HEAVY MOVABLE STRUCTURES, INC.
NINETEENTH BIENNIAL SYMPOSIUM
October 17-20, 2022

CSX New River Bascule Bridge Emergency Coupling Replacement

Robert Algazi P.E., Amaka Anderson P.E., David Nyarko P.E, Roger Khouri P.E.
WSP USA, FL, NJ, and NY, USA

MARRIOTT'S RENAISSANCE HOTEL AT SEAWORLD
ORLANDO, FLORIDA

ABSTRACT:

The CSX New River Bascule Bridge is a single leaf Scherzer-type bascule bridge carrying freight rail traffic over the New River in Fort Lauderdale, FL. During an annual in-depth mechanical inspection of the CSX New River Bascule Bridge, significant cracks were observed at both span drive main pinion couplings. Further investigations determined that the couplings had failed and required immediate replacement.

Extensive investigations were performed to determine the coupling failure as a part of the replacement design. Significant collaboration was required between the Engineer, FDOT, and Contractor to ensure the project could be completed within the limited time frame. As an additional challenge, CSX railroad deemed the bridge needed to be operational throughout construction. As result the bridge was operated on a single pinion while the coupling was replaced in a 1-month period.

This paper will go over the significant challenges overcame during the coupling replacement and the findings of the coupling failure investigations.

Photo 1: The CSX New River Bascule Bridge in the Open Position

1.0 INTRODUCTION BACKGROUND

In 2020, the CSX New River Bascule Bridge faced significant failure of the two main span drive pinion couplings. Both couplings had cracks which caused the couplings to fail, affecting the operation of the bridge and required immediate replacement. The necessary repairs required a quick design of a new replacement with limited interruption to freight traffic which the bridge serviced. This paper will go over the significant challenges overcome during the coupling replacement and document the findings of the coupling failure investigations.

The CSX New River Bridge is located in Fort Lauderdale, Florida over the south fork of the New River just south of interstate I-95. It is a Scherzer Type Rolling Lift Bascule Bridge with an overhead counterweight. The bascule span is 104’ from the tip of the bridge to the center of roll and 20’-6” from main girder center to center. The span carries daily heavy freight rail traffic over a 70’ navigable channel. To allow for marine traffic to pass under the bridge, it is generally left in the open position when not in use. Construction was completed in 2017.

Photo 2: Span Drive Machinery

A machinery room is located above the railroad and is accessible in both the open and closed position. The span drive machinery consists of two 60 hp A/C electric motors which drive a gear train terminating at a rack and pinion which operate the bridge. There are a pair of span lock machinery used to lock the bridge in the down position and a pair of tail lock machinery used to lock the bridge in the open position. The bridge rotates about a 25’ radius tread and track assembly. The machinery is controlled by a PLC system.

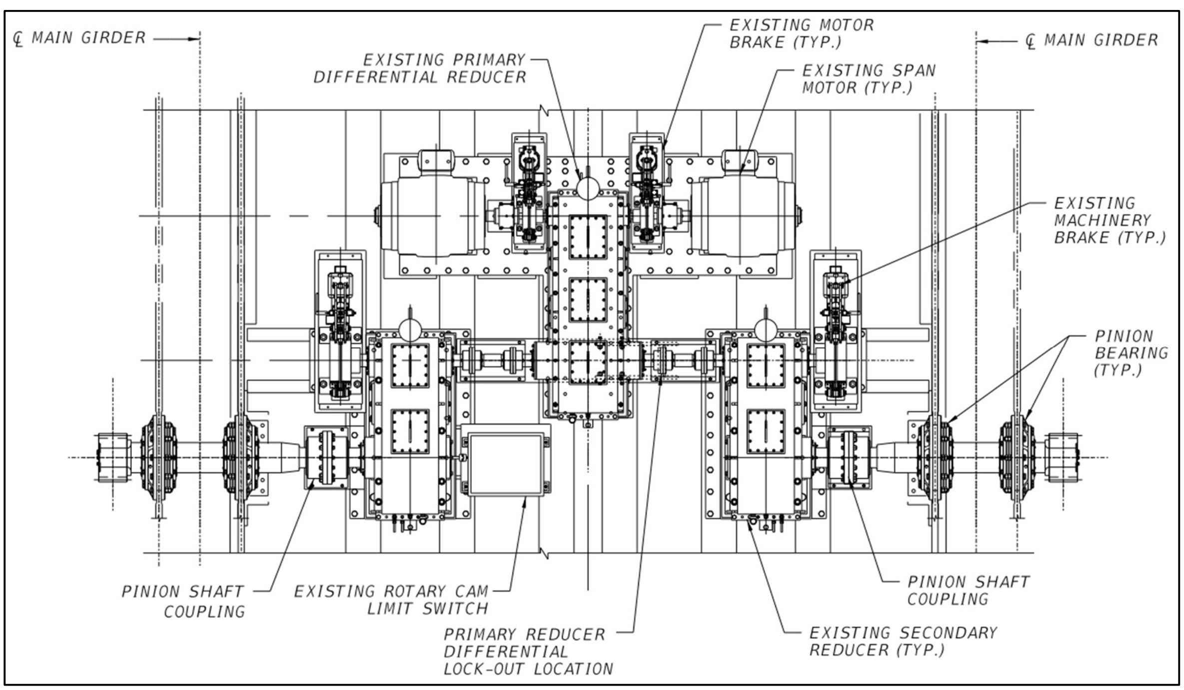

Figure 1: Span Drive Machinery Layout

1.1 CRACK DISCOVERY

During the 2020 annual mechanical/electrical inspection performed by Stantec and Hardesty & Hanover (H&H), a crack in the eastern main pinion shaft coupling hub was discovered. A similar crack in the western main pinion shaft coupling was also discovered. The cracks were emanating from the corner of the coupling keyway up through the body of the hub. Over time the cracks propagated until the entire hub was split in half.

