

**HEAVY MOVABLE STRUCTURES, INC.
FOURTEENTH BIENNIAL SYMPOSIUM**

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**Mystic Bascule Bridge Rehabilitation –
Balance Truss Re-Alignment**

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INTRODUCTION

ConnDOT Bridge No. 00362 in Mystic, Connecticut dates to 1922 and is one of the few remaining Brown bascule bridges in this country. Although similar in appearance to a Strauss Heel Trunnion, the distinguishing feature of the Brown bascule is a fifth (balance) link that enables the bridge to achieve a greater opening angle in a smaller window than other bascules. It is this feature that has made the bridge indispensable to the bustling community of downtown Mystic through which it carries 2 lanes of U.S. 1 over the Mystic River. With approximately 2000 bridge openings for marine traffic each year, and with 90% of the openings occurring in prime tourist season between the months of May and October, the bridge serves as a focal point for the area. Recognizable by its balance truss tower and exposed operating and support linkage, the bridge celebrates the age of industry and contributes to the historic and artistic flair of the community.



The southern Connecticut coastline is apparently a difficult place to build a bridge that will stay in one place. Bridges across several of the bays and rivers that empty into Long Island Sound have experienced unusual foundation behavior. The crossing of the Mystic River between Groton and Stonington in the town of Mystic has been no exception. A bridge built in 1854 was replaced in 1866. The bridge that replaced it in 1904 had such foundation issues that it too was replaced in 1922. This replacement exhibited evidence of foundation movement as early as 1929. There was a significant scour event in the early 1980's which is believed to have precipitated substantial differential settlement of the pier 1 which supports the counterweight tower over a short period of time. Despite the fact that the resulting misalignment led to failures within the operating machinery in 1985 and accelerated wear of the balance truss bearings, the bascule span has remained serviceable. Due to the landmark status of the bridge and its significance in the community, replacement of the bridge is not an option.

This paper shall discuss the collaboration between the bridge Owner, Engineer and Contractor during the implementation of the phased repairs to restore the original counterweight truss alignment which was altered as a result of differential pier settlement. Salient aspects of this work include

- The novel plan developed by the Contractor for temporarily supporting the counterweights which was needed for restoring the original alignment of the balance truss and for replacing the existing balance link.
- The existing conditions which were discovered during the disassembly and re-alignment process and had to be corrected prior to re-assembly.
- Revisiting the prohibition on using liquid nitrogen as part of the process for shrink-fitting large steel pins and the eventual successful use of this cooling media to perform the work.

Background

The Brown bascule at Mystic comprises a single leaf 84'-5" in length from heel trunnion to toe. The leaf rotates a full 90 degrees to the fully open position where it provides a clear channel of 75 ft. When closed, the bridge provides a 33 ft. wide roadway and a 5 ft. sidewalk on either side. The leaf is connected to overhead concrete counterweights situated on top of A-frame type support towers located to the approach side of the heel trunnions. Each bascule leaf girder is connected to its independent counterweight via a balance link. The link, which is comprised of multiple sections allowing several points of rotation, was central to Brown's stated intent to "avoid the limitations of parallelism entirely"¹ and to balance the bridge through all position of rotation. While a mathematically accurate balance of a bridge requires a large number of points of rotation, Brown proposed that three or even two points of rotation may produce a balance sufficiently accurate for all practical purposes.²



The actual balance link utilized at Mystic is limited to three sections: the eye bar, the short link and the butt link. The short link, which is rigidly secured to the eye bar through a bolted connection, was provided to facilitate construction and is not a truly independent link. Therefore, the assembled balance link affords two points of rotation. During operation, the balance link pivots about its connection to the girder for the first 38 degrees of leaf rotation at which point the butt link contacts a hard stop on the movable leaf. This contact prevents further rotation of the butt link and forces the balance link to pivot about its connection to the butt link until the leaf is fully open. The net result is that as the span rotates through 90° of motion, the rotation of the counterweight is limited to 69°. Further, the length of

the balance link is chosen to provide an unbalancing in the fully open position to prevent opening the bridge too far and to serve as an automatic buffer. While this configuration did not provide for an exact balance during operation, Hovey reports that the maximum error was limited to approximately only one-half of one per cent³.

