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Pennington Avenue Bridge Trunnion Bearing Replacement

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Introduction

The Pennington Avenue Bridge includes two side by side double leaf bascules that span across the Curtis Creek in Baltimore, MD. The span was constructed in the mid-1970's and carries vehicular traffic in both the east and west directions, connecting points between Anne Arundel, MD on the east side and the City of Baltimore on the west side. For reference, the bascule spans are located just north of Interstate 695 and provide access to the Curtis Creek, which accommodates both the US Coast Guard facility and the US Army facility.

Photo 1: Pennington Avenue Bridge, Aerial View

Each bascule shares the following characteristics:

- each leaf extends 125 feet from the centerline of trunnion to its toe
- each leaf is 41 feet wide, accommodating two vehicular lanes and a sidewalk on its outboard side
- each leaf weighs approx. 1500 kips and is supported by two trunnion bearings
- each leaf can rotates 74.9 degrees to its full open position, providing approx. 200 feet of navigable channel width
- each leaf can operate from its full closed position to its full open position in approx. 160 seconds
- prior to the rehabilitation effort, the bridge opened approx. 500 to 750 times per year
- the bridge is manned 24 hours per day and 7 days per week

In general, each bascule leaf is comprised of steel framing in the form of two bascule girders, floorbeams and longitudinal stringers. The two bascule girders are used to support not only the steel framing but the roadway grating and fill, roadway barriers, railings and counterweight. Each bascule leaf utilizes two trunnion shafts, each of which supported by a bascule girder and trunnion girder. The trunnion shafts are located on a common axis, used to support the bascule leaf and provide a means to allow the structure to rotate. For this bridge, the trunnions utilize spherical roller bearings to allow for leaf support and rotation.

In addition, each bascule leaf is equipped with operating machinery, center lock machinery and tail lock machinery. The operating machinery is electro-mechanical and used to open and close the leaf. The center and tail lock machinery is also electro-mechanical and used to support and/or secure the leaf in its closed position. The center lock machinery uses lock bars that fit within guides located at the toe of each leaf, providing a means for vertical live load to transfer from one leaf to the adjacent leaf.

Background

In 2007, the City of Baltimore DOT and Maryland DOT State Highway Administration were provided with a set of rehabilitation plans for the Pennington Avenue Bridge. The plans had been put together along with the necessary provisions to complement the current condition of the movable structure and its accoutrements. In general, the rehabilitation effort was to include the following major work items:

Structural

- sidewalk and deck repairs
- concrete pier repairs
- structural steel repairs
- new drive machinery enclosure and supports
- new center lock platform and supports
- new tail lock platform and supports
- painting and balance

Mechanical

- drive machinery rehabilitation
- new center lock machinery
- new tail lock machinery
- trunnion rehabilitation

Electrical

- new power distribution system
- new motor control center
- new span motors, brakes and drives
- new center and tail lock motors and limit switches
- new submarine cables
- new control desk
- new control system
- new limit switches and sequence interlocking
- new navigation and bridge lighting

The rehabilitation effort was awarded in October of 2007 with work scheduled to begin as early as December 2007. The Contractor’s proposed schedule included beginning with the north bridge in order to have better access to the Control House for future electrical efforts. The mechanical effort began with the inspection of the existing trunnion bearings, which was intended to confirm that the approx. thirty year old bearings were still in good condition. For the most part, the inspection seemed to be going as expected until the last bearing revealed a 240 degree circumferential crack along the centerline of its outer race.

This paper will focus on the planned efforts associated with the trunnion rehabilitation, the inspection findings, some impacts to the construction effort and the required resolution to permanently address the failed bearing.

