HEAVY MOVABLE STRUCTURES, INC.
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The Broadway Bridge Rall Wheel Replacement Project

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MARRIOTT'S RENAISSANCE HOTEL AT SEAWORLD
ORLANDO, FLORIDA

Bridge Background

History & Background

The Broadway Bridge in Portland, Oregon, a Rall type rolling bascule bridge, was designed by Ralph Modjeski and Strobel Steel Construction Company of Chicago, IL and built by the Pennsylvania Steel Company of Steelton, PA in 1913. The Strobel Steel Construction Co. had control of the Theodor Rall's patents for the Rall type bascule. The Broadway Bridge is the largest example of the Rall type bascule in existence. The bridge is a double leaf riveted through truss bascule with each leaf being 139'-0" from center of trunnion to the center of span and 50' wide from center to center of truss. It provides a 250' wide channel with 65' of vertical clearance when closed (at high water) which increases to unlimited when fully open. Each bascule leaf weighs roughly 4.2 million pounds. It was the longest bascule bridge in the world when completed.

The advertised advantages of the Rall type bascule bridge are similar to that of the Scherzer type bascule. The use of rolling action increases the efficiency of the bridge while allowing a shorter bascule span for a given channel width since the bridge rotates and translates away from the channel while opening. It was also advertised to have an additional advantage that when seated the Rall wheel was lifted off the track and could be replaced without jacking the structure, however, this is not the case for all Rall type bascules, including this bridge.

Photo 1: Broadway Bridge, 1929

The existing bridge operation is explained in Figure:2 Sequence of Bridge Operation. The span drive machinery, shown in red, is turned by the motor which in turn pulls the operating strut, shown in orange. The operating strut pulls the Rall wheel back towards the approach causing the control strut to rotate pulling the counterweight down and opening the draw span. When closed the bridge rests on the bearing shoe shown in blue and has an anchor strut which is placed into the top chord to carry live load when the bridge is seated.

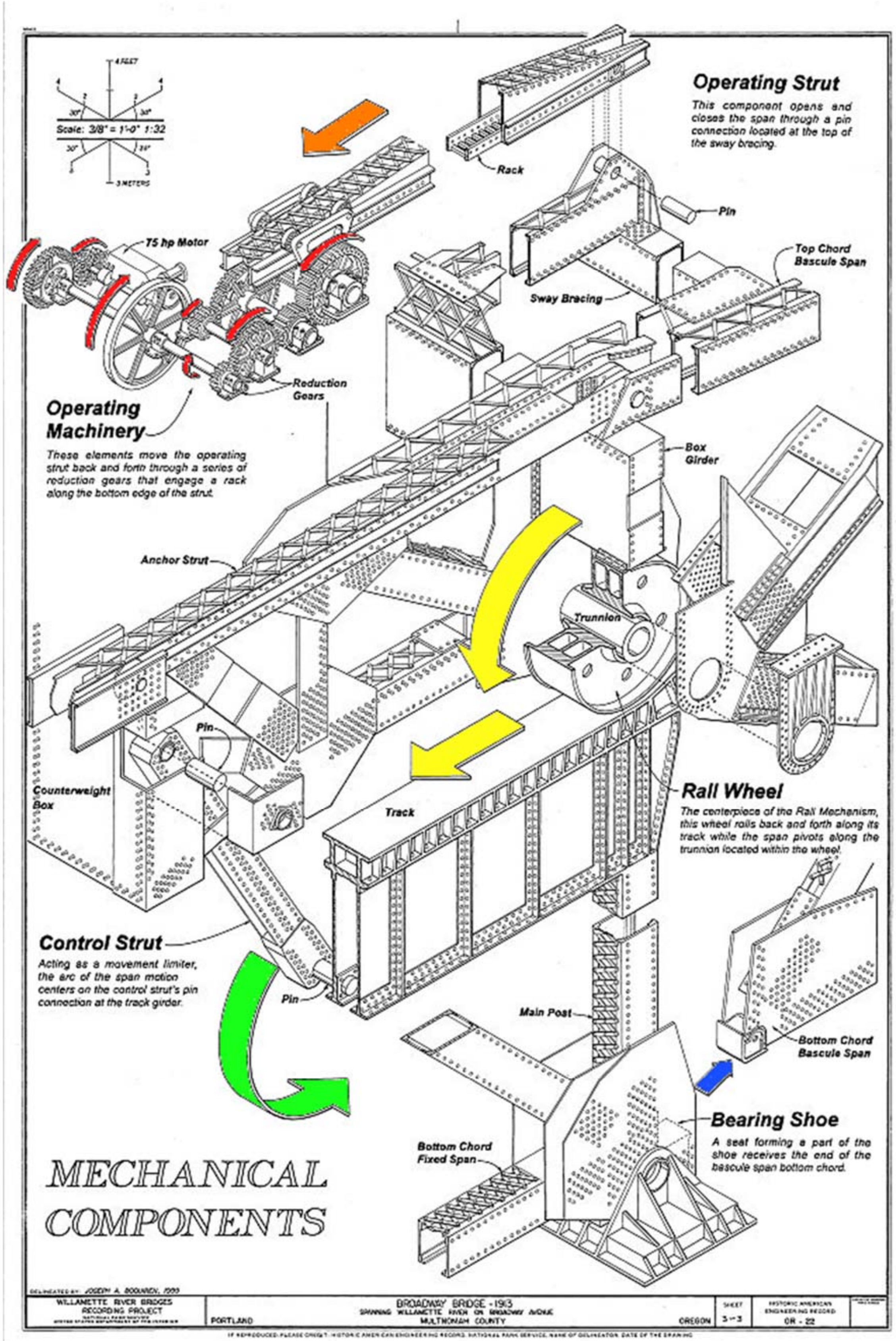


Figure 2: Sequence of Bridge Operation

The purpose of this project was to replace the original 1913 Rall wheels, tracks, and control struts. The Rall wheels have always been a challenging part for the bridge. The load on the wheels highly stresses the 100" diameter 40" wide wheels. The original wheels were made from 52,000 psi yield high grade nickel chrome castings which appear to have been experimental at the time. The final design was a highly reinforced triple webbed design shown below in Figure 4.

Ultimate Strength	102,000
Elastic Limit	52,000
Elongation	14%
Reduction	17%

The above are the results of actual tests made of Nickel Chrome Cast Steel, containing .40 Carbon, and were discussed with Mr. Modjeski April 16th 1912. We propose, for the 4 Rollers, to use the same character of steel, with physical results reasonably close to the above.

Figure 3: Material Properties of the Original Wheel

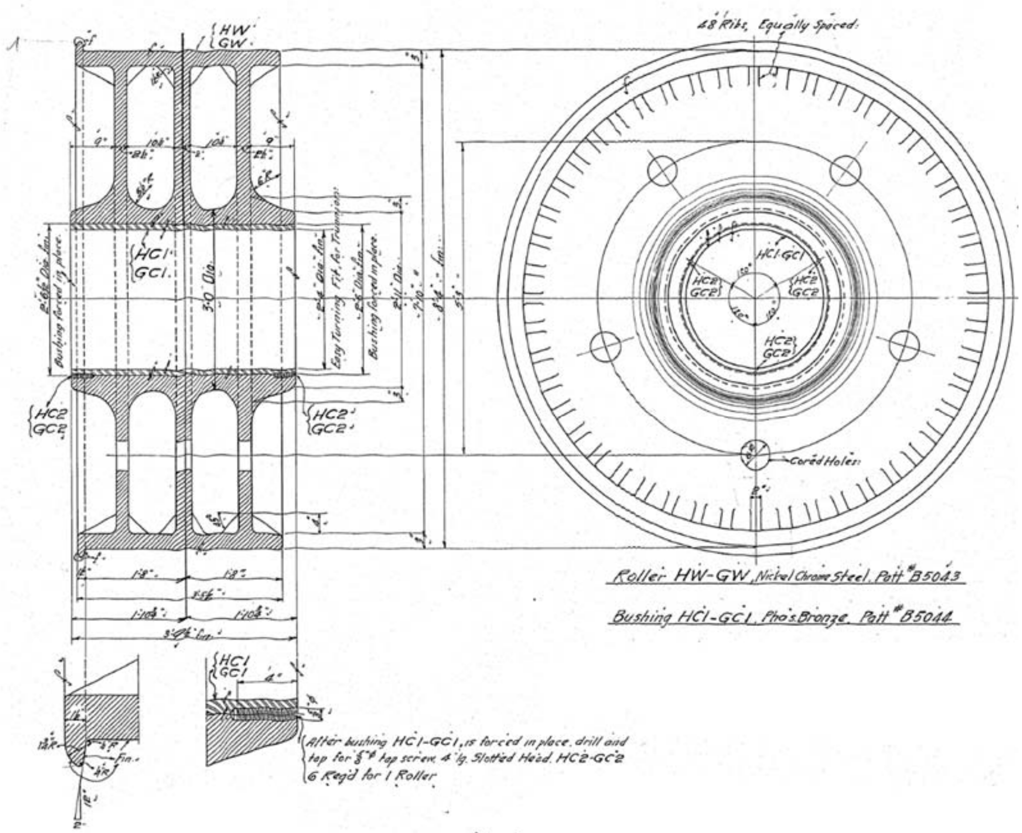


Figure 4: Drawing of the Original Wheel

The original plans show that there was some debate as to how make such a high strength wheel with the technology available in 1913. The Hertzian rolling stresses for this wheel and requirements for a monolithic casting are high enough that an alternative wheel with rolled steel tires was considered during design of the original wheel.

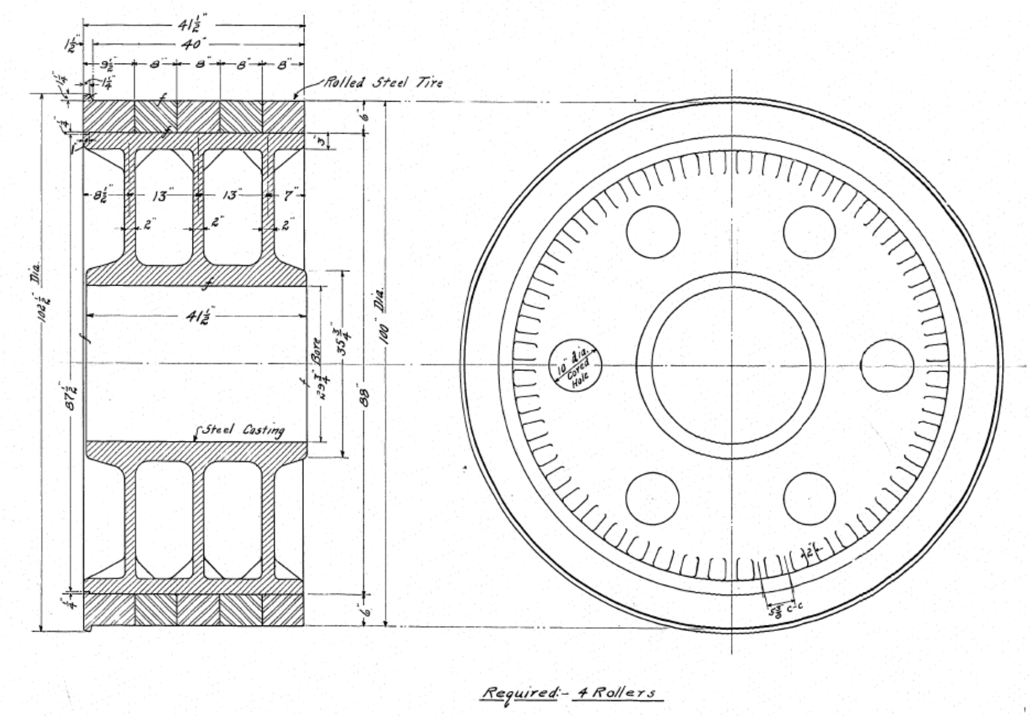


Figure 5: Drawing of an Alternative Wheel

The original tracks for the Rall wheels were cast from the same material as the wheels using a highly stiffened double webbed design. These are incredibly complex cellular castings requiring many cores per 32’-8” long casting. Although no drawings of it still exists, the original design of the track was likely triple webbed to match the wheel. The original design for the track girder was also to be triple webbed, however, this was revised to a double-web design by the Pennsylvania Steel Co. likely due to constructability challenges.

