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Obtaining Acceptable Load Sharing & Gear Action without a Differential

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Introduction

During an inspection of the Bridge over Middle Harbour at the Spit (the Spit Bridge) just north of Sydney, Australia, which is a single leaf bascule bridge, an unusual wear pattern was observed on one of the two main pinions. Plans were being developed to upgrade the span drive machinery and electrical control system, but the Owner desired to retain these main pinions. The abnormal wear was concerning enough to warrant an in-depth investigation and to develop repair plans to mitigate the wear. What follows are some unexpected findings for causes of this wear and possible unintended consequences from original design decisions.

Photograph 1 – General view of the Spit Bridge

The Spit Bridge

The Spit Bridge crosses Middle Harbour between the towns of Seaforth and Mosman, just north of Sydney, in New South Wales, Australia (see Photograph 1). The bridge carries four vehicular traffic lanes and two pedestrian walkways, and is comprised of seven spans. The central span is a single leaf bascule span, 105’-8” from trunnion to toe, providing an 80’ clear marine channel. Completed in 1958, the span drive and control system had not been updated as of 2012. The span was driven by a single 125 HP, 750 RPM electric motor and open gearing (see Figure 1).

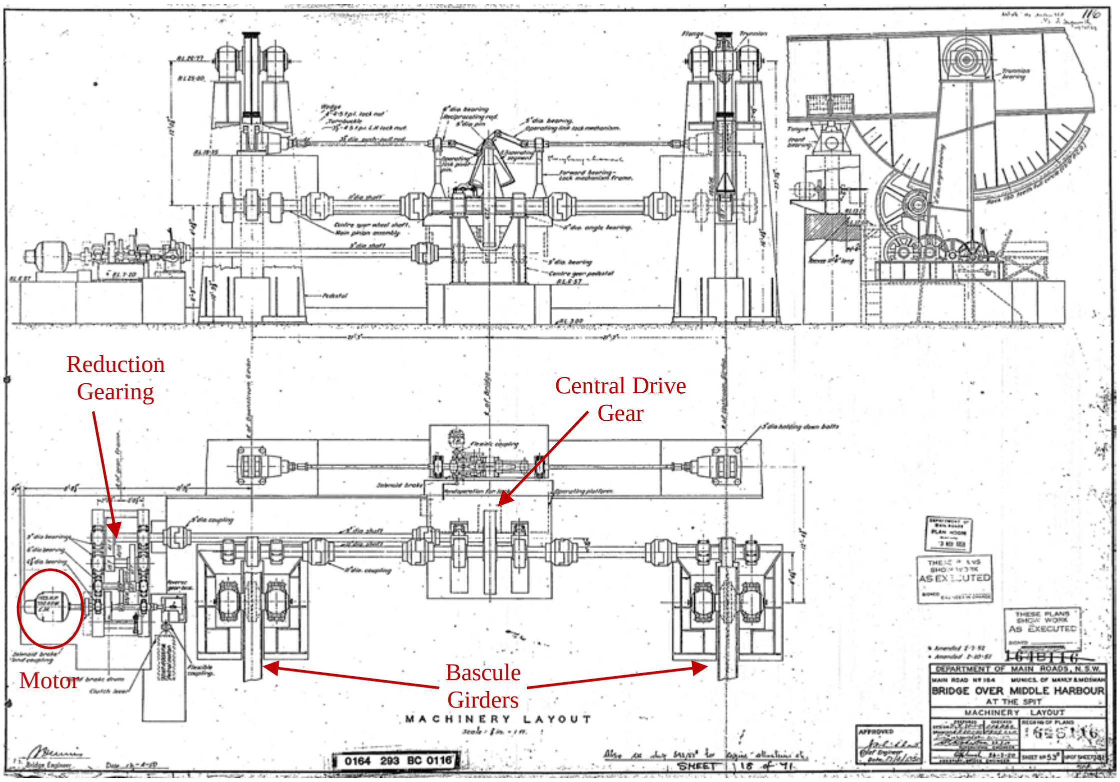
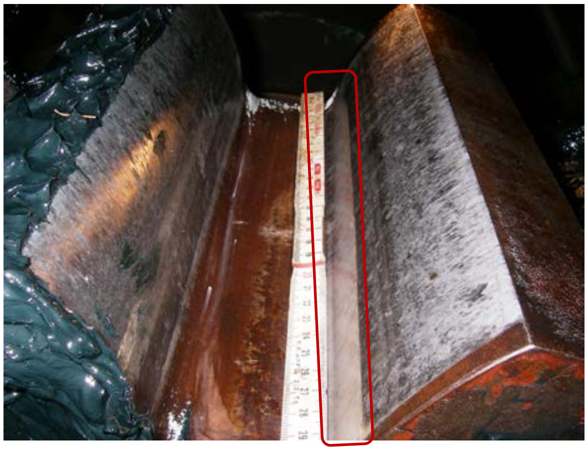


