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# Vertical Lift Bridge Transverse Load Sharing Interplay of Indexing, Imbalance, and Other Complications

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# Introduction

The equalization of span drive machinery loads between ends and quadrants is a common goal for vertical lift bridges and often takes the form of adjustments in imbalance to meet desired criteria. Equalization of machinery loads between ends (longitudinal) is generally achieved with weight changes to the main counterweights. It is also desirable to equalize machinery loads in the transverse direction between quadrants (corners) at a given end, and construction documents for vertical lift bridges will specify transverse load sharing accordingly, typically in the form of a tolerance on transverse imbalance.

A typical expectation is that transverse imbalance changes would be achieved through weight shifts between counterweight pockets. In practice, however, transverse imbalance adjustments at vertical lift bridges have yielded mixed results due to the interplay of several factors such as machinery indexing, counterweight pocket locations, live load support elevations, and other complications. Sometimes engineers specify a transverse load sharing requirement which would consider all loads on the machinery, not just imbalance. The potential problems with achieving load sharing are significant.

Lessons learned from transverse imbalance and load sharing adjustments at numerous vertical lift bridges are presented herein. These are provided for consideration when determining imbalance and load sharing criteria and when performing field services such as machinery installation, indexing, and balance testing.

# Transverse Imbalance Changes

The bulk of the experience presented in this document has its roots in unexpected test results when attempting to modify the transverse imbalance of vertical lift bridges. Recommendations are typically based on dynamic strain gage measurements of operating loads at the span drive machinery.

The dynamic strain gage method of balance testing includes recording torques in the bridge operating machinery using strain gages and performing an analysis to derive balance results. This method presupposes that the recorded torque is due solely to imbalance and system friction. If there are external loads acting on the span during operation (weather loading, abnormal or varying friction, or other sources), the operating torques may be affected along with the accuracy of the results. In addition, transverse imbalance calculated from strain gage data, though calculated from accurate physical measurements of the load at the span drive machinery, cannot account for complicating factors such as indexing, live load support elevations, or other physical differences in the machinery that may affect the load sharing and the calculated imbalance. For this reason, this document qualifies the transverse imbalance analysis of strain gage measurements as a *perceived* transverse imbalance.

Recommended changes for transverse imbalance are typically accomplished by the removal, addition, and/or relocation of counterweight ballast at main counterweights. The theory of applying transversely added counterweight ballast to the lift span is relatively simple; added counterweight ballast is distributed to the lift span proportionally based on ratios of the distances to the added ballast and the distance between the counterweight rope groups.

One common difficulty in making transverse imbalance adjustments is due to the location of the counterweight pockets or limited availability of counterweight pocket space. For large transverse imbalance changes at the lift span it is helpful to have counterweight pocket space close to, or even outboard of, the rope connections. Sometimes there are limitations due to counterweight pockets being previously filled and sometimes the counterweight design simply has less transverse adjustment capacity. **See Figures 1 and 2.**