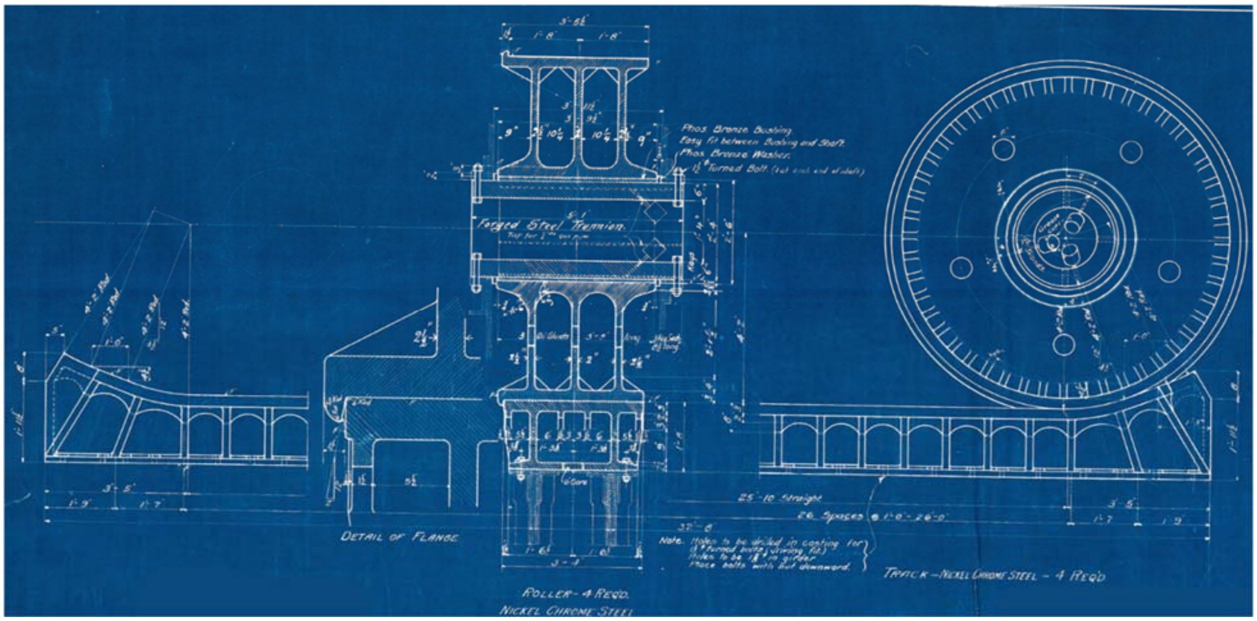


Figure 6: Design Drawing of the Track and Wheel

The original 22'-11 $^{5}/_{32}$" long control struts were replaced in 1982 due to wear and were replaced again during this project to provide length adjustment to help keep the bridge tracking straight.

Existing Conditions

The existing wheels and tracks were highly worn. Over the years the surfaces of the parts deformed from the bearing stresses, causing the wheels to become out of round and the tracks to have up to ¼" bow at the center. Some of the wheels and tracks had cracks and both the wheels and tracks had many small dents from running over debris over the years. Guides had been added to one of the tracks to help keep the wheel flange from riding onto the track, however, the track had developed a large crack due to the challenging requirements of welding this type of nickel chrome casting properly. After 105 years in service it was simply time for replacement.

Photos 7, 8, and 9: Existing track and Wheel Condition

Photos 10 and 11: Existing Track and Wheel Condition

The operating struts were in good condition and were found to have negligible wear at the time of removal, however, were replaced for additional adjustability to assist the bridge track without rubbing the thrust flanges of the Rall wheels and tracks excessively.

Design of Replacement Components

Rall Wheel Design Options

Several options were explored while determining the best way to replace the existing wheels. Castings, weldments, and forgings were all considered as options, each with their own merits and drawbacks.

Castings were considered to match the original fabrication of the wheels and preserve the historic nature of this bridge to the greatest extent; however, it was determined that the stresses of the existing castings did not meet the requirements of modern code. To meet the strength requirements the material properties would need to be increased above the original design which would limit the number of suppliers. There are limited US suppliers for large complex castings regardless of the material choice and it would be difficult to simplify the casting significantly without having casting issues due to material thickness changes.

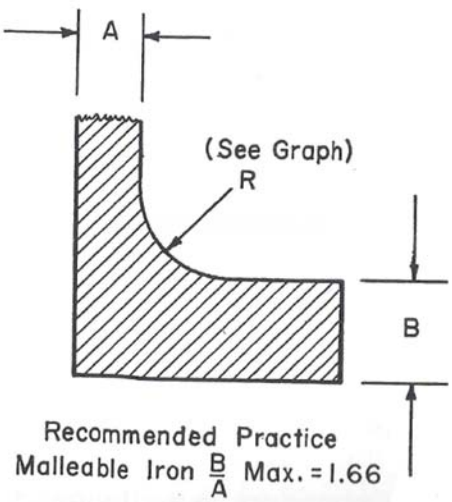


Figure 12: Casting Design Practice

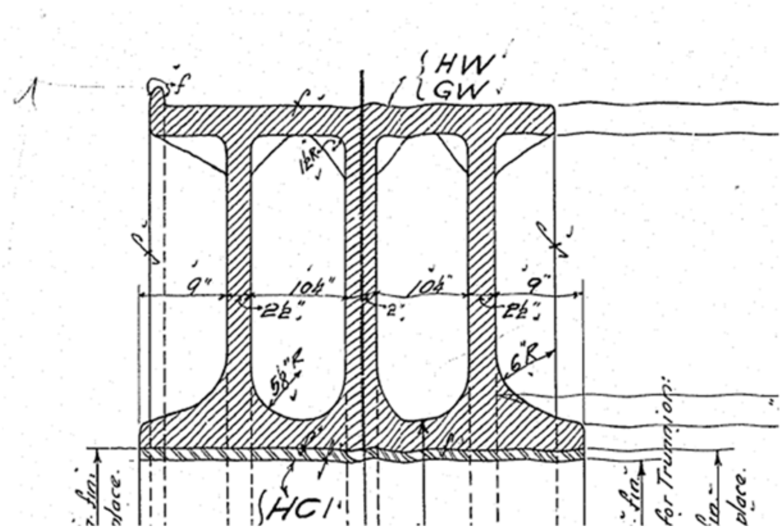
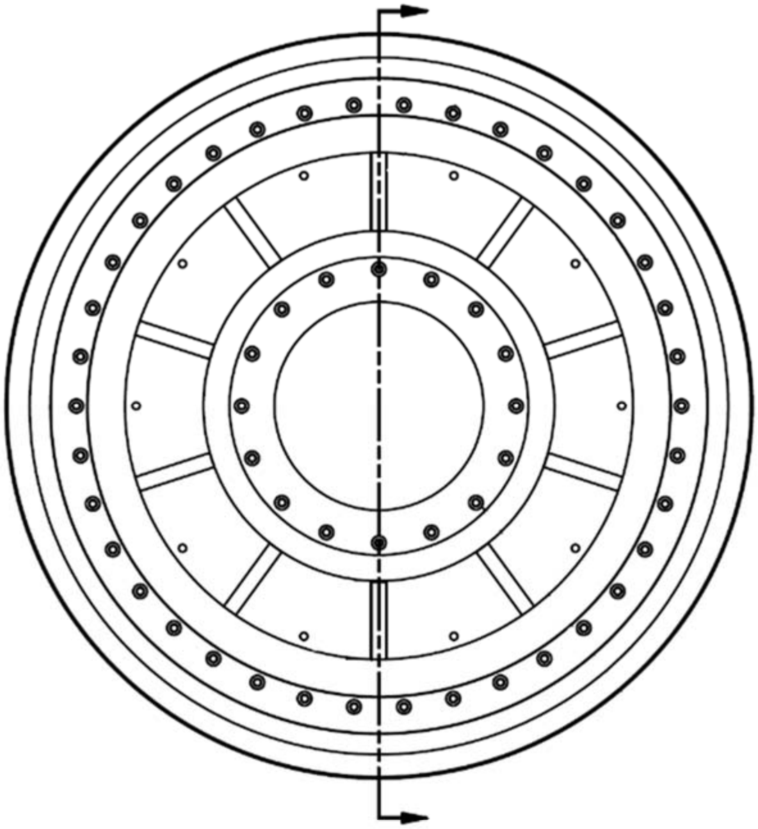
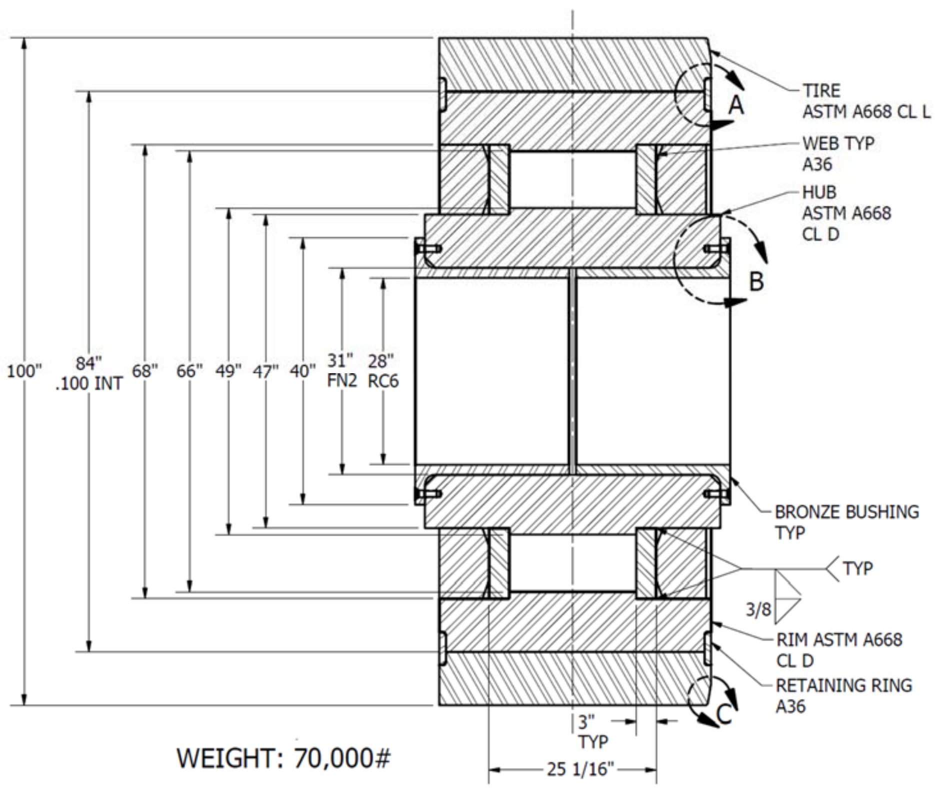