Figure 1 – Original configuration of span drive machinery

Abnormal Gear Wear

The machinery for the Spit Bridge was inspected in January 2011 to gather details for designing the upcoming upgrades. While taking measurements of the main pinions which engage the rack gears, an unusual wear pattern was observed on the east pinion. The wear was located in a band just below the pitch line of the pinion (see Photograph 2), and while corresponding wear was not immediately apparent on the rack teeth, heavier wear was noted in the addendum, especially at the tooth tip. This wear pattern was not found at the west pinion and rack gearset.



Photograph 2 – Band of increased wear just below the pitch line of the east pinion (box).

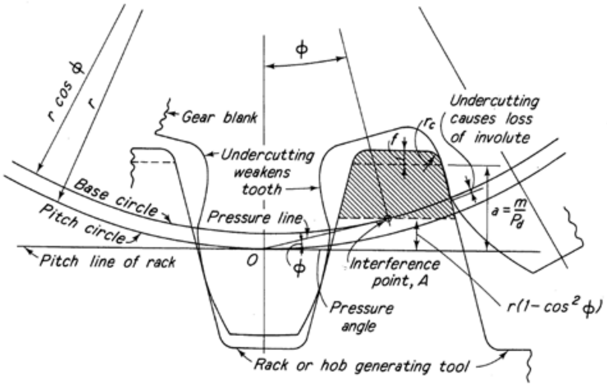


Figure 2 – Description of undercutting from fabrication

The wear pattern observed was reminiscent to undercutting, which can occur during the fabrication process of a gear. A gear with a small number of teeth, as a result of fabrication, can result with an "undercut" area in the dedendum near the root (see Figure 2). Undercutting is undesirable because "…from a load-carrying standpoint, the undercut pinion is low in strength and wears easily at the point at which the undercut ends" [Dudley, Handbook of Practical Gear Design, 1994, Section 3.5] and measures are generally taken by the gear designer/fabricator to avoid undercutting in the fabrication process. Some of these steps taken are to limit the minimum number of teeth on a gear, and to change the tooth form. In the case of the main pinions on the Spit Bridge, the tooth form chosen was the Nuttall Stub involute tooth form, which resulted in a shorter tooth than the standard full depth involute tooth form. Also, for stub teeth, the minimum number of teeth recommended to avoid undercutting is 14 teeth. The main pinions on the Spit Bridge have 15 teeth, which eliminates undercutting from the fabrication process of these gears. Since it is unlikely that the observed wear was caused by undercutting during fabrication, the term "undercutting" as used herein shall apply only to describe the wear pattern observed.

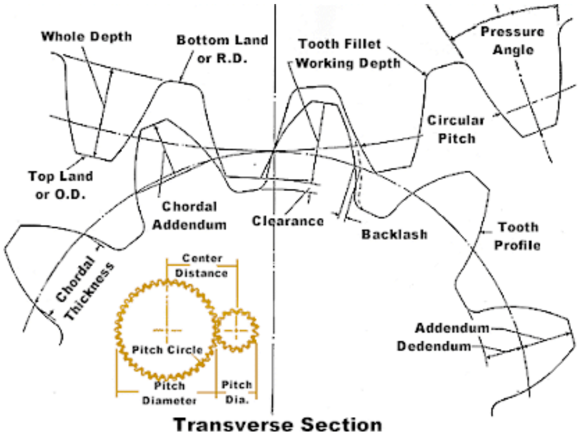


Figure 3 – Properly engaged gears with pitch circles just touching

Another possibility of the cause of the wear is an over-engagement of two mating gears. When properly aligned, the pitch circles of gears should "touch" but not overlap (see Figure 3). Any overlap in the pitch circles is an over-engagement of the gear set. When gears are over-engaged significantly, the tip (addendum) of the larger gear can interfere with the lower portion (dedendum) of the smaller gear. In the case of the subject bridge, the addenda of the east rack teeth appeared to be interfering with the dedenda of the east pinion gear. This interference would result in irregular wear in the root area of the pinion teeth, very similar to what was observed on the east gearset. The west pinion and rack do not have observable undercutting wear, so the above stated interference is most likely not present at the west gear set.

Detailed Investigation

In order to determine the presence and severity of any interference at the east gear set, a detailed investigation was performed on both rack and pinion gears. The following inspections were performed:

Visual Inspection of the Racks and Pinions

- All rack gear teeth (with exception of those in engagement when the bridge is fully lowered) were thoroughly cleaned, inspected, and photographed.