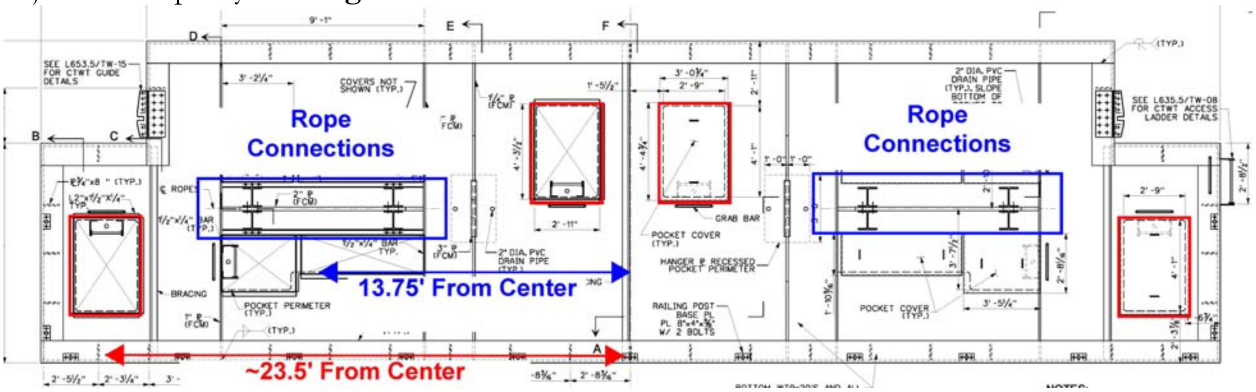


**Figure 1. Plan View of Counterweight Pocket and Rope Locations, Example 1.**

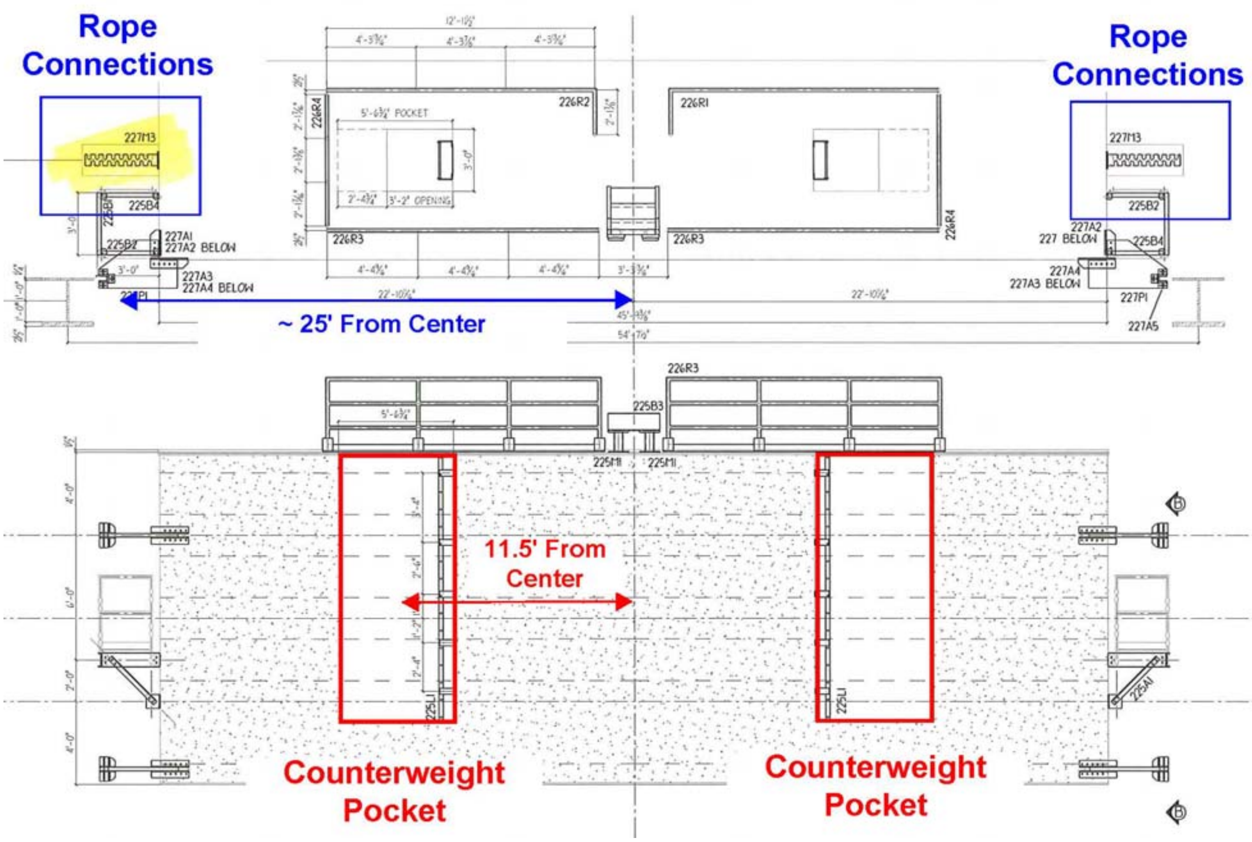


**Figure 2. Plan (Top) and Elevation View of Counterweight Pocket and Rope Locations, Example 2.**

The first example (Figure 1) depicts a counterweight design with counterweight adjustment pockets outboard and inboard of the rope connections providing significant capacity for transverse imbalance adjustments. The second example (Figure 2) depicts a counterweight design with counterweight adjustment pockets inboard of the rope connections and provides a more limited capacity for transverse imbalance adjustments. A ratio of the distances between the centerline of the counterweights to the pockets / rope connections helps to quantify the difference between the two designs. For the design shown in Figure 1, the ratio is 1.71, whereas the design for the design shown in Figure 2 is only 0.46. The disparity in ratios does not provide a complete picture. The desired target is total capacity for a transverse imbalance moment about the centerline of the counterweight. In other words, the evaluation should include the magnitude of capacity in the pockets. In this case, given the disparity of ratios, the pockets in Figure 2 design would need nearly four times the capacity as for the design shown in Figure 1. When considering significant transverse modifications to lift spans, the capacity for transverse imbalance adjustments based on the counterweight design and the remaining space in the pockets should be reviewed.

Even when counterweights have ample transverse adjustment capacity in theory, the predictions sometimes yield inaccurate results. When the calculations do not provide accurate predictions, then one has to conclude that the testing methodology is not providing actual transverse imbalance and possible complicating factors should be evaluated. Some of the reasons for inaccurate predictions are related to machinery indexing, quadrant backlash differences, or poor seating at the live load supports. These issues are discussed in greater detail in other sections.

## Load Sharing Versus Transverse Imbalance

One of the goals for minimizing transverse imbalance is to achieve load sharing at the two quadrants at a given end of the bridge. Sometimes project criteria will outline a required load sharing between two quadrants as a percentage of total load. The distinction between load sharing and transverse imbalance is that load sharing encompasses all loads on the machinery including imbalance *and* friction. This distinction is an important consideration when determining the appropriate criteria by which success will be measured. There are potential complications that may make achieving load sharing within a certain percentage of the total load challenging or impossible including:

- Substantial differences in friction between two quadrants would increase the disparity in percentage of load sharing, even if the two quadrants are well balanced transversely. See Figure 3 as an example.

  As noted before, because operating loads include just friction and imbalance for the bulk of operation, a large disparity in friction will directly affect load sharing. Any criteria for load sharing must consider any relative difference in the friction between quadrants.