Trunnion Rehabilitation

The trunnion rehabilitation effort was developed to complement the existing trunnion assembly components, confirm the condition of existing spherical roller trunnion bearings, provide a means to more readily access these bearings for future condition monitoring and adjust any gross misalignment of the trunnion arrangement. The rehabilitation effort included the following major work items:

- purge, clean, inspect and re-lubricate the existing spherical roller bearings
- remove, modify and reinstall the existing bearing housing end covers and lock plates
- measure the alignment of the trunnion shafts
- if necessary, adjust the trunnion shaft alignment using the existing trunnion girder eccentric connection
- replace high strength bolts at the trunnion collars and eccentric connections
- replace bearing housing grease seals and gaskets
- functionally test bearings once the work is complete
- clean and paint the exterior of the existing bearing housings

Description – Trunnion Bearings

As mentioned previously, the existing trunnion bearings are spherical roller bearings. Widely accepted as an alternative to spherical plain bearings, precision roller element bearings offer standardized geometry, high radial load capacity and minimal frictional resistance when called upon to rotate.

In basic bearing nomenclature, the existing trunnion bearings are referred to as an 800 SD 32K. The bearings were supplied as metric sized spherical roller bearings with a tapered inner ring. The bearings were also supplied with a lubrication groove and three oil holes in the bearings outer ring as well as pin type retainers. According to the bearing manufacturer, this vintage bearing had the option to utilize a pin type retainer versus the standard independent land riding retainers, which allowed for a greater number of rollers in the load zone and therefore a higher load carrying capacity.

The bearings tapered inner ring refers to its bore geometry. The bore is defined with a nominal diameter on its smaller end, which tapers 1” per foot on diameter across its width. To complement this geometry, the trunnion shaft extension is tapered as well. Installation of the bearings requires the orientation of the taper to complement and the bearing to be pushed up onto the tapered shaft until the bearings recommended internal clearance is achieved. For this size bearing, the standard internal clearance, i.e. diametral clearance (DC), ranges between 0.024” to 0.030”. During installation, the internal clearance is reduced by 0.011” to 0.014” resulting in an installed internal clearance between 0.010” to 0.019”. Reduction of internal clearance is achieved by moving the bearing further up the tapered shaft thereby expanding the inner ring. Once the desired internal clearance is achieved, a lock plate is secured to the end of the trunnion shaft to further secure the axial position of the bearing.

The existing trunnion bearings are supported by cast steel housings. The housings are made from material meeting the requirements of ASTM A27, Standard Specification for Steel Castings, Carbon, for General Applications.

Photo 2: Typical Trunnion Bearing Assembly, Plan View

The housings are comprised of three main components; the base, the cap and the end cover. Internal dimensions of the housings that interface with the bearings outer ring define whether or not the bearing assembly is considered fixed or free to float in the axial direction.

For the Pennington Avenue Bridge, the bases are secured to concrete pedestals/columns by means of anchor bolts. The base locations define the position of the bascule leaf. The caps are then mated to their respective base and secured with studs. Each cap is mated to its base at the housing split line, which coincides with the centerline of trunnion shaft. An end cover is then introduced to the outboard side of the housing to further secure the two halves and protect the bearing from external elements. It should be noted that on the inboard side of the housing, both the cap and base are provided with a grease seal recess, which allows for the introduction of a single lip seal. The single lip seal mates with a non-tapered section of the trunnion shaft, just inboard of the bearing to prevent external contaminants from entering into the bearing housing.

Inspection – Trunnion Bearings

As described within the rehabilitation plans and specifications, each of the eight (8) trunnion bearings were to be purged of existing grease, cleaned, inspected and re-lubricated. In addition, and in conjunction with, the bearing housings end cover and lock plate were to be removed and modified for future inspection efforts.

As a safety precaution, it was required that the Contractor develop and submit a bearing protection plan and inspection procedure to ensure that the bearings would be completely protected from debris at all times, particularly when the end covers and seals were removed. In addition, it was required that the Contractor measure the bearings internal clearance prior to removing the lock plates for modifications. Additionally, the Contractor was required to install temporary retainer clips to perform the function of the lock plates while they were being modified.

The Contractor requested the inspection services of SKF USA Inc., originally thought to have been the manufacturer of the existing trunnion bearings. The inspection was performed by field service engineers familiar with bearing condition analysis.

