HEAVY MOVABLE STRUCTURES, INC.
TWENTIETH BIENNIAL SYMPOSIUM

October 7-10, 2024

Gear Couplings: Design, Maintenance, and Inspection Lessons Learned from Past Issues

Adrian E. Soltys, PE.
Wiss, Janney, Elstner Associates, Inc.

SHERATON HOTEL
NEW ORLEANS, LA

Introduction

Couplings are used in industry to transfer rotational movement and torque through otherwise disconnected shafts or machinery units. Various commercial coupling designs are available to be selected by engineers, depending on the desired performance characteristics and application of the couplings. The AASHTO LRFD Movable Highway Bridge Design Specifications, AREMA Manual for Railway Engineering and the CSA-S6 Canadian Highway Bridge Design Code all identify gear couplings as the preferred type of coupling between movable bridge machinery components, except for couplings connecting machinery shafts to electric motor or internal combustion engine shafts. Grid couplings are most commonly used in those applications because of their superior shock capacity. The preference for gear couplings is due to multiple factors, including having multiple alternative manufacturers in the domestic marketplace with decades of proven performance, the ability to accommodate a wide range of shaft sizes, torques, and speeds, and simplicity of installation and maintenance.

Gear couplings require maintenance in the form of periodic lubrication of the internal gear teeth with an appropriate grease, which may vary depending on coupling manufacturer and rotational speed of the shaft. The purpose of the grease is to protect the internal gear teeth, which transfer torque between the coupled shafts, from corrosion and to reduce friction and wear when misalignment (and therefore sliding movement of the teeth) is present. The absence of lubrication in the gear coupling will result in degradation of the gear teeth until they fail. Although not common, failures of gear couplings have been found to occur suddenly, making the machinery inoperative until a repair can be put into place. These repairs are typically costly and may take large amounts of time to complete due to the complications of replacing couplings in the field and long lead times of custom machined coupling hubs. The remainder of this paper will discuss three anonymized case studies where a coupling failed, the cause and consequences of the failure, the repair process and lessons learned.

Case I

Bridge Type: Span Drive Vertical Lift Bridge
Machinery Subsystem: Span Drive Machinery

Coupling Use Case Description

The machinery for the bridge exemplified in Case I used a total of 16 identical single engagement gear couplings and 2 double engagement flanged sleeve spacer couplings. All noted couplings transfer the same torque and rotations along a line shaft that connects the high speed machinery at the center of the lift span to two low speed machinery assemblies at either end of the lift span. The flanged sleeve spacer couplings and 14 of the double engagement gear couplings are located outdoors and are exposed to the weather year-round, with the only protection being metal covers intended to protect personnel from the rotating machinery. The weather remains hot and humid throughout the year and is prone to intense rainfall. The remaining 2 couplings are located indoors within a temperature-controlled room, housing bridge control systems and the high speed span drive machinery.

Failure Description

The bridge was in service for approximately 10 years prior to experiencing an extreme longitudinal skew condition of the movable span, indicative of a mechanical failure. The immediate cause or location of the failure was not known. The initial assessment indicated that during an attempted bridge operation, one of the low-speed machinery assemblies failed to move while the other end continued to open. The unequal raising of the span was undetected by the remote operating system and continued until the extreme longitudinal skew caused the machinery to jam up and stall the motors.

Remediation Efforts

The initial challenge was twofold: identify what failed and take steps to safely lower the span to reopen to traffic, and then assess the extent of collateral damage and develop immediate repairs restore operation of the lift span. Mechanical engineering/inspection personnel responded on an emergency basis as part of a team with a bridge industry Contractor to assist in this initial effort. A remote visual inspection of the machinery via videoconference was performed. This inspection identified several line shaft couplings with external evidence of internal corrosion. See Figure 1. A coupling failure was immediately suspected.

Figure 1: Coupling immediately after failure. Note fretting on exterior of the coupling sleeve, indicating internal corrosion of the coupling.