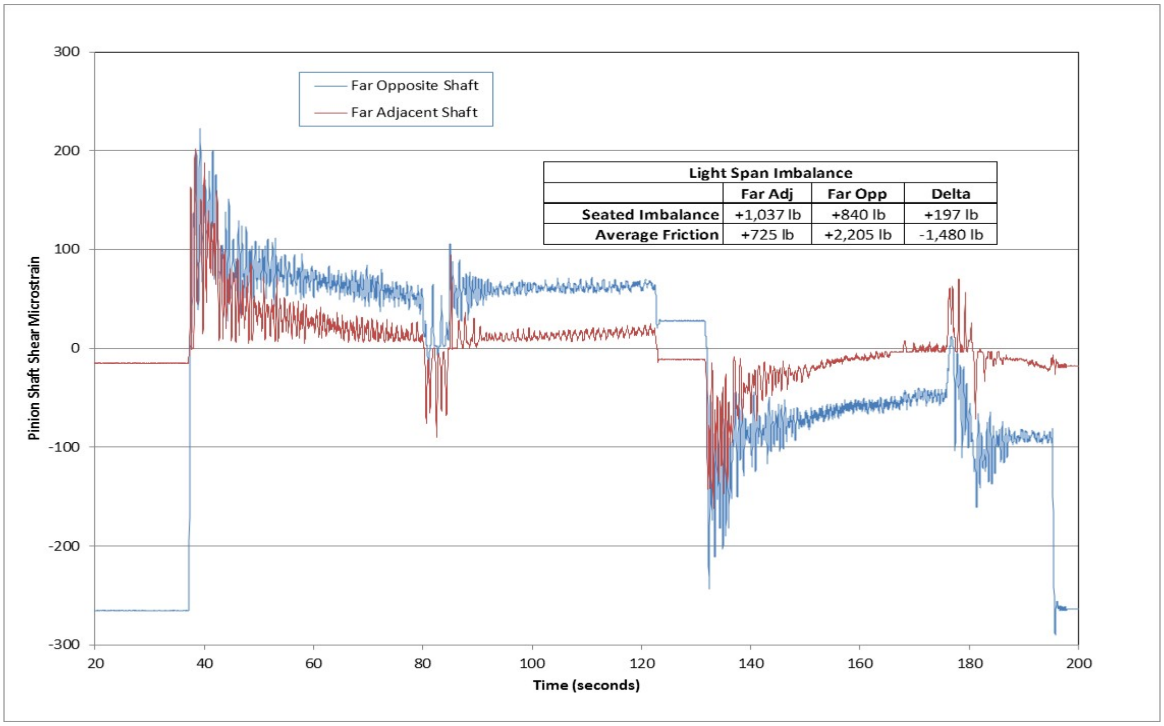


**Figure 3. Far End Strain Gage Recording, September 22, 2005. Route 13 over the Inland Waterway Canal, Point Pleasant, NJ.**

- The total imbalance of the lift span can be expected to change throughout operation based on system characteristics (rope transfer over the sheaves, auxiliary counterweight systems, etc.). One would ideally expect equal changes in imbalance between corners. In actuality, however, this is not always true; sometimes there is a difference in *change* in imbalance between quadrants from the seated to the raised position. Significant differences in quadrant change imbalance changes may be due to the asymmetry of a droop cable installations, differences in auxiliary counterweights systems between quadrants, or even physical differences within the machinery that affect load sharing based on the position of the bridge.

  As noted before, because operating loads include just friction and imbalance for the bulk of operation, a large change in the imbalance between quadrants will directly affect load sharing. Any criteria for load sharing must consider any relative difference in the change in imbalance between quadrants.

- Another potential complication with percentage load sharing requirements is apparent when loads are very light. With light loads the differences in the percentage of load can be substantial, even if the magnitude of the differences is small. Figure 4, which follows, shows an example strain gage recording from one tower of a tower drive vertical lift bridge where the percentage of load sharing varied substantially throughout operation. Load sharing is very good when beginning to raise the span from the seated position, where loads are highest due to the addition of friction and imbalance. In contrast, when starting to lower the bridge, the imbalance is nearly equal to friction and the two quadrants have minimal load. With these light loads, the magnitude of the *differences* in quadrant friction and imbalance overwhelm the goal of equal load sharing and the net result is one quadrant takes nearly all of the load in this part of the run.