Figure 13: Cross Section of Existing Wheel

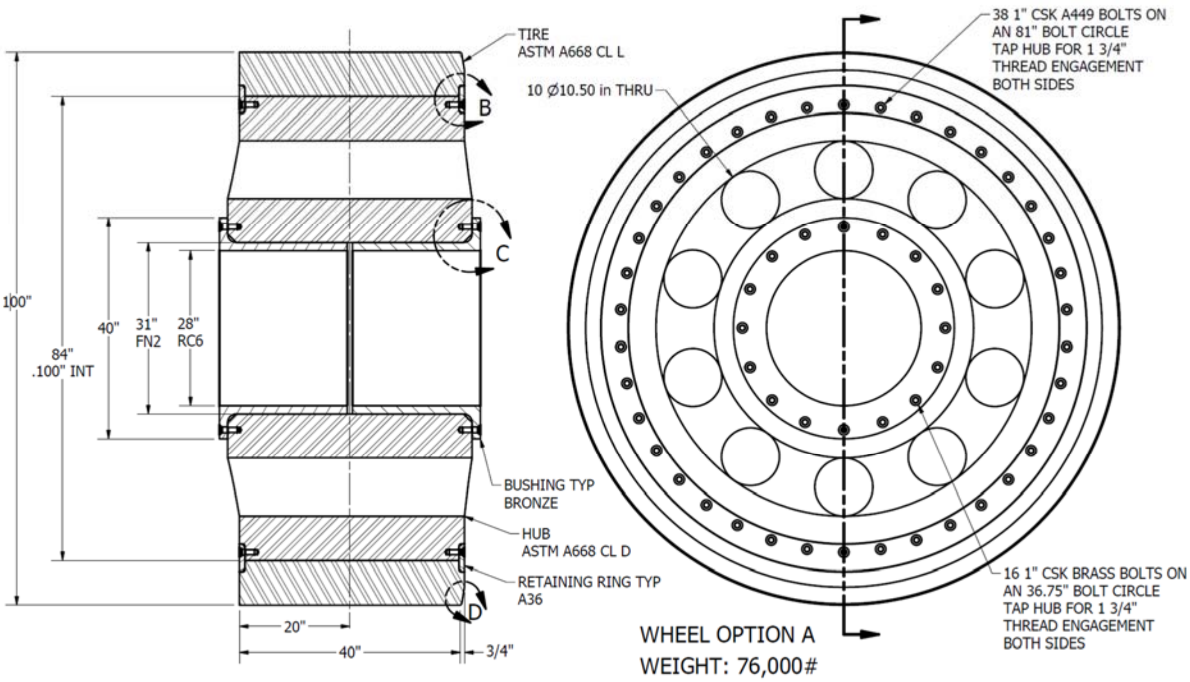
Weldments were considered as they are often used to replace complex castings. Although possible, this proved to be a cumbersome solution. The riding surface of the wheel required ASTM A668 Class K forgings (100ksi ultimate/75ksi yield) to withstand the Hertzian stresses on the treads. This would require special welding practice because the rim would be a highly restrained part and would crack if not properly handled. To avoid this issue, a softer more weldable rim was considered with a shrink fit tire, however, this also proved to be less than ideal for a few reasons. First, it required welding of plates more than 4" thick; secondly, it required a thick rim and tire to apply the necessary shrink fit without overstressing the materials since the Hertzian rolling stressing will compound the shrink fit stresses especially near the surface of the tire. These compounding stresses required an A668 Class L tire instead of Class K, which by itself is not a reason to avoid this design. The biggest drawback to this approach is that fabrication is complex and provides very little material savings after the thicknesses of the hub, rims, and tires were calculated.





Figures 14 and 15: Weldment Wheel Concept

Forgings with a shrink fit tire were considered. A soft forging could be easily made to carry the internal stresses and a Class L tire used to withstand the Hertzian stresses and distribute the load for the softer core material.



Figures 16 and 17: Forging Wheel with Tire Concept

The tire material stresses were determined by combining the Hertzian stresses due to rolling loads with the hoop stresses from the shrink fit into a Von-Mises stress. The combined stresses were held below 75% yield at any point and the Hertzian (cyclical) portion of the stress was kept below the endurance limit of the material to prevent fatigue. It was determined that a 0.1" interference could be installed with 300 ºF preheat and would provide approximately 725psi of shear resistance at the interface while only 550psi was required. This option was feasible, however after consultation with numerous fabricators it was determined that eliminating the tire was preferred due to simplicity and availability of large high-grade forgings.

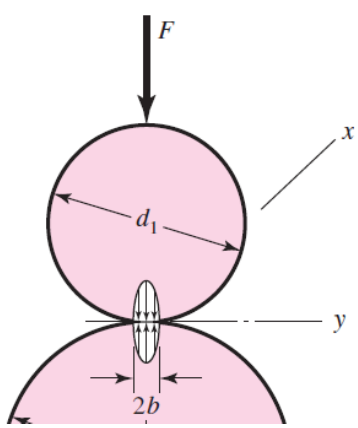


Figure 18: Hertzian Stresses

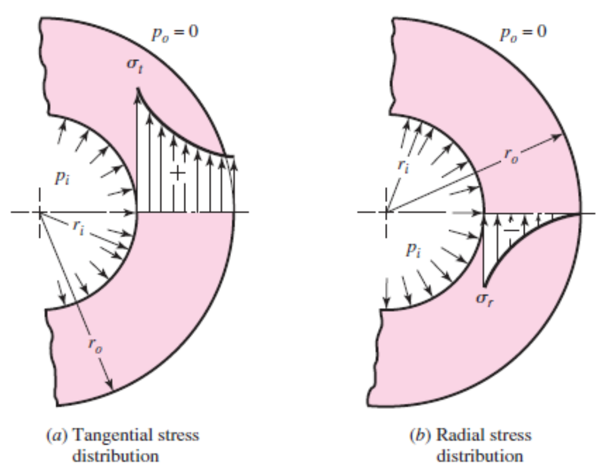


Figure 19: Shrink Fit Stresses

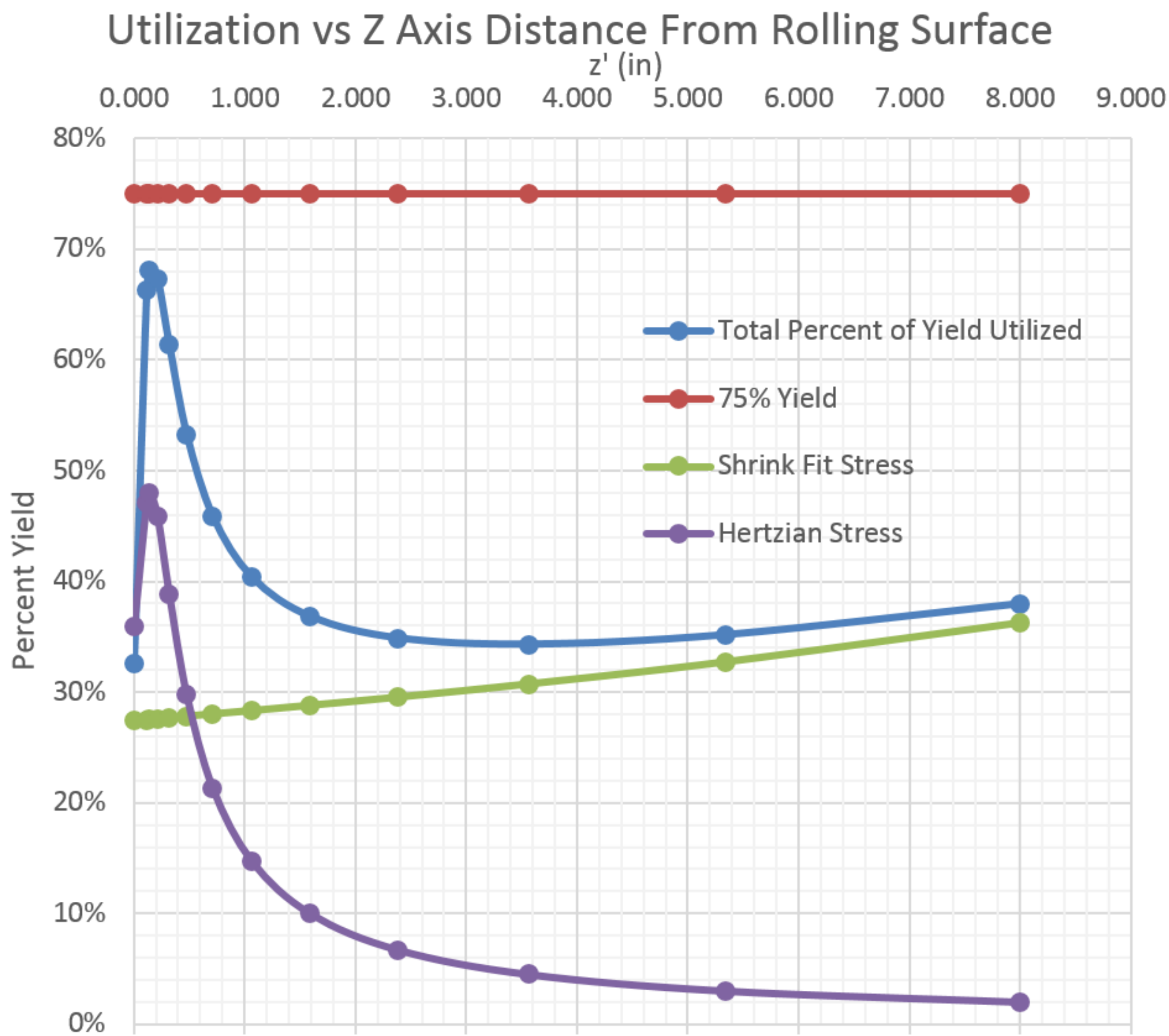


Figure 20: Combined Hertzian and Shrink Fit Stresses

A one-piece forged wheel made from high grade steel is what was ultimately used for this project. This option is the simplest to design and because steel prices were low at the time of fabrication the most cost effective to procure given the amount of labor and steel required for the other options. In this design the Hertzian stresses were plotted based on distance from the surface and