- Chordal tooth thickness measurements were recorded at the pitch line with gear tooth calipers at every 3rd gear tooth on each rack. A complete profile of two gear teeth addenda (one worn, one non-worn) on each rack was recorded at 0.100” variations (approximately 20 measurements per tooth).

- All pinion gear teeth (with exception of those in engagement when bridge is fully lowered) were thoroughly cleaned, inspected, and photographed.

- “Span” measurements of the main pinions were recorded with vernier calipers at several gear tooth pairs and also at unworn locations for each pinion.

- Complete profile of pinion tooth recorded at 0.100” variations (20 measurements per tooth) for two teeth addenda on each pinion (worn and non-worn).

Ultrasonic Testing

Ultrasonic testing was conducted on both trunnions to check for internal deficiencies, such as cracks

- Ends of trunnions were ground smooth to allow for precision testing.

- Testing was conducted from both ends of each trunnion.

- Testing occurred on 100% of the area at the end of each trunnion.

Rack and Pinion Runout

- Non-contact inductive distance sensors were used to determine rack and pinion runout (change in radius about center of rotation) during span operations.

- Linear range of sensors is 0.12” to 0.59”
- Repeat accuracy is +/- 0.0005”

Backlash Measurements

- Backlash in the gear mesh was measured with feeler gauges where bridge could be stopped (5 locations): 0° (fully lowered), 44°, 50.6°, 57.5°, and 69° (fully raised).
- Soft lead wire (1/8” diameter solder) was used at other locations on east rack.

Precision Survey of the Racks and Pinions

- A precision survey (with laser tracker) of both racks was performed with measurements recorded for every 2nd tooth to establish geometric center of each rack gear.
- Survey conducted on 7 teeth for each pinion to establish geometric center of each pinion gear.
- During bridge operation, the rotational center of each rack and pinion was determined.
- A precision survey of the outer diameter of the trunnion shafts was conducted to establish a centerline between the trunnions.
- A global coordinate system was established to reference these surveyed components to the centerline of trunnions.

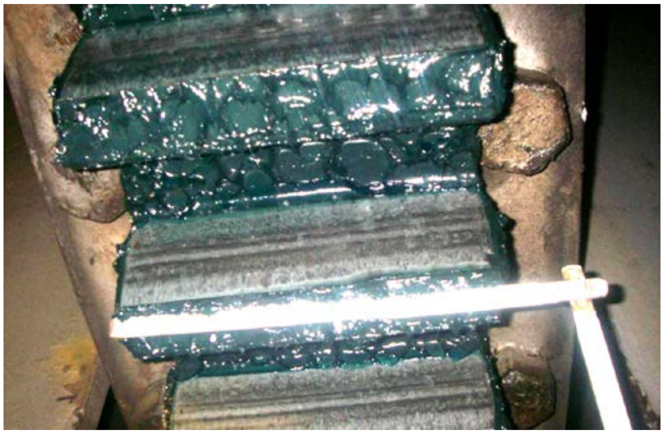
Data Collected

Visual Inspection of Racks and Pinions

The gear teeth were numbered so that data could be tracked to specific locations on the racks and pinions. Tooth number 1 on both gears is engaged with the span seated. The rack and pinion gears have good face contact. Photographs 3 and 4 show the contact pattern prior to the grease being removed from the teeth for inspection.

The wear on the rack and pinion gears is not excessive for machinery of this size and age. The maximum wear measured is in the area of the rack where the braking is applied, approximately 2% of the tooth thickness, which is acceptable. The wear along the rack in the areas of constant speed operation are less than 1%.

Photograph 3 – East pinion contact pattern prior to grease removal.


Photograph 4 – East rack contact pattern prior to grease removal

For the pinions, span measurements (measurements taken across two adjacent teeth) were recorded as well as chordal thickness. Also, on the east pinion, the undercut area was measured with a straight edge and feeler gauges to determine the amount of material removed. In addition to span measurements, chordal thickness measurements were recorded (similar to those taken for the rack) to observe the tooth profile. The wear on the pinions was also minimal, but the east pinion had slightly more wear than the west.

Based on visual observations, the east pinion teeth 12, 13, and 14 have undercutting that is closest to the root of the gear. These teeth are engaged with the rack as the span approaches the fully raised position (approximately 68° to 69°). The remaining east pinion teeth exhibit undercutting type of wear, however; the wear is not as close to the pinion root. This is consistent with other findings, discussed later, that the radius of the rack increases from the “fully seated end” (south end) of the rack to the “fully raised end” (north end) of the rack.

Ultrasonic Testing of Trunnions

There were no significant findings. There were numerous discontinuities (mainly reduction of backwall readings) due to the geometry of the trunnions with numerous lubrication passages proceeding radially from lubrication fittings. However, these discontinuities were shown on the original drawings for the trunnions and were not relevant indications or recordable indications.