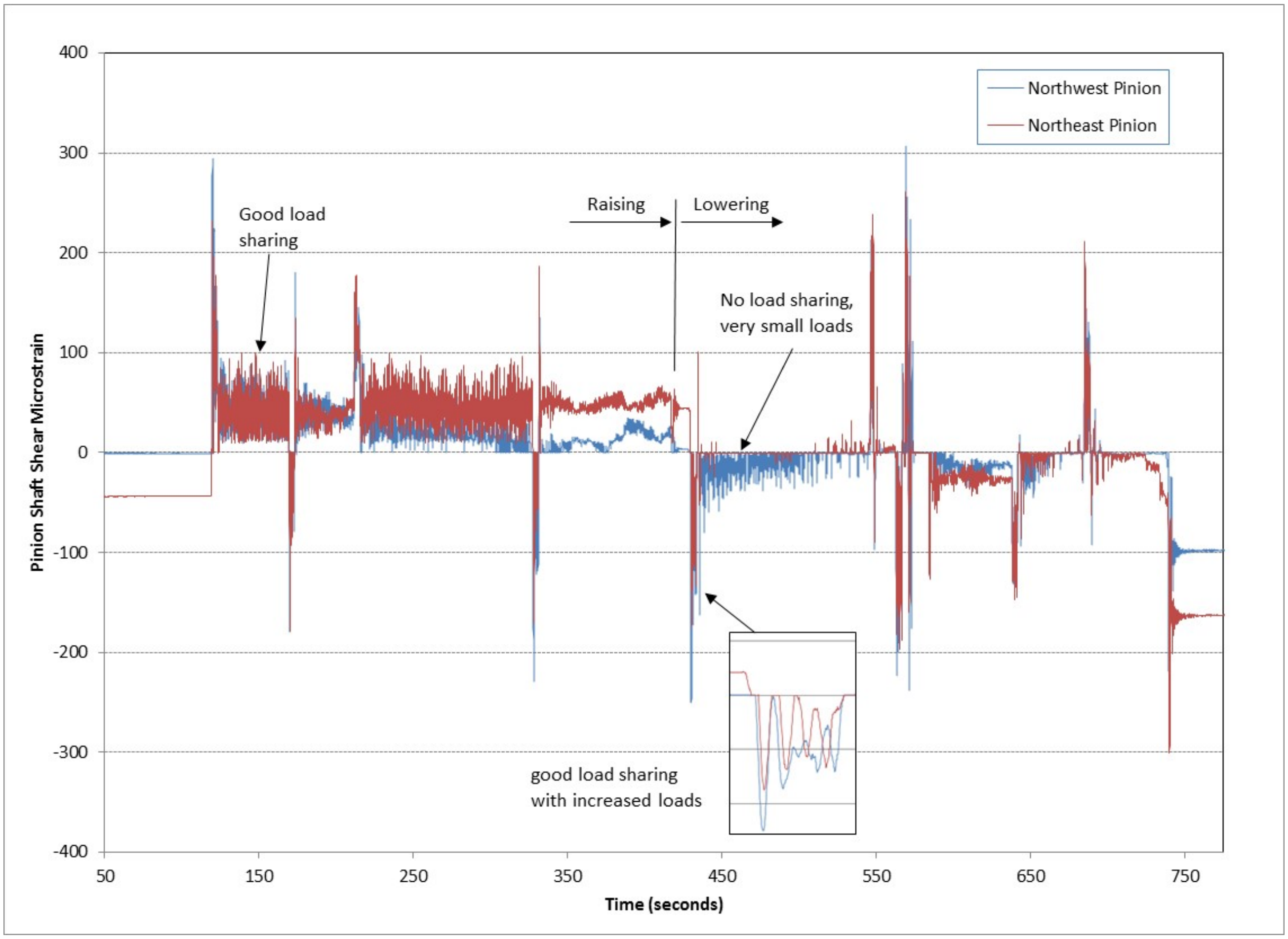


**Figure 4. Strain Gage Recording at one tower of a Tower Drive Vertical Lift Bridge.**

## Machinery Indexing

Indexing of the span drive machinery for movable bridge machinery is the relative adjustment of a machinery quadrant(s) to align the driving machinery when the quadrants are driven by a common motor or set of motors. Improperly indexed machinery for span drive machinery for vertical lift bridges can result in poor load sharing, seating issues, or even, in severe cases, binding of the machinery. As a minimum, indexing should be used to avoid binding between machinery quadrants and to allow for proper seating of the bridge. Often machinery indexing is performed to try to achieve equal loading between span drive machinery quadrants.

The means for machinery indexing takes several forms for vertical lift bridge machinery. For span drive vertical lift bridges, indexing is generally performed by making operating rope adjustments to set the relative position between quadrants. For tower drive vertical lift bridges, the span drive machinery is typically provided with a device between tower quadrants that enables their relative adjustment, including indexing couplings, lockable differential assemblies, or clutches.

Indexing attempts to achieve equal load sharing for two quadrants must consider the balance condition and friction at the bridge. The following examples outline the effects of two balance and friction conditions on the load sharing equalization through indexing. For both scenarios, the baseline analysis is simplified by the following assumptions: no transverse imbalance, equal friction between quadrants, equal total gear backlash between quadrants, and proper seating of the bridge with no twisting of the lift span due to machinery loads.

1. Span heavy bridge with imbalance exceeding system friction throughout operation

When the bridge imbalance exceeds system friction, the bridge would tend to operate on the "opening faces" of the gearing (the sides of the gear teeth that are in contact when raising a span heavy lift span) both when raising *and* when lowering the lift span. For this example, indexing may simply be setting the gears in the two quadrants into opening face contact with the span in the seated position. With the assumptions above, then we would expect equal load in both the raising and lowering directions.

If the two quadrants are indexed differently, one may see a negative impact on the load sharing. In an extreme example, one could index one quadrant for opening face contact and the second quadrant for closing face contact (in the seated position). The expectation is that the load sharing disparity would increase as the quadrant with opening face contact would pick up additional load when raising and lowering the bridge. By shifting the load from one quadrant to the other, the perceived transverse imbalance changes.

2. Bridge balanced within system friction throughout operation

When the bridge is balanced within system friction, the bridge would tend to operate on the opening faces of the gearing when raising the lift span and on the closing faces of the gearing when lowering the lift span. With the assumptions noted above (equal quadrant backlash, no transverse imbalance, etc.) one would still expect equal loading when raising and lowering the lift span if the two quadrants are indexed similarly. If the assumption of equal quadrant backlash is not true, then the behavior of the bridge that is balanced within friction will behave differently than the bridge that is span heavy beyond friction. This is discussed further in the next section.

If the extreme indexing case from the first scenario is considered, one would again expect to see an impact on load sharing, though the effect would likely be more severe.

In either balance scenario, a difference in quadrant indexing would clearly affect the load sharing, and thus the perceived transverse imbalance as calculated by strain gage recordings. In practice the effect of the indexing may be mitigated by structural deflections of the lift span, but the significant impact of indexing on load sharing and perceived transverse imbalance has been repeatedly verified using strain gage recordings of machinery loads and, although the baseline assumptions listed above (equal quadrant backlash, no transverse imbalance, etc.) are never fully realized in practice, the impact of indexing is nevertheless clear. An example demonstrating the dramatic effect of indexing is provided in the two figures that follow.

