Heavy Movable Structures, Inc.

SEVENTH BIENNIAL SYMPOSIUM

November 4 - 6, 1998

Grosvenor Resort
Walt Disney World Village
Lake Buena Vista, Florida

"Rejuvenating Movable Bridges"

by

Nicholas Altebrando, P.E., Paul Skelton, P.E., & Jeanne Denney, P.E., Hardesty & Hanover, LLP

REJUVENATING MOVABLE BRIDGES

by Nicholas Altebrando, P.E. Partner
Paul Skelton, P.E. Associate
Jeanne Denney, P.E.

Hardesty & Hanover, LLP

Abstract

After many years of operation under heavy loads, extensive rehabilitation in movable structures is inevitable. It is common in the rehabilitation of movable structures to encounter the most difficult problems at the interface between moving and stationary elements. Often the juncture of load transfer, between the heavily loaded moving part and its support, is where rehabilitation is most critical and most difficult to effect without major interruptions to marine or vehicular traffic. With careful planning, construction sequencing and consideration to the relationship between structural and the mechanical elements, these critical areas can often be selectively rehabilitated while minimizing channel and roadway closures. This paper examines the successful rehabilitations of two such historic bridges: the Duluth Aerial Lift Bridge in Duluth, Minnesota and the Middletown Swing Bridge in Middletown, Connecticut.

Nicholas J. Altebrando P.E.
Partner – Hardesty &Hanover, LLP

Partner at Hardesty & Hanover since 1994, Mr. Altebrando has more than 20 years of experience in all aspects of bridge design, inspection and rehabilitation for rail and vehicular traffic as well as special structures. An acknowledged specialist is movable bridge engineering, Mr. Altebrando has been project manager and principal in charge of many bridge projects of this kind, as well as conventional bridge and highway design, rehabilitation and construction projects. Mr. Altebrando's responsibilities have included the supervision of inspection, evaluation, ratings and analysis, new design, rehabilitation design, development of contract documents, reports for fixed and movable bridges, all for both rail and vehicular traffic. Current projects engineered under the direct supervision of Mr. Altebrando total over $ 200 million in construction costs. Mr. Altebrando has been very active in the development of movable bridge and professional standards and codes, participating in the development of the State of Florida movable bridge standards, the Canadian National Movable Bridge standards, the D1.5 AASHTO/AWS Bridge Welding Code, the D1.1 Structural Welding Code and the AREA Chapter 15, Movable Bridge Design Specifications. He holds a bachelor's degree from Hofstra University (BSES 1976) and a master's degree from the Polytechnic Institute of New York (MSSE 1984)

Paul M. Skelton, P.E.
Associate – Hardesty & Hanover, LLP

As Hardesty & Hanover's Chief Mechanical Associate Engineer, Mr. Skelton is in responsible charge for the Mechanical Engineering design of movable bridges. He has been involved in the inspection, rehabilitation, and/or design of over 80 movable bridges (swing bridges, bascule bridges and vertical bridges). Because of Mr. Skelton's extensive experience with movable bridges, he is considered an expert in the complexities and coordination requirements for the structural mechanical-electrical interfaces of movable bridge work. Various projects have required field inspection and evaluations, review of maintenance systems and recommendations for improvement, and design of complete machinery systems for all types of movable bridges. He has written movable bridge maintenance manuals and has directed bridge maintenance crews. For the Florida D.O.T. he wrote the section, "Recommended Design Standards and Acceptance Test Procedures for Mechanical Drive Systems for Movable Bridges" and "Lubrication Design Standards and Recommendations for Bascule Bridges". He is presently the chairman of Heavy Movable Structures, Machinery/Mechanisms Committee. He is also a member of AREA Committee 15, Steel Structures and the Movable Bridge subcommittee. Mr. Skelton holds a bachelor's degree from the State University of New York – Stony Brook (BEME 1985)

Jeanne M. Denney, P.E.
Hardesty & Hanover, LLP

Ms. Denney is a licensed professional engineer in New York and New Jersey who has participated in a wide variety of movable bridge projects in her fifteen-year career. Ms. Denney has served as project engineer on rehabilitation of numerous movable bridge projects. She has also had primary responsibilities in movable bridge design for new construction, movable bridge inspections, reports and type studies in addition to conventional bridge and highway design projects. Ms. Denney has particular experience in the structural/mechanical interface and machinery support design for rehabilitations of this nature. In addition to her experience in bridge engineering, Ms. Denney is the engineer of record for a 60,000 square foot medical office building in Jersey City, NJ and numerous smaller building projects and designs. Ms. Denney holds a bachelor's degree from The Cooper Union for the Advancement of Art and Science (BSE 1983).