As a result, FDOT hired HNTB to design a temporary collar which was installed on both couplings to help prevent the hubs from separating. Bridge operation times were increased and closing of the span for rail traffic was limited to reduce the loading on the couplings and reduce the risk for catastrophic failure without impeding freight rail traffic. It was understood this would be a temporary solution with a permanent coupling replacement required. Also, since construction of the bridge was recently completed, a review of the cause of failure and prevention of future issues was mandatory.


Photo 3: Crack in Coupling Hub

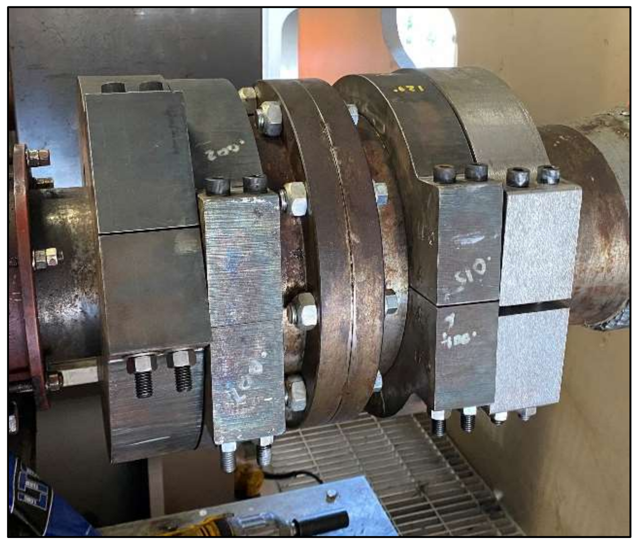
Photo 4: Collar assembly on the pinion coupling.

1.2 INITIAL INVESTIGATIONS

WSP was retained by FDOT to design a replacement for the coupling and perform an in-depth investigation into the cause of the failure of the coupling. Additionally, due to the accelerated nature of the emergency repair, Middlesex Corporation was contracted to perform the repair work at the start of the project with Lee Mechanical Inc (LMI) as the millwright, EON Integration Services for Electrical and H&H as the contractor's engineer.

The design and construction teams performed an initial inspection of the existing bridge and all components, including the couplings, to identify potential causes of the failure. Inspection of the existing pinion couplings confirmed the cracks were emanating from the corners of the hub keyways. Each keyway corner was cut at a hard angle with no radius provided. Side clearances were present at the keyways allowing the keys to move freely under hand contact. Additionally due to the split in the coupling hub, the interference fit required at the hub-shaft interface was lost.