The means of operating the bridge is by a segmental bull-gear connected via operating strut to the bascule girder. The linkage was so arranged to provide the smallest angle between segmental gear and operating strut in the fully lowered and fully open position so that the members act as a toggle. This arrangement was chosen to provide the following stated benefits: to generate the greatest leverage in the lowered position to provide maximum power in starting the span from its seat, to form an effective lock to hold down the movable span on its seat when lowered, and to provide the greatest leverage in the fully open position to hold the leaf against the wind pressure. Further, the incorporation of worm gearing into the operating machinery provided the stated benefit of allowing the drive machinery to be placed below the bridge floor and thereby eliminate the need for machinery houses.⁴



Although not central to this paper, it is pertinent to note that Brown's success at Mystic was short lived. Strauss was granted patent 1,583,705 in 1926 which eliminated the perceived deficiencies highlighted by Brown in his earlier heel trunnion design. Strauss's design subsequently went on to widespread success

in comparison to the Brown design, possibly due to a superior and more robust design. However, the impact of successful marketing cannot be discounted in the proliferation of particular bridge types.

SCOPE OF REPAIRS

Stafford Bandlow Engineering contracted with the State of Connecticut in 2001 to prepare mechanical rehabilitation plans of ConnDOT Bridge No. 00362 in Mystic, Connecticut as part of a team with Lichtenstein Consulting Engineers, Inc. (now Transystems Consulting). A major constraint for the project was the need to maintain two way vehicular and pedestrian traffic throughout the course of all phases of the construction work and to limit marine closures to a very short window between December and April. Following the conclusion of a scoping study, the total scope of work to be performed over three winter construction seasons was established as follows:

- Season 1: Structural repairs and complete painting of the structure.
- Season 2: Correcting the misalignment of the balance truss which resulted from pier settlement and replacement of the balance links.
- Season 3: Replacement of the control house and the mechanical and electrical span operating machinery.

A more detailed description of the scope of the Season 2 work which is the subject of this paper is as follows:

Jacking of Counterweights

The counterweights must be temporarily supported to unload the balance truss for the restoration of the truss/trunnion alignment and the replacement of the balance links. As there is no provision to support the counterweights as part of the original design, the Plans indicated that temporary piles would need to be driven to provide a foundation for a jacking tower to support the counterweights.

Restoration of Truss/Trunnion Alignment

The balance truss must be moved in the vertical, longitudinal and transverse directions with the goal of putting the two counterweight trunnions, which are mounted in the truss, in line with each other and at the proper location relative to the heel trunnion. Precise movement of the truss will be required to ensure that the truss is located within the specified tolerances.

Replacement of Counterweight Trunnion Bearing Assemblies

As the balance truss must be jacked for the restoration of the trunnion alignment, the counterweight trunnion bearings will be replaced which would not have been otherwise possible or practical. A connection was designed between the new trunnion bearings and the existing trunnion tower to accommodate the change in location of the bearing atop the tower (the location of the north counterweight trunnion is displaced over 1" from its original location and the south counterweight trunnion is displaced over 4" from its original location)

Replacement of Balance Link Assemblies

As there was severe wear of the balance link bearings resultant from the misalignment and fatigue concerns due to the higher than normal loads the balance link components were replaced in their entirety.

CONSTRUCTION

In 2009 the State of Connecticut advertised for bids to rehabilitate the Mystic Connecticut Bridge, including adjusting the movable structure to compensate for the foundation movements which occurred during years past. Much like taking your back to a chiropractor or your car to have the frame straightened after it has been in a collision, re-aligning the mechanical structure of a movable bridge is a real technical challenge. The tolerances that are desired to be achieved are similar to those of the transmission in your car; only this transmission is the size of a good sized house.

Something that the Connecticut Department of Transportation did, which should be encouraged of all bridge agencies developing plans to be bid competitively, was to include in the contract documents a detailed method for supporting the counterweights and ultimately moving the bearings into their orthogonally correct locations. Providing a baseline design for all bidders to use minimizes the chances that the bidder who leaves the most out or has the least experience will get the job. The bid documents also permitted alternate designs to be utilized, but only if they provided a similar level of assurance that the work could be accomplished safely and to the accuracy desired.

