HEAVY MOVABLE STRUCTURES, INC.
THIRTEENTH BIENNIAL SYMPOSIUM

October 25-28, 2010

Bridge Number 7 Identifying and Correcting the Errant Roll of a Scherzer Rolling Lift Bridge for the Norfolk Southern Railroad

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CARIBE ROYALE RESORT
ORLANDO, FLORIDA

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Introduction

The Norfolk Southern Railroad Bridge No. 7 is a double track single leaf Scherzer style rolling lift bridge located in Norfolk, Virginia. Although the bridge is called bridge 7 the actual bridge number is 6.66. The Bridge was originally constructed in 1908. The tread plates and flat tracks were replaced in the early 1990's. The new pintle design replaced the original rectangular pintles with round pintles. The curved track radius was set to 28'-8 ¼" where as the original radius was 28'-6". The reason for this radius change is unknown. The bascule leaf had been walking laterally which resulted in severe pintle wear and interference between the movable span and the access ladder on the north rack support.

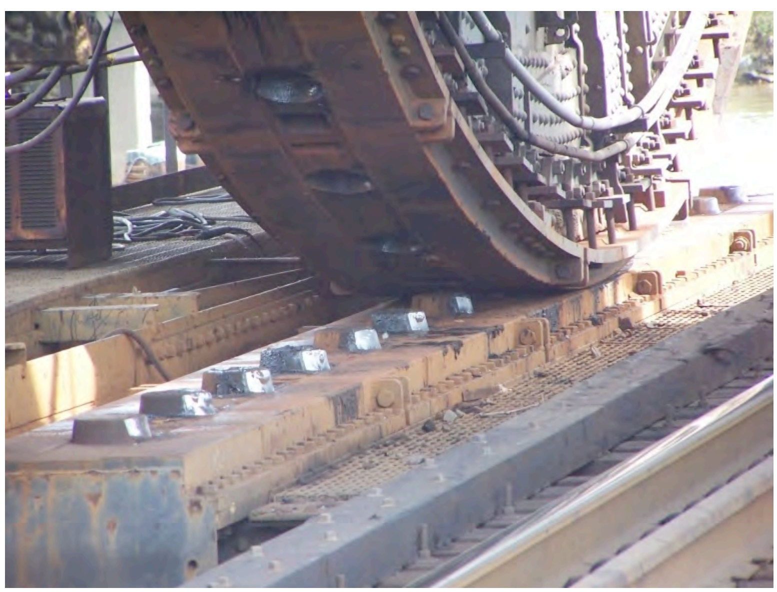


Photo No. 1: View looking northeast at the north segmental girder and flat track for Norfolk Southern Bridge 7. Note shiny spots indicating wear of pintles.

On October 6, 2005 there was a meeting with Norfolk Southern Railroad "NS" in Norfolk Virginia to discuss the remote operation of two bridges in Ohio. During this meeting a site visit to Bridge 6.66 was conducted to See the remote operation at that facility. During this site visit, extreme pintle wear was observed. It was also observed that the bridge was walking off of the flat tracks.

Based upon discussion with the local maintenance staff, the observed wear had been ongoing for many years. As the wear progressed, the bridge toe drifted to the north which resulted in seating problems. The local maintenance staff remedied the seating problem by installing shims on the bridge guides and relocated the approach track. It was noted that the shims had been adjusted several times as the bridge alignment continued to deteriorate. The bridge had walked to the north sufficiently to come in contact with the access ladder on the rack support frame.

Photo No. 2: View looking northeast at the south segmental girder and flat track Note shiny spots indicating wear of pintles.

Photo No. 3: Shims installed at the span guide at the toe of the bascule girder.

Photo No. 4: Close up view of Pintle. Note extensive plastic flow.

Field Investigation

Prior to the field investigation a list of potential causes that would make the span walk of off the flat tracks were examined. A plan was developed that indicated what measurements should be taken in the field in order to verify each of the potential causes on our list.

There were two main prevailing theories. The first theory was that a mechanical problem caused the machinery to apply more load at the south pinion than at the north rack pinion. This unbalanced load would cause the south girder to travel faster than the north girder. An unbalanced loading at the pinions could be seen in the uneven wear of the gear teeth. The second theory was structural in nature. The movable span is founded on four independent circular pier shafts (See Figure No. 1). There is a pier shaft located at either end of each track girder. The track girders support the flat tracks on which the segmental girders roll. If one of these column foundations were to settle, one flat track would no longer be level. The theory was that the span would have a tendency to roll down hill. Therefore, if the south flat track was lower than the north flat track the span would have a tendency to move north during operation.