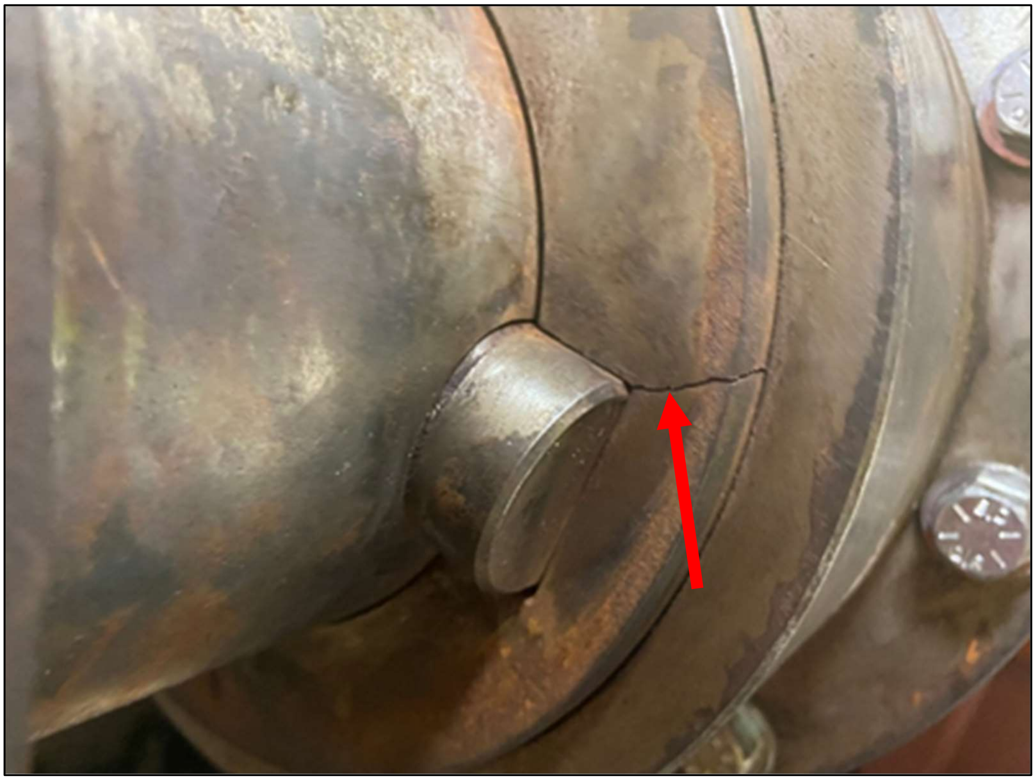

Photo 5: Hub crack during bridge operations. Note gap between hub and shaft

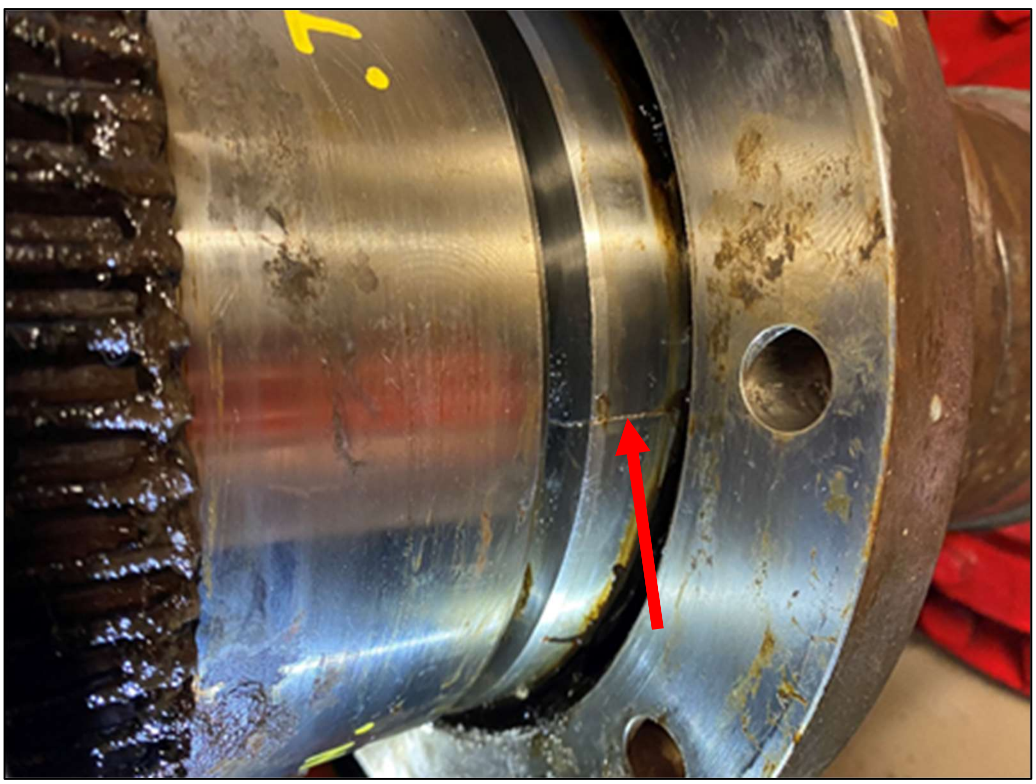

Photo 6: Note crack through pinion hub (radially and longitudinally) at coupling center.

Photo 7: Clearance between west pinion hub key and keyway. Note crack at SW corner

A clearance was measured between the cracked pinion hub and shaft at both couplings (See Photo 7). The cracked and loose pinion hub would move against the pinion shaft during bridge operation. The excess hub clearance was not reported until after the coupling hub cracked and is likely a result of the hub cracking; however, as there are no as built records, this cannot be confirmed.

The existing alignment of all span drive machinery couplings was measured. Measurements at all couplings indicated general misalignment when compared to the manufacturer's recommended alignment tolerances but were within the operational tolerances. Backlash and tip clearances were measured at the rack/pinon assemblies with no binding or cross mesh recorded. Additionally, wear and alignment at the tread and track was measured; however, there were no notable findings.

WL3 Solutions performed a laser alignment scan of the span drive machinery shafts and positioning of the pinion shaft centerline/center of roll with respect to the curved tread plate at various bridge angles of opening. The results of the alignment survey identified the pinion shafts were not in line with each other and additionally they were not parallel. This was expected because the pinion bearing bores in the girders were not line bored together during original fabrication. Even with the parallel offset of the pinion shafts, the alignment of the east and west pinion couplings, which connects the pinion shafts to the secondary reducer output shafts, were all within operational tolerances.