An observant person once said: "The best idea comes last". Sometimes this is too late to be employed, but unusually, this project had a long gestation period for ideas on how to handle the support and movement of the counterweights and upperworks. The project was scheduled to be performed over three seasons: winter 2010-11, winter 2011-12 and winter 2012-13. (Writing a paper on a project that isn't complete does seem like tempting fate, but the major structural work that is the topic of this paper is complete and to all appearances has been successful.) This gave the contractor a year to consider (and discard) several concepts of how to accomplish the work.

During the development of the contractor's bid a lot of concern was caused by one feature of the method shown on the bid documents. This was the installation of new piles to be driven adjacent to existing structures abutting the project site. At least one of these structures exhibits past pile settlement behavior and new pipe piles, driven to rock, were very likely to cause additional movement of that structure as well as exacerbate the existing condition of the bridge foundation itself. This was certainly on the mind of ConnDot as the special provisions included the requirement for continuous monitoring of the adjacent structures for foundation movements. Such movements often generate monetary damages and can cause projects to come to a standstill while resolution to the problem is found.

A second concern was that the relatively tall pile structures might not be rigid enough to allow the miniscule movements of the counterweight structure to be controlled with a predictable level of accuracy. Moving 400 tons of steel and concrete predictably requires a rigid thing to push against and a rigid thing to stop against. Pushing with a spring behind you can cause the object being moved to overshoot its desired location when the static friction is overcome and you can't stop pushing soon enough.

Given these concerns, an alternative method for providing the needed support structure was seen as a needed way to manage the overall risk of the project. The first question to ask in a situation like this is: "How did the original builders construct this bridge?" A careful examination of the original drawings offered an exciting possibility. In a corner of one drawing is a statement that each of the approach girders below the counterweights were to be designed for a counterweight load of 406 kips "*...to carry this load during erection and future adjustments.*" Wow, those original designers knew what they were doing. Using just the existing structure would certainly eliminate a lot of risk, not to mention a lot of cost. Prudent thinking dictated that if something appears to be too good to be true, then it probably is. An analysis of the existing girders showed that even with no live load the girders would be overstressed, at

least over what we thought the allowable stresses might be. However, this gave us the idea that utilizing the existing foundations by adding supplemental supports over the girders was a distinct possibility.

We initially conceived that pairs of trusses could be installed below the counterweights that would mimic the supports shown on the contract drawings, albeit oriented at 90 degrees to that configuration. Supporting the bascule counterweights and the balancing trusses requires that most of the load can be caught immediately at the counterweights, but that a small portion of the loads, less than 5%, would need to be supported forward of the counterweights. The design that came with the contract plans envisioned a separate set of piles and jacking beams for this need. We decided that the trusses below the counterweights could be extended and carry these loads as well. This gave us an approach that would achieve a level of risk that was acceptable, the details could come later.

It's funny how a year can go by so quickly, and then one day you realize by working backward from when something will be used, that you have waited almost too long to get started. The first season's work was well underway and thoughts of that second season's work started to become a reality. In dusting off the original truss concept it became apparent that a plate girder would be a more efficient solution than a truss, especially in terms of design and fabrication time, which was becoming a concern. The plate girders offered a seemingly efficient solution for a while. After designing the plate girders and sending them off to our fabrication group for their consideration, we were dismayed to learn that the time to procure and fabricate them was going to be longer than the time we had left. It added to the growing concern as to what their value would be after this project was done. They had begun to look like they were destined to become large pieces of scrap, a terrible thing to consider for us *green* construction structures engineers.

Here again, thinking to how an earlier engineer would approach this problem suggested a nice solution. Stanley Grossman came up with the idea over twenty-five years ago that it was often cheaper and easier to make a six foot deep girder by bolting two 36 inch deep rolled beams together flange-to-flange than it was to weld one together from steel plates. Although we had never actually seen anyone else do this or even seen one done by Stan Grossman, we decided that this was a structural possibility. There were several benefits to this approach: it used materials we could get quickly, fabrication was pretty straightforward, erection was eased by reducing the piece weights to be handled and best of all when taken apart our four 70 foot "plate girders" went back to being eight W36 beams whose value would be much greater (*and greener*) than the original plate girders would have been.

We were satisfied that this approach would give us a rugged, rigid support from which to manipulate the counterweights and the balancing truss. Additionally, it eliminated the risk of settling the neighbors' buildings. Now all we had to do was build it, put it in place, jack the counterweights up and nudge things into their historically correct position.