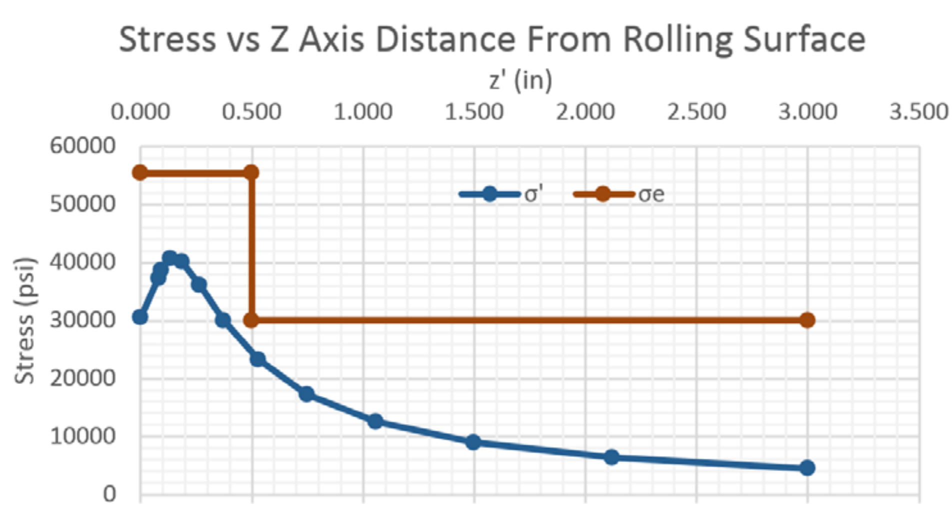
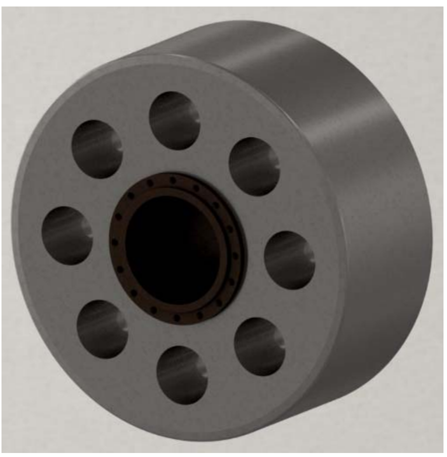


Figure 21: Hertzian Stresses and Material Requirements

compared to the quench charts. Given the size of the forging, AISI 4340 steel was chosen because of its ability to be quenched deeply and its high forgeability. Figure 21 shows the calculated stresses in the wheel versus the required minimum allowable endurance limit at various depths. Due to the large size of the wheel, it falls outside of the range of ASTM A668. Although forgers would agree to follow the A668 specification, it needed to be supplemented to reflect the needs of the project and the size of the part being made. These requirements were provided on the design drawings. The first ½" of the wheel riding surface was required to be at a minimum 300BHN and the remainder of the section only was required to be 37,500 psi yield and 75,000 psi ultimate strength. The note in Figure 25 was utilized to specify the wheel material on the drawings. The original constraints of the project were to keep the wheel at about or below 75,000lb for the crane pick. The model shown below in Figure 22 is per the design, however, the holes used to lighten the wheel were omitted to reduce cost once the lifting plans were further developed and it became clear that an 88,000lb wheel could be lifted safely.



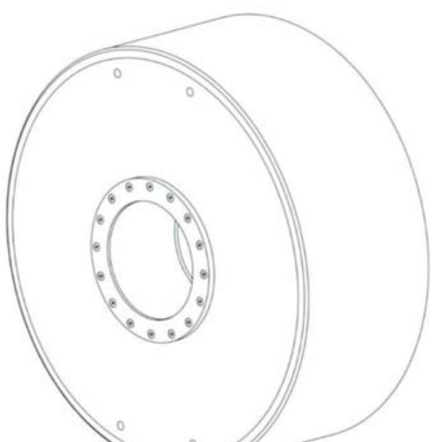
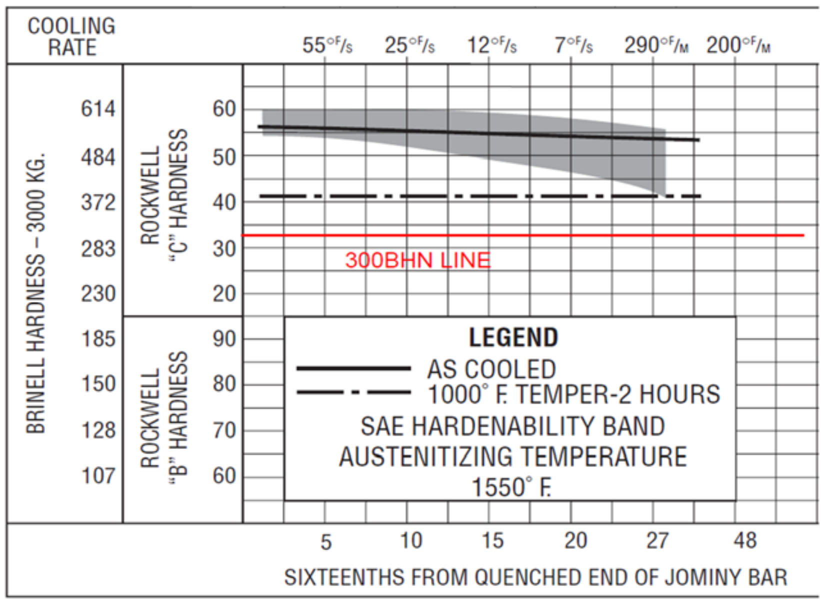


Figure 22 (above): Proposed Wheel Design
Figure 23: As Built Wheel Design



WHEEL SHALL BE ASTM A668 CL M MODIFIED AS SPECIFIED BELOW DUE TO THE FORGING EXCEEDING THE SIZE LIMITATIONS OF THE ASTM SPECIFICATION. CHARPY V NOTCH TESTS SHALL BE PERFORMED PER ASTM A788 S13 BETWEEN 70 TO 80°F AND REPORTED. ULTRASONIC EXAMS SHALL BE IN ACCORDANCE WITH ASTM A788 S20. TEST LOCATIONS SHALL BE AS PER SECTION 7.1.4.5 OF A668 WHERE T=1" EXCEPT THAT 3 LOCATIONS SHALL BE TESTED. THE FINISHED OUTSIDE DIAMETER OF THE WHEEL TO A DEPTH OF ½" SHALL BE AT A MINIMUM 300BHN, 75KSI YIELD, AND 100KSI ULTIMATE STRENGTH. THE REMAINDER OF THE WHEEL SECTION SHALL HAVE A MINIMUM 37.5 KSI YIELD AND 75 KSI ULTIMATE STRENGTH.

Figure 24 (above): Chart of Hardenability for AISI 4340 Steel
Figure 25: Specified Wheel Material Requirements

Rall Wheel Track Design Options

Similar to the wheel, a few different options were considered for the track design to obtain the best durability while minimizing cost. Castings have many of the same complicating factors as the wheels. The materials required to make the riding surface would have to be very high grade to withstand the stresses, and the casting itself would have to be very complex. To meet the strength requirements a forged riding surface was considered, however, the track needed to be thick to prevent curling under load. A thicker track required a thinner cast base to maintain the overall height of the assembly. The cast base was thinned by the track to the point where it would need to be cast in two pieces and joined with a key. The sharp geometry of a key is undesirable under high loads in a casting and it was determined that the keyway would likely crack.

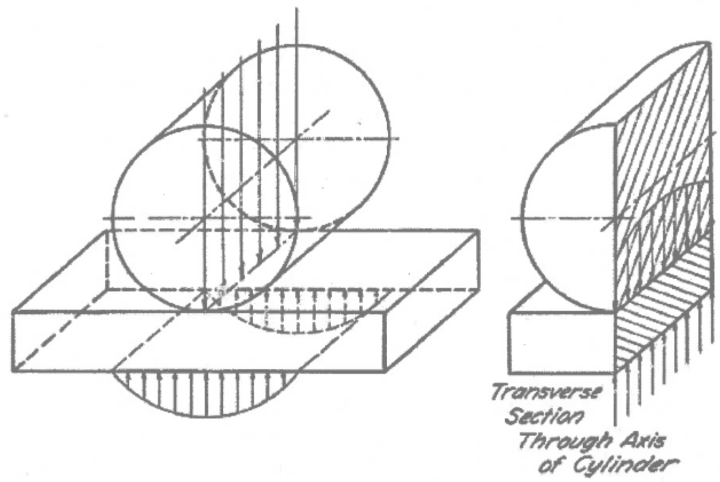


Figure 25: Stresses Tending to Cause Curling of Track Plates

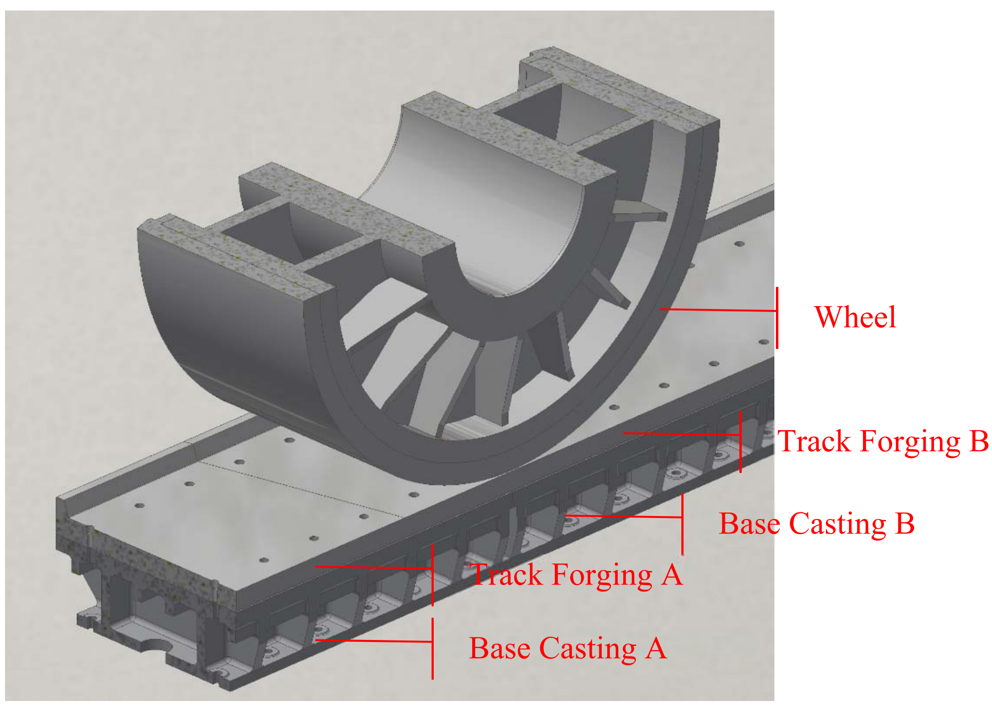


Figure 26: Cast Base with Forged Track Concept

A forged base was considered to replace the casting. A forged base could be made in one piece and although much more steel would be required, the cost for this steel would be low enough that the material savings of a casting does not have an advantage. The concept used a three piece track similar to the cast version with a forged steel track and counterbored bolts.