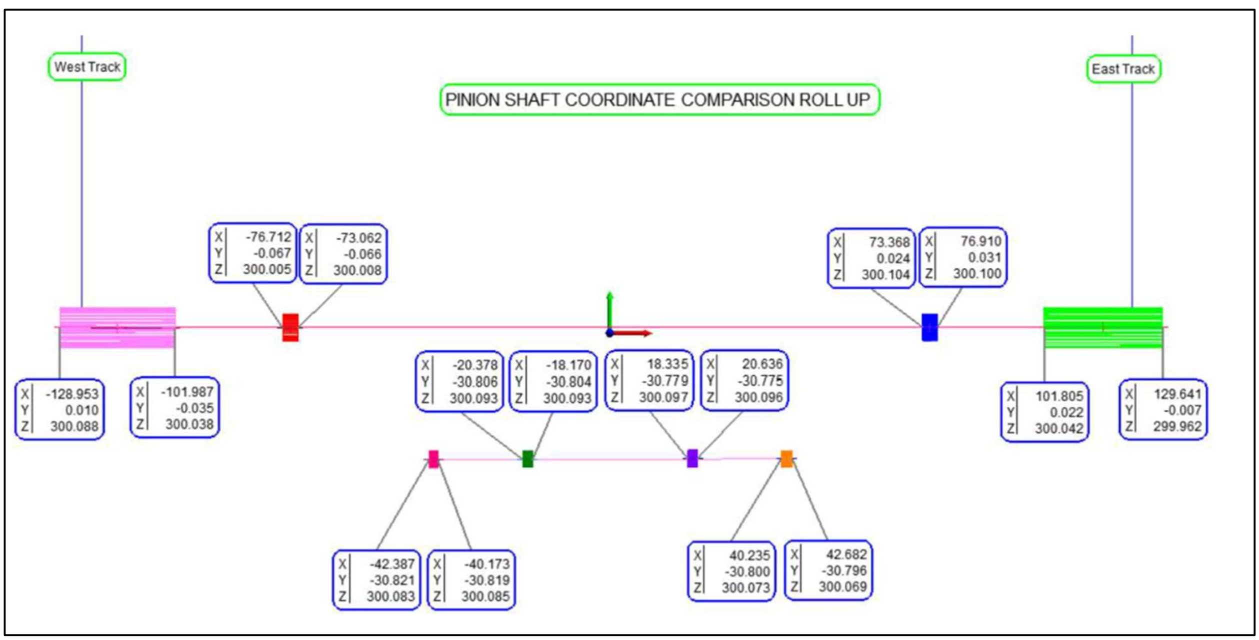

Figure 2: Existing Machinery Alignment Laser Survey Results

A dynamic strain gage balance test was performed to measure the existing balance condition and the span drive machinery torques seen during operation. Testing was performed at half the normal bridge operation speed in order to reduce loading on the couplings. Testing revealed the bridge was well balanced with fairly equal load sharing between east and west pinions; however, several spike loads where present at the starting and deceleration phases of operation. When the results were compared to the 2017 final construction span balance report, it was found the spike loading in the 2017 report was above the AASHTO allowable 150% motor torque rating. It is not clear how long the bridge was operating under these high peak torques.

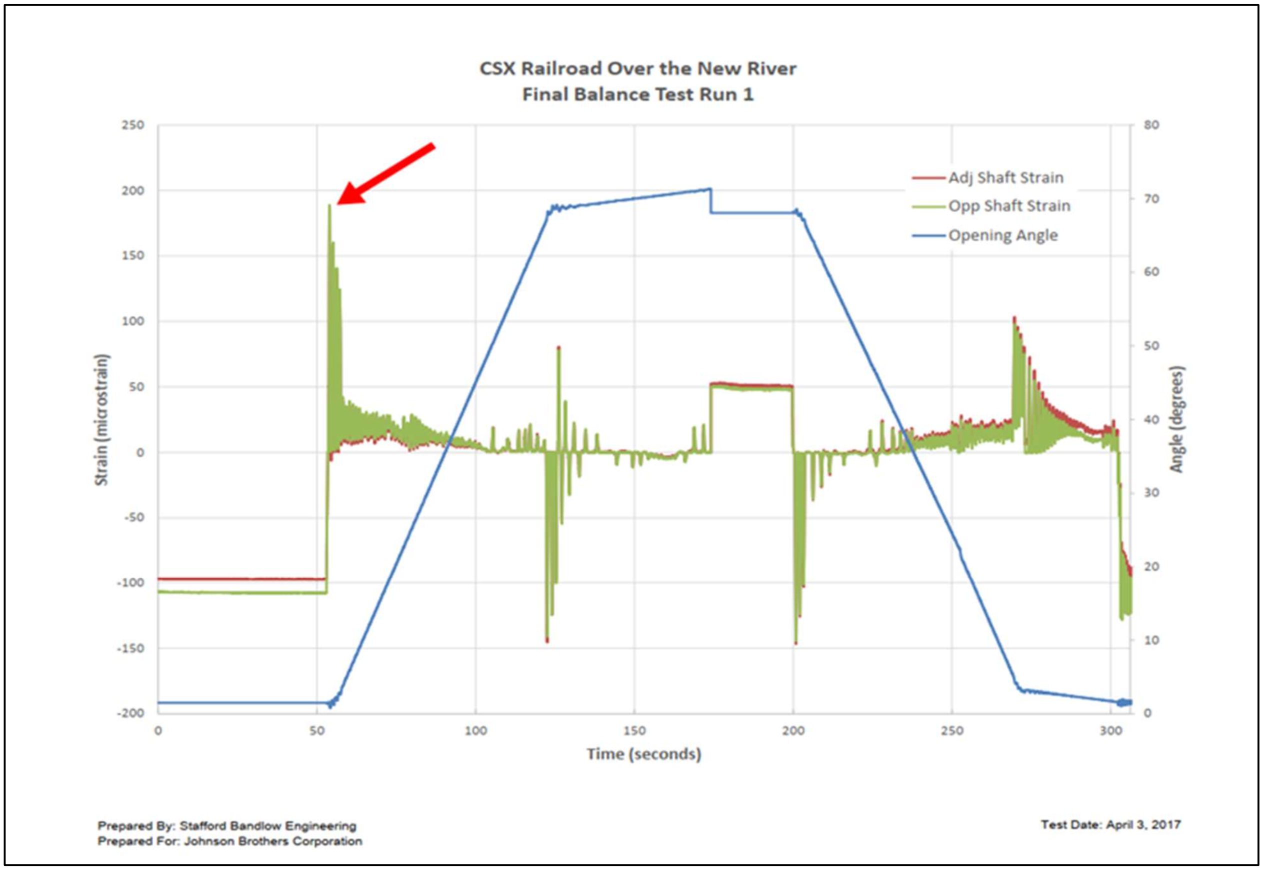

Figure 3: 2017 Construction Balance Report Strip Chart

After completion of the initial field investigations, it was agreed that a larger coupling would be required in order to prevent a reoccurring failure. Modifications to the span drive control system would also be necessary to reduce the spike loading seen on the bridge during operation. Additionally, since the spike loadings were occurring during periods of braking, adjustment to the brake timing would be made as necessary. Special care would be taken to measure and record and document all fits and alignment during the replacement.