A safe and efficient erection begins with a thorough plan. Consideration of what rigging is available and how the pieces can be configured assures that the erection proceeds smoothly and without any oops. The installation of the girder pairs required extended traffic closures and was therefore accomplished at night. The transverse support frame and the counterweight saddles required shorter duration road closures and were able to be installed during the day shift. The installation of the jacks, shim plates, and containment blocking followed accordingly.



Somehow the counterweights seemed to have grown larger, the closer the falsework came to them. As we approached the day to start jacking the counterweights they seemed to loom over us menacingly. We hoped we had estimated their center of gravity correctly and that it wasn't behind the supports which would mean the counterweights and balance truss would flip over backwards when we cut the balance links.



The day came when we were ready to start our jacking operations. The goal was to re-establish the centerline between the counterweight trunnions to be parallel and square to the centerline between the leaf trunnions. This meant rotating the entire counterweight-balance truss assembly about the south trunnion 0.3 degrees or 2.36 inches east at the north trunnion. The north trunnion needed to be lifted 3.13 inches up and the south trunnion 0.97 inches up. Finally, the entire upperworks assembly needed to be moved 1.77 inches south. We initially thought that leaving the counterweight links attached between the

leaf and the balance truss would help us align things. As we lifted the counterweights to start taking their load onto the support falsework, we found that the upperworks truss rotated about the trunnions and the links were bottoming out on at the leaf and actually pushing back against us. We lifted the upperworks assembly at the forward falsework support points and found we had to juggle our jacking to keep the jack loads balanced. Once we had observed that we had lifted all load off the trunnion bearings we removed the bolts holding the bearings to their supports. Next came the wedges that had held the upperworks longitudinally. Time to try some moving:



With the balance links still attached, thinking that this would help us square up the upperworks with the leaf, we began jacking east at the north counterweight to rotate the upperworks about the south trunnion bearing. The south trunnion bearing still had one 2 inch bolt left in place to act as a pin about which to pivot the upperworks. Simultaneously, we began jacking south at the two forward falsework support points to further encourage the upperworks to rotate as desired. Initially it seemed like things would work. We moved the north counterweight about 1/2 inch east easily, but then found that moving became difficult fast. The pushing at the forward locations was likewise not showing any success and when we released the pressure on the jacks found that the upperworks followed us back to all but that first half inch of movement. Regrettably, the balance links had to go. In the back of my mind I had counted on the balance links as a backup stability load path: the upperworks couldn't go very far as long as they were still attached. Without them, the stability of our 500 tons of counterweights and balance truss depended exclusively on the transverse stiffness of our falsework, which as was noted above was looking much smaller in reality than it did on paper. More importantly, when we went to start pushing the upperworks

around again there was a possibility that we could slide it right off the falsework supports if we weren't careful. The composition of the blocking which held everything in place and which often is provided on a catch-as-catch-can basis suddenly became foremost in our thinking. After some focused attention was made, what had been an assortment of this-and-that was transformed into a consistent pattern at all locations. The upperworks would now have to leap up into the air to get free, which we felt was an unlikely possibility.

With the counterweights and upperworks securely blocked in position, we now began the fateful step of removing the counterweight link bars. On January 31, 2012 the two sets of link bars were cut and removed from the upperworks. We closely monitored the upperworks with a total station while the links were cut. The south side truss moved about 1/8 inch longitudinally and less than 1/16 inch transversely and vertically. The north side truss moved less than 1/16 inch in all three axes: our blocking was doing its job.



We now could move the counterweights and the upperworks as we wanted. All the vertical support points had lubricated Teflon and stainless steel sliding surfaces. By carefully loosening our blocking, and jacking horizontally at specific locations, we could adjust the counterweights and upperworks precisely, at least by structural standards. After two rounds of precision jacking efforts on separate days two weeks apart, we had the centers of the counterweight trunnions, our primary focus, close to or within 1/16 inch of where we had wanted them.

That was the good news. The bad news was that while both the centers of the north trunnion pin and the south trunnion pin were in the right place, the bores for the ends of the north side trunnion pin varied by 3/16 inch longitudinally and the bores for the ends of the south side trunnion pin varied by 1/8 inch vertically. Obtaining the final machine tolerances would be up to the millwrights and machinists, at the mechanical engineer's direction, of course.