A plan was developed to utilize a barge mounted crane to raise the end of the span that failed in order to level the span out. During this process the line shafting was observed and the location of the failed coupling was confirmed. The span was then lowered slowly and incrementally, using the crane at one end and the span drive machinery at the other end. This was completed within 18 hours of the initial failure, just as the mechanical engineering/inspection personnel were arriving at the site. The next morning, damage assessment and evaluation commenced. The failed coupling was disassembled, and inspection was performed to determine the cause of the failure. It was found that the coupling gear teeth were severely deteriorated due to wear and corrosion. No grease was present within the coupling. See Figures 2 and 3.

Figure 2 (Left, Sleeve) and 3 (Right, Hub): Inspection of the failed coupling. Note lack of grease, excessive corrosion and wear present.

In order to return the bridge to service, a temporary fix was proposed to allow time for procurement of a new coupling for a permanent repair: weld the coupling sleeve to the coupling hub around the circumference of the sleeve-hub interface. This would effectively transform the flex-flex coupling into a flex-rigid coupling. Prior to proceeding with this course of action, the alignment of the coupling was measured and it was determined that the coupling was very well aligned. It was decided by the Owner that welding was an acceptable temporary repair and the work was executed by the Contractor, photographed in Figure 4. The lift span was authorized to be operated at a reduced speed and a reduced frequency of operation to limit the number of cycles on the weld and remaining line shafts/couplings.

Figure 4: Weld was placed at the hub-sleeve interface of the failed coupling, marked in pink.

Following the immediate temporary fix of the failed coupling, all remaining couplings were disassembled and internally inspected. The coupling sleeves were marked for location relative to each other and the hubs to preserve the indexing of the machinery. Afterwards, the coupling sleeve bolts were loosed, and the sleeves removed to reveal the internal condition of the couplings.

The internal condition of the couplings varied greatly. At the couplings that were filled with grease that was in good condition, the gear teeth were in as-new condition. However, numerous couplings were found partially filled with grease that was in poor condition. The grease was dry and hardened or gummy and had lost all lubricative qualities. At these locations, corrosion was present on the covered portions of the coupling hubs and sleeves, and the gear teeth were in various stages of deterioration. Figures 5 and 6 show the typical view of a coupling in poor condition immediately after being disassembled. Multiple couplings were found with enough damage to warrant replacement. Although some couplings were found to be in good condition, there did not appear to be a pattern as to which couplings were affected.

The procedure for a permanent repair prioritized risk reduction of an extended bridge outage. In order to reduce the risk, as much work as possible was performed at machine shops off site. While the bridge was semi-operational with existing machinery, a new replacement shaft was manufactured for each floating shaft that had a damaged coupling hub and shipped on site. While this method did not reuse potentially functional shafts, it eliminated risk of an extended planned or unplanned bridge outage due to field installation of coupling hubs.

The double engagement flanged sleeve spacer coupling was installed on a gearbox reducer output shaft on one end and a roller bearing supported shaft on the other. Removing the roller bearing and reducer to a shop was impractical, therefore it was necessary to replace the spacer coupling hubs in the field. Multiple precautions were taken to ensure that the in-field removal and installation work would go as planned per the outage schedule. Any issue with the installation had the capability to delay the machinery outage potentially by weeks. Some steps taken to ensure the success of the replacement included the following:

Figure 5: Coupling immediately after disassembly. Note hardened grease covering gear teeth.

1. The shaft diameters were field measured adjacent to the existing coupling hub prior to disassembly. These diameters were compared to the original shop drawings.

2. The original design of the structure called for an FN2 fit at the keys. After modelling the expansion of the coupling hubs and keys/shafts due to thermal deformation, it was found that to make it theoretically possible to install the system with an FN2 fit at the keys, it would be necessary to employ a combination of heating the coupling hub and cooling the shafts and keys. This was not practical to do in field conditions and greatly increased the chance of getting the coupling hub stuck on the shaft during installation, with potential impacts to the machinery outage of weeks. To mitigate this risk, it was proposed to modify the fit from FN2 to ANSI B17.1 Class 2 Fit, which had a fit range of 0.001” interference to 0.002” clearance. ANSI B17.1 is a standard that establishes a uniform relationship between shaft size and key size for parallel and taper keys used by general industry. The Engineer agreed to this proposal.