2.0 COUPLING REPLACEMENT

The design of the coupling replacement occurred on an accelerated schedule over a period of 2 months. Meetings were held weekly at a minimum between the design team, the Contractor's team, and FDOT to coordinate the progression of design and ensure all goals were met. In general, the goals for the project were to replace the existing failed couplings and address all potential sources of the original failure.

Upsizing the new coupling to increase the torque rating was essential to ensure this failure did not repeat again and was necessary based on the loading seen in the strain gage testing. The maximum peak torque measured during the opening acceleration phase was approximately 196% of the full load motor torque (422.2 kip*in). This is above the machinery 150% Full Load Torque (FLT) of the Motor rating per AASHTO/AREMA. Increasing the original coupling size from a Falk 1045 G20 to a Falk 1055 G20 increased the torque capacity by approximately 75%.

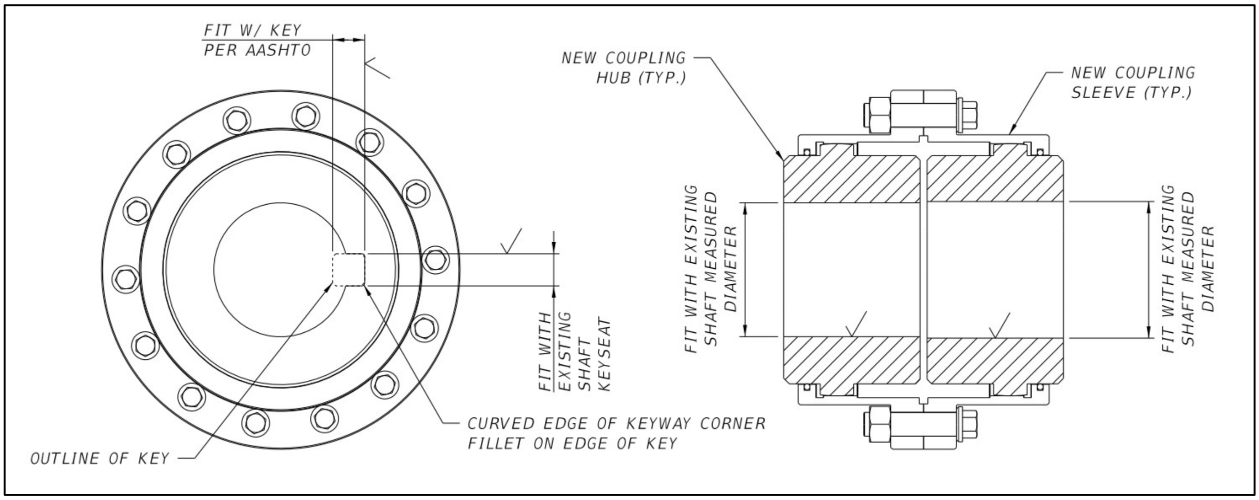

Figure 4: Sketch of Coupling Design Considerations

An additional concern with the existing couplings were the fits at the key/keyways and the hub/shaft. When the crack split the original coupling hub, the fits were lost at these locations. There was also potential damage to the existing shaft surfaces and keyseat and potential tapering of the keyway walls based on preliminary feeler gauge measurements. Measurements of the existing shafts would need to be taken after the existing couplings were removed. Additionally, time was allotted for potential machining to the existing shafts and keyways. Field measurements would need to be approved by the design team in real time to minimize the construction downtime. Careful coordination between the design team and the contractor's team was done to prepare this to go as smoothly as possible.

The corners of the original coupling keyways were sharp with no notable radii. This acted as a stress riser resulting in the crack forming from the corner. Although radii are required per AASHTO, AREMA does not have such a requirement and ANSI B17.1, which dictates the recommended dimensions for keys and keyways, notes that in general chamfered keys and filleted keyseats are not used. The design team made sure to include provisions for the radii at the keyways in the repair plans and confirmed they were provided during shop drawing review and fabrication of the coupling bores.

2.1 SINGLE PINION OPERATION

Originally, the intent was to perform the pinion coupling replacement during a complete bridge outage. The bridge would be locked in the open position for a period of 18 days; however, this would mean CSX freight rail would not be able to cross the bridge during this time. This was not unacceptable and an alternative method of operation was required.

Several options to maintain bridge operation were investigated including alternative modes of lifting the bridge such as pullies or cranes. The final solution was to operate the bridge in a single pinion configuration. In this arrangement, one pinion would be out of service to allow for replacement of the coupling while the other would remain in service to operate the bridge. This did not eliminate all bridge outages, as it was not reasonable to operate with single pinion on the failed coupling. Instead, the failed coupling half would be replaced with a sacrificial coupling half during a 24-hour complete bridge outage. The sacrificial coupling half would be the same size and type as the existing and connect to the non-failed half of the existing coupling.

