HEAVY MOVABLE STRUCTURES, INC.
NINETEENTH BIENNIAL SYMPOSIUM

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Emergency Response: Bascule Bridge Drivetrain Failure

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Introduction

This paper will present the emergency response to a span drive machinery failure for one leaf of a double leaf bascule bridge. The failure occurred at the rack pinion shaft bearing mounting bolts resulting in loss of operation and control of the leaf. The span drive machinery is a Hopkins Frame arrangement that was in service for approximately 32 years at the time of the failure.

Failures such as this are rare on movable bridges as the machinery is typically designed and constructed in accordance with the American Association of State Highway and Transportation Officials (AASHTO) specifications. The allowable stresses prescribed by AASHTO and other conservative aspects of the specifications ensure that failure of a machinery component is highly unlikely.

This paper presents the initial response provided to investigate the failure and determine the cause of the failure, and the subsequent repair efforts to minimize outages. The investigation of the failure included inspection of all machinery and structural components subject to impact loading as a result of the loss of control of the leaf to identify any damage caused due to the failed components. Based on the failure analysis the second leaf was removed from service. Temporary and permanent repairs were expedited to restore bridge operation. This paper will also discuss the subsequent analysis of the drivetrain based on current AASHTO requirements.

Machinery Description

The span drive machinery for the subject bridge is a Hopkins frame arrangement that includes two electric motors that are coupled to a double extended input shaft of a differential reducer. There is one spring-set thrustor-released drum brake located on the non-driven end of each motor. There is an open spur pinion (P2) located at each output shaft of the differential reducer. Each pinion is engaged with a G2 gear that is mounted on the inboard end of one of the two rack pinion shafts. The rack pinion shafts are engaged with curved racks that are mounted to the bascule leaf. All shafts are supported in bronze bearings. All components are secured to a Hopkins Frame welded steel assembly, which is clevis-mounted to the bascule pier. Outboard of each rack pinion shaft there is a link arm that connects the rack pinion shaft to a shaft at the counterweight side of the Hopkins Frame assembly at a position colinear with the axis of rotation for the leaf. The span drive machinery is depicted in Figure 2, and includes identification of the location of the failure.

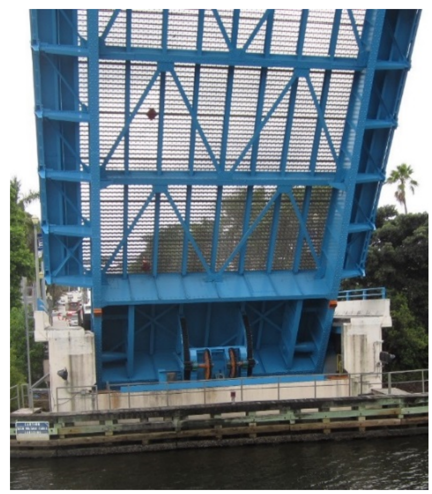

Figure 1. Representative leaf in the open position with Hopkins frame span drive machinery.

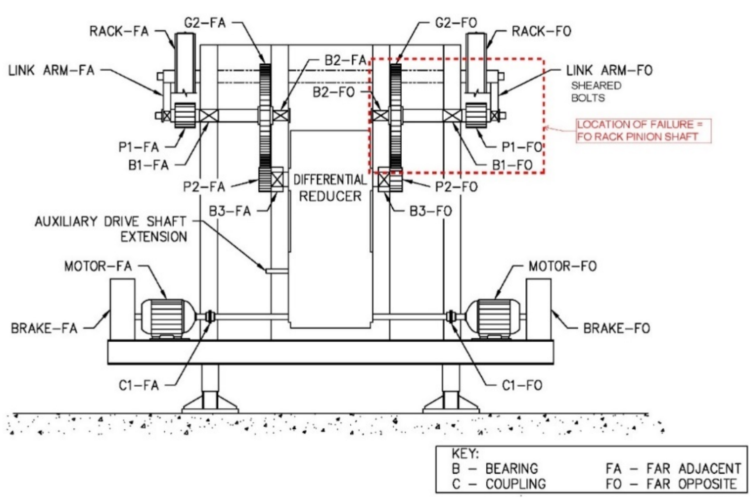

Figure 2. Hopkins frame span drive machinery layout.