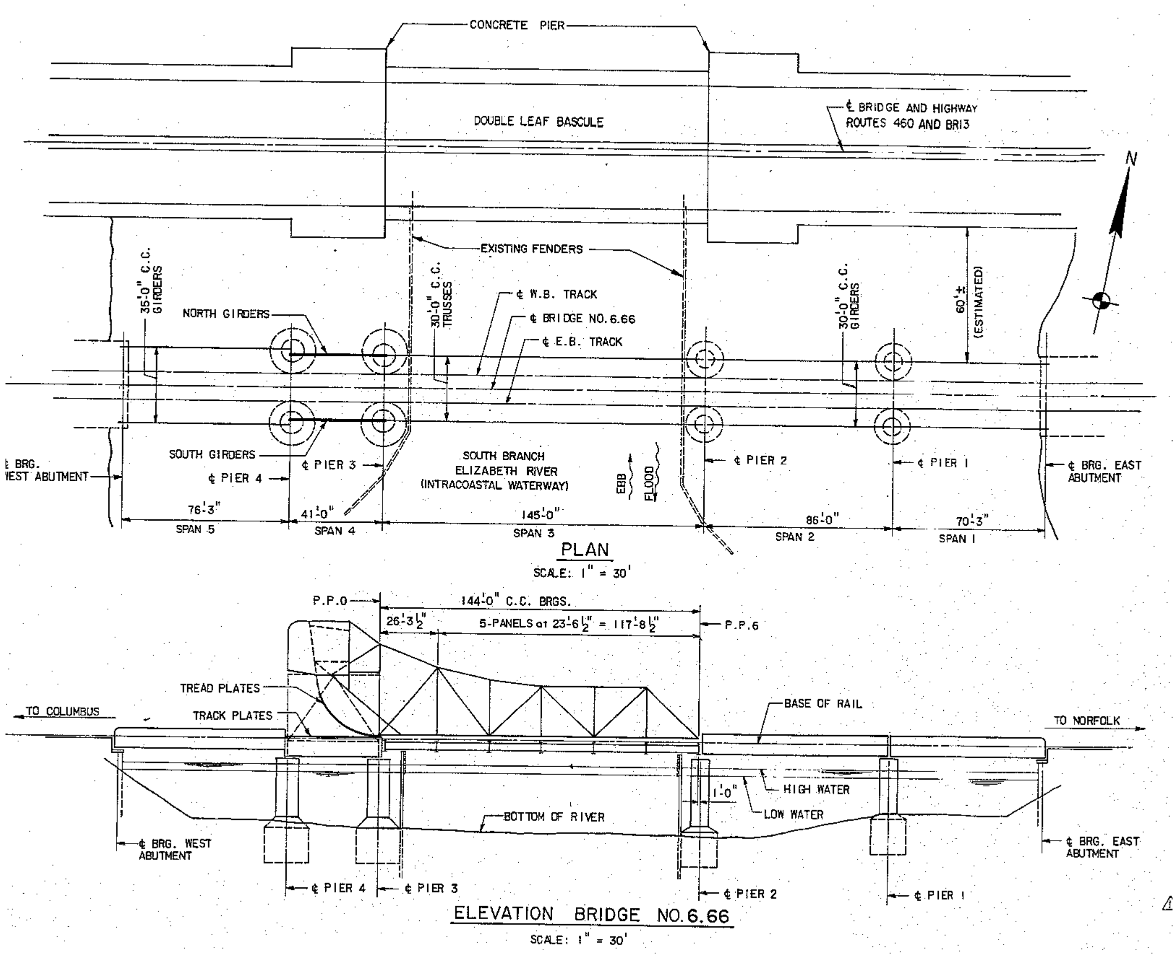


Figure No. 1: General Plan and Elevation

As we discussed our field inspection procedures we determined that we needed to accurately document the wear on the pintles. In order to validate any theories on how the bridge was moving we would have to predict the wear pattern, and our predictions would have to match the actual wear pattern that we measured in the field. We needed a fast and accurate method to measure the wear patterns. A cardboard cutout of the original pintle shape was fabricated in the office. We figured that we could slip the cutout over the pintle and mark the limits of wear on the edge of cardboard template (See Photos No. 4 and 5). This method would allow us to measure the wear pattern on all the pintles in less than an hour.

In order to investigate the potential causes of the pintle wear we planned to make the following measurements and inspections during our field investigation:

1. Identification of Pintle Wear location.
2. Inspection of Curved Track for wear and deficiencies
3. Inspection of Flat Track for wear and deficiencies
4. Inspection of Flat Track Elevations
5. Inspection of Curved track Radius
6. Inspection of Pinion and Rack Gear wear patterns
7. Investigate the squareness of the flat and curved tracks

A site visit was conducted on October 26, 2005 with a team consisting of senior mechanical and structural engineers and a surveyor. During the site visit the pintle wear measured. The gear tooth wear at the rack and pinions was inspected. The flat tracks were surveyed. Points were shot on bridge during operation. Distances were also measured between the segmental girders at various locations, and the distances from the center of roll to the flat tracks were measured at each segmental girder. These measurements were to be used to determine if the bridge was square.

Pintle Wear Locations

The location of the pintle wear was measured at each pintle location to determine if an observable pattern existed. The measurements were performed by placing a cardboard template (See Photo No. 5) over each pintle and marking the start and finish of the wear pattern.

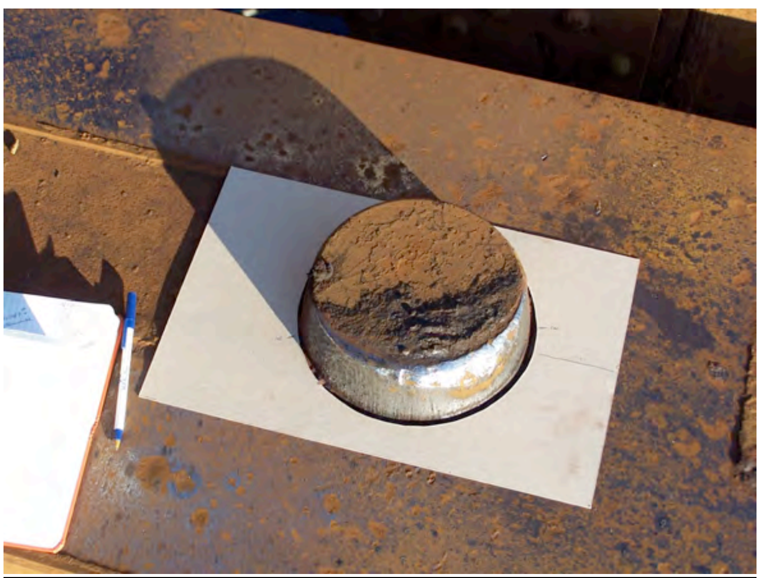


Photo No. 5: Pintle Wear Measurement – Note Template Used to Locate Extent of Wear.

The results of these measurements are presented in Tables 1 through 3. Tables 1 and 2 indicate the location and magnitude of pintle wear at the north and south flat tracks respectively. Table 3 shows the remaining pintle width at the north and south track pintles. The most severe wear occurred on the south track pintles. The wear pattern for the north pintles indicate decreasing wear to the front side of the pintles as the span is opened (See Table 1). The wear pattern for the south pintles is consistent along the length of the track (See Table 2).

Table 1: Pintle Wear at North Flat

Track

Pintle	Angle 1 (Degrees)	Angle 2 (Degrees)	Total Angle (Degrees))
1	9	155	164
2	16	155	171
3	13	153	166
4	16	144	160
5	16	133	149
6	2	137	139
7	1	149	150
8	2	149	151
9	-11	137	126
10	-14	144	130
11	-18	155	137
12	-24	153	129
13	-32	153	121
14	-32	153	121
15	-38	141	103

Note: Pintles are numbered from East (toe) to West

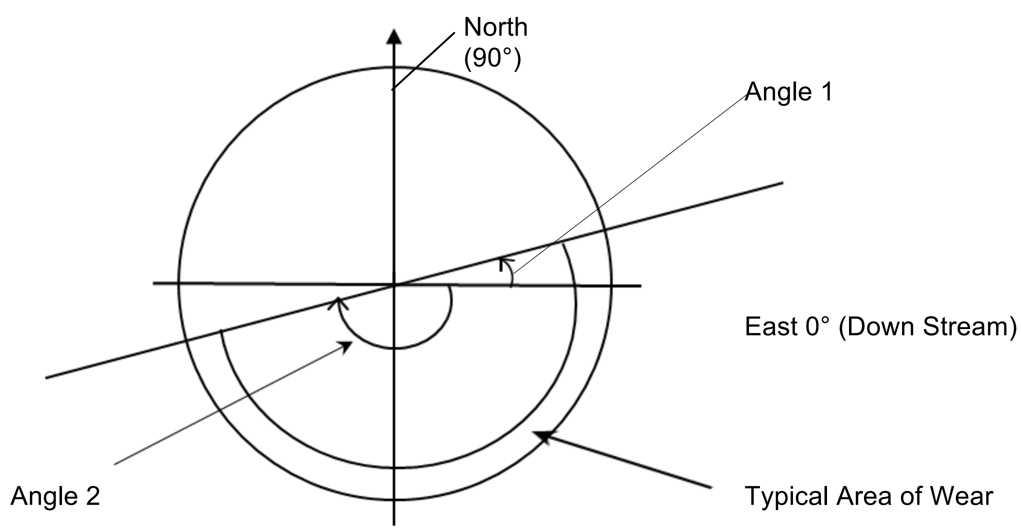


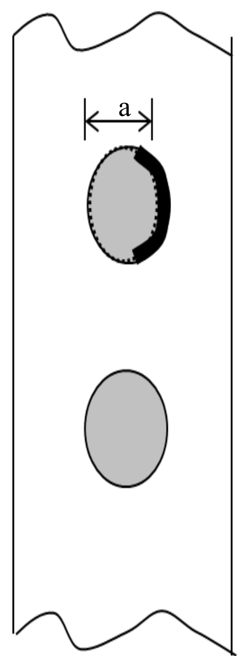
Figure 1: Pintle Wear

Table 2: Pintle Wear at South Flat Track

Pintle #	Angle 1 (Degrees)	Angle 2 (Degrees)	Total Angle (Degrees))
1	4	155	159
2	4	164	168
3	1	164	165
4	1	164	165
5	1	166	167
6	-4	166	162
7	No measurement		
8	No measurement		
9	-7	166	159
10	-11	164	153
11	-6	164	158
12	1	158	159
13	-13	158	145
14	4	155	159
15	4	155	159

Note: Pintles are numbered from East to West

Table 3: Remaining Width of Pintles



Pintle No.	North Track "a" Pintle Width (inches)	South Track "a" Pintle Width (inches)
1	7.500	7.375
2	7.375	7.000
3	7.000	7.375
4	7.250	7.000
5	7.250	6.750
6	7.250	6.875
7	7.250	7.000
8	7.250	7.000
9	7.250	7.125
10	7.250	7.250
11	7.250	7.250
12	7.000	7.250
13	7.000	7.250
14	7.250	7.125
15	7.875	7.875

Note: Pintle width is measure across top of pintle

Tread Plate Wear and Deficiencies

The tread plates on the curved segmental girders were visually inspected for wear and other deficiencies. These tracks are comprised of six (6) segments (A through G). The track segments were connected to the segmental girders as well as interconnected by bolts.