EXISTING CONDITIONS

As is the case with any rehabilitation project of this nature, it can be expected that there will be a number of previously unknown existing conditions discovered through the course of the work. In the case of this project there was a protracted period of time between when the scoping work was performed (2001-2004) and when the Contract was awarded to begin the repairs (2010). Given the fact that there were very short construction time windows it was essential to meeting the project schedule that the risk of unforeseen existing conditions be mitigated to the greatest extent possible. For this reason the following measures were taken as part of the development of the Plans:

1. None of the mechanical components were indicated to be re-used. This would ensure that the new components could be manufactured in advance and be approved and ready for installation prior to the start of the closure periods. This measure minimized the field machining work to achieve the required fits between new and existing components. which could not take place until after the the existing mechanical components were disassembled.
2. The Contractor was required to mobilize a field machining company that would be prepared to perform field machining work to clean up the existing bores in the structural steel to accept the new balance link and counterweight trunnion components. After disassembly of the existing components the existing bores were to be inspected. Field machining was then to be performed only if necessary.
3. All of the new bearing housing components that fit up into the existing structural steel were rough machined with a finish stock allowance to allow the bore to be oversized if necessary. After confirmation of the existing bore size or machining of the bores the new component was finished to meet the fit requirements of the Contract.

Even with these precautions there were a few unexpected surprises:

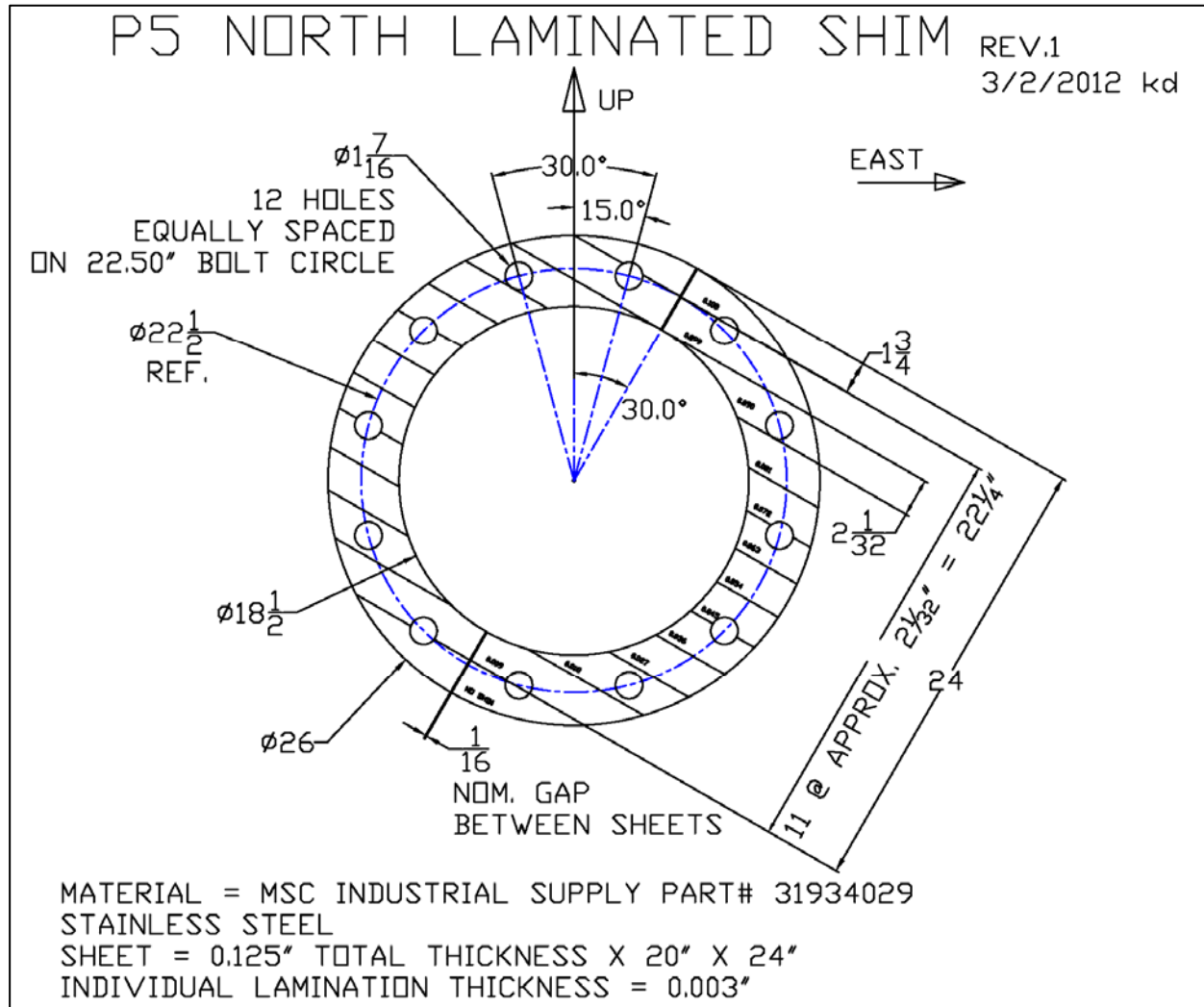
Pack Rust



When the bearing housings for the upper balance link pins were removed from the truss, there was a significant amount of pack rust discovered which had separated the plates which built up the web. It was necessary to remove additional rivets. Using heat and hammering to vibrate loose the corrosion that had built up between the plates the plates were then drawn back together before machining the bores.

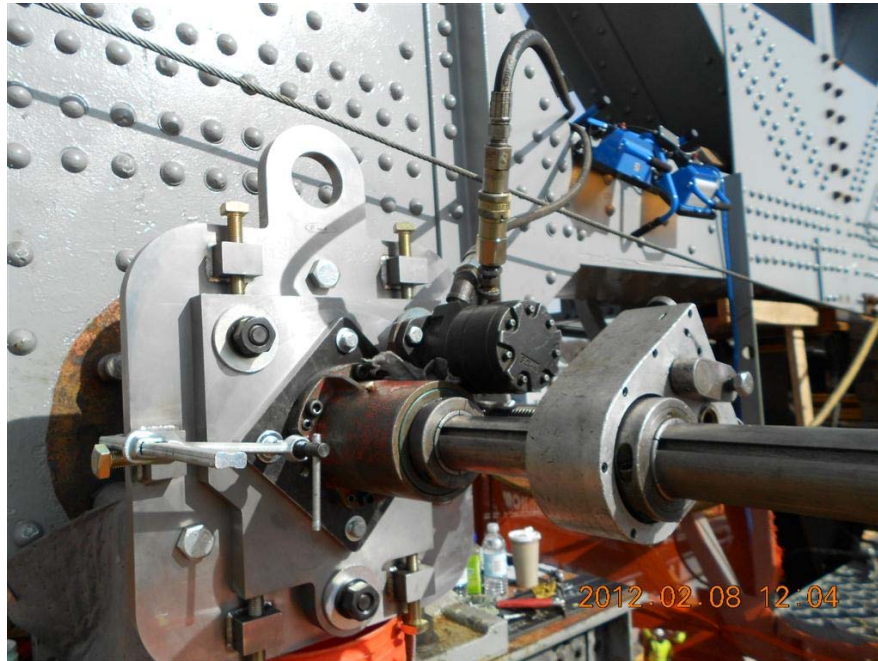
Web Plate Misalignment at Upper & Lower Balance Link Pins

Another problem with the installation of some of the new bearing housings was the finding that the webs of the girders and trusses were not parallel. There was a provision for shims at all of the bearing housings for the balance links. The solution in this case was to utilize laminated shims that could be stepped to quickly fabricate a very accurate feathered shim without the time consuming process of machining them. Using the stepped laminated shims the bearing housings were able to be installed so that the bearing bores were properly aligned parallel to the axis of rotation.



Web Plate Misalignment at Counterweight Trunnions

A similar issue presented itself at the web plates for the counterweight trunnions: Once the truss was re-aligned it was found that the pre-existing misalignment had plastically deformed the web plates so that they were skewed relative to the axis of the trunnion. It was impossible to compensate using feathered shims due to the fact that the original design did not include any shims at this location. In this case it was necessary to bore and face the web plates to produce the proper final alignment of the counterweight trunnion. Fortunately with the field machining crew already mobilized to perform the boring operation they were able to quickly transition and perform the facing operation without significant delays to the project.



Counterweight Trunnion Pin Shrink Fit.