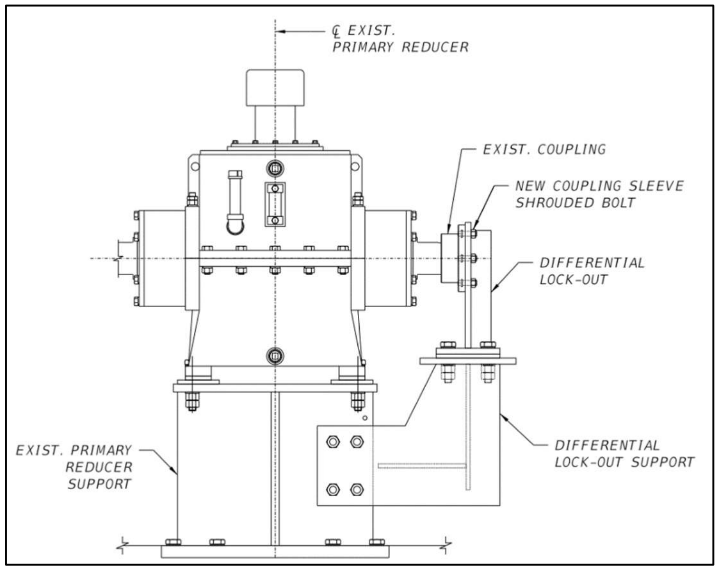

Figure 5: Primary Reducer Differential Lock-out Mechanism

In order to operate the bridge in a single pinion configuration, a differential lock out mechanism was required. The primary reducer had a differential which would mean that disconnected output shaft must be locked in place in order for the connected output shaft to function properly. A new lock-out mechanism was provided for this purpose. It was mounted to a temporary support mounted to the existing reducer support. After construction, the lock-out mechanism and temporary supports were returned to the department and can be used in the future if other repairs are necessary.

3.0 REPLACEMENT PROCESS

The coupling replacement was broken into three phases. First a sacrificial coupling was installed at the east pinion coupling, second, the west pinion coupling was replaced with the final coupling, and third the east sacrificial coupling was replaced with the final coupling. The sequence for each phase was relatively similar with few exceptions. Below is a general breakdown of the replacement process.

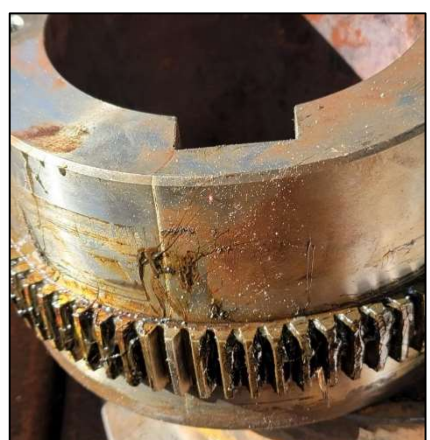

Photo 8: Original Coupling Half After Removal

Step 1: Mobilize Equipment and Set Up

Before the coupling could be removed the area needed to be set up for the work. Several components including the secondary reducer needed to be temporarily relocated to provide enough space for the coupling to be removed. During phases 2 and 3, the bridge would be operational; therefore, all components moved needed to be secured to the bridge.

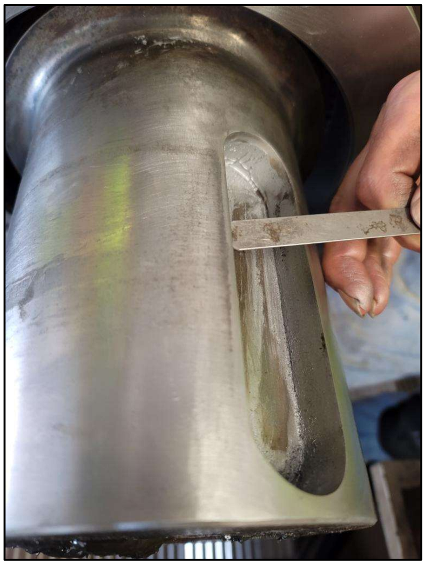

Photo 9: Existing Shaft Keyway Measurements

Step 2: Removal of The Existing Coupling

Once the couplings were ready for removal, the coupling cover was pulled back and the existing hubs were pulled off the shaft. All temporary collars installed on the couplings were also removed. It was clear once the existing couplings were removed that the whole hub had completely split indicating a complete failure of the component.

Step 3: Measure Existing Shaft and Keyway

In order for the coupling replacement to be successful, it was crucial to provide the required fits at the shaft and keyseats. To do this, the existing shaft diameters and keyseat dimensions were measured at several location. Differences in the measurements could prevent the required fits to be achieved and would need to be machined in the field. In addition, a visual inspection was performed to check for any damage. Luckily there was no major damage and only minor hand surface refining work to the shafts was required. The keyways had to be machined in the field due to the tapered wear of the walls.

Step 4: Final Bore the Couplings

With the exact measurements of the shaft and keyseats known, the dimensions of the coupling keyway and bores could be finalized and machined. The shop had all couplings pre-bored as to speed up the turnaround for final machining. For the sacrificial coupling, final machining and boring was performed prior to the outage based on the original as-built shop drawings. This was done to reduce the outage period.

Photo 10: Shop Machining of The Sacrificial Coupling Bore

Photo 11: Shop Machining of The Sacrificial Coupling Keyway

Step 5: Install the New Coupling

After all machining was done and the couplings were shipped to the job site, the new couplings were installed. Alignment of the machinery was checked and corrected when the machinery was reassembled. Functional testing was performed after each phase since the coupling that was just installed would now be the primary mode of operation.