Photo No.6: Close-up view of socket wear

The interference between the pintles and the sockets caused wear and plastic flow of the socket material (See Photo No. 6). The socket wear was, as expected, consistent with the pintle wear. In addition to the wear inside the sockets several of the curved tread plate segments had broken fasteners (See Table 4). The bolts appear to have failed in tension. The NS staff reported that the tread plate bolts had been breaking and they had been replacing them on a somewhat regular basis (See Photos No. 7 and 8).

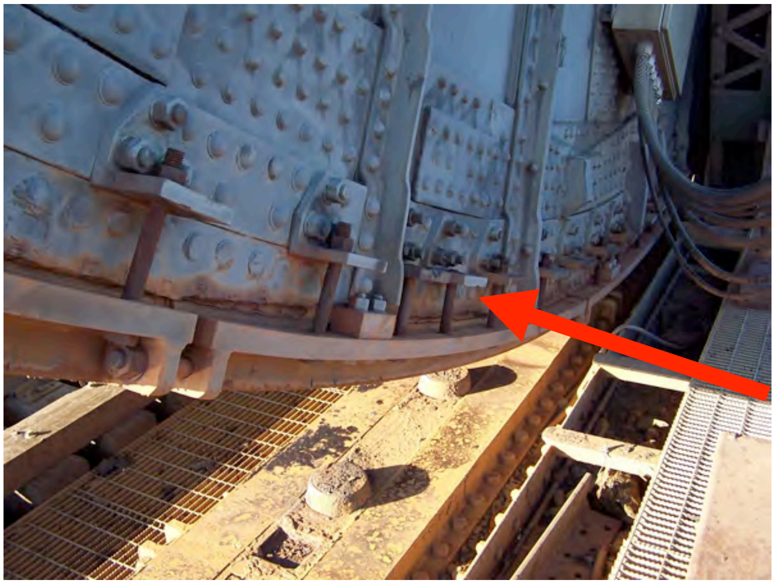


Photo No. 7: Missing connection bolt between curved track plate and segmental girder

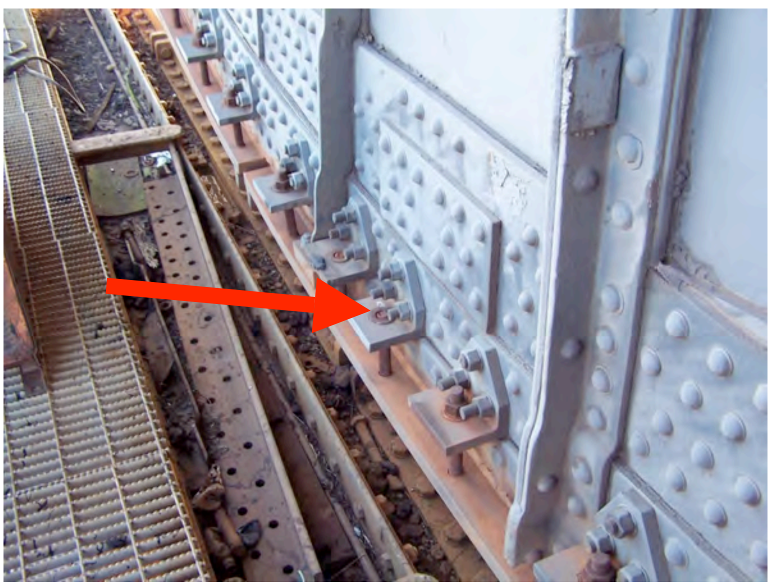
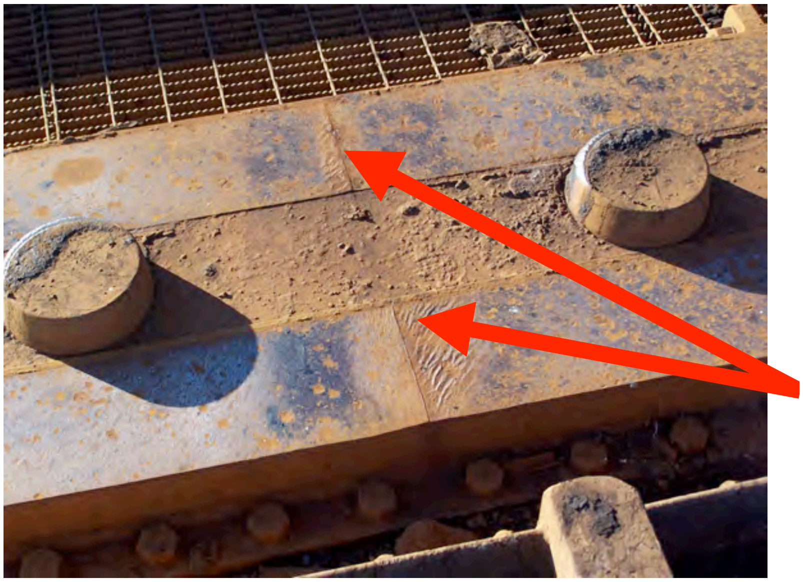


Photo No. 8: Broken connection bolt between curved track plate and segmental girder. Note number of broken bolts alongside flat track

Flat Track (Rolling Surface) Wear

The flat tracks were visually inspected for signs of abnormal wear. The first few segments of the flat tracks exhibited plastic flow of material at the joints (See Photos No. 9 through 11).

It is interesting to note that the front side (towards the channel) of the joint indicates a sliding motion where the back side of the joint indicates a rotation motion. This wear pattern is consistent for both the north and south tracks.



Plastic flow

Photo No. 9: Looking south at north flat track. Note: plastic flow pattern at the joint in the casting

Photo No. 10: Looking north at south flat track. Note: plastic flow pattern.