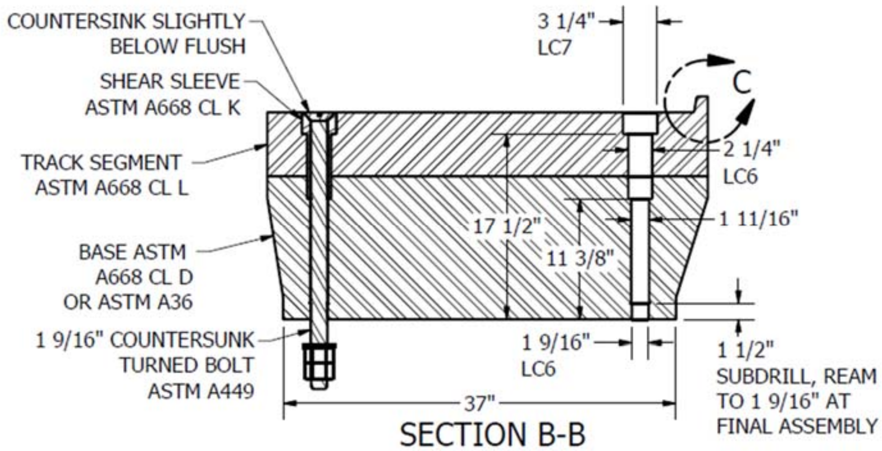


Figure 27: Cross section of the Forged Base with Forged Track Concept

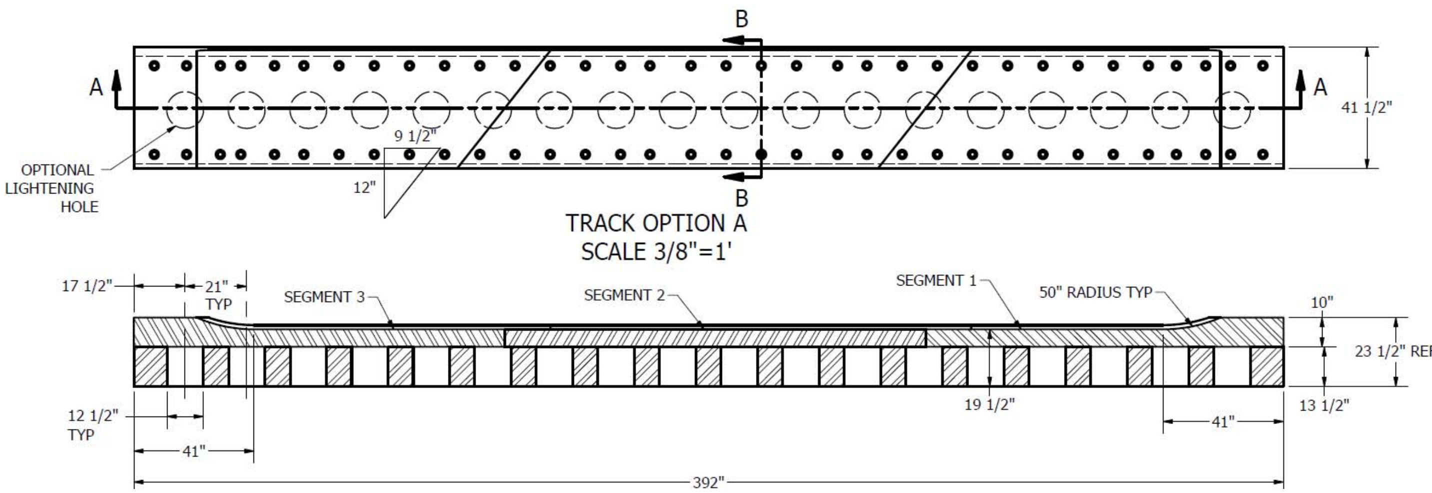


Figure 28: Forged Base with Forged Track Concept

Consideration was given to the fact that fewer track segments provides a better quality riding surface. It was additionally considered that base could be fabricated from rolled steel if it were thinner and that the base does not require the material properties of a forging. Lastly, it was determined that the shear connections between the track and base were too complex for the given coast guard outage windows permitted to replace the track. The shear sleeve is used to obtain a bearing connection between the track and the base, and the bolt was used as a turned bolt connection between the base and the track girder. It would be very difficult to achieve and maintain alignment during installation because of the 392" length of the track. To simplify the shear connection and track and base components a system which used a one piece forged track and a rolled steel base was considered and is was eventually built. The design uses the additional thickness gained by thinning the base for rolling to provide a one piece forged track with a flange that eliminates all fasteners on the riding surface. The bolts were designed to provide a turned bolt connection between the base and girder then fix the track to the base through 1/8" clearance holes through the top flange of the base. Horizonal shear was developed using fitted shear studs down the center of the track such that the base and track would behave as one piece. This allowed for the shear connection between the track and base to be made in the shop, and the turned bolt connection between the base and track girder to be reamed in the field without effecting the track and base connection.

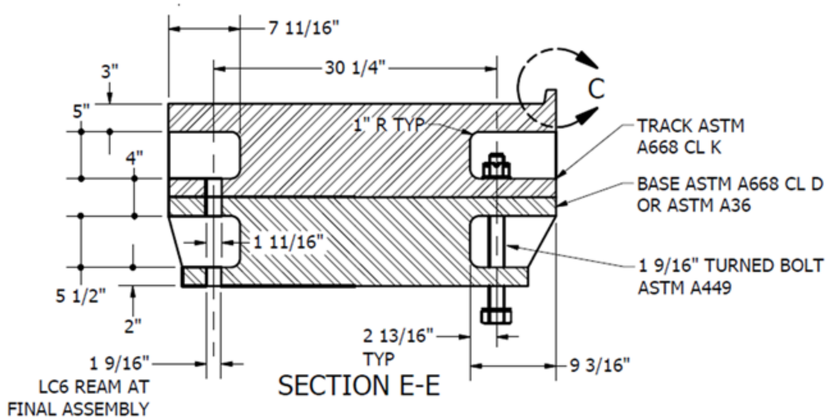


Figure 29: Cross section of the Rolled Base with Forged Track Option

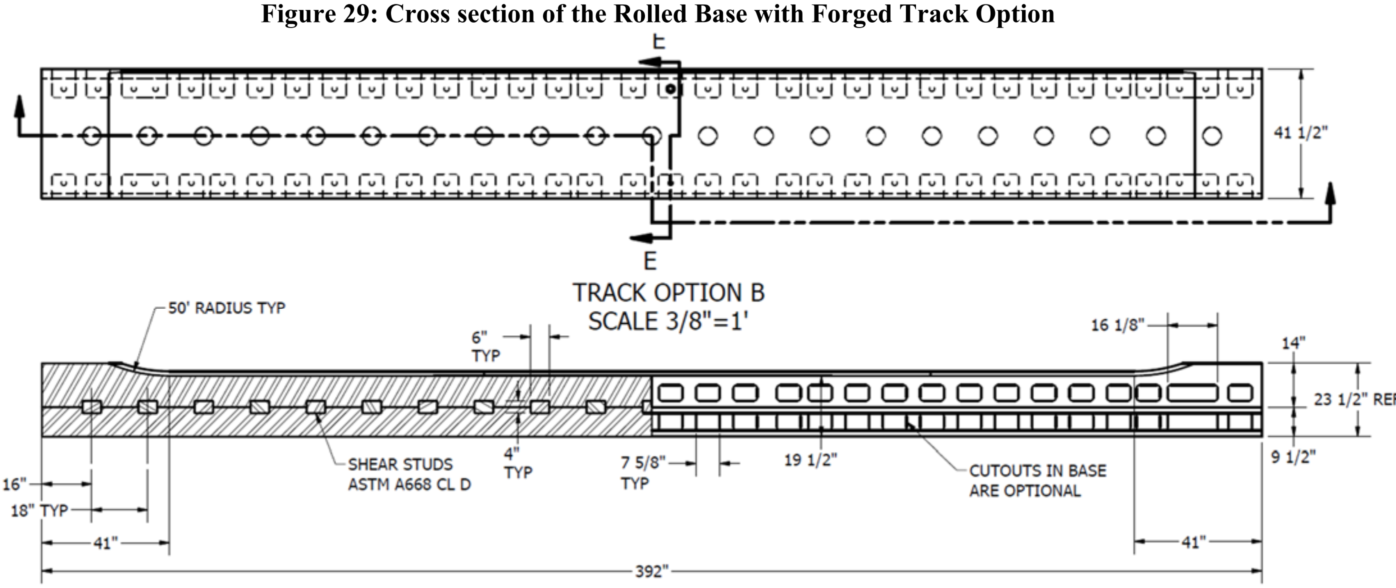


Figure 30: rolled base with Forged Track Concept Showing Shear Studs

The most serious challenge of this design is determining the magnitude of shear in the shear studs installed between the base and track. Because the track does not behave as a simple beam, the forces could not be directly determined by hand calculations effeciently. To determine the shear forces due to the relative deformation of the track vs the base a finite element model was used to determined the reaction of the shear studs given the wheel load positioned in 1” increments along the track. A snapshot of the track stresses is provided in Figure 31 to give a visual indication of how the elastic properties of the steel distributes the load into the studs. Below that in Figure 32 a plot of the shear forces output by the model when the bridge is near full open or closed. The force results were then superimposed with the shear forces induced by the deflection of the track girder assuming that the track does not act composite with the track girder. The worst case shear force per stud was determined to be 56,500 lbs.

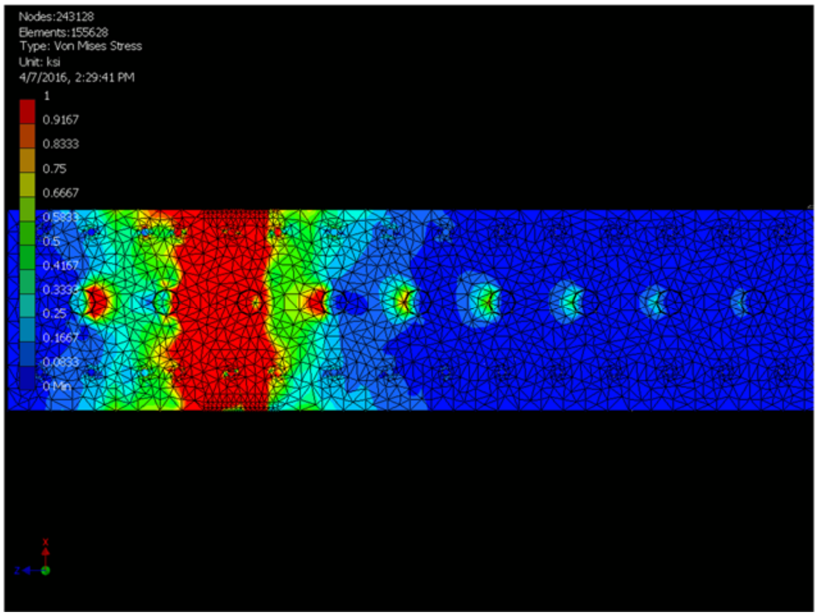


Figure 31: Stresses in Track Due to Distortion Under Load Being Restrained by Shear Studs

