elimination of significant friction sources on other large movable structures. In addition, the work points to the importance of ensuring adequate lubrication and proper alignment, particularly at the primary support bearings.