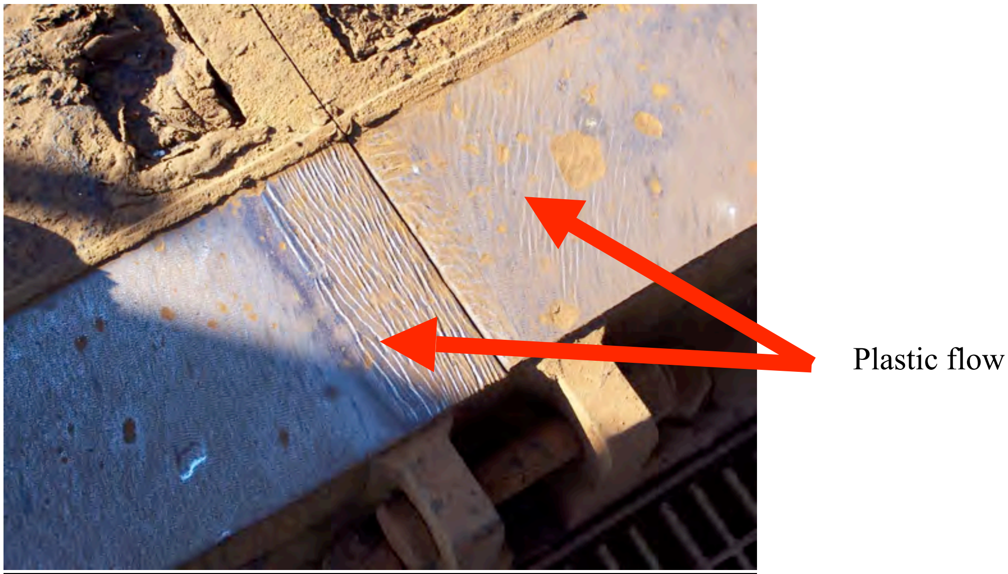


Photo No. 11: Looking south at south flat track. Note: the change in plastic flow pattern.

Flat Track Elevation

Elevations along the flat tracks were measured using a survey level. The measurements indicated that the elevation of the two tracks were different, and varied along the length of each track (See Table No. 4). The river side (east) of the tracks is lower by approximately 3/8 inch (under pier 3) than the land side (pier 4).

The north track was higher than the south track. It was not possible to determine if the measured elevation differences were due to pier settlement or poor workmanship during the rehabilitation. It is normal practice for the flat tracks to be level and at the same elevation to prevent the movable span from walking in the downhill direction.

Table 4: Flat Track Elevations

	Elevation in Inches	
Location	South Track	North Track
East End of Track	0	+3/8
9'-0" from East End of Track	0	+3/8
5'-0" from West End of Track	+7/16	+11/16

Tread Plate Radius

The radii of the curved tread plates on the segmental girder were measured using a steel tape. The radius of roll could not be measured directly. The top of the tread plate to the outside of the pinion shaft was measured. The radius of roll could be calculated given the diameter of the trunnion and the thickness of the tread plate,.

These measurements were taken at three locations for each segmental girder with the bridge in the closed position. The first measurement was vertical (under load) while the other two were equally spaced to approximately 30 degrees from vertical. The measured values were adjusted to account for the radius of the 12 inch pinion shaft plus the 4 ½ inch tread plate.

The measured values are as follows:

Location	Measured Value	Adjustment Value	Total
N – Vertical	27' - 10 11/16"	10.5"	28' -9 1/16"
N- 15 deg	27' - 9 5/8"	10.5"	28' – 8 1/8"
N- 30 deg	27' - 9 3/8"	10.5"	28' – 7 7/8"
S – Vertical	27' - 10 "	10.5"	28' – 8 ½"
S – 15 deg	27' - 11 3/8"	10.5"	28' – 9 7/8"
S – 30 deg	27' - 11 3/8"	10.5"	28' – 9 7/8"

Due to difficulties in access, these measurements were very crude and the accuracy was most likely not within ¼ inch. The design value for the radius of roll was 28' - 8 ¼". The differences in radii between the two girders were surprising considering that tolerance should be on the order of a hundredth of an inch. If one curved track radius is 1" greater than the other radius, over 70 degrees of roll, one girder would attempt to travel 1.2 inches more than the smaller radius girder.

A second site visit was conducted to confirm the original measurements. For the second site visit, a fixture was used to perform the radius measurements (See Photo No. 12). The measurements taken are as follows:

Location	Measured Value	Adjustment Value	Total
N – Vertical	28' – 10 ¼"	-2 ½"	28' – 7 ¾"
N- 15 deg	28' – 7 ¾"	-2 ½"	28' – 5 ¼"
S – Vertical	29' – ¾"	-2 ¾"	28' – 10"
S – 15 deg	28' – 9"	-2 ¾"	28' – 6 ¼"

These measurements confirm the difference in radius between the North and South curved tracks. The average difference between the measurements taken at similar locations in the North and South tracks is approximately equal to 1 ½". This difference in tread plate radius causes the south track to roll approximately 1.9" more than the North track when the bridge is opening, thereby inducing a clockwise rotation of the span. The other significant finding was that the radius was not consistent. The most likely explanation for the radius difference between tracks is that during the early 90’s rehabilitation job the north track was set to the original radius, 28’ – 6”, and the south track was set to the new 28’-8 ¼” radius. The average number of the vertical and 15-deg measurements for each track shows this hypothesis.

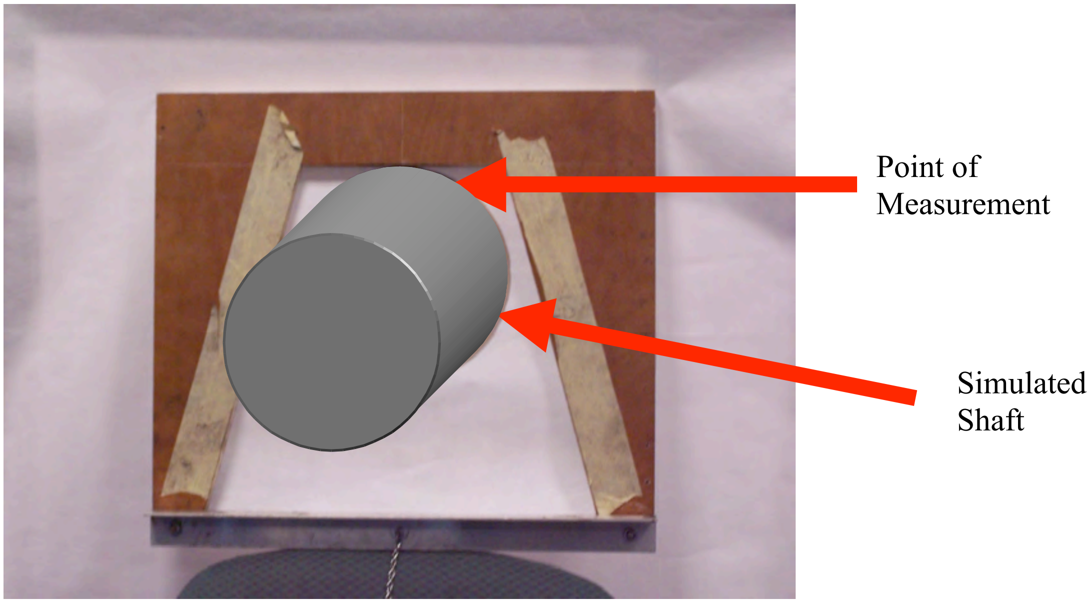


Photo No. 12: Fixture used to measure the radius of roll

Rack and Pinion Gear Wear Patterns

The wear patterns of rack and pinion often provide important information regarding movable bridge mechanics. The pinion gears are both bottomed out in the racks when the bridge is closed.

Photo No.16 shows the damage at the root of the gear tooth for the south rack. The lubrication patterns on the rack indicate that the south pinion is doing most of the work to open the span while the north pinion is doing most of the work to close the span. The exception to this observation is the first few degrees of opening where both pinions are bottomed out.