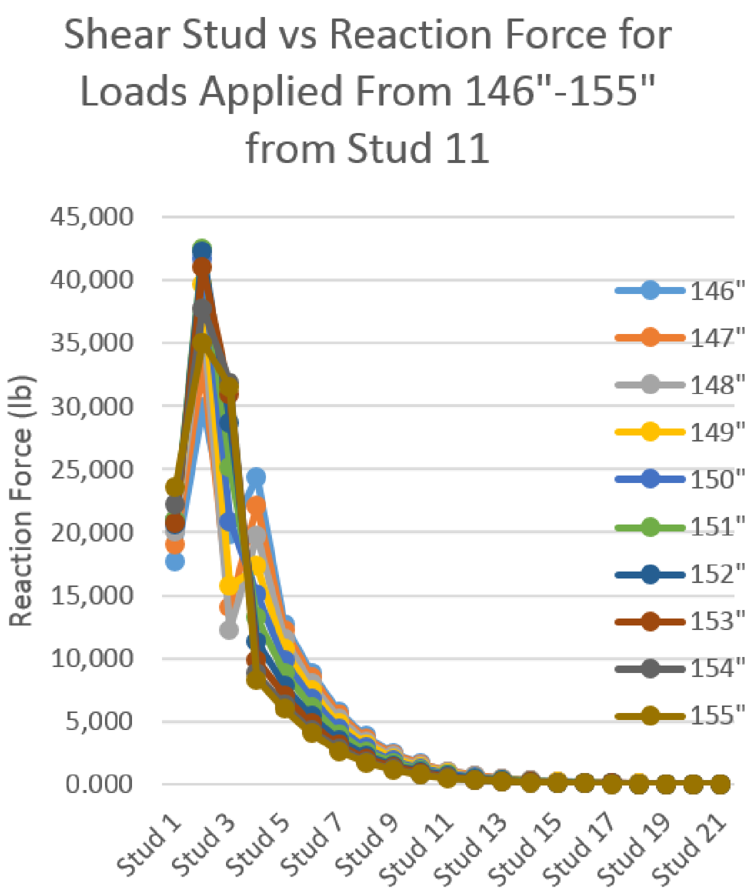


Figure 32: Shear Forces in Shear Studs Due to Distortion Stresses in Track

Fabrication and Installation

Fabrication

Included below are a few photos of the manufacture and installation of the Rall wheels. There were many challenges along the way, however, the team assembled to fabricate and install the parts worked extremely well with both the bridge owner and designers enabling quick and effective resolution of any issues encountered.

Photo 33: Wheel Forging

During the forging process a large reduction in cylinder height was used to consolidate the material at the center of these large wheel forgings to prevent discontinuities. This caused scale to be folded into the surface of the forgings which propagated into cracks when the wheels were quenched. To mitigate the scale inclusions slightly shorter cylinders were cast and the outer surface of the wheels were machined off prior to quenching. For reference, some sample material properties obtained after tempering are included below in Figure 35. These properties were tested at a distance 1" from the finished surface of the wheel and are included in because this type of information is not readily available for forgings this large.

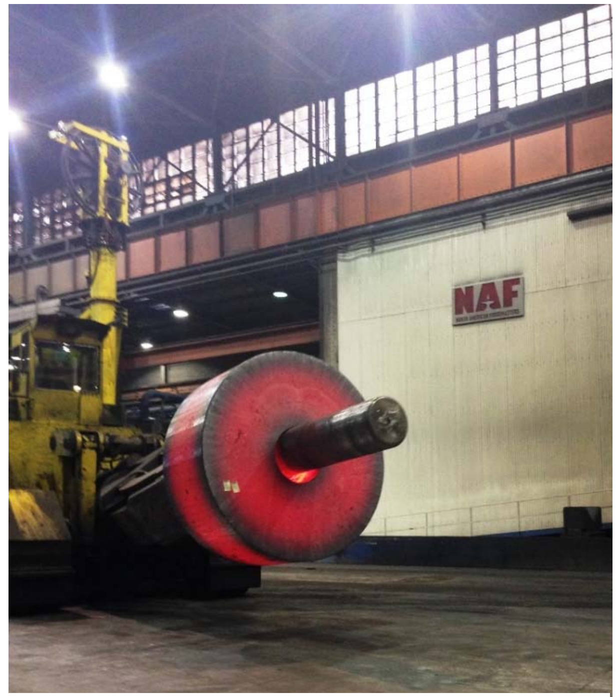


Photo 34: Wheel Forging

Surface Hardness (BHN)	UTS (ksi) – 3 locations	0.2% Offset Yield (ksi) – 3 locations
332, 327, 331, 334	184.7, 187.1, 187.5	172.4, 174.6, 174.9

% El (info only) 3 locations	% RA (info only) 3 locations	Charpy V-notch @ RT (ft-lbs) (info only)
16.0, 15.6, 16.4	51.4, 55.2, 53.0	31, 31, 31, 34, 34, 32, 35, 33, 33

Figure 35: Sample Wheel Material Properties at 1" from Riding Surface


Photo 36: Measuring the Bore of the Wheel

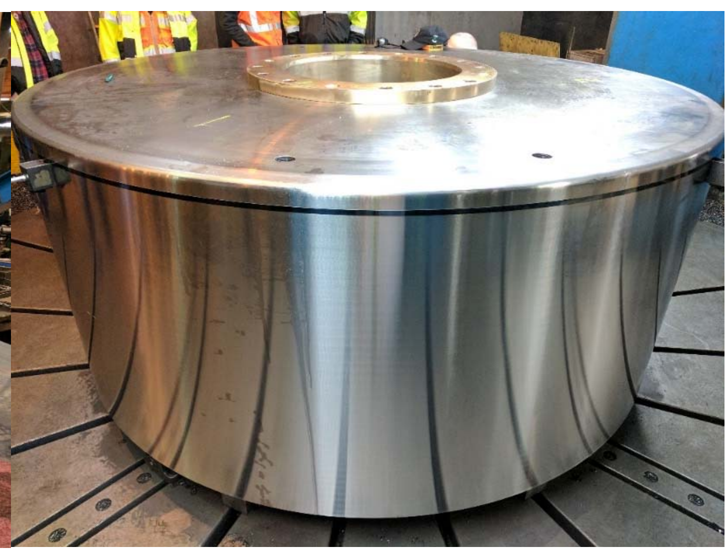


Photo 37: Measuring the Outside Diameter of the Wheel

Photo 38: Rough Machined Bases

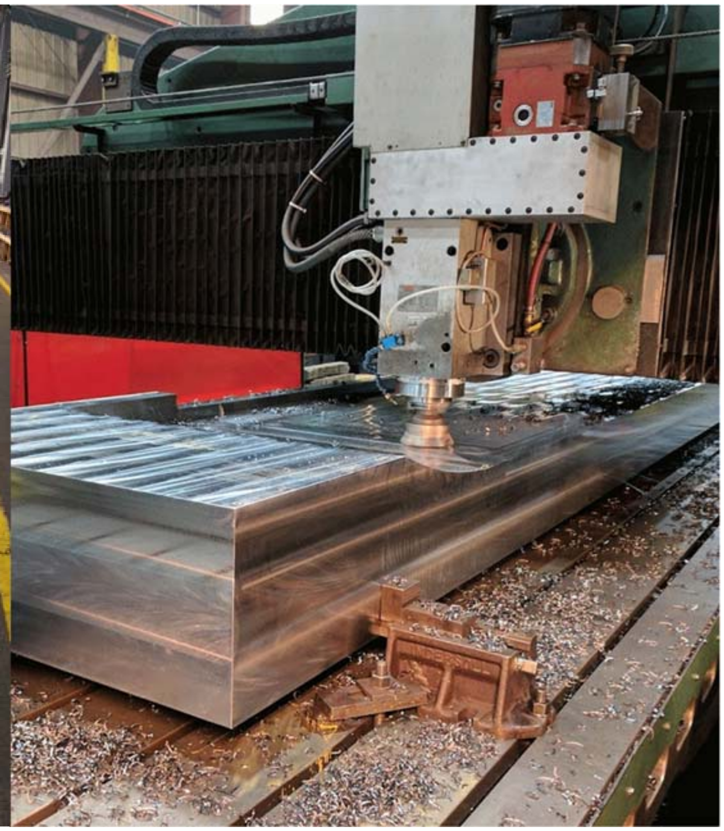


Photo 39: Rough Machining of the Tracks

One alteration of note from design for fabrication was that instead of the track and base being drilled together then each being bored separately off the pilot hole locations, the shear stud holes were bored full size while assembled. This change eliminated the step of disassembling the track, relocating the holes, and eliminated differential movement between track and base as material was removed which guaranteed the shear stud holes would be aligned. The shear studs were already fabricated when this decision was made and because time was a constraint, spacers made from rolled bar stock were added under the shear studs to position them properly in the shear plane.

Photo 40: Spacers and Shear Studs

Photo 41: Boring the Shear Stud Holes with the Tracks Assembled

Installation

Removal and installation of the tracks and wheels were not without challenge. To remove the tracks and wheels the bridge must first be lifted off the tracks to unload the trunnions for removal. This was accomplished by installing posts through the deck of the bridge (blocking one of two lanes of traffic in each direction) to the foundation and lifting the superstructure of the bridge next to the Rall wheels using two 880 ton jacks (Figure 42). More information on this system can be found at: **ftp://ftp.odot.state.or.us/Bridge/16_BR_DSGN_CONF_PDF/Session_4/4B_Broadway_Br_Rall_Wheel_Rplcmnt_Shoring_G_Rayor_K_Alldritt.pdf**