Failure

On the afternoon of Sunday January 27, 2019, the far leaf of the bascule bridge experienced a span drive machinery failure that resulted in loss of control of the leaf. The failure occurred on a Hopkins frame span drive machinery arrangement. See Figure3. The failure originated at the far opposite rack pinion shaft bearing (B1-FO). See Figure 2. Upon failure of the B1-FO it appeared that the B2-FO mounting bolts failed resulting in the unsupported rack pinion disengaging with the rack. This resulted in the loss of control of the leaf and the rack pinion shaft falling, deforming the Hopkins frame link arm that remained connected to the shaft. The arrangement of the Hopkins frame relies on a central differential speed reducer and brake assemblies located at the motor shafts. The design of a differential allows the output shafts to rotate at different speeds to provide load sharing. The downside of this arrangement is that if an output shaft fails or is otherwise disconnected from the drive, the motors and brakes at the input shaft of the differential become ineffective. As a result, the leaf was unable to be controlled when the rack pinion disengaged from the rack. It was assumed that the far leaf impacted the live load supports upon loss of control.

Figure 3: Unsupported rack pinion shaft resting on the motor, attached to the deformed Hopkins frame arm.

Inspection Findings

A complete inspection of the mechanical, electrical and structural components was conducted to assess any further damage from the failure. In addition to the obvious failed components, bearing B1-FA base was shifted relative to the Hopkins frame and light impact damage was noted on pinion P2-FO and gear G2-FO. The Brake-FO assembly was damaged and the Motor-FO housing had some cooling fins that were cracked. The gearing was subjected to magnetic particle testing to verify the integrity of the components for re-use. Additionally the Hopkins pipe was subjected to ultrasonic testing. The remaining machinery that was not out of place or deformed was in good condition and could be reused to provide reliable long term operation. A visual inspection was performed of all impacted machinery and no crack indications were found in the remaining machinery components.

Figure 4: Bearing B1-FO. View of the failed mounting bolts remaining in the bearing base.

Inspection of the failed mounting bolts for the B1-FO bearing indicated that one bolt exhibited corrosion in the fracture plane, indicating the bolt failure initiated prior to the operational failure, while the remaining three bolts also had evidence of crack initiation although to a lesser extent.

Root Cause of Failure

A review of the machinery loading compared to the strength of the bearing bolts was also conducted. The review concluded that the bolts, as installed did not meet AASHTO machinery design requirements. Subsequently, rehabilitation plans were reviewed and the intent of the bearing mounting was that the bearing bases were to be mounted with the combination of bolts and dowels to provide the required resistance to meet the intent of AASHTO machinery design. As shown in Figure 4, no dowels were noted to be installed and as a result the bearing mounting shear capacity did not meet the requirements of the rehabilitation plans. The installation provided 30 years of service until the bolts were ultimately subjected to loading that resulted in failure.

Near Leaf Investigation

Due to this failure, the far leaf remained in the seated position, enabling vehicular traffic to be unaffected by the failure. To facilitate marine traffic, the near leaf remained in service and operated routinely for vessels. Due to the root cause of the failure being the lack of bolt shear capacity as compared to the design intent per the rehabilitation plans, the integrity of the near leaf bearing mounting bolts were in question. Upon visual inspection, no physical signs of damaged bolts was evident and no movement during operation was noted at the bearings. The near leaf bearing B1, B2 and B3 mounting bolts were evaluated using the ultrasonic test methods. The result of the testing was that several bearing bolts had an indication of crack initiation. Near leaf operations were halted until the bolts in question could be replaced. The replacement of the questionable bolts at the near leaf needed to be performed in an expedited manner to restore operation of the movable bridge to facilitate single leaf operation. Calculations were performed to replace the existing bearing B1, B2 and B3 bolts on the near leaf one at a time with temporary bolts. The temporary bolts were designed to secure the bearings under machinery loading developed when operating the leaf in wind speeds below 25 mph.