Rack and Pinion Runout

The runout (change in radius) of the rack and pinion gears was measured using non-contact inductive distance sensors. The sensors were focused on a pinion tooth and a rack tooth near the rack/pinion mesh (see Photograph 5). When the span was operated, the distance was recorded as each pinion and rack tooth passed by their respective sensor. This data for the east rack and pinion is presented in Figure 4, the west set is similar (note: the pinions have 15 teeth, since the first reading is on tooth 4, the reading for tooth 18 marks one revolution, and tooth 19 represents the 2nd reading of tooth 4).


Photograph 5 – Measuring gear runout during operation with inductive non-contact distance sensors

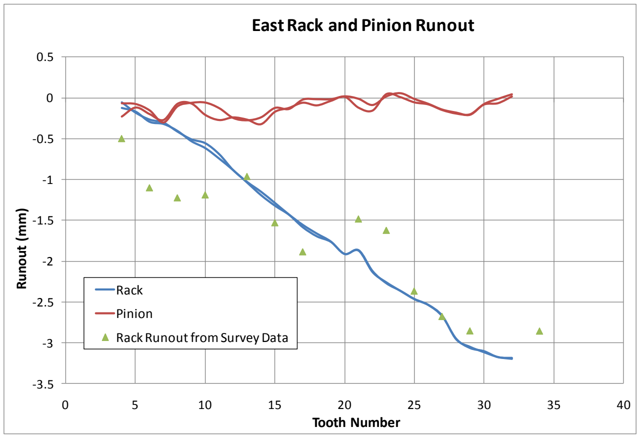


Figure 4 – Runout measurement data

The runout data shows both east and west pinions having very little change in radius, which is a desirable finding because it eliminates the possibility of a bent or bowed pinion shaft at the east pinion. However, the runout data shows that both east and west racks increase in radius from tooth 4 to tooth 32. This radius increase is approximately 0.120” (3mm) for both east and west racks. This radius increase effectively increases the engagement (“moves” the gears closer to each other) between the rack and pinion as the span moves from the seated position to the raised position. This action causes the clearance between the rack and pinion teeth, also referred to as backlash, to decrease. The corresponding reduction in backlash, for a decreased center distance of 0.120” (3 mm), is 0.082” (2.05 mm).

Backlash Measurements

Because the east rack and pinion were the main interest of this investigation, the backlash was roughly determined for the whole length of the rack by placing lengths of soft lead solder on the lowering faces of every second rack tooth (see Photograph 6). When the span was raised, the solder passed through the gear mesh and was flattened by the lowering face of the pinion. The thickness of the flattened pieces of solder approximated the amount of backlash between the rack and pinion (Photograph 7).

Photograph 6 – Lead solder used to determine backlash during operation

Photograph 7 – Flattened lead solder after operation

Using the approximate backlash measured using the solder; an area of the rack was identified for further investigation. During several operations, the span was stopped at three locations between the seated and fully raised positions, and the backlash was measured more accurately with feeler gauges. These locations are when the pinion is engaged with rack teeth 20, 23, and 26 (opening angles 44°, 50.6°, and 57.5°). The measured backlash was found to be very close to the backlash measured with the solder. The east backlash measurements are presented in Figure 5. The backlash measurements show that the backlash decreases to approximately 0.016” (0.4 mm) on the east rack/pinion, and to approximately 0.071” (1.8 mm) on the west rack/pinion.

The decrease in backlash coincides with the data recorded with the inductive distance sensors. When the minimum backlash is compared to the backlash at the seated position, the decrease is larger than that indicated by the distance sensors, which is likely because the wear is greater at the seated position due to repeated and high loads from starting, accelerating, and braking at the seated position. A similar, higher wear, condition exists at the fully raised position, where the braking repeatedly occurs, and can be seen in the backlash data.

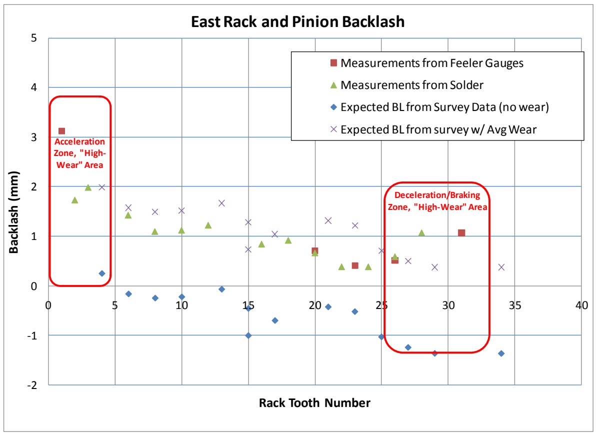


Figure 5 – Measured backlash data

Bearing Wear

Another factor that can affect the backlash at the rack and pinion mesh is the clearance between the shaft and journal in the pinion bearings, which allows the pinion shaft to move radially within the bearings. The rack gears rotate with the bridge on the trunnion bearings which were also measured for clearance. These clearances were measured and found to be within the recommended range for in-service bearings, and were not considered to be a factor in the rack and pinion mesh.