Photo 12: Final Coupling Installation

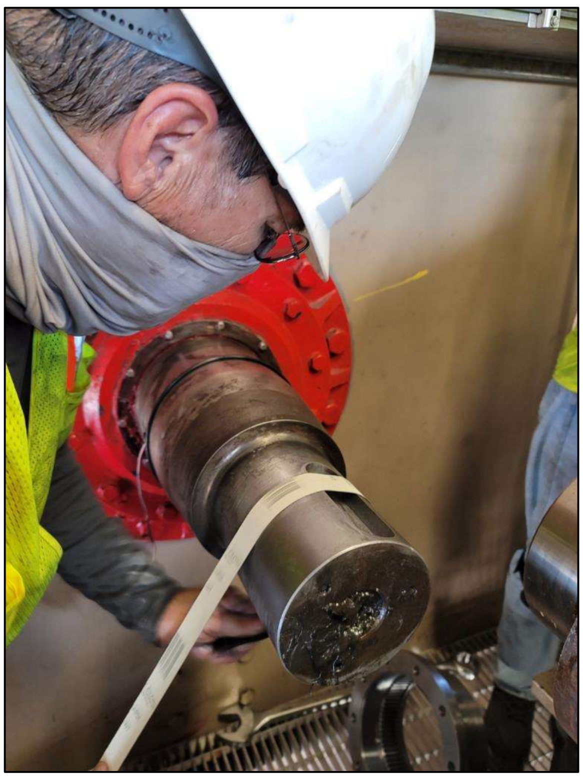

Photo 14: Millwright Polishing Shaft Surfaces

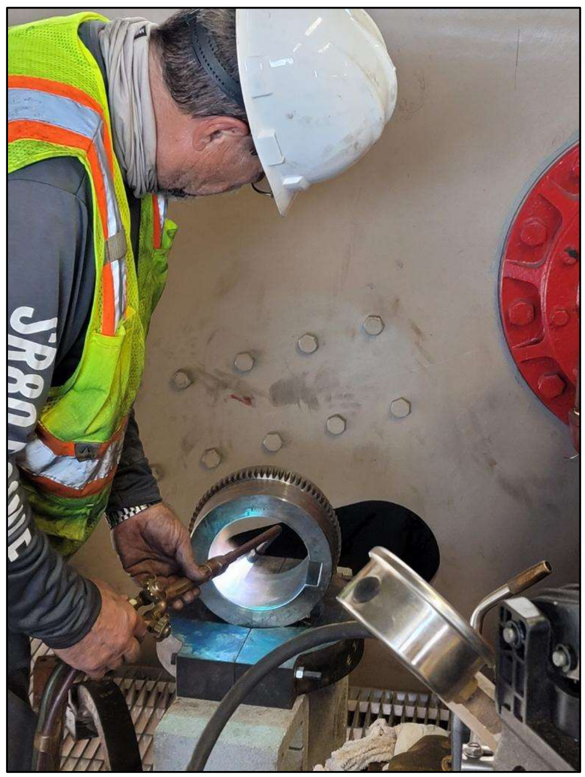

Photo 13: Millwright Heating Coupling Hub for Installation

3.1 CONTROL SYSTEM ADJUSTMENTS

During the course of the repairs, the controls for the motor drive was modified several times. First, the bridge operating time was double when the crack was discovered. This was to reduce the loading on the coupling by increasing the time to accelerate/decelerate. The controls were later modified during construction to account for the single pinion operation. During single pinion operation and when the primary reducer differential has one output shaft locked out, the other output shaft will spin at twice the original output speed. As such, the speed of the motors needed to be reduced to account for this. Additionally, the maximum allowable motor torque was reduced in addition to the timing adjustment for longer openings to further decrease the actual loading on the failed couplings during replacement.

After the repairs were completed, the control system was adjusted one final time. Due to limitations with accessing the PLC program, modifications to the control system for opening and closing ramping time could not be adjusted. This limited the adjustments that could be made. The "Do Not Exceed Torque" was reset to 150% of the motor rated torque to ensure it was not providing more horsepower than the machinery was rated to. Second, the span operational time was adjusted to 90 secs for a total opening time with 20 seconds for acceleration and deceleration phases each. For comparison, the original as-built plans called for 70 second full opening time with 10 seconds for acceleration and deceleration. Additional modifications were made to the motor and machinery brake set timings to limit braking torque on the system.

After all adjustments were made and after completion of the coupling repairs, the bridge was operated several times while measuring the torque in the pinion shaft using strain gages. Dynamic strain gage testing is typically performed during ideal conditions (no wind or weather), however poor conditions such as high wind and rain will increase the loading the machinery system. Therefore, to account for this and ensure the machinery was conservative, the measured torque was not allowed to exceed 70% FLT (less than half the machinery rating). Final balance testing confirmed the spike loading and overall machinery torques were reduced and generally improved the operation of the bridge.

4.0 PROBLEM STUDY

The cause of the coupling failure does not appear to be attributed to one singular issue but a combination of several. The discussion below is an assessment summary based on the Phase 1 field investigations, design calculations, and discussions with Rexnord, the coupling manufacturer's Engineers. Several potential causes for the cracks in the coupling hubs have been identified and are listed below:

<u>1. Peak Torque Overload During Bridge Operation:</u>
The original Falk 1045G20 double engagement coupling had a torque capacity of 371.7 kip*in, which exceeded the Contract Plan required coupling torque rating of 304 kip*in and the AREMA requirement to meet 150% full load motor torque (FLMT 323.3 kip*in). The original coupling provided a service factor of 1.73 at full load motor torque. However as previously noted, the 2017 construction final span balance report measured high peak loading during operation due to shortened acceleration and deceleration phases that exceeded the coupling torque rating. A peak torque overload could initiate a coupling failure mode of a hub burst or crack over a corner of the keyway. Failures can occur at the keyway location due to that generally being the weak point of the hub.