Figure 5: Bearing B2 installed with temporary mounting bolts.

Restoration of Operation under Wind Restrictions

Once the near leaf was operational, efforts were made to restore operation to the far leaf. The bearings, bull gear, shaft and pinion were still intact and reusable. All of the span drive machinery components were visually inspected, the gearing was inspected using Magnetic Particle testing and the Hopkins pipe was ultrasonically tested. The Hopkins frame link arm was damaged and needed to be replaced. A temporary Hopkins frame link was designed and installed to replace the damaged link arm. The machinery was reinstalled using temporary bolts and both movable leaves were operational using temporary mounting bolts. The motor was limited to a predetermined amperage to prevent the machinery from operating at wind speeds above 25mph. This was accomplished by February 14, 2019. Both movable leaves were operational within 18 days of the failure.

Figure 6: Far opposite rack and pinion contact on the opening face. Machinery secured with temporary bolts.

Permanent Repairs

Once both movable leaves were operational under a 25mph wind restriction relying on temporary mounting bolts and link arm installations, the work to replace the temporary components with permanent components began. Shop drawing approval and procurement of these components took approximately one month. Once these items were procured the alignment of the open gearing and bearings was performed.

The alignment of the open gearing and bearings of the far leaf was determined by measuring the bearing clearances using thickness gages, measuring the backlash using thickness gages and applying bluing compound on the gear teeth surface and running the bridge through an opening cycle and evaluation evaluating the contact. From these measurements it was determined that the alignment of the machinery could be adjusted to improve the alignment prior to installing the permanent bolts. The machinery was adjusted to provide the best possible alignment prior to drilling for the new turned bolts.

To determine if any adjustments were needed from the temporary installation to the permanent installation, alignment measurements were taken at the rack and pinion gearset and the G2/P2 gearset. For the rack and pinion gearset 5 rack teeth were marked and coated with bluing. The contact was evaluated based on bluing transfer. The backlash was not accessible at this gearset. For the G2/P2 gearset four locations on the G2 gear equally spaced were cleaned and coated with a bluing compound. The bluing transfer was evaluated at these four locations after a bridge operation. The backlash was also measured at both ends at all these four locations. A correlation was noted between the amount of contact and the taper in the backlash. The larger the taper the smaller the contact.

The goal of the re-alignment was to achieve 80% contact between the gears on the far leaf after reinstallation. This is a typical alignment requirement for new spur gears, and is based on an assessment of the contact patterns visible in lubricant or bluing after operation. The 80% contact target was met at the far adjacent P2/G2 gear set, but was not met for the far-adjacent rack and pinion or either of the far-opposite gear sets. The following field issues complicated efforts:

- The far opposite G2 gear was warped. Measurements with a dial indicator at the rim of the gear demonstrate a run-out of approximately 0.150” during operation. Note that this issue was not noted at the far adjacent G2 gear. It is possible that this is damage from the time of the failure when the gear and shaft assembly disengaged from the drivetrain. A visual inspection performed of the gear prior to temporary re-installation did not indicate any significant damage.
- The existing gears were worn. The existing gears had provided decades of service. The teeth have worn-in to accommodate any misalignment from the original installation. Depending on the original condition of the gear teeth, the wear varied. The failure of the drivetrain resulted in the disengagement of the far opposite rack pinion shaft. Without match-marks, it is nearly impossible to locate the previously meshed teeth at either the far opposite Rack/P1 or the G2/P2 gearset.

Given the above limitations, the achieved alignment was considered to be acceptable.