REJUVENATING MOVABLE BRIDGES

by Nicholas Altebrando, P.E. Partner
Paul Skelton, P.E. Associate
Jeanne Denney, P.E.

Hardesty & Hanover, LLP

Introduction

The field of movable bridges is unusual in civil engineering in that it requires a unique synthesis of structural, mechanical and electrical engineering to move the heavy loads of a bridge structure rapidly, on a regular basis and for many years of continued use. The provision for maintenance and ongoing repair is paramount in a well-conceived movable bridge design. However, even in an exceptional design, more extensive rehabilitation is a fact of life after many years of use. It is not uncommon in the rehabilitation of movable structures to encounter the most difficult problems at the interface between mechanical and structural elements. Often the interface between the heavily loaded moving part and its support is where rehabilitation is most critical and most difficult to effect without major interruptions to marine or vehicular traffic. Yet with careful planning, construction sequencing and consideration to the relationship between structural and the mechanical elements, these critical areas can often be selectively rehabilitated while minimizing channel and roadway closures. In this paper we will examine the successful rehabilitations of two historic bridges: The Duluth Aerial Lift Bridge in Duluth, Minnesota , and the Middletown Swing Bridge in Middletown.

These bridges have several common attributes. Each bridge is relatively large for its type. Each bridge is a historic resource in its community and has played a critical role in the development of the region surrounding it. Each continues to have moderate to heavy current use, playing a critical role in the present local economy. Finally, this heavy use necessitated that the critical work be done with very minimal disruption to traffic in each case. These two bridges differ in type, offering examples of selective rehabilitation of two of the most common movable bridge types in use in this century: swing and lift.

Duluth Aerial Lift Bridge

Project Background

The Duluth Aerial Lift Bridge in Duluth, Minnesota is a landmark American bridge which spans the busiest inland port in the world and provides the only vehicular link between the city of Duluth and the Park Point Peninsula. Built in 1905 as a motorized ferry system and converted to a lift span for vehicular traffic in 1929, it is notable for its size, its importance to both regional and national economy and its dominant physical presence on Duluth Harbor and the skyline of Duluth (See *Figure 1*).

Vertical lift bridges are of two types: tower drive and span drive. This bridge was originally a span drive, meaning that it utilized a system of operating ropes driven by a common drive located at the center of the span. In the 1985 conversion, it was made into a hybrid between span and tower drive when two synchronized but independent drives were located at each span end. The span is counterbalanced by weights located within the tower legs. Several wire ropes drape over each of the four large counterweight sheaves, connecting the span to the counterweight. The counterweight sheaves are essentially pulley type elements at the top of the vertical lift tower that both support and guide these lifting ropes in their travel. They are very critical elements, providing support for all moving loads, both span and counterweights.