Figure 6: Coupling shown in Figure 5, after grease debris was removed. Note heavily worn and degraded gear teeth.

3. The coupling hubs were machined to provide the specified fit for the bore and keys based on the field verified dimensions.
4. Calculations were prepared to determine the hub bore size after heating for assembly.
5. Custom shaft sleeves were manufactured to mimic the diameter and key locations of the coupling hubs after they were to be heated. These custom sleeves were used as a “go/no go” gauge prior to attempting to install the new coupling hubs. If these sleeves were able to be installed onto the shaft and keys at ambient temperature, then the coupling hubs theoretically would be able to be installed when heated.
6. The existing hubs were cut over the key prior to being pulled off to minimize the potential for damage to the shaft. The existing keys were removed and discarded if the key was damaged during cutting of the hub.
7. The shafts were cleaned and checked with the custom sleeve. It was discovered that each shaft and keys needed to be dressed up with sand-paper and flat stones before the sleeves were able to be installed with ease. See Figure 7 for a photo of the custom sleeve hub shown placed over the dressed-up shaft.

Figure 7: Custom coupling sleeve slid over the shaft, indicating the new coupling hub may be installed.

The coupling replacement work was executed flawlessly by the Contractor with no further impacts to marine navigation beyond the planned limited outages.

Case II

Bridge Type: Trunnion Bascule Bridge
Machinery Subsystem: Span Drive Machinery

Coupling Use Case Description

The machinery for the structure exemplified in Case II used a total of 4 single engagement gear couplings. The couplings transfer torque through floating shafts and effectively are exposed to equal amounts of torque and rotations. The couplings have no covers; however, the couplings are in a difficult to reach location and are exposed to the weather. The bridge on which the couplings are installed is low lying and spans over a salt water channel. The weather remains hot and humid throughout the year and is prone to intense rainfall.

Figures 8 & 9: Photos showing the internal condition of the failed coupling. Note excessive wear and corrosion on gear teeth, with similarity to couplings shown in Case I. Also shown burn marks were inflicted during coupling disassembly from shaft.

Coupling Failure Description

The couplings were in service for approximately 6 years prior to experiencing a catastrophic failure in 1 of 4 couplings. The coupling failed in such a way that neither rotational movement nor torque were being transferred from the coupling hub to the coupling sleeve. As the machinery system was operating, the coupling hub appeared to be rotating within the stationary sleeve as the internal coupling gear teeth were unable to mesh.

Remediation Efforts

Emergency work was authorized after the coupling failure to return the machinery back into service as quickly as possible after the coupling failure. All couplings were disassembled for internal inspection. It was discovered that 3 of the 4 couplings contained adequate amounts of grease, while the remaining coupling did not appear to be greased. The non-greased coupling was the unit that experienced the failure. The failed coupling showed wear and corrosive damage to the gear teeth, which were no longer able to mesh and transfer torque. Figures 8 and 9 show photos of the internal condition of the failed coupling.

Procurement for a replacement coupling hub proceeded immediately after the coupling failure. It was found that a stock replacement coupling hub that was finished bored and keyed was immediately available from a warehouse. A review of the tolerances for this coupling found that while the fits for the bore and key were not ‘per Code’, they would meet the requirements of the coupling manufacturer. The ability of using the stock bore size of the coupling greatly reduced the total duration of the outage of the machinery. The new stock coupling was installed and operation of the leaf was restored within 48 hours of the failure. Subsequent to the emergency repair a new floating shaft was procured as a permanent repair.

Case III

Bridge Type: Span Drive Vertical Lift Bridge
Machinery Subsystem: Span Drive Machinery

Coupling Use Case Description

The machinery for the structure exemplified in Case III used a total of 16 single engagement gear couplings. All noted couplings transfer torque through multiple line shafts and floating shafts. The couplings are located outdoors and are exposed to the weather year-round, with the only protection being metal covers intended to protect personnel from the rotating machinery. The bridge on which the couplings are installed spans over a salt water channel. The weather is generally cold throughout the year and is prone to high winds.