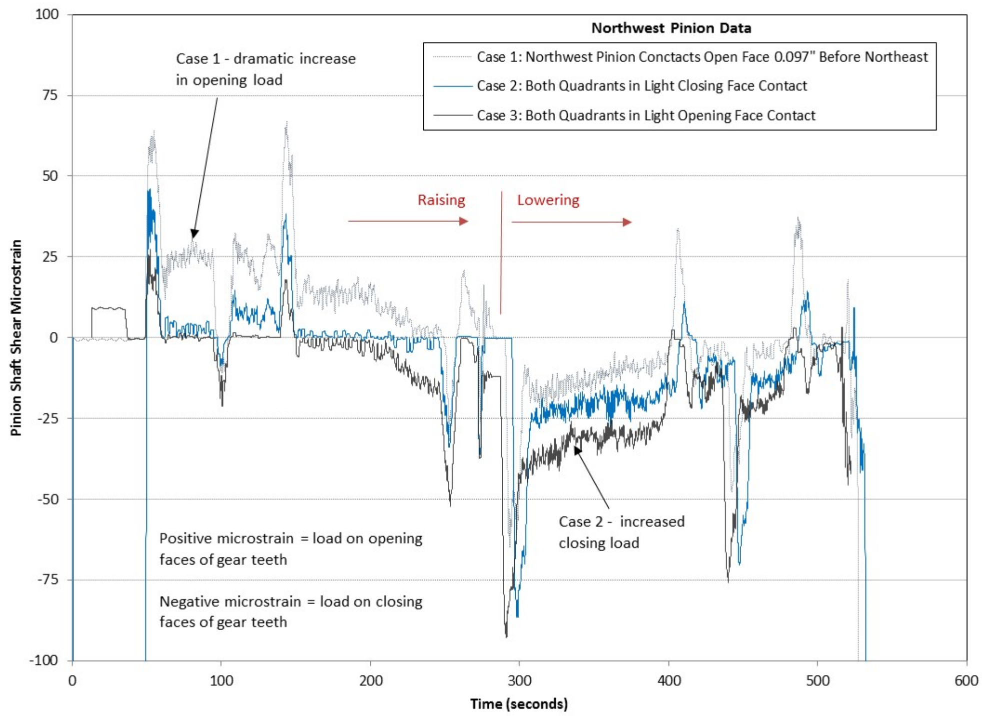


**Figure 5. Strain Gage Recording at Northwest Rack Pinion, North Tower. Portage Canal Lift Bridge, Houghton and Hancock, MI. June 24, 2015. Compare with Figure 6.**

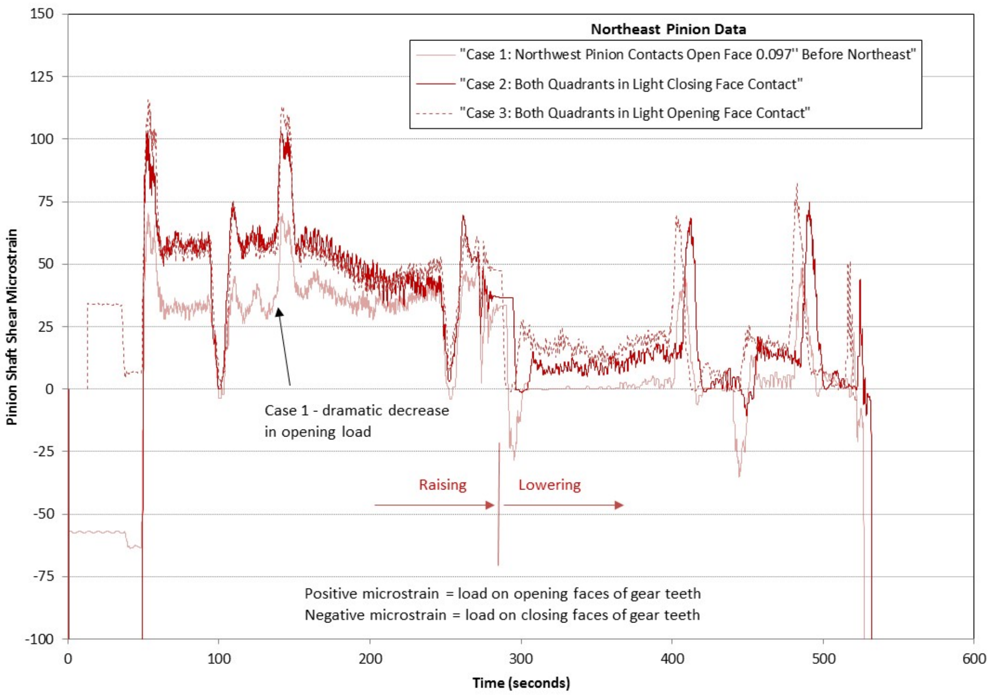


**Figure 6. Strain Gage Recording at Northeast Rack Pinion, North Tower. Portage Canal Lift Bridge, Houghton and Hancock, MI. June 24, 2015. Compare with Figure 5.**

The previous two figures from the Portage Canal Lift Bridge demonstrate the dramatic impact that indexing can have on load sharing and the perceived transverse imbalance. Based on the strain recordings the imbalance at the north tower was calculated for each of the three cases. The results of the balance analysis are presented in the following table, where the impact on the perceived transverse imbalance is identified. Note that the experience for this particular example was complicated by live load support elevation issues, a perceived transverse imbalance, and some minor gearing backlash differences, however the indexing impact is clearly substantial.