In Photo No. 14 the corrosion on the face of the rack gear teeth indicates little contact between rack and pinion during opening. The polished tooth face on the closing side of the rack gear is shown in Photo No.15. Photo No. 18 indicates light contact between the north pinion and the rack during closing, as compared to the polished surface in Photo No. 15.

Photo No. 13: View looking North at South pinion. Note wear on top of gear from contact with rack gear.

Photo No. 14: South rack looking west. Note: wear from tooth number 30 to the end of the rack indicating no contact between pinion and rack while closing.

Photo No. 15: South rack looking east. Note: wear of rack teeth indicates contact between pinion and rack during opening.

Photo No. 16: South rack/pinion interference at gear tooth 13 through 20. Note: severe binding between pack and pinion during opening, and damage to countersunk bolt heads

Photo No. 17: View looking at North pinion with the bridge in the closed position.

Photo No. 18: View of the North rack at the fully opened position. Note gear contact for closing and minimal contact on opening.

In general, the operating machinery (direct drive, no differential gear set) is worn. This gear wear results in one pinion generally doing more work than the other pinion. The balance condition of the movable span is unknown; however, it is reasonable to assume that the bridge is span heavy. This assumption is based upon the gear wear patterns for the closing side of the rack gears.

Please note that the pinion gears bottoming in the rack would not be caused by pier settlement since both the flat tracks and the rack supports are tied to piers 3 and 4. The pinion gear bearings did not indicate excessive motion (generally an indication of extreme bearing wear).

Analysis

The results of the various measurements presented a complex and conflicting representation of the bridge operation. The key factors in understanding the basic cause for the pintle wear laid in the gear tooth loading during opening and closing, the pintle wear patterns, the basic flat track elevation measurements and the radii of roll.

The elevation of the flat tracks indicated that the movable span had a tendency to move to the south, or roll downhill. The overall wear pattern on the pintles was located on the south side. If the span was attempting to move downhill, then the pintle wear would be on the north side of the pintles. Based upon the location of the wear, the flat track elevation was discounted as the primary cause of the observed pintle wear. If you look at the pintle as having four quadrants (See Figure 2). As the bridge closes the tendency would be for the span to roll down hill moving the center of the socket into Quadrant.1 (SE). This would cause wear in the Quadrant 3. This didn't match the wear pattern observed in the field.

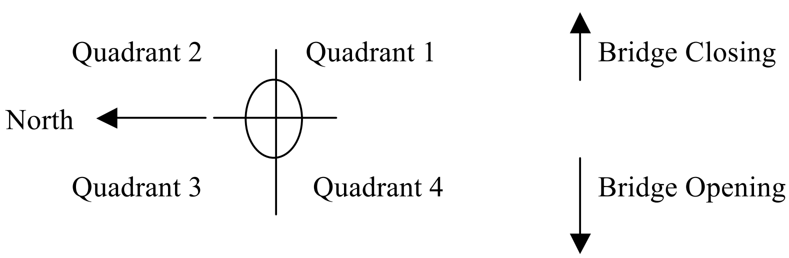


Figure 2: Pintle Quadrant Layout

The south rack gear wear indicated that the south pinion gear was doing most of the work during the opening sequence and the north pinion was doing most of the work during the closing sequence. Since the pinion was mounted on the movable span, a clockwise rotation was induced during opening. This rotational motion would have moved the center of the socket into Quadrant 3 which would have caused wear in Quadrant 1. This was in part the wear observed in the field. However, during the closing sequence the clockwise rotation caused by driving the north pinion would have moved the center of the socket into pintle Quadrant 1. This would have caused wear in Quadrant 3. This didn't match the wear observed in the field.

It was concluded that the pintle wear was the result of an induced rotation in the movable span during opening and closing operations. Since the south tread plate radius was larger than the north tread plate radius the south tread plate would have traveled a greater distance during opening and closing. This means the bridge would have experienced a clockwise rotation during opening and a counterclockwise rotation during closing. During opening the center of the socket would have moved into Quadrant 3 which would have caused wear in Quadrant 1. During closing the center of the socket would have moved into Quadrant 2 causing wear in Quadrant 4. This combination of wear in Quadrant 1 and Quadrant 4 closely matched the wear pattern observed in the field. The interference between the pintle and socket as the bridge opened/closed was approximately 0.16 inches.

Additionally, as the tread plate passes interferes with the pintle, there is an increase in bending of the tread plate. This bending would increase the tension in the bolts resulting in the breakages observed.

Final Design

The project had some major problems with which to contend. The bridge experienced heavy usage with an average of 30 trains and 10 openings a day. There were limited outages allowed. The bulk of the work had to be done during a 36 hour rail outage over either the Thanksgiving or New Years holiday. Unknown conditions could have greatly impacted the construction. The radii of roll were different at the two girders, and the radius of each varied. The bottoms of the existing girders had been cut during the 1990 rehabilitation. The cuts were very rough and irregular. Lead sheet had been installed between the webs of the girders and the curved tread plates to smooth out the irregularities. The lead plate had flowed out over the years due to the heavy loads (the bridge weighs about 2 million pounds). To complicate matters, this project was a high profile project for a very important client in Norfolk Southern. A fool proof repair was needed that would correct the errant roll and that could be performed in a short period of time despite many unknown field conditions.

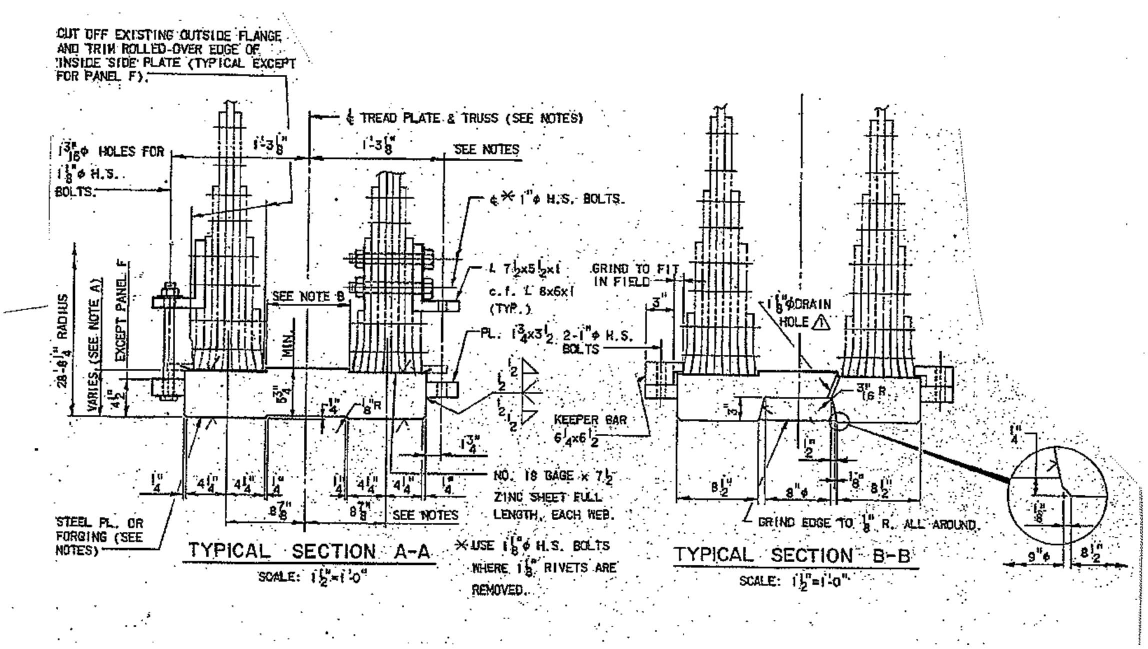


Figure No. 3: Sections through Segmental Girders. Note spread in web plates at the bottom of web.