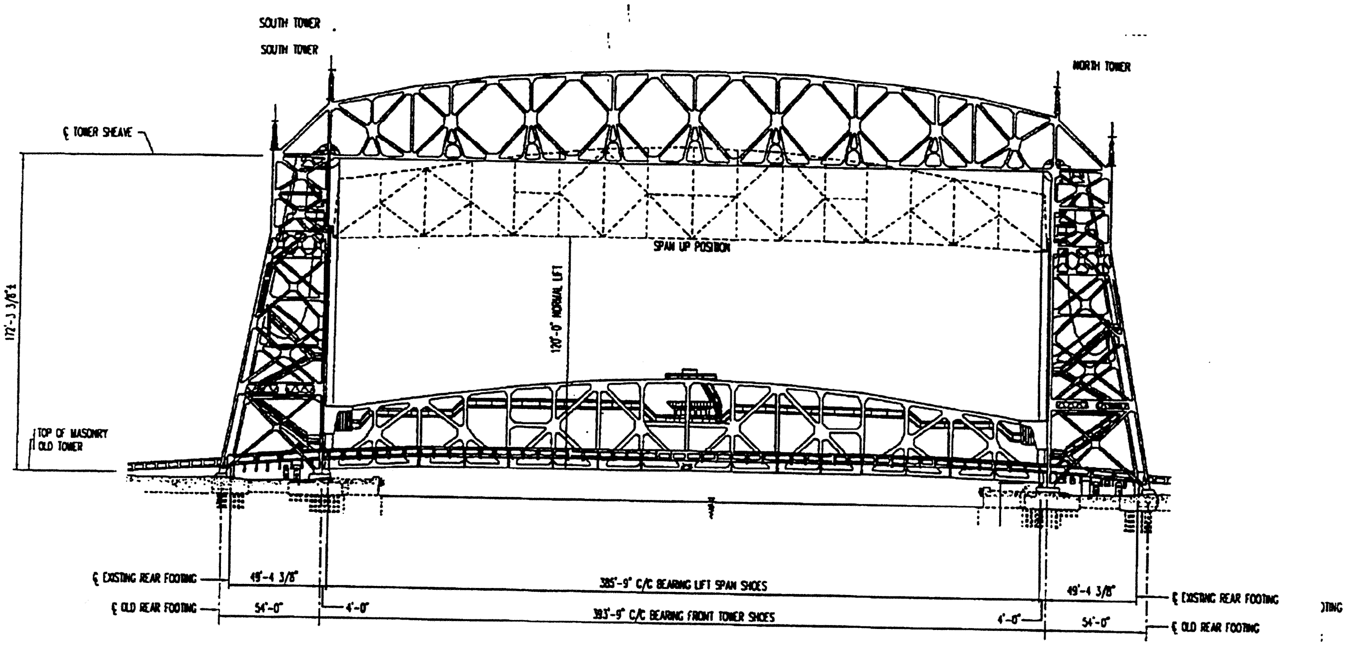


Figure 5 – Elevation of Duluth Aerial Lift Bridge

The load transfer from sheave to tower is accomplished through a trunnion shaft and bearing. The trunnion shaft, fixed to the sheave and rotates in a bearing mounted on the structure. The trunnion shaft is essentially the axle of the pulley, is in effect a short beam with a circular cross-section supported on either side of the sheave on a bearing which transfers the load of the span into the towers. Unlike most structural beam elements, however, it is completely symmetrical and rotates numerous times with each opening (See *Figure 6*). Because the extreme fibers of the trunnion shaft go through cycles of compression and tension with each opening, it is sensitive to fatigue. The total lift span weight is approximately 2,000 kips (8896 KN), counterweighted by 1,000 kips (4448 KN) at each tower. The load on each counterweight sheave on the Duluth Aerial Lift Bridge is 1032 kips (4590 KN). Since the span lifts more than 200 feet (61 m) in the air for each opening, each trunnion shaft goes through 6.5 rotations for every lift cycle. In addition, the seventy year old bridge opens over 5000 times per year. It was likely that fatigue would become a critical factor in the maintenance of the counterweight sheaves and their trunnions in this situation, and this turned out to be the case.

Involvement with the bridge began in (1996) when H&H was selected to perform inspection, analysis and rehabilitation mainly concerning repeated problems with counterweight sheave performance and numerous nuisance problems with electrical system reliability. The main operating machinery, including drums, ropes and attachments, were replaced in 1985 and were in reasonably good condition, however the city felt that the sheaves, now observed moving relative to their trunnion shafts, could no longer be maintained by interim repair projects and scheduled a major capital repair program. After seventy years of intensive use, it was thought that the counterweight sheaves were in need of replacement. One of the trunnion shafts which had been replaced in 1991 because of movement relative to the sheave appeared to be in movement again. It had further been discovered in 1995 that the interference fit between the trunnion shaft and counterweight sheave bore had been lost and it was apparent that extensive material deformation had occurred. When the trunnion caps were removed during the inspection, a visual crack at the fillet obvious in one of the four trunnion shafts. One of the cracks was found to be up to 5/8 inch (16mm) deep, extending 270 degrees around the trunnion circumference. The ratio of the shaft diameter to journal length had indicated a probable sensitivity to fatigue cracking in this location.