Figure 6 – Scale drawing of rack/pinion mesh over-engaged 0.200” (5mm)

Precision Survey

Both rack gears were surveyed by recording the position of a survey target placed on the top lands of several rack teeth along the length of the rack. Both pinions were surveyed in a similar manner, as well as both trunnion shafts. The results of the survey indicate that the pitch circles of the east rack and pinion “overlap” by approximately 0.100” (2.5 mm) near fully seated to approximately 0.200” (5 mm) near fully open. The west rack and pinion pitch circles also overlap but not nearly as much; from 0.020” (0.6 mm) near fully seated to 0.120” (3 mm) near fully open. This means that the effective center distance of the east rack and pinion is less than the effective center distance of the west rack and pinion by about 0.080” (2 mm). This decreased center distance corresponds to a difference in backlash of 0.054” (1.37 mm). The difference in backlash that was measured using feeler gauges is 0.055” (1.4 mm). The survey data therefore reinforces the backlash and measurements stated above.

Figure 6 shows over-engagement of the east rack pinion by 0.200” (5 mm) and includes the average wear of the rack and pinion. For comparison, Figure 7 shows a gear set with proper engagement and no wear.

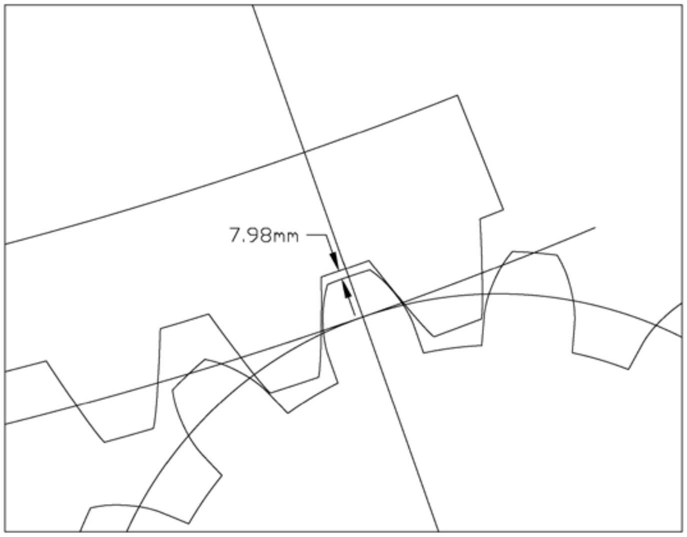


Figure 7 – Scale drawing of rack/pinion mesh with correct engagement

The survey data was plotted to determine the “Expected Backlash” at the various rack teeth for which data was collected. Figure 5 includes this data for the unworn east gear set. The survey data closely follows the actual backlash data collected, with the differences due primarily to gear wear (especially in the “high-wear” areas).

The survey data was also used to calculate the distance between the tips and roots of the mating gears throughout operation. Measurements indicate the east rack and pinion are very close (less than 1/8” or 3 mm) to “bottoming out” at the raised position of the span. This correlates with the visual observations of undercutting near the roots of east pinion teeth 12 and 13.

Strain Gauge Testing

Torque in the two floating shafts was recorded during bridge operations using strain gauges. This data can be seen in Figure 8 (at end of this report). A lack of load sharing is evident in the data, with the west shaft taking about twice as much load as the east shaft. At the spikes in the closing direction (negative torque on the graph), the east shaft has slightly more load. Since these spikes are repeated at every operation, the gears have worn to share slightly better.

Conclusions and Findings

The maximum wear measured on the gearing is approximately 2.5%, which is in the east pinion. The max wear on the racks is 1.9%, which is in the deceleration/braking zone of the east rack. More importantly, each rack is made of segments with breaks between teeth 8/9, 18/19, and 28/29. It is common that there is some variation in tooth spacing (pitch) at these locations, which causes higher wear in the teeth immediately before and after the split. The amount of wear measured is not excessive, especially for gearing of this size, and is not cause for alarm.