It was decided that using bolts to transfer load from the curved tread plate into the web of the segmental girders was not a good approach for two reasons. First and foremost, the amount of time that would be required to remove existing rivets and ream holes for new bolts would preclude this type of work in the limited closures time allowed. Also, access was a big concern.

Each segmental girder had two independent multi-ply webs that were 17 ¾ inches on center (See Figure No. 3). Bolting through the web would require cutting several hand holes for access. Therefore, we needed a design repair that would achieve full bearing between the new tread plates and the irregular cut segmental girders. There wouldn't be enough time to machine the web to a set radius in the allotted window.

An innovative approach was taken to achieve full bearing by using molten zinc for our application. The design used continuous clip angles to secure the tread in place and molten zinc was poured in-place between the web and the tread plate to achieve full bearing to the riveted web plates. Zinc filler, as far as we know, has never been used for this application.

Flame Cut Web

Photo No. 19: Looking at the edge of the curved tread plate. Note the irregular radius cut to the bottom of the segmental girder web.

The new design incorporated a continuous guide plate along either edge of the tread plates thereby eliminating the potential for any drift when the tread plate socket disengages from the pintle and before the next socket has a chance to engage the next pintle (See Figure No. 4). This provides the transverse alignment of the bridge. The existing pintles were reused to provide the longitudinal alignment of the span. The new design also provided continuous curved flange angles used to connect the tread plates to the web. This connection was not intended to transmit

100 percent of the stresses from the tread plate to the web during the roll. The bearing stresses would be transmitted through the zinc once it was solid. The continuous angle was meant to provide a better connection during construction (See Figure No. 5). A curved fill block was located between the flange angle and the tread plate. The fill block provided a form for the molten zinc and also provided a pour hole where to molten zinc could be poured to fill the void between the tread plate and the segmental girder web (See Photo No. 28). Interior bulkhead plates provided a form for the inside face of the molten zinc filler. A keyway was cut into the webs of the segmental girders and a matching key was provided in the first curved tread plate segments at each girder to prevent slippage of the first tread plate sections relative to the segmental girders and to provide for full bearing to the existing webs when the bridge was closed and subject to live loads. Overlapping tongue and grove connections were provided to lock the tread plate segments together (See Photo No. 28).

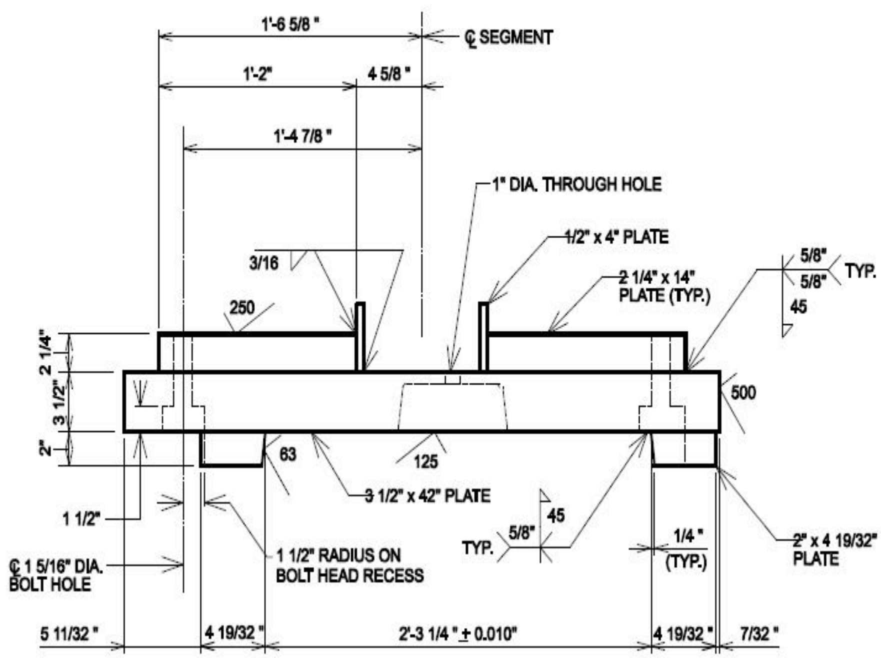


Figure No. 4: Typical Tread Plate. Note offset of guides based on verified field conditions.

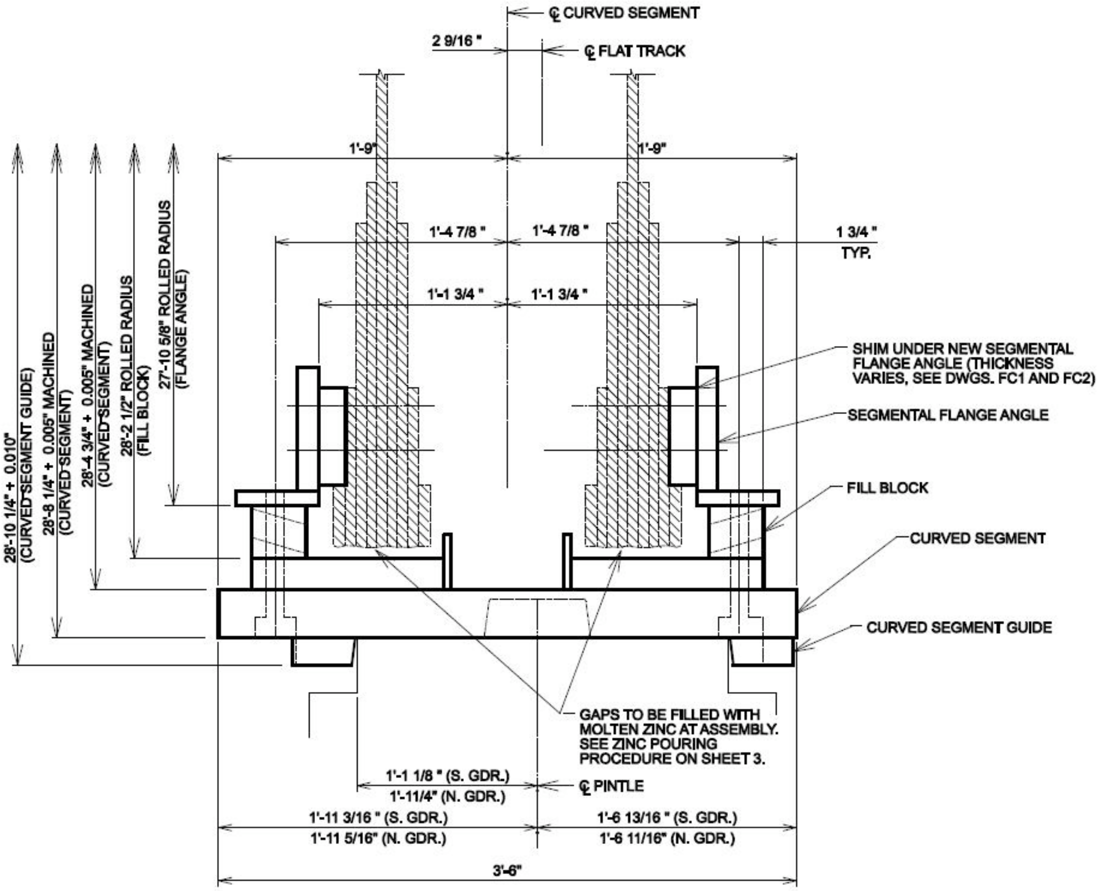


Figure No. 5: Typical detail showing connection of new tread plate to existing web. Note the holes in fill blocks through which molten zinc was poured.