| Case | Desciption | Northeast Imbalance | Northwest Imbalance | Perceived Transv. Imbal. |
|---|---|---|---|---|
| Case 1 | Northwest Pinion Contacts Open Face 0.097" Before Northeast | +2,525 lb | +1,581 lb | +944 lb |
| Case 2 | Both Quadrants in Light Closing Face Contact | +5,128 lb | -375 lb | +5,503 lb |
| Case 3 | Both Quadrants in Light Opening Face Contact | +4,960 lb | -851 lb | +5,811 lb |
| A positive (+) imbalance indicates a span heavy balance condition in the seated position. | | | | |

**Table 1. NE and NW Seated Imbalance, North Tower. Portage Canal Lift Bridge, June 24, 2015.**

# Impact of Total Quadrant Gear Backlash on Load Sharing

The previous section outlined the impact of indexing when trying to achieve load sharing or address a transverse imbalance for a vertical lift bridge. A review of the presented assumptions alludes to some of the factors that can complicate this process. One of the complicating factors that can arise is disparities in total quadrant gearing backlash, with "total" quadrant backlash defined as the total backlash in the quadrant's gear train starting from the span drive motor and ending at the rack and pinion or drum. Substantial differences in quadrant backlash are indicative of the quality of the machinery installation. These issues are not easily addressed without substantial effort and therefore typically must be accommodated when performing field adjustments for load sharing or transverse imbalance work.

It is helpful to review the impact of quadrant backlash disparities for the two balance scenarios that were previously reviewed for machinery indexing:

1. Span heavy bridge with imbalance exceeding system friction throughout operation

For the lift span that is heavy beyond system friction, the disparity in quadrant gear backlash does not have to be an issue when raising and lowering the lift span. If desired, the quadrants can both be indexed for opening face contact with the span seated and, all other things being equal, one would expect equal loads when raising and lowering the lift span. However, if the quadrants are indexed for open face contact there is a significant issue at seating that cannot be addressed. If one quadrant has substantially more backlash, then the quadrant with less backlash would contact the closing face first at seating and the load in this quadrant of the machinery would have to increase until the other quadrant "catches up." The result is a significant disparity in seating loads. Conversely, if the indexing at both quadrants is set for closing face contact to achieve equal seating loads, then the load sharing when raising and lowering the lift span will likely suffer.

2. Bridge balanced within system friction throughout operation

For the lift span that is balanced within system friction, the disparity in quadrant gear backlash limits the ability to achieve load sharing throughout operation. This scenario guarantees that one cannot adjust the system to achieve equal contact between the quadrants in both the open direction and the closing direction. The magnitude of additional load on one quadrant when raising the lift span and the additional load on the opposite quadrant when lowering the span would be challenging to predict even without other complications such as a *real* transverse imbalance and the accuracy of live load support elevations. Solutions may involve some compromise of the targeted load sharing and transverse imbalance criteria, and would be best determined using iterative field testing with strain gage recordings and physical seating checks at the live load supports.

## Live Load Supports

The installation of the live load supports is a critical element when trying to achieve span drive machinery load sharing and are thought to have a significant impact on the accuracy of transverse imbalance predictions. Measurements of equal span drive loads with strain gages will not, on its own, provide assurance of adequate seating of the bridge. In effect, the issue is that the measured loads at the span drive machinery are indirect. Some of the span drive machinery loads may actually be driving the lift span into the live load supports to address gaps at the live load supports. In other words, without reviewing the live load supports it is unclear how much, if any, of the recorded span drive machinery loads are being used to twist or "rack" the lift span structure when seating the span.

It is desirable to have all or most of the seating load be transferred directly from the span drive machinery into the live load supports with little loss due to twisting the lift span structure. When this is optimized, the span drive loads that hold the span against the live load supports can be limited to the extent required to ensure no movement at the live load supports under traffic.

Apart from creating a disparity in seating loads, improperly set live load supports may also impact the ability to achieve load sharing through span drive machinery indexing. For this reason, when possible, indexing efforts should include physical checks of the seating of the lift span against the live load supports. These checks can be used concurrently with strain gage load recordings to determine if the live load support elevations, the indexing of the machinery, imbalance, and the seating loads are all appropriate to ensure no movement of the lift span under traffic. Two simple checks include checking for movement at the live load supports with traffic and looking for movement of the lift span relative to the live load supports when there is no traffic on the bridge and the span drive brakes are slowly released.

The importance of proper live load support elevations was evident during 2007 work at the Burlington Canal Lift Bridge (tower drive vertical lift bridge in Burlington, Ontario, clutches provided for indexing). At the time of the work the bridge had a known history of seating issues including differences in seating loads and movement of supports under traffic. As part of this work the machinery was indexed to try to improve the load sharing for seating loads to address the movement under traffic. The seating load disparity was improved but the load sharing during operation was negatively affected, with one quadrant carrying the majority of the load for the tower. This imperfect solution was short-lived. With repeated operations the load sharing was returned to its original pre-indexing state, either through slippage at the clutch or through slippage at the counterweight ropes. From this effort it was clear that improvements in the seating (i.e., equal load sharing at seating) was not achievable through indexing at the machinery. Additional efforts later confirmed through physical checks that the live load supports were not properly set, confirming that indexing and the machinery load sharing disparity at seating were not the cause of the seating issues.