The field analysis was performed using three main tools; piano wire bent 90 degrees with a diamond shaped point, flashlight and feeler blades. Access was noted as being limited due to the following details:

- without complete disassembly, access was limited to the outboard side of the bearing
- the outboard side exposed the independent pin type retainer, which limited access to the inner ring
- independent retainers allow each row of rollers to operate independently but often located themselves offset, which limited access to the inboard side of the outer ring

As noted within the SKF Service Report, dated September 1, 2008, the inspections were performed on the following dates:

Location	Date	Internal Clearance	Approx. Location	Inspection Findings (abbreviated)
NW Outboard	7/21/08	0.037”	12 o’clock	Outer ring roller path w/ frosted load zone btw. 4 to 9 o’clock
NW Inboard	7/21/08	0.035”	12 o’clock	Outer ring roller path w/ frosted load zone btw. 4 to 9 o’clock
NE Outboard	8/11/08	0.037”	12 o’clock	Outer ring roller path very smooth, except for some minor dents
NE Inboard	8/11/08	0.044”	12 o’clock	Outer ring roller path and rollers show some small dents
SE Inboard	8/14/08	0.032”	12 o’clock	Outer ring roller path with 75 deg. load zone, frosted with small areas of etching
SE Outboard	8/14/08	0.036”	12 o’clock	Outer ring roller path with 90 deg. load zone, frosted and water etched
SW Inboard	8/21/08	0.044”	12 o’clock	Outer ring roller path with 90 deg. load zone, frosted w/ dynamic corrosion on outer edges
SW Outboard	8/21/08	0.051”	12 o’clock	Outer ring roller path with circumferential crack noted at 6 o’clock position and extending 240 deg. Crack appears to be located in center of W33 groove.

The report recommended that the bearing installation clearances be reviewed and compared with measured internal clearances. It also noted that since the existing housings were being modified with inspection ports, that the bearings be monitored at a set interval.

During the inspection effort SKF personnel noted that several of the bearings unique design characteristics eliminate it from their product line. As it turns out, the original bearing manufacturer was Torrington and the bearing was actually a transitional design between their old SD style and newer YMB type.

Photo 3: SW Outboard Location, Outer Ring, Crack Location

Review – Trunnion Bearings

A copy of the service report was made available on September 4, 2008 in an effort to determine what, if any, immediate action might be necessary. Based on the SW outboard inspection findings, limited knowledge as to why or when the bearing failure occurred and the importance of keeping the navigable channel operable for both the US Coast Guard and US Army, it was recommended that the SW bascule leaf be immediately opened to its fully raised position and secured for the foreseeable future. This would result in the south span being closed to vehicular traffic, however the inconvenience to the public could be considered minimal as the north span had been scheduled for a similar closure. In the meantime, an investigation into what may have caused the bearing failure was being considered, as well as possible replacement solutions, whether temporary or permanent.

Inquiring into the availability of an 800 SD 32K proved to be somewhat disappointing. As it turned out, most domestic based bearing manufacturers capable of fabricating this size bearing and familiar with the requirements of our industry were completely backlogged by orders generated from wind turbine projects as of September 2008. And therefore, no matter how one might phrase the importance of our single bearing order, it just couldn't be reprioritized. Quotations received noted deliver lead times ranging from 9 months to 3 years depending upon the manufacturer.

Still, having considered several short and long term recover plans, it was recommended that the failed bearing be replaced in-kind, i.e. with a modern day spherical roller bearing of proper interfacing dimensions and that the necessary analytical and measurement steps be taken to determine whether or not the existing bearing housing required any remedial work or replacement.