After re-aligning the trusses and finishing the boring and facing operation on the web plates, one of the final steps of re-assembling the structure was to install two large counterweight trunnion pins, one at each truss. These pins transfer the dead load of the upper balance truss to the trunnion sleeve which is supported in a plain bronze bearing at the top of the tower. The requirement was to install the 12 inch diameter, 30 inch long forged pins with an ANSI FN1 interference fit. The combination of the location of the components at the tops of the towers, the access at that location, the size of the components and the horizontal orientation of the parts made this a relatively difficult interference fit. The Specification imposed a restriction on the Contractor: The pin was not allowed to be cooled using liquid nitrogen. The prohibition on the use of liquid nitrogen has become commonplace in the movable bridge industry primarily as a result of several well-known historical incidents at the Miami Avenue Bridge and the Brickell Avenue Bridge where trunnions cooled in liquid nitrogen and installed in their hubs cracked the hubs during temperature normalization. Cianbro felt that the use of liquid nitrogen as a cooling media was the only method that would shrink the pins adequately to allow enough time to install the pins into the truss bore. They felt that dry ice cooling would warm too quickly and requested permission to use nitrogen instead.

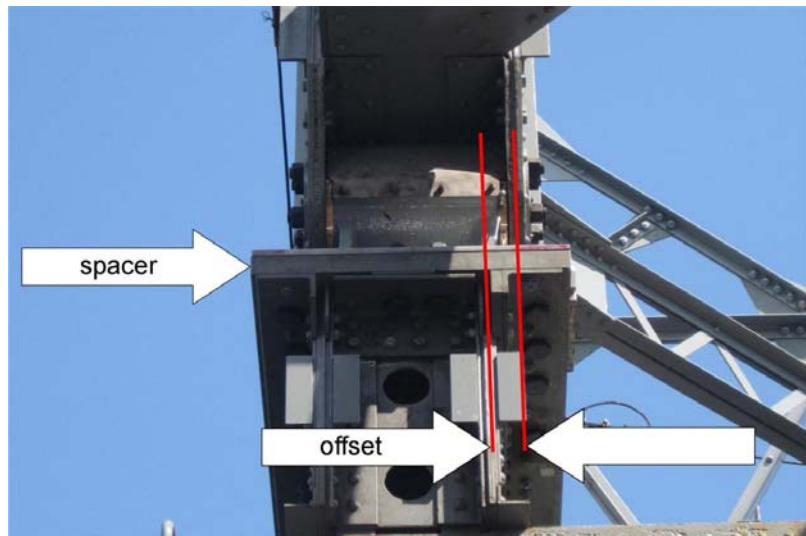


Upon review of the research performed by FDOT evaluating the risks and benefits of using liquid nitrogen it was determined that this was a situation where there were not significant risks associated with using liquid nitrogen based on the configuration of the truss and the fact that there was a relatively light interference fit used. Cianbro also performed a test-cooling using one of the old pins which had been removed from the truss. This test showed that the nitrogen cooling had not affected the old pin and that the amount of time that elapsed before the pin resumed its original size would be adequate to get the new pin into the truss bore. Permission was given with the restriction that the trunnion pin was not permitted to be placed into direct contact with the liquid nitrogen until the temperature differential between the pin and liquid nitrogen was 200 degrees or less (i.e. the pin had reached -121 degrees) in order to avoid large thermal gradients of the order of 300 to 400 deg. F.