The live load support issue can also significantly affect the perceived transverse imbalance and the ability to modify the perceived transverse imbalance. During 2016 work to equalize the drive loads at the Portage Canal Lift Bridge (tower drive vertical lift bridge in Houghton and Hancock, MI, indexing coupling provided), live load support elevations appeared to directly impact the perceived transverse imbalance and the sensitivity to perceived transverse imbalance changes. The example provided in Figures 7 and 8 show recorded pinion shaft microstrain at the north tower. Figure 7 shows the baseline operation. With the baseline condition it was found that perceived transverse imbalance shifts at the counterweight were ineffective in addressing the load sharing / perceived transverse imbalance. Figure 8 shows the impact of adding a 1/8" shim to the northwest corner live load support *combined* with a very minor transverse shift of ballast between counterweight pockets.

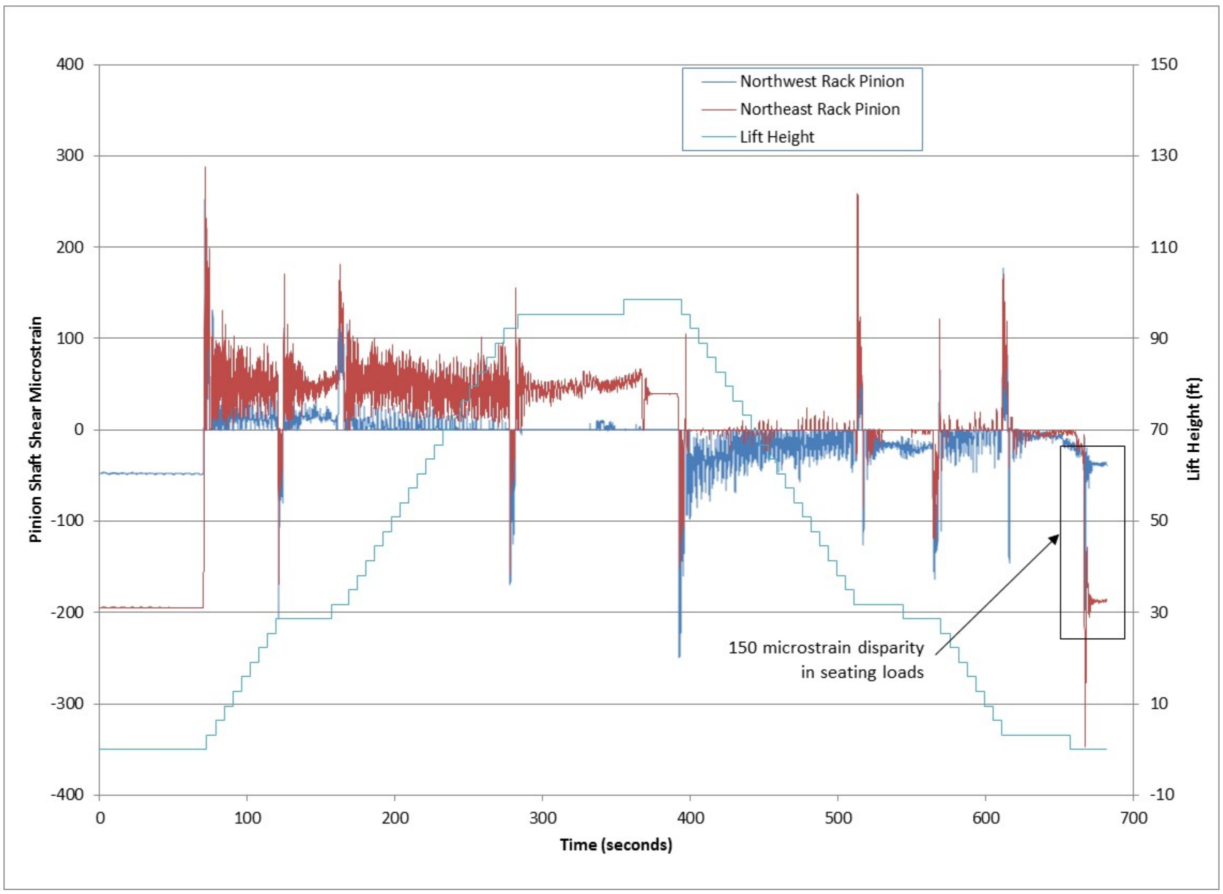


**Figure 7. Portage Canal Lift Bridge Strain Gage Recording from April 21, 2016, Baseline with No Shim at the Live Load Supports.**