The east pinion has a wear pattern referred to in this paper as “undercutting” which is attributed to the over-engagement of the east rack and pinion. The undercutting is located nearest the root of the pinion teeth in the area of the pinion that is engaged with the rack at the nearly raised position. The wear at the undercut area is approximately 1.3% of the tooth thickness at the worn area (which is greater than the tooth thickness wear at the pitchline). The “undercutting wear” is a separate issue from the other “normal wear", but can have significant impact of the "normal wear" process. The undercutting wear removes material near the root of the tooth which has several negative impacts:

- Reduced strength due to loss of section
- Increased stress concentration factor
- Loss of involute (decrease in effective "Line of Action" and "Contact Ratio")
- Chance of "Bottoming-Out" in root of pinion

Calculations were performed to estimate the loss in bending strength due to the existing undercutting. The loss in bending capacity due ONLY to the undercutting on the east pinion is approximately a 13.5% loss in capacity. Approximately 10% of this loss comes from an increase in the AGMA "Stress Correction Factor Kf" and the remaining increase is due to loss of section near the tooth root (approximately 0.044"). With no corrective action, the actual loss in capacity could increase substantially depending upon the stress concentration factor developed by on-going undercutting wear. If a "step" or corner were to develop, this would increase the stress concentration factor and effectively reduce the capacity significantly.

The alignment of the west rack provides good face contact with the pinion through the majority of span operation and the backlash range is acceptable. The east rack alignment provides good face contact with the east pinion, however; the backlash range is not adequate.

The east main pinion and rack are over-engaged compared to the west and also compared to theoretical (as shown by the overlapping pitch lines from in the precision survey results). This alone will result in some amount of undercutting with this gear tooth form (especially with the low number of pinion teeth). There is significantly less backlash in the east main pinion and rack mesh. Most of this appears to be due to the over-engagement, but this has several contributing factors. Due to the reduced backlash on the east relative to the west, it is likely that the east mesh has assumed a greater portion of load for a significant portion of the bridge life. This would result in accelerated wear compared to the west. This is supported by the wear shown to be higher in the east than the west.

The measured minimum backlash for the east main pinion and rack mesh is unacceptably low (0.016"). A new installation should have a backlash range of 0.090" to 0.120". The current backlash range for the east is 0.016" to 0.120" and for the west is 0.075" to 0.170".

Possible Cause

The over-engagement of the east rack and pinion gear set appears to be an as-installed condition. Since the clearance at the east trunnion bearing is not excessive, we can conclude that the over-engagement was not caused by bearing wear. The rigid structure between the trunnion and pinion shaft also would prevent relative movement between the two gears over time. Since there is no differential between the two pinions, it is presumed that the original builders would have attempted to match the backlash to ensure good load sharing between the pinions. So it is puzzling why the original backlash was not more closely matched at original construction.

Load sharing may actually lead to the answer. The original central bull gear shaft, floating shafts, and pinion shafts were all keyed to large jaw couplings with no provision for fine tune indexing of one pinion relative to the other. It may have been the case that the pinions were slightly out of index once the machinery was assembled, and the only adjustment available was to move one of the pinions. If the west pinion was in contact with the rack and the east pinion was not, due to a slight offset in index, over-engaging the east pinion would bring it into contact on one face. Absent any way to precisely index the pinions, this may have been the best method available to attempt load sharing.

Corrective Action

The span drive machinery was planned to be replaced up to (but not including) the final pinions in mid-2012 (see Figure 9). Having the existing machinery removed and the bridge inoperable for a defined period of time provided an opportunity to adjust the east pinion so that the backlash would match the west pinion, providing the best load sharing available in both directions. At the bridge owner's preference, the new machinery would not incorporate a central differential, so an ability to fine tune the pinion indexing was included in the new span drive arrangement. A shrink disk was planned to be added to one of the central reducer's output shafts, which would allow one pinion to rotate relative to the other before locking into position.