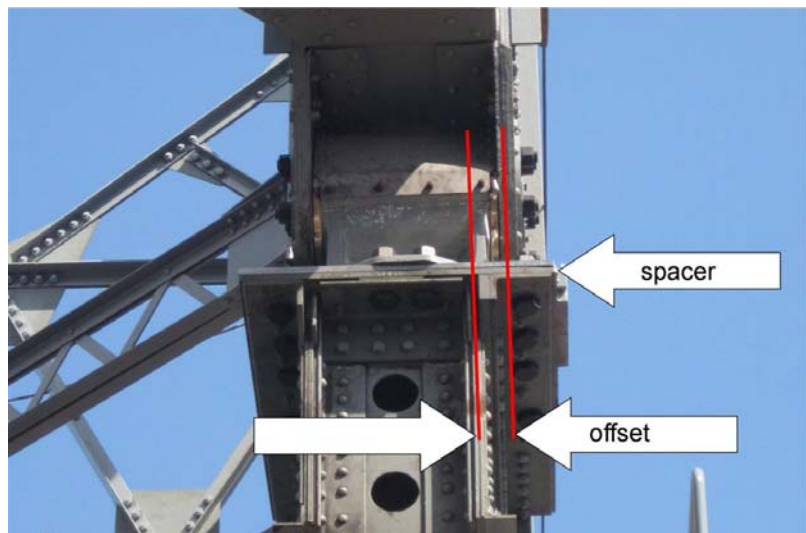


CONCLUSIONS

**North Counterweight Trunnion
Bearing Final Condition
(Transverse to roadway)**



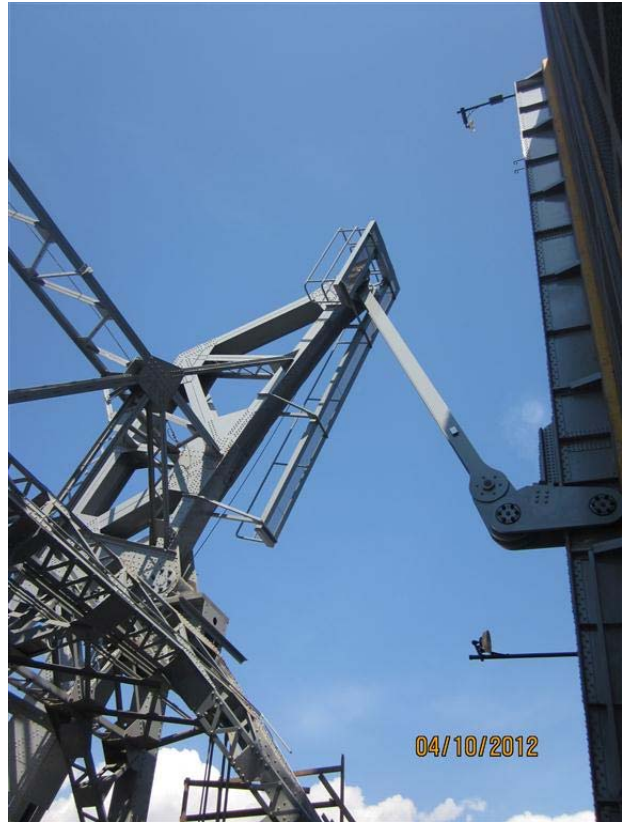
**South Counterweight Trunnion
Bearing Final Condition
(Transverse to roadway)**



On March 27, 2012 the supports under the counterweights were jacked down and the counterweight links were once again loaded while being monitored with strain gages to confirm equal loading. A final precision survey was performed of the counterweight trunnions to decide if the adjustments which had been made had survived the re-loading process. The survey revealed that the counterweight trunnion pins were now within 0.01 inch of being at the same elevation; within 0.02 inches of being at their desired north-south location; and within 0.06 inches of being at the same east- west location. This was all in all a remarkable feat of construction engineering, and ironworker and millwright craftsmanship. The photos above depict the final connections between the counterweight trunnion bearings and the towers. The varying thickness of the spacers installed between the tower and the bearings and the visible offset between the tower column and the bearing illustrate the amount of movement that was required to re-establish the correct alignment of the balance truss.

On April 10, 2012 the bridge was lifted using its new mechanical components for the first time. It had taken two weeks to remove all of the temporary access structures which had been installed to facilitate the rehabilitation work. There wasn't a creak or a groan as the span was lifted and lowered for the first time, an indication that even the guy who had greased the bearings had done a thorough job.

The success of this endeavor took the combined efforts of all of the participants. That the project had been prepared as well as could be going into the outage shows how seriously the Connecticut DOT team and their consultants, as well as the constructor, had approached this effort. That as few problems as were encountered is a testament to the mechanical engineering design. It is a credit to the entire team that when unexpected conditions presented themselves everyone worked to solve them in a positive and pro-active way.



James Rollins, a bridge foundations engineer from a century ago, when faced with a nearby challenging project on the Connecticut coast said it well: "Everybody worked for the best interest of the job; no pet schemes or new theories were tried out, for we all realized that we had a most difficult problem, which was a new one for all of us, and that it needed thought, brains and the most diligent attention, in order to be carried through with success."



¹ U.S. Patent 1,270,925. Page 1, Line 65

² U.S. Patent 1,270,925. Page 2, Line 64

³ Hovey, Movable Bridges, Vol. I (1926), Page 133

⁴ U.S. Patent 1,519,189. Page 3, Line 5