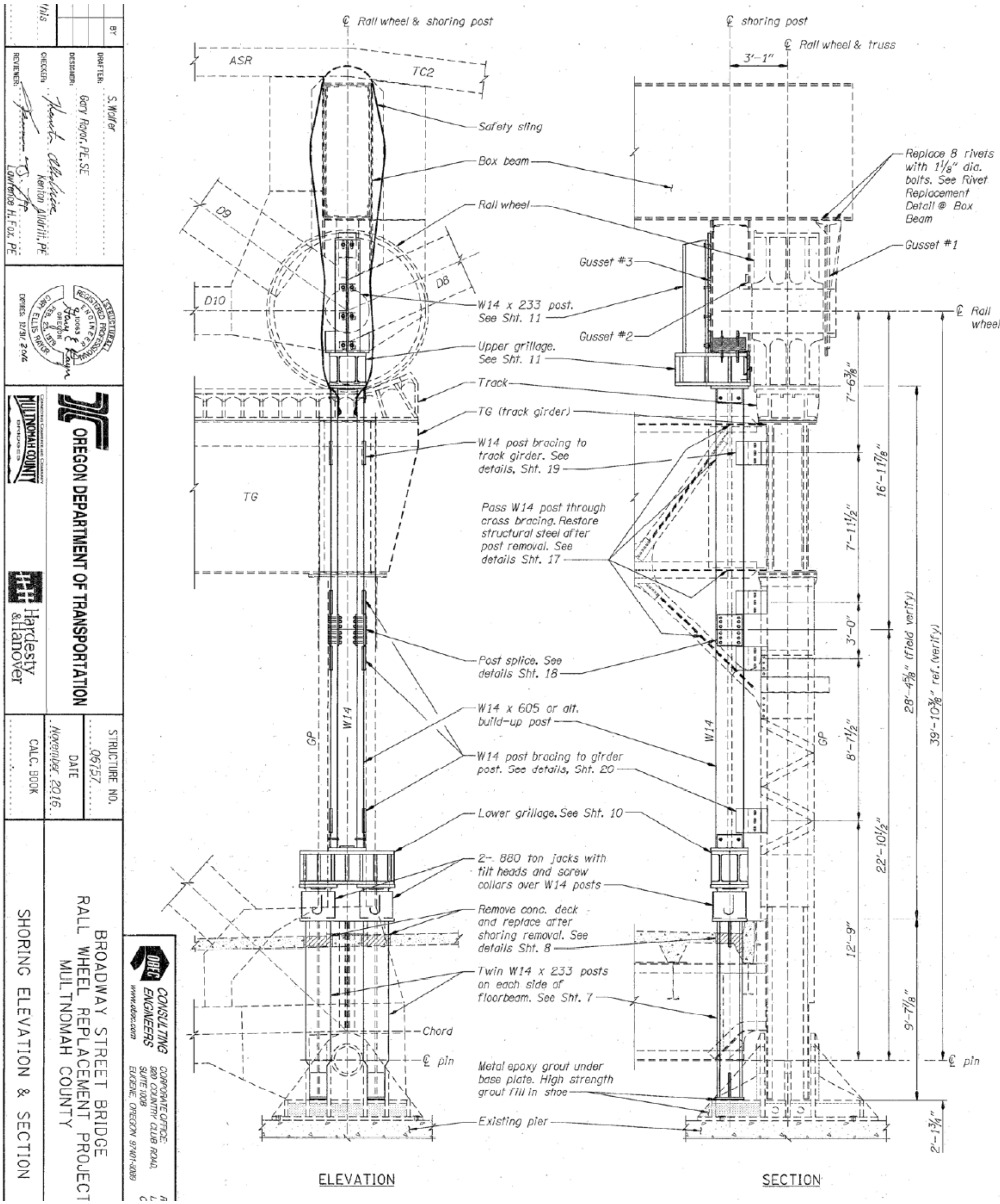


Figure 42: Jacking System Overview

Several of the trunnions were stuck inside the wheel hubs requiring the use of heat and 300,000lb of force to remove. Additionally, the truss located above the track locations meant the crane booms would have to be placed directly under the truss and compact lifting arrangements were used to place the tracks and wheels.

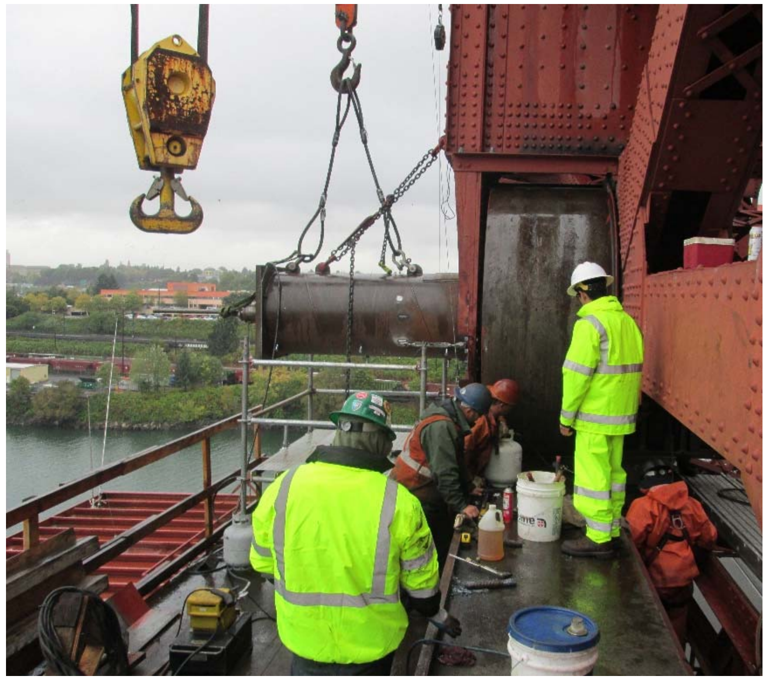


Photo 43: Pulling the Trunnion on the NW Corner

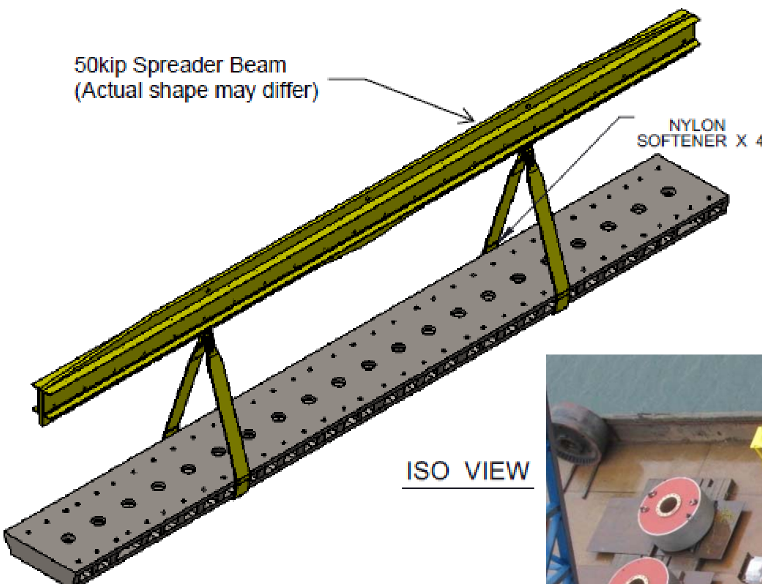


Figure 44: Lifting Arrangement for the Track/Base

Photo 45: Various Parts on a Barge

Once removed from the bridge, the existing trunnions were brought to the machine shop to be measured so the new trunnion's retaining bolt holes could be matched to it. Using the existing trunnion as a template guaranteed the hole locations would be aligned if the original holes were not template drilled. This also ensured the distance between hubs would be kept the same regardless of the hubs tendency to move around once free.

Photo 46: Inspecting the Old Trunnion's Retaining Bolt Locations

Photo 47: The New Trunnion Setup for Locating Retaining Bolt Holes

Without the tracks and wheels obstructing access, the condition of the hubs and track girder surfaces were inspected. These parts were found to be in good condition once cleaned and displayed their original machining marks. The bridge was painted Golden Gate Red in 1963. The original black paint which was inaccessible during prior painting projects with the wheel in place shows in this photo before its removal from the bridge. Note that the bridge is supported on the jacking sysem inboard of the hub in this photo.

Photo 48: The SW Corner Without its Track and Wheel

Photo 49: Chatter Marks from The Original Hub Machining

Photo 50: Original Planing Marks on SE Track Girder Flange

Photo 51: The New SE Track and Wheel Installed

Field Alignment and Challenges

Assuring everything is aligned is a serious challenge on a bridge like this. Machined parts require tolerances on the order of 0.001" and the structure itself is at best accurate to $^{1}/_{16}$". Additionally, live loads and the rolling deadload of the bridge deflect of the structure, as does uneven heat from the sun. Surveying was conducted early in the mornings when possible to minimize the temperature effect, however, the first two simply cannot be eliminated. Further complicating efforts, before the tracks were removed, their distorted surfaces were the only feasible reference point that could be measured from and the shims had to be premanufactured. Shims were calculated based on averaged measurements from the old track for the initial installation. Measurements also showed the trunnions were not aligned with each other or the tracks which had caused the bridge to track off its centerline in the past. The NW corner was brazed and field line bored to correct some of the offset of the hub location.

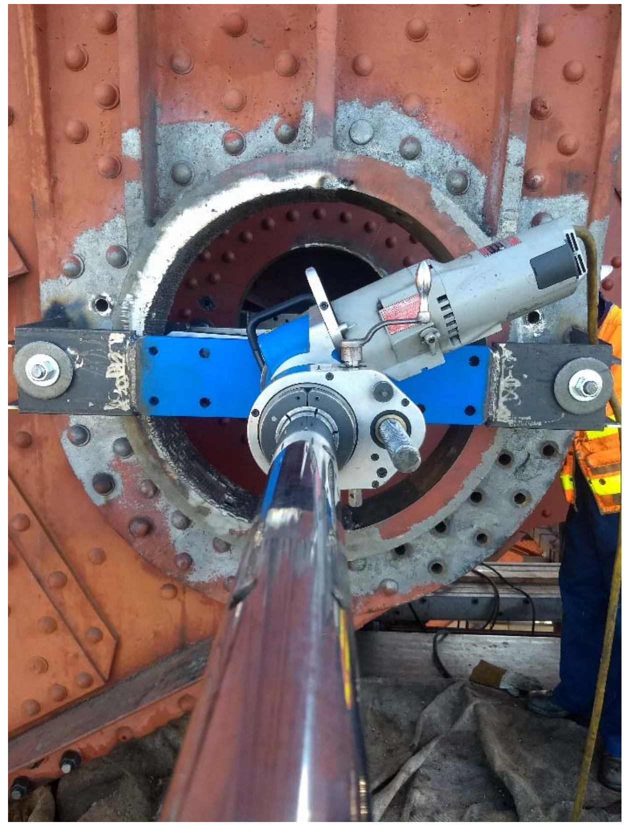


Photo 52: Boring the NW Trunnion Hub

Photo 53: Brazing the NW Trunnion Hub

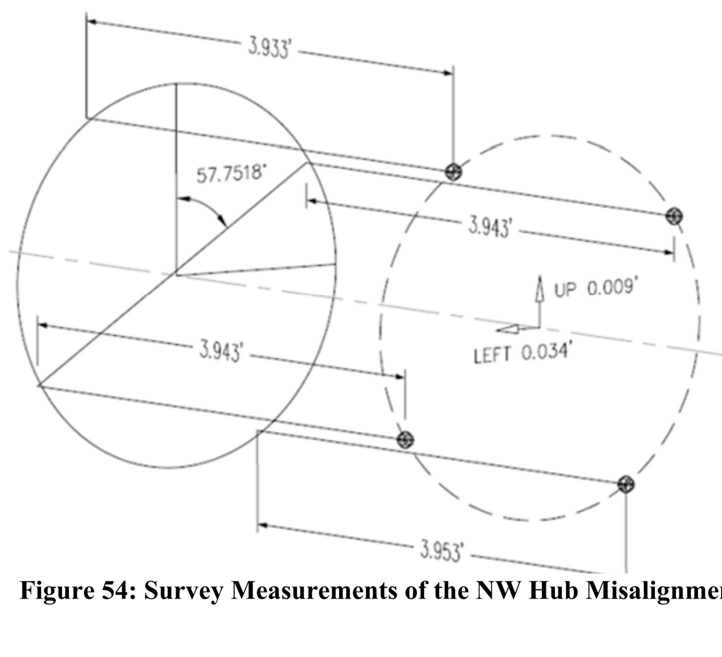


Figure 54: Survey Measurements of the NW Hub Misalignment

The original plans for the bridge required that tracks be set on a $^{3}/_{8}$” slope to account for the $^{3}/_{4}$" deflection of the support structure for the track girder as the bridge weight shifted during operation. Field measurements showed that the West leaf was set at 0.369”/0.500” and the East leaf was set at 0.653”/0.710”. Correcting the East leaf taper was found to require a thin tapered shim, which would be difficult to manufacture. After more measurements it was found that the East track girder deflected $^{3}/_{4}$" as per the plans but the West leaf deflected 1” justifying the larger slope. The West tracks were set at a 0.369” slope and the East tracks at a 0.468” slope which helped reduce the challenges of manufacturing shims.