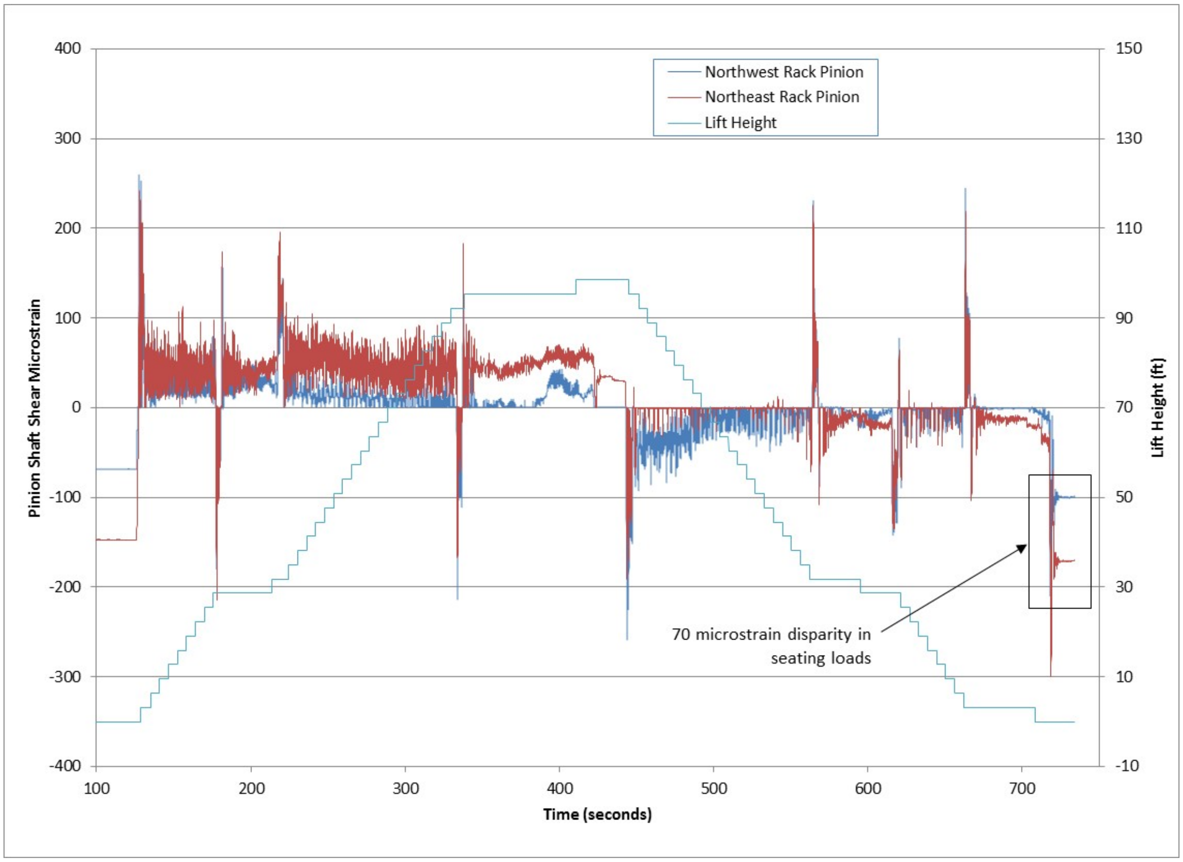


**Figure 8. Portage Canal Lift Bridge Strain Gage Recording from April 21, 2016, 1/8" Shim at Northwest Live Load Support with Minor Counterweight Shift.**

The loads are extremely low in the closing direction and the change in the load sharing is small in magnitude. In the opening direction, however, it is clear that the load sharing was improved. In addition, the disparity between the seating loads in the closing direction was reduced. Whereas substantial transverse counterweight shifts had negligible effect prior to adding the shim, the small minor counterweight shift performed with the shim made a significant improvement. In total the net effect of the 1/8" shim was an improvement in the seating loads *and* a dramatic improvement in the sensitivity of the perceived transverse imbalance based on the changes at the counterweight. Physical checks at the live load supports confirmed that this shim change was appropriate.

The conclusion from the examples above and from other experiences is that setting the proper elevation at the live load supports is critical. Consideration should be given to performing a physical review of the contact at the live load supports before and during attempts to equalize quadrant loads or seating loads through indexing.

## Effect of Counterweight Rope Slippage on Indexing

Load sharing and seating issues can sometimes arise due to slippage of the main counterweight ropes over the counterweight sheaves. With relative slippage between two corners this could effectively index the machinery or change the alignment of the lift span to the live load supports. High loads due to impact or other issues, or poor alignment at the live load supports may be contributors to rope slippage.

**Figure 9. A painted line is used to monitor rope slippage at this counterweight sheave.**

When performing indexing and/or adjustments to the live load support elevations, consideration should be given to marking the counterweight ropes relative to the sheaves, typically with a painted line, to check for slippage during the process (see Figure 9).

## Conclusions

As is clear from the presented data, transverse imbalance and load sharing adjustments at vertical lift bridges are complicated due to the interplay of several factors. The typical expectation that transverse imbalance changes are be achieved through weight shifts between counterweight pockets has yielded mixed results. Achieving load sharing, which requires equalizing the combination of imbalance and friction, provides more challenges. Challenges can include the interplay of numerous characteristics of the bridge including the counterweight design, differences in quadrant friction, quadrant differences in the change in imbalance over the lift span operation, live load support elevation issues, the overall imbalance compared to the system friction, and indexing.

Due to the number and interplay of the factors that may be affecting the loads at the bridge, addressing load sharing and transverse imbalance issues in the field will likely require extensive time commitments with troubleshooting that includes iterative lift span operations while recording operating loads using strain gages. Because of the commitment (i.e., costs) required to resolve load sharing and perceived transverse issues, it is critical for designers to consider the practical complications when specifying load sharing and transverse imbalance criteria. Depending on the required load sharing/transverse imbalance tolerance, it may not be sufficient to simply specify that the results be achieved by counterweight adjustments and/or indexing based solely on strain gage measurements at the span drive machinery. To avoid disputes regarding scope and costs, the required scope of testing and troubleshooting should be explicitly outlined in contract documents. The testing and troubleshooting should be prepared based on the designers' knowledge of the existing systems, but may include a review of the live load support elevations, indexing efforts, and transverse adjustments to the counterweights. When the appropriate field effort is explicitly identified, combined with load sharing/transverse imbalance criteria that is accommodating of the operational characteristics of the bridge, then load sharing and transverse imbalance can be optimized.