Figure 10 (above): Photograph showing coupling obscured by its protective cover.

Coupling Failure Description

The installation date of the couplings was not available; however, the couplings could have been in service for as long as 55 years prior to experiencing catastrophic failure in 1 of 16 couplings. Similar to the previous two cases, the coupling failed in such a way that neither rotational movement nor torque were transferred from the coupling hub to the coupling sleeve. As the machinery system was operating, the coupling hub appeared to be rotating within the stationary sleeve as the internal coupling gear teeth were unable to mesh. It was noted during the inspection efforts that the metal covers over the shafts and couplings were difficult to remove, and the couplings were difficult to access for maintenance purposes, shown in Figure 10.

Remediation Efforts

Inspection of the remaining couplings was undertaken immediately after the failure. The couplings were disassembled and were found in various stages of deterioration. Most couplings had issues of corrosion and excessive wear due to lack of lubrication and moisture intrusion. The couplings that only had light corrosion, and whose teeth appeared to be in good condition, were left in service. Otherwise, couplings that exhibited corrosive pitting, a battered appearance, any damage on the coupling gear teeth, were replaced (Figure 11).

Figure 11: Photograph showing coupling with corrosive damage to be replaced.

WJE personnel had limited involvement with the decisions regarding the procurement and installation of new couplings hubs. It was noted that the couplings were replaced without meeting the specified fits per the Code as a temporary repair and the structure was replaced shortly thereafter.

Lessons Learned

There are several lessons learned from these three cases:

1. All of the coupling failures could have presumably been avoided if the couplings had been completely filled with lubricant and received periodic relubrication. The lack of grease filling the interior of the coupling allowed the internal surfaces to corrode from moisture intrusion and increased the wear on the gear teeth.
2. While lack of lubrication is the primary root cause, the progression of the internal deterioration was externally evident, in some cases, in the form of corroded wear debris seeping out of the couplings past the seals. As such, these conditions could have been identified through external visual inspection, prompting internal inspection before the couplings were degraded to the point of failure.
3. All three cases involved machinery that is installed in an exposed location on bridges in severe corrosive environments. Proper maintenance and inspection procedures are especially important at these locations. Consideration should be given to removing plugs from couplings to evaluate the internal condition of the lubrication and/or coordinating with maintenance personnel to purge old grease from the coupling during inspections to ensure that the lubricant in couplings is in adequate condition. For any locations where the lubricant is found to be degraded or inadequate, disassembly for internal inspection should be recommended.
4. Access for inspection and maintenance is important. For two of three cases, the couplings were covered. While covers may offer some benefits in terms of safety, they interfere with visual observation of the covered components. Consideration should be given to using alternatives to covers, such as guard rails, for protection of personnel from rotating machinery.
5. In Case I, the replacement couplings utilized an ANSI B17.1 Class 2 Fit for the key/keyseats, instead of the FN2 fit with which the couplings were originally specified. This change reduced significant risk associated with getting the coupling hub “stuck” halfway on the shaft in a time critical procedure. Note that the topic of replacing the standard FN2 fit for keys and keyways with the fits shown in ANSI B17.1 has been brought to discussion in both AASHTO and AREMA. The August 2023 revision of AASHTO LRFD Movable Highway Bridge Design Specifications has already transitioned to the ANSI B17.1 Class 2 Fit for keys 1” and less in size. These changes to the movable bridge design code bring the movable bridge industry to conform with other industries that utilize the ANSI B17.1 standard, which improves part compatibility without the need for custom machining. The change also improves the practicality of installation of keys and keyed hubs, especially for shafts utilizing two keys.
6. As discussed in Case II, the time from coupling failure to bridge returning to service was significantly cut down by the ability to use an “off the shelf” coupling. Designers may consider selecting shaft and key sizes to suit stock couplings whenever possible.