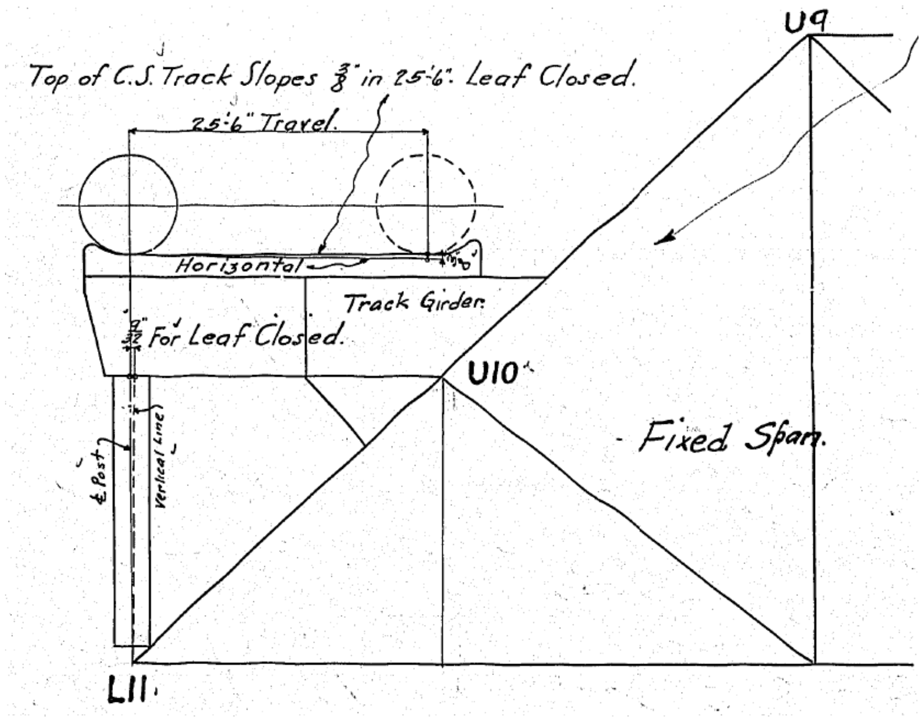


Figure 55: Track Camber Diagram

To verify alignment between tracks and wheels after installation the strains in the double web track girders were measured. Test shims were used under the wheel to determine how much load a given shim would shift to the opposing web and tapered shims were fabricated to keep the loading as even as possible on the track girders. This method was used to correct transverse misalignment to get the wheel bearing over its 40” width. Vertical misalignment was not corrected beyond the original measurements due to limitations in the accuracy of measurements and the flexibility of the structure.

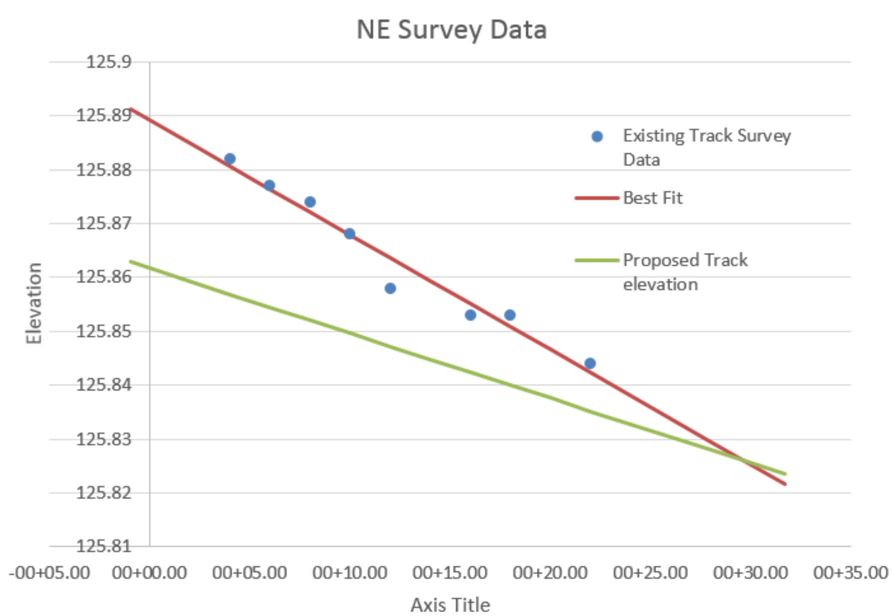


Figure 56: Plot of NE Track Slope

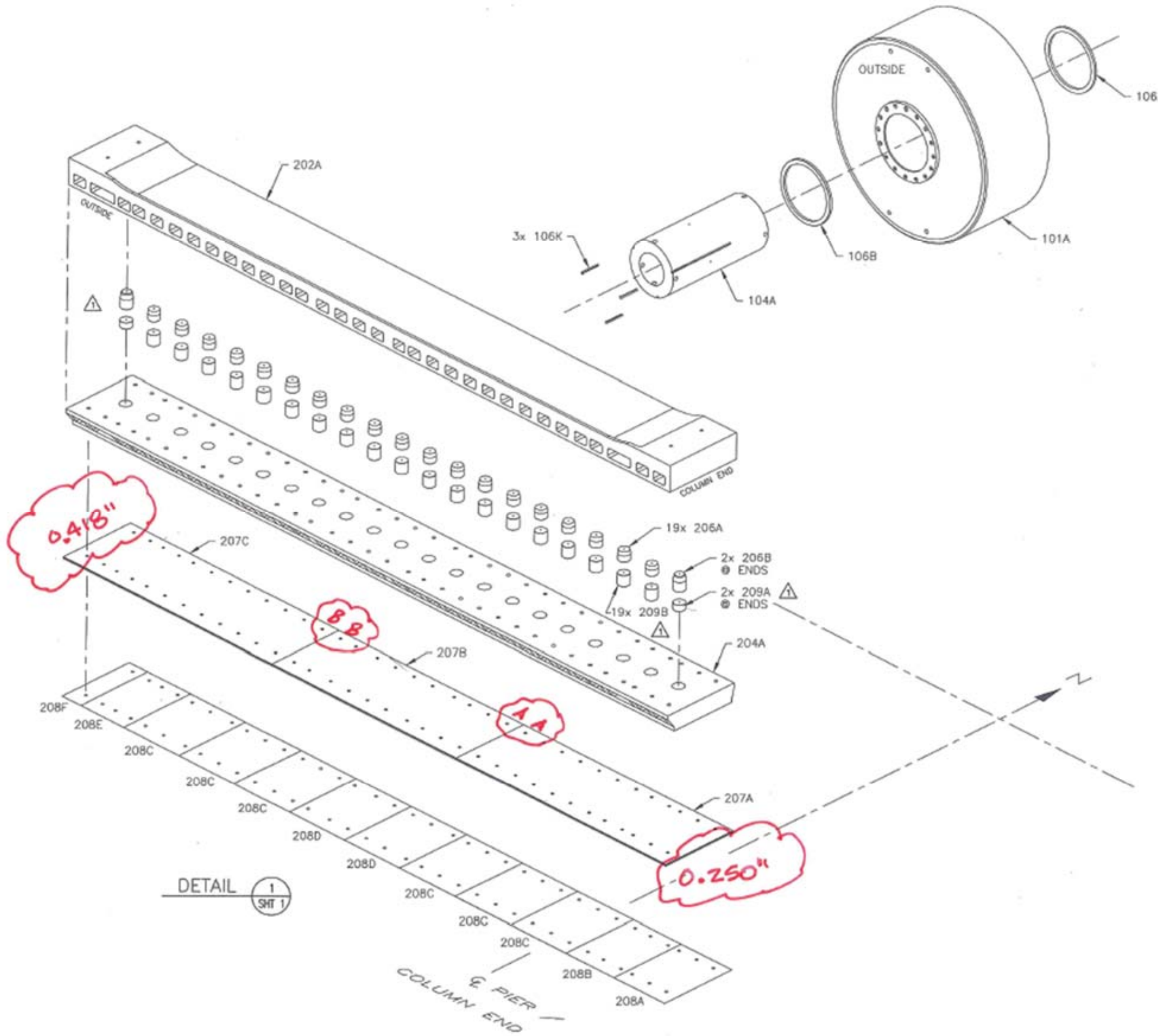


Figure 57: Typical Assembly Drawing Showing Tapered Shims

Given the flexibility of the Rall wheel carriers, the clearances on the thrust faces, and the tendency of the bridge to favor one side, the now tighter clearance between the new track and the truss was used up and the track had to be re-machined to clip off ½" of the front corner where a splice plate was rubbing during closing. Based on measurements, the pin locations of the control struts varied considerably, possibly contributing to the tendency of the bridge to favor one side. The control strut lengths were differentially shimmed to help the bridge roll true.

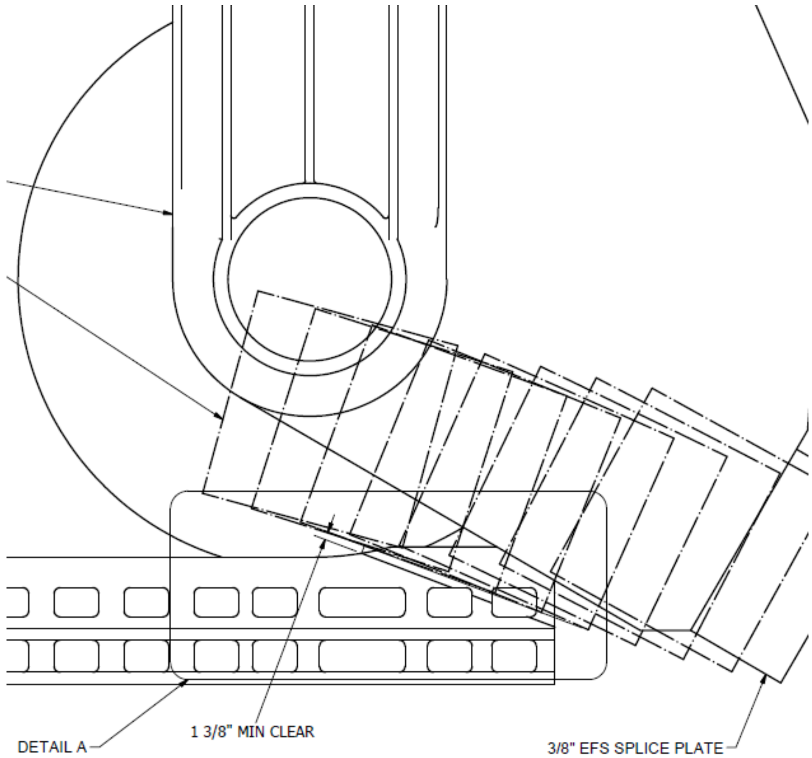


Figure 58: Diagram of Travel of the Interfering Splice Plate

Conclusion

Many challenges were encountered during the replacement of this wheel. Careful planning and cooperation was required to come up with solutions which would meet the requirements for strength, space, fabricability, construction outages, and installation techniques available for this project. Due to constraints for bridge outages, and the amount of field measuring and fitting this project required incredible teamwork and dedication by all those involved to complete successfully. Close teamwork between Multnomah County (owner), Hamilton Construction Company (Construction Manager/General Contractor), Vigor (Machinery Fabricator), OBEC Consulting Engineers (Jacking System Designer), Schneider Consulting, LLC (Resident Engineer), and Hardesty & Hanover LLC was the key ingredient to the success of this project.

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