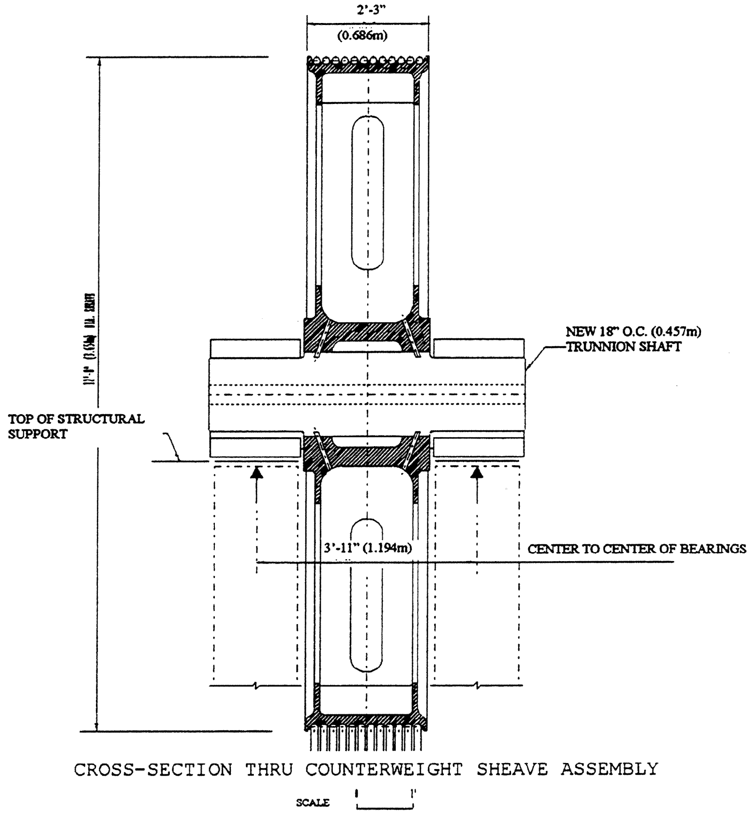


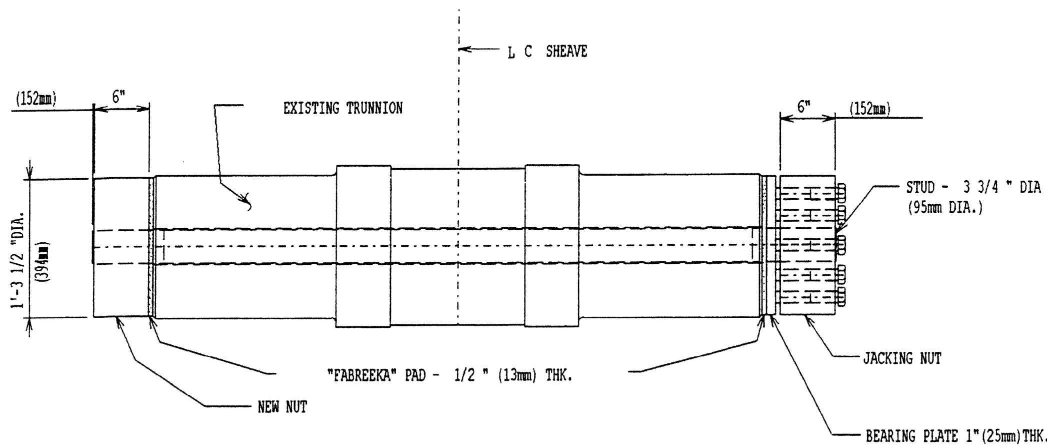
Figure 6 – Duluth Aerial Lift Bridge

The discovery of cracks such as this in a highly critical, nonredundant members with significant, regular stress reversals with each opening was clearly an emergency situation. There is a history of other vertical-lift bridges having failed in this manner. Openings were immediately limited, while discussions were held with fatigue and fracture mechanics experts assessing the existing condition . An immediate closure in this situation would have trapped several large ships in port with no other means of egress. Closure to vehicular traffic on the other hand, would have eliminated all access to the Park Point Peninsula, a Lake Superior island. Full channel closure for trunnion replacement was scheduled for January when the natural freezing of Lake Superior interrupts ship traffic. During this time, Hardesty & Hanover had a double task: first, to design an emergency repair that would keep the bridge safely in operation for one month until January, when a trunnion shaft replacement could be started, and second, to detail two new trunnion shafts which would be fabricated and installed for the January closure. This needed to be accomplished while assessing the root causes of the trunnion movement and sheave cracking and making provisions to relieve these conditions if possible.