Course of Action – Trunnion Bearings

In accordance with a meeting that had taken place at the job site on October 2, 2008, the Contractor was instructed to complete the following action items:

- order the forging for the new bearings outer ring with 1/8” additional stock on the outside diameter, which would allow the bearing manufacturer to perform final machining of the outer ring diameter to suit the final field dimensions of the housing bore, yet to be determined
- make arrangement to remove the bearing housings cap, work to be done within the next three weeks to permit further investigation and will also be required during future jacking operations to replace the bearing
- make arrangements to have experts and equipment on site to perform precision measurements of the existing bearing housing bore and cap
- make arrangements to have experts on site to perform a visual examination of the bearing cap, once removed, to confirm whether or not the bearing cap is within acceptable tolerances for future use
- determine feasibility for machining the bore of the bearing housing on site
- determine feasibility of jacking the leaf for bearing replacement work with the span in the open (to navigation) position
- coordinate with the US Coast Guard to determine maximum feasible window for navigation closure during bearing replacement work

To comply with the noted action items, measurements were taken of the unobstructed portion of the SW outboard bearing housing bore. These measurements occurred with the cap and base bolted to each other. In addition, measurements were taken of the SW outboard bearing caps half bore, at points across its width after it had been removed from the base. To complement these measurements, similar measurements were taken at other designated locations for comparison.

The measurements revealed the following:

- in all cases, the bores were out-of-round between 0.011” to 0.016”
- in all cases, the out-of-round shape, if exaggerated, was elliptical
- in all cases but one, the larger diameter of the ellipse was in line with the vertical axis of the bearing assembly
- in only one case, the larger diameter of the ellipse was offset from the vertical axis of the bearing assembly
- the noted offset occurs at the SW outboard bearing and for all practical purposes was in line with the center of the noted crack
- in all cases the removed caps retained their circular shape

In general, it was concluded that measurable deflection occurs in the housing base due to the imposed dead load. The connection between the base/cap causes similar deflection in the cap/bearing, which results in a slight out-of-round shape when loaded. If a replacement bearing of similar type were to be used then the out-of-round shape would need to be qualified and the noted offset corrected by virtue of the replacement bearing not being flawed. A request was made through the Contractor to have Timken perform analytical work to determine the viability of a replacement bearing in an existing bearing housing. It was expressed to Timken that what was of greatest importance was to confirm that the replacement bearing would perform satisfactorily within the existing housing. That this would require analyzing the loaded new bearing within the distorted housing, i.e. within a housing bore that matches measurements taken by the Contractor. The purpose of the analysis would be to determine service life, which should include “floatability”.

Analysis – Trunnion Bearing

The following is a summary of the analysis performed by Timken as reported in their memo dated February 9, 2009 with subject, “Analysis of SRB Used on Pennington Avenue Bridge Application”.

An analysis of the replacement spherical roller bearing, i.e. part number 232/800K YMD W874 C2, mounted in an existing housing assembly was performed with the following considerations:

- overall housing dimensions
- field measured housing deformation, i.e. out-of-round housing bore
- loading conditions

The purpose of the analysis was to compare the calculated stress levels, life and bearings ability to “float” within existing housing versus what was expected to be a more desirable scenario, i.e. a perfectly round housing bore.

In general, two 3-Dimensional finite element models were created to evaluate these scenarios. The first model used the housing and outer ring dimensions and considered the out-of-round housing bore. The second model also used the housing and outer ring dimensions but as if they held perfectly round features. In an effort to define the housing bore, field measurements were taken with a Faro arm in an area of the bore that extended beyond the existing bearing. The analysis resulted in the following information:

Scenario	Bore Shape	Dimensions	Radial Load	Load Zone	Total Contact Normal Force	Axial Load
Out of Round (Existing)	Elliptical	Maj. Dia. 55.9349” Min. Dia. 55.8964”	750 K	9 Rollers	886 K	177 K
Round (Ideal)	Circular	Dia. 55.9156”	750 K	7 Rollers	829 K	165 K

The axial loads noted above are based on a coefficient of friction between the outer ring and housing that is no larger than 0.2.