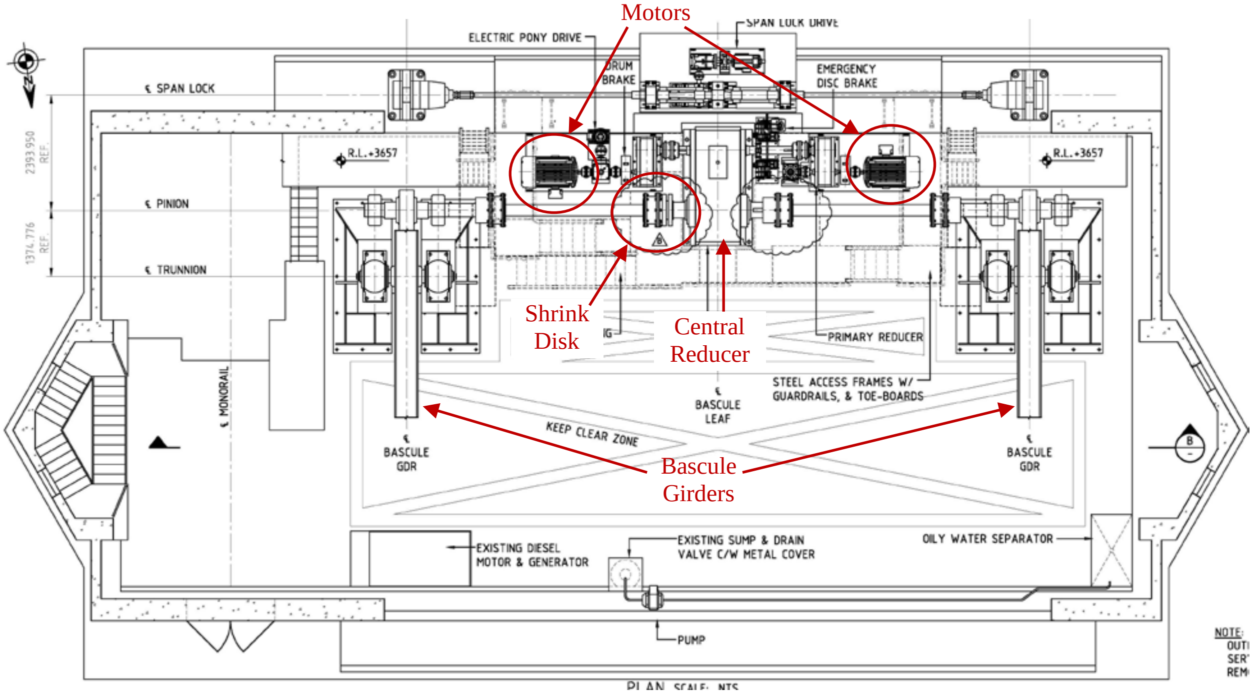


Figure 9 – New configuration of span drive machinery with shrink disk assembly on central reducer output shaft.

During the machinery installation, the marine channel was shut down for two weeks, and with the existing machinery removed, the east pinion bearings were available for adjustment. The over-engagement had been measured at about 0.080" (2 mm). However, due to the mounting arrangement of the pinion bearings, this small movement in the downward direction would have required drilling and reaming new mounting bolt holes. Alternatively, the bearings could be shimmed outward in more of a horizontal direction. This was not as efficient of a movement, but was much easier to accomplish. So the pinion was planned to be shimmed about 0.315" (8 mm) away from the mounting surface, which would place the pitch circles at the correct center distance. Since the machinery between the pinions was not yet installed, the position of the center machinery could be set so that the required alignment would be maintained between the pinion shafts.

During construction, the shims were adjusted until the backlash matched that of the west pinion and rack, which required about 0.395” (10mm) of pinion movement. Once the new span drive machinery was installed, the shrink disc coupling was left untightened while the pinions were manually indexed so that the raising and lowering faces of both pinions contacted their respective rack gears. To check the effectiveness of load sharing, strain gauge testing was performed with the new span drive system and compared to test results prior to the work (see Figure 10). As can be seen in the graphs, load sharing is much improved with the span near the lowered position, and the sharing diverges somewhat as the span approaches the raised position. Since the combined loading is higher with the span near the lowered position, it was decided to leave the indexing as is, rather than adjust the indexing to match elsewhere in the span operation.

CONCLUSION

Investigating sources and repercussions of abnormal gear wear can lead down interesting paths. Investigating the cause for this particular wear led to an appropriate corrective action. Planning the corrective action led to a possible cause from original design considerations. This reinforced the need to add the ability to fine tune the indexing between the two pinions in the planned upgrades.

Including a differential in a bridge span drive system automatically accounts for many inconsistencies in the machinery, but it must take into account several factors like the arrangement of the span drive machinery and the flexibility of the structure. For instances where a differential may not be prudent, a method of indexing the machinery shafts after a split is essential to get the best load sharing possible.