Construction

The prime Contractor selected to install the new rack segments was Fenton Rigging and Contracting Inc. of Cincinnati, OH. JC Industrial Manufacturing Corp. of Miami, FL was subcontracted to fabricate the rack segments and Berding Surveying was subcontracted to perform the field survey.

We understood that the fit was a major concern during construction. Therefore the contractor was required to field verify the location of the girders, the flat tracks and pintles, as well as the location of all the rivets and bolt holes that we would use for connections. All the fabricated parts would have to fit up perfectly since the short outage would not allow time for field modifications.

The Contractor used a 3-D laser survey to locate a comprehensive set of points and surfaces on the bridge during a 4-hour bridge outage. The survey required three separate set-up locations in order to capture all the data necessary on both sides of each track girder (See Photo nos. 20 and 21). It was critical that the bridge remain in one position, unmoved, during the survey in order to obtain a direct relationship between the inner and outer faces of each track girder (the open position was selected to allow river traffic to pass during the survey).

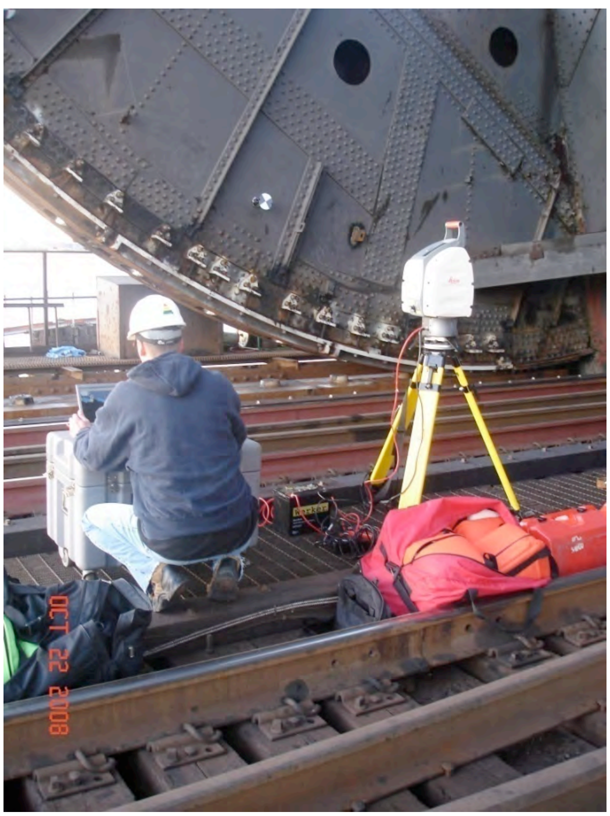


Photo No. 20: Laser survey of the segmental girders.

Photo No. 21: Survey Targets set up on the
North face of the South Segmental Girder

The survey data results were in the form of a 3-D scatter of points on the structure (See Photo No. 22).

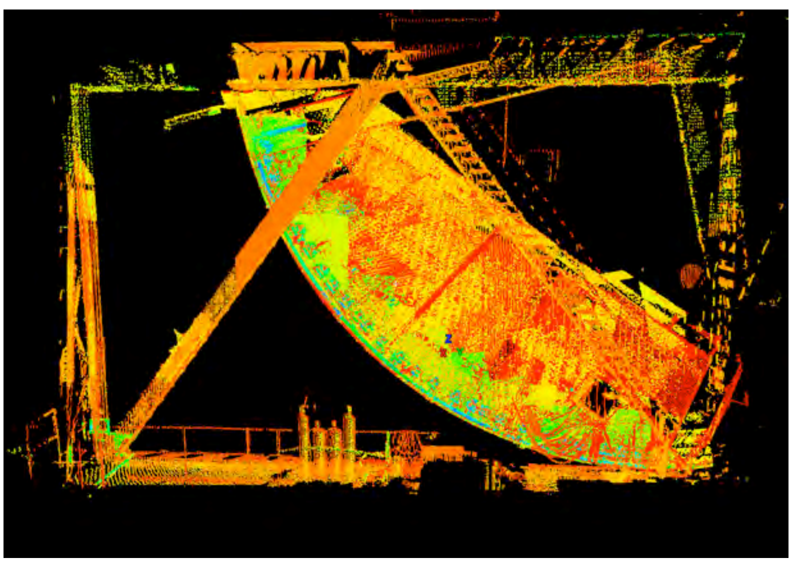


Photo No. 22: 3-D Laser Survey –
Elevation of Track Girder

The survey data indicated that the bascule girders were not centered on the flat tracks nor parallel to the flat tracks and that the web plates were not straight. Berding Surveying extracted the critical data that was used to develop detailed shop drawings and translated the data to CAD format. The critical data included the location of every rivet and bolt to be used in connection of the new steel plates (See Photo No. 23), the location of the face of the web plates at which new flange angle would be bolted, the location of the flat track and the center of each pintle, and the location of the center of roll. This information was used to aid in the development of detailed shop drawings, however correction of the data was necessary in order to use it for fabrication of the tread plates and connection angles.

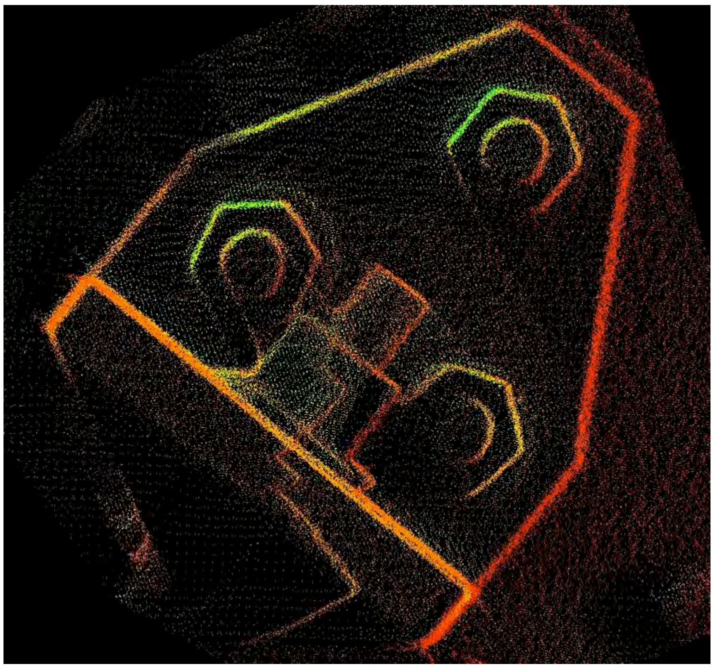


Photo No. 23: 3-D Laser Survey – Survey of Bolt Heads

All the information provided to HDR by the surveyor was for the bridge in the open position, with the center of roll somewhere between the beginning and end of the flat track. HDR took the data provided and translated and rotated the 3D survey of the bridge back to the position it would have been if the bridge were closed. This was done in order to tie the moving portion of the bridge to the stationary flat track at the first pintle, and to define the end of the first segment to be replaced. A new centerline of tread plate was defined transversely for each track girder to accommodate mating off center to the flat track (See Figure No. 5). A new centerline of tread plate was defined longitudinally to correct the existing curvature and the non-parallel nature of the track girders. The control of the transverse alignment of the new segments was provided by shims between the existing girder web plates and the new curved flange angles. The thickness of every shim on each side of each track girder was calculated so that, theoretically, the new segment would line up exactly where it needed to be. In this way, the new segments were fitted to the bridge on the computer (in the office) long before they were installed in the field. This was done to minimize reaming or field adjusting of bolt holes during installation, and to ensure that the first pintle socket would line up with the first pintle and the bridge would roll straight down the track.