Results from Timken’s analysis indicate that the out-of-round housing measurements for the bearing will increase the total contact normal force between the outer ring and housing by 7% compared with the same bearing in a perfectly round housing. This results in a similar 7% increase in axial load to float the bearing in the housing. However, the results also indicated that the difference in noted geometry will not significantly change the loads or stresses in the bearing. With this in mind, the housing bore would need to be measured with the damaged bearing removed to confirm the unloaded shape of its bore and surface finish quality. These additional findings would then be used to determine if remedial work was required to complement installation and use of the replacement bearing.

Installation – Trunnion Bearing

In general, the installation of an 800mm diameter bore rolling element bearing requires careful thought and planning, even when performed in a shop environment. Having to remove an existing bearing of the same size in a confined work space out in the field presents its own unique challenges. In order to consider the installation of this replacement bearing a success, the existing bearing would need to be removed without damaging the existing housing and trunnion shaft. In addition, the trunnion shaft would need to be modified so as to incorporate a circumferential groove, which could be used to assist with the installation of the replacement bearing or, if need be, its removal. The rehabilitation team decided to tackle these efforts as follows:

Existing Bearing Removal – Initial Steps

- remove bearing housing end cover and lock plate
- jack leaf to remove weight from bearing and temporarily secure
- cut the bearings outer ring across its width to create two pieces
- remove upper and lower halves of outer ring
- remove the bearing rollers from the cage/inner ring
- remove the cage rings (i.e. roller retainers)

Existing Bearing Removal – Final Steps

- wrap inner ring with insulating material
- wrap inductive heating coils around insulating material
- install custom hydraulic pulling device
- heat inner ring to approx. 400-500 deg. F and then methodically pull inner ring

Photo 4: SW Outbound Bearing, Heating Coils and Puller Device

- remove bearing inner ring from trunnion and inboard seal
- remove hydraulic puller device
- clean and inspect exposed trunnion, housing bore, seal support surfaces and seal riding surfaces
- hand work minor surface anomalies found on exposed trunnion or housing bore
- assemble housing cap with base and measure bore diameter

- determine if remedial action is required, if not then proceed with installation

Existing Shaft Machining

- mount custom adapter plate to trunnion shaft end
- mount cutting machine to adapter plate
- align cutting machine concentric with trunnion shaft
- machine approved circumferential groove
- remove machine and adapter plate
- drill approved cross hole and connecting hole into trunnion shaft

New Bearing Installation

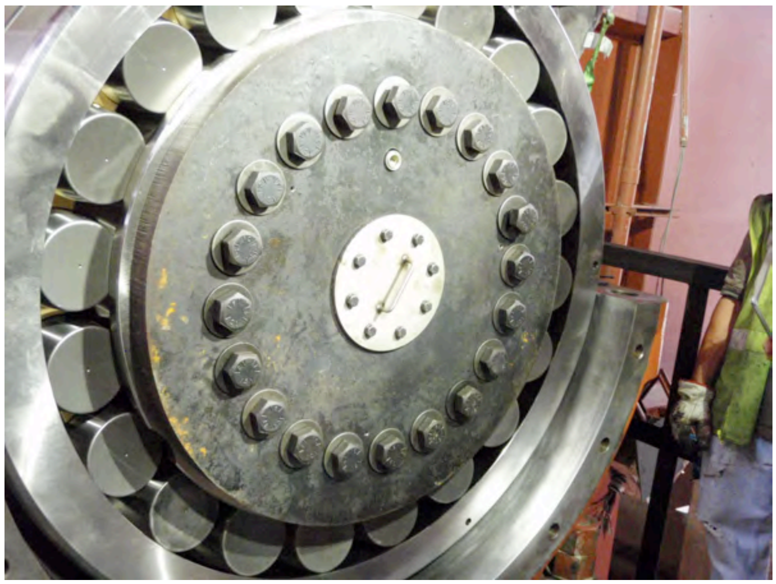

Photo 5: SW Outboard Bearing, Partially Rehabilitated

- install new inboard seal
- using nylon slings and overhead hoist, slide bearing assembly onto trunnion shaft until there is line-to-line contact
- secure end plate onto trunnion shaft end
- set up dial indicator to measure axial movement of bearings inner ring
- incrementally tighten lock plate bolts using a star pattern and note axial movement of bearing relative to trunnion.