*The replacement coupling is a Falk 1055G20 double engagement coupling with a rated torque capacity of 655.2kip*in. The replacement coupling size has an increased service factor of 3.04 at full load motor torque which meets the coupling manufacturer recommended service factor for heavy shock loading (3.0). Additionally, since the finding of the coupling cracks, the operation time has been increased from 70 seconds to 140 seconds, resulting in lower operational and peak torque loadings. These lower torque values* *were confirmed during the Phase 1 strain gage testing. The motor control timings are to be adjusted as a part of the emergency repairs to limit the peak torque loading.*

Coupling	Existing 1045G20	New 1055G20
Torque Rating (kip*in)	371.7	655.2
Service Factor to 100% FLMT	1.73	3.04

* FLMT = Full Load Motor Torque

<u>2. Hoop Stress Exceeds the Coupling Hub Material Allowable Stress:</u>
The original coupling shaft diameter was within the manufacturer published maximum allowable coupling bore diameter. AREMA does not require a hoop stress calculation on proprietary components, but one was performed for the in-depth analysis. Per the analysis, the coupling hub hoop stress due to the hub-shaft interference fit exceeded the hub material allowable stress. Additionally, the coupling hub wall thickness did not meet the AREMA recommended wall thickness *(AREMA 15.6.5.22, Where practicable, the length of all hubs shall be not less than the diameter of the bore, and for gears also not less than 1.25 times the width of the teeth. The thickness of the hub should not be less than 0.4 of the diameter of the bore)*. This is particularly important at the coupling keyway where the wall thickness is reduced and is where the hub crack formed. This supports the theory that the coupling could not handle the current excessive peak torque loads and a coupling failure mode of a hub burst or crack over a corner of the keyway initiated.

<u>3. Existing Coupling Keys Were Loose in Keyways:</u>
There were relatively large clearances present between the original coupling keyways and corresponding keys on both the pinon shaft and reducer shaft hubs. Additionally, on the pinion side hub, the key would “rock” in the keyway and the crack in the hub would “open” up noticeable during opening and closing of the movable span. Per the as-built drawings, an FN2 (forced) fit was required between the key and keyways sides. All keyway side clearance measurements taken during field investigations varied from 0.012” to 0.080” and confirmed that the designed specified FN2 fit was not present. Additionally, clearance measurements varied, suggesting that the existing keyway may be tapered and not seat parallel.

Due to the amount of clearance that exists, it was very likely that the required FN2 fit may not have been provided at installation, however, this cannot be confirmed since no construction quality control documents were available. Without an effective fit, the torque may not be transmitted properly by the coupling key to the shaft as required by AREMA 6.5.22.B. This will also cause the transfer of torque to be dependent on only the FN2 force fit between the hub and the shaft, which per our analysis below was not adequate to transfer the full 150% FLMT.

Keyway dimensions of the existing shafts were taken at disassembly and the keyway, and were field machined as required. The replacement keys were specifically made to conform to the FN2 fit requirements based on the final field measured dimensions.

<u>4. Torque Capacity from Coupling-Shaft Interference Fit is Less Than Coupling Torque Rating</u>
Per AREMA 6.5.22.B, the total machinery torque is to be transmitted by the coupling key; however, torque can also be transmitted through the hub-shaft FN2 interference fit. Due to the lack of proper fit at the coupling keys, the machinery torque was transmitted only by the hub-shaft interference fit. Per our analysis, the existing coupling interference fit is not sufficient to transmit the full rated coupling torque capacity alone, allowing the shaft to potentially slip in the coupling.

5. Possible Excessive Interference Fit at Coupling Hub and Shaft:

During discussions with the coupling manufacturer's engineer, it was noted that coupling hub cracking is typically caused by excessive interference fit between the hub and the shaft. The field measured east and west pinion shaft diameters were 6.383" and 6.382" respectively. These measurements were taken directly outside of the hub during the Phase 1 investigations. The pinion shaft diameter measurements exceed the approved shop drawing shaft maximum diameter of 6.3805". The larger diameter shaft would result in an excessive interference fit with the coupling hub which can lead to crack propagation by increased hoop stress; however, based on the available documents provided to us, there is no quality control documentation of the coupling hub measurements taken during construction to verify this.

Both secondary reducer shaft diameters were measured to be 6.255" which is within the maximum allowable diameter of 6.255" as indicated on the as-built shop drawings. Since these measurements were taken outside of the hub, there will be a need to confirm the two diameters when the hubs are removed during the emergency repair.

For the new coupling design, final machined dimensions of the new coupling hub bores will be finalized from field verified measurements of mating existing pinion and reducer shaft dimensions.

6. Lack of Radii in Existing Coupling Keyway Corners

Radii were not provided at the corners of the coupling hub keyways. As previously noted, radii at the corners of coupling keyways is only required in AASHTO and not AREMA nor ANSI B17.1 and are only provided by coupling manufacturers upon request. In general, unrounded keyway corners act as stress risers where a hub could split due to high impact loading or high stresses due to an FN2 side key fits, or a crack could initiate and propagate due to continuous fatigue loading. Due to the observed excessive side clearances, the latter is likely the case.

5.0 CONCLUSIONS

The existing failed pinion shaft couplings were successfully replaced on the accelerated schedule. Operating the bridge in a single pinion configuration worked to minimize the impact to the CSX railroad while not impeding the navigational waterways. By establishing an effective team between the designer, contractor, and owner the project was able to proceed in an extreme accelerated schedule.

The cause of the coupling failure cannot be attributed to one singular issue but a combination of several listed in the paper. The observed high torques beyond the coupling capacity and the cyclical fatigue loading from key movement likely caused the cracks at the coupling keyway corners where radii were not machined to provide stress relief. The new coupling has higher capacity and the machinery torques were lowered by adjustments to the control system effectively reducing the chance of another failure.