To address the emergency condition, a post-tensioning device was immediately designed to provide compressive stresses in the trunnion shaft. (See *Figure 7)* This was done by means of inserting a very high-strength tensioning rod through the center bore of the trunnion and installing a series of clamping plates on the exterior of the shaft to distribute the load. This device had two purposes. First it served as a retainer that would inhibit the shaft from completely severing in the event of a shaft failure. Second, it minimized the detrimental tensile stresses at the tip of the crack during its rotation. A Fabreeka, or resilient fiber, pad was also introduced between the bronze plate and the shaft to allow small deflections and relieve bending in the highly tensioned rod. After this was installed, two openings were allowed per day. This scheme was in place within approximately one month of the crack detection.

Once these temporary retaining devices were installed, work began on the design, concurrent purchase and rough machining of two new trunnion shafts. Because lead time for these sheaves is minimally six months, it was decided that the sheaves would not replaced at this juncture. However, special welded repair details and welding procedures to temporarily repair large cracks in these components were designed by H&H and Lincoln Electric Company based on chemical analyses. When it was time for the trunnion replacement, the damaged trunnion shafts were jacked horizontally out of their sheaves. The machinists set up a horizontal boring machine to clean up each sheave bore, as it was necessary to machine the existing sheave bores concentric with the rope pitch diameter. The final diameter was then measured, and the trunnions were final machined in the shop to achieve an FN2 fit. An FN2 fit provides between 0.0075 and 0.0116 inch interference between the shaft and hub.

The insertion of the shaft into the bore was the last remaining task. This procedure, commonly called shrink fitting, requires using temperature differentials between shaft and bore to allow insertion of an oversized bore without damage. Blankets were draped over the sheave bore in a heated enclosure to achieve the required expansion, while Duluth's ambient air temperature in January was more than adequate to cool the trunnion shafts. An average temperature difference of 260°F was used to obtain approximately 0.017 inches clearance between the hub and shalft. The trunnions were successfully placed in about ten minutes, and when temperatures equalized, the span was lowered back into position. These critical emergency repairs allowed for nearly unobstructed traffic both over and under the Duluth Aerial Bridge during a highly critical emergency and allowed the City of Duluth an opportunity to push a larger scale rehabilitation into more favorable funding time frame. Plans for that rehabilitation and replacement of all four sheaves are now in progress.



POST TENSION ASSEMBLY

Figure 7 - Post-tensioning Assembly - Duluth Aerial Lift Bridge

Conclusion

Movable bridges require much more stringent tolerances for fabrication, finish, and fit than most other common structures to insure long term performance. Distortions and deformations, caused by deficiencies in the original design, poor construction, initial misalignments or long-term service all result in a downward spiral of performance in operation, subsequent high maintenance, and eventually to failure of key components. A thoughtful rehabilitation of these structures must address precise alignment of replacement parts (usually under much less favorable conditions than the original installation) as well as the alignment and correction of the remaining structural distortions for it to be truly effective. These successful rehabilitation projects demonstrate that it is possible to make selective, high precision repairs on these structures and, with the result, that these relatively low cost projects can greatly extend the life of old movable bridges, still so critical to their communities.

Acknowledgements

We would like to gratefully acknowledge the State of Connecticut Department of Transportation/ Rails Bureau, and the City of Duluth Department of Public Works, for the opportunity to serve them in completion of these complex projects. These projects would have been impossible without the craftsmanship brought to them by Cianbro Construction Co. (Middletown Swing Bridge and Middletown Swing Bridge), and Lakehead Constructors and their subconsultants (Duluth Aerial Lift Bridge).

We also wish to thank our subconsultant for the Duluth Aerial Lift Bridge, LHB, for their technical support at the site.

References

1. Hoole and Kinne, Movable and Long-Span Steel Bridges, New York, 1923
2. Hovey, Movable Bridges, Volume II – Machinery, London, 1927

Middletown Swing Bridge

Project Background

The Middletown Swing Bridge is a center bearing swing bridge constructed in 1