Per Timken, from line-to-line contact, the bearings inner ring should displace 0.165" to 0.210" axially in order to achieve the recommended internal clearance.

- if necessary, use the circumferential hydraulic groove to reduce friction and force required to install the tapered ring onto the tapered shaft
- once the desired internal clearance has been achieved, lock wire the lock plate bolt heads to prevent them from backing out
- remove the temporary supports used to hold the leaf in the jacked position
- lower leaf to transfer weight onto the bearing
- re-install the bearing housing cap and grease pack the bearing assembly
- re-install the bearing housing end cover and prepare for testing

Conclusion

The new bearing was delivered by late June of 2009, slightly ahead of schedule. The anticipated delivery had been coordinated with the US Coast Guard, who had defined a navigation closure period from mid July 2009 to late August 2009. Considering that the SW bascule leaf had been in the raised position for the prior 10 months, the Contractor had to reconfigure the original construction schedule to accommodate the unforeseen condition of the SW outboard trunnion bearing and continue with the rehabilitation efforts. Simultaneously, the Contractor was required to develop the necessary jacking plan, submit the plan for review and approval, fabricate the necessary equipment and have it ready for the dedicated closure period.

During the trunnion bearing replacement effort, the existing bearing, housing and trunnion shaft were thoroughly inspected and scrutinized to determine if any remedial work was required. During the bearing removal process, the existing bearings outer ring had to be split in order to more practically remove the remainder of its components. Inspection of all existing bearing components, after the removal process, revealed no obvious abnormalities or flaws that had not already been reported. The existing trunnion shaft was then visually inspected and measured to confirm that its taper complemented the replacement bearing. Precision measurements showed that the shafts taper was slightly larger than the bearings taper. After review, it was determined that although this would increase the stress on the inboard end of the bearings inner ring, it would not adversely affected its performance. In addition, the existing housing was visually inspected and measured to confirm that its geometry was in-line-with what had been measured when loaded and that it would properly support the replacement bearing. Precision measurements showed that the housing bore was approx. 0.006” over the recommended tolerance range as well as two areas of slight non-uniformity. After review, it was determined that the condition was likely original and, considering the circumstances, noted as less than ideal but tolerable.

Based on the inspection findings, it was recommended that the circumferential groove be incorporated into the trunnion shaft, that minor hand dressing of the housing bore be performed, that original machine marks located on the housing bores inboard end be blended smooth and that the replacement bearing be installed.

Ultimately, the SW bascule leaf was jacked in the closed (0 degree) position, with a total of 29 days transpiring before the replacement bearing was considered officially installed and ready for use. The installation process had justified the reuse of both the existing trunnion housing and shaft, however, it had not presented an obvious reason for the bearing failure. Looking ahead, the City of Baltimore will need to monitor the performance and condition of all eight trunnion bearings currently in service. The inspection will take place through inspection covers that have been added to the existing end covers allowing visual and limited hands-on inspection of the outboard ends of the bearings. As discussed with the bearing manufacturer, these inspections will likely occur annually and focus on the bearings wear surfaces in the load zone and monitor previously reported clearances.

As of August 26, 2009, the replacement bearing has been fully operational, allowing the Contractor to continue with the completion of rehabilitation efforts.

Acknowledgements:

Rehabilitation of Pennington Avenue Bascule Bridge over Curtis Creek

Bridge Owner and Operator:
City of Baltimore Department of Transportation, Baltimore, MD

General Contractor:
Cianbro Corporation, Baltimore, MD

Specialty Sub-Contractors:
In-Place Machining, Milwaukee, WI
Direct Dimensions Inc., Owings Mills, MD
Bolt Tech Mannings, Dover, NJ

Bearing Manufacturers:
The Timken Corporation, Canton, OH
SKF Industrial Division, Kulpsville, PA

Machinery Fabricator:
Steward Machine Co., Birmingham, AL

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