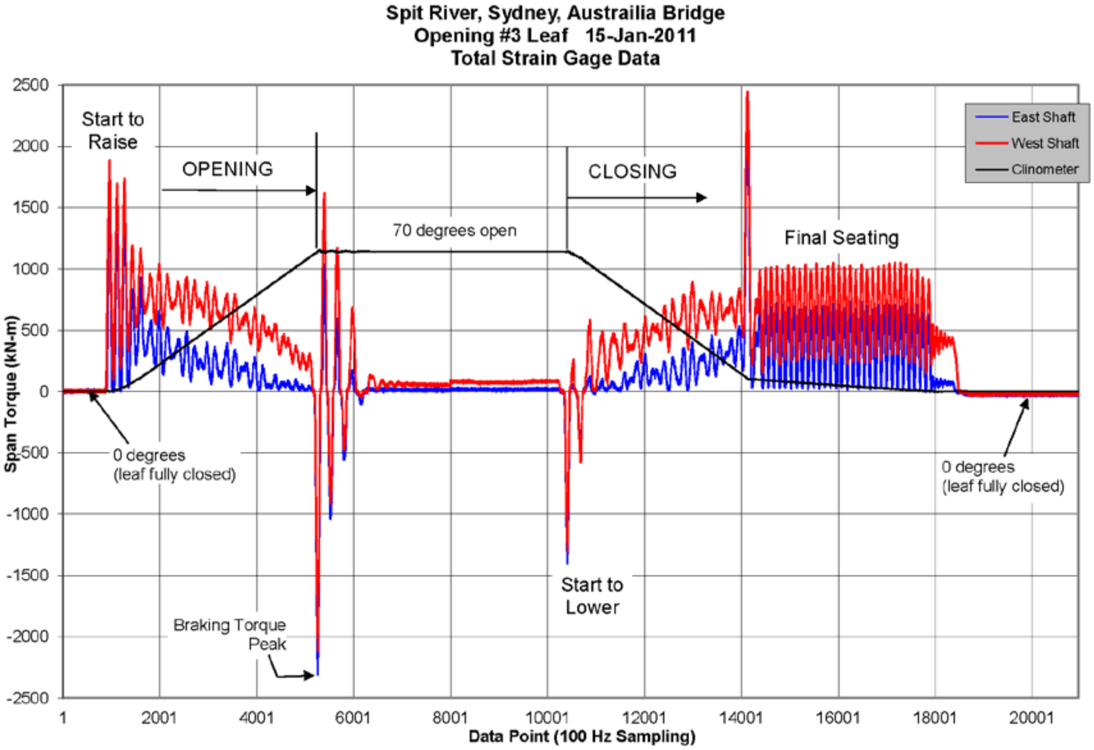


Figure 8 – Initial strain gauge test data (prior machinery replacemetn) showing east pinion with higher loads than west pinion

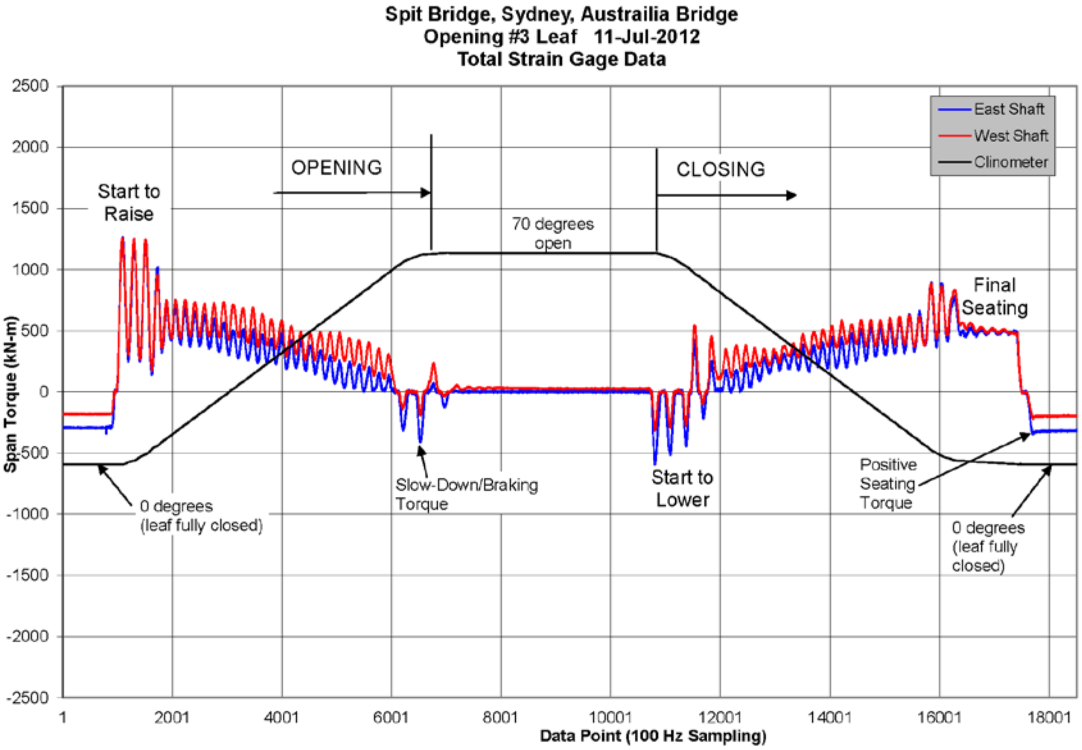


Figure 10 – Final strain gauge test data after installation of new span drive machinery, with improved load sharing between pinions