Detailed drawings were provided to the contractor showing the arrangement, alignment of and cross-section each of six tread plate segments and flange angles, the location of every bolt and the thickness of every shim necessary for connection (See Figure No. 6).

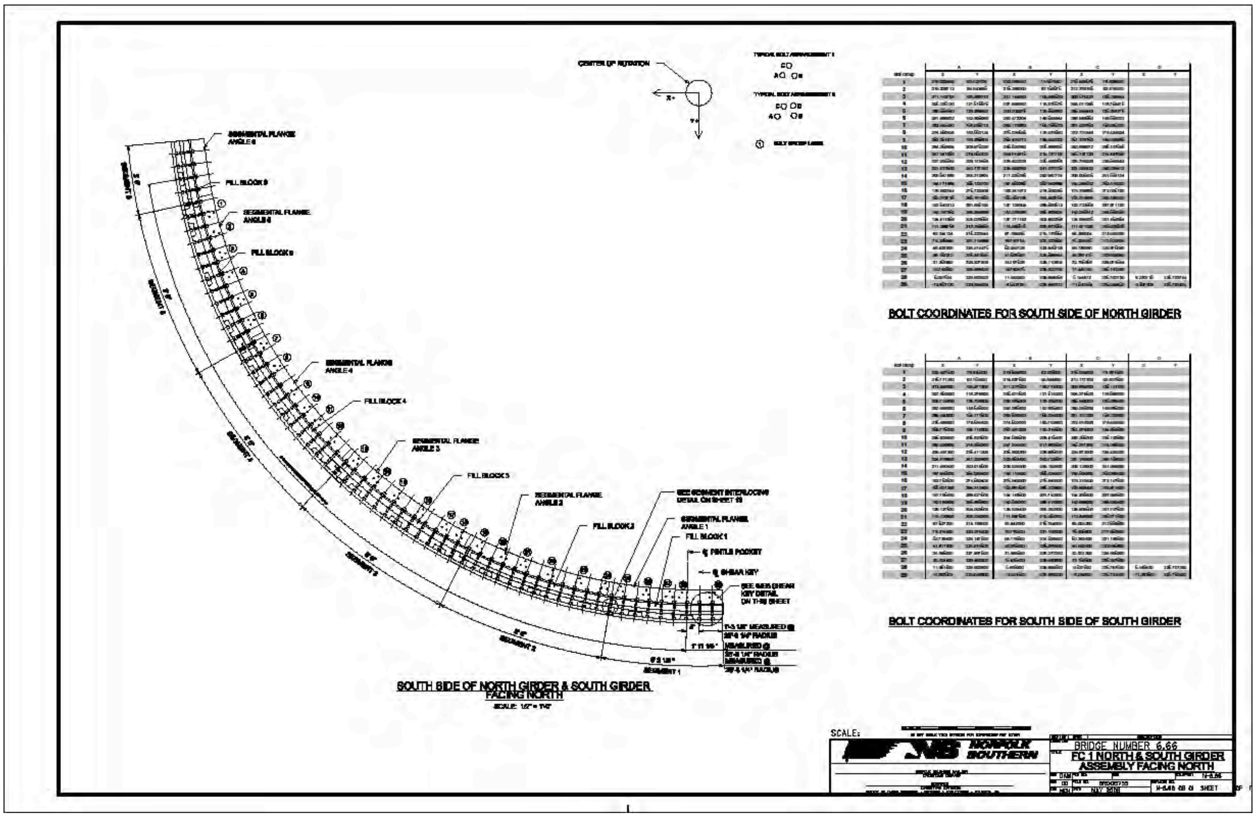


Figure No. 6: Drawing locating connection bolts.

Using this information the contractor fabricated and installed the flange angles and shims prior to the bridge outage, and fabricated the first segment to be installed in the bridge outage (See Photo nos. 24 to 26).

Photo No. 24: New tread plate segments.

Photo No. 25: View of bottom of tread plate segment. Note circular sockets to match existing pintles, interlocking tongue and grove connections between the segments. Also note that the locations of the holes for bolted connections to flange angles are different on the two sides of the tread plate.

The installation of the first segment took place in a 36 hour rail outage over the New Year weekend of 2008. The contractor opened the bridge so that the existing first segment was disengaged from the flat track and then removed then existing segment. This was saved and sent to the shop to be modified and resued in subsequent stages. The new segment no 1 was moved and offered up to the pre-installed flange angles. This was the time when we discoveded whether the painstaking work of survey and shop drawing development has been successful. The contractor installed the bolts that connected the new segment to the flange angles with relative ease and it was evident that the pintles and track guides would align (See Photo no. 26).

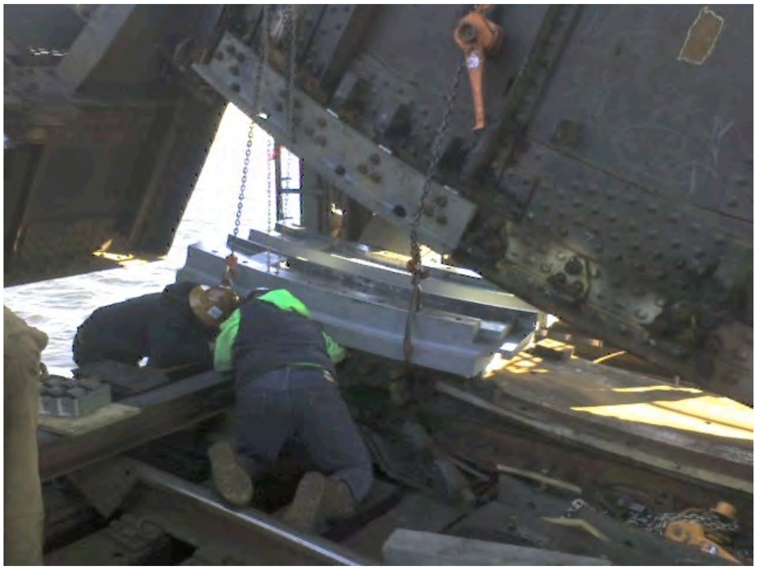


Photo No. 26: Installation of Segment 1.
Note pre-installed flange angle.

The Contractor then set up zinc ovens and set about installation of the molten zinc in the void between the top of the tread plate and the bottom of the web girder (See Photo No. 27).

Photo No. 27: Installation of Segment 1.
Pouring Zinc.

Subsequent segments were fabricated in the shop, either new or re-fabricated from segments removed from the bridge, and installed in the same manner described in shorter rail outages, until all 6 segments had been installed (See Photo Nos. 28 and 29).

Photo No. 28: Installation of Segment 2. Note tongue and groove connection and fill hole for molten zinc in fill block.

Photo No. 29: Installation of Segment 2.

Conclusion

The bridge is now rolling on new tread plates, no longer deviating from its path, and is rolling in a straight line. With the survey information provided, the HDR design team was able to accurately determine the exact location of hundreds of bolts for the flange angles and shim plates and was able to minimize field modifications and aid the Contractor to install the segments in the tight construction window.