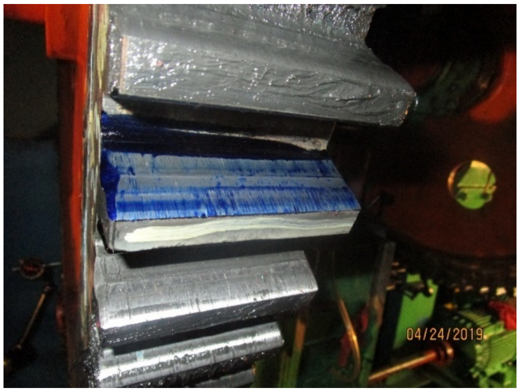

Figure 7: Contact at the Far Adjacent G2/P2 with a taper in the backlash of 0.000"

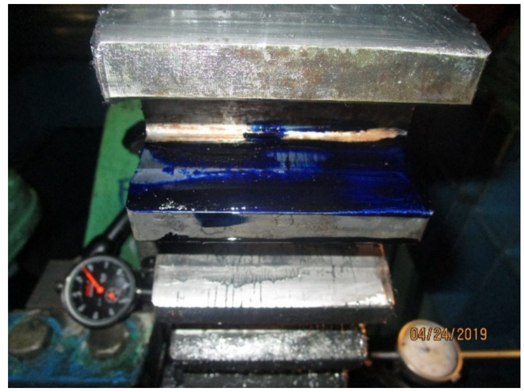

Figure 8: Contact at the Far Opposite G2/P2 with a taper in the backlash of 0.005"

Consequences of Failure

This failure resulted in the following:

- Loss of control of the far leaf and free fall of the bascule leaf into the live load supports
- Potential of damage to the bascule leaf due to the free fall into the live load supports
- Marine closures
- Damage to the machinery
- Alignment challenges

Failure Mitigation

It would be ideal to be able to prevent this failure to mitigate the above mentioned challenges. This type of failure is not only applicable to Hopkins Frame bascule machinery but to any bascule machinery that does not have machinery brakes located on the output shafts of the differential reducer. A system with a differential reducer is reliant on both rack pinion shafts being engaged with the movable leaf. In case of a failure of one rack pinion shaft as was the case with this system, the movable leaf can experience a loss of control.

AASHTO Movable 2007 Section 5.6.1 states power operated bridges shall be provided with two sets of brakes. One set, designated as the motor brake as near the shaft of the prime mover as practical and other set, designated as the machinery brake, as near the operating ropes, pinion and ring gears as practical. This AASHTO requirement is particularly relevant when using differentials to ensure that machinery brakes are placed outboard of the differential reducer. In case of a failure of this nature it would prevent the uncontrolled fall of the movable leaf and eliminate the damage due to an uncontrolled impact.

For existing movable bridges it is important to determine the condition of the B1 and B2 bearing mounting and anchor bolts. It is also important to note if there is any movement relative to the support during operation. The integrity of these bearings is critical to ensure that this type of failure does not occur especially with movable bridges equipped with a differential reducer. After this failure the owner initiated a program of testing the mounting bolts for the B1, B2 and B3 bearings using the ultrasonic testing method for all Hopkins Frame Bridges. The testing is performed periodically and if indications are present, the bolts are replaced. The failure at the bearing mounting bolts at this bridge could not be determined via visual inspection as the failure point of the mounting bolt was at the interface of the bearings and the support. Therefore it is necessary to use a method similar to the ultrasonic testing to see if there are any indications of crack initiation in the bolt. If noted those bolts should be replaced prior to a failure.

Conclusion

Failures such as this are rare on movable bridges. The root cause of this failure was a bearing mounting installation that was not installed to meet the intended design. This highlights the importance of designing and installing machinery to meet AASHTO specifications. The use of non-destructive testing is invaluable when performing condition assessment on components that are not readily available for direct inspection. Any bolt in a movable bridge drive train that exhibits excessive corrosion, movement, deformation, or any sign of distress should be considered for further evaluation and NDT testing to verify the integrity of the component. The evaluation of the bearing mounting bolts using the ultrasonic testing method was critical in preventing the second leaf from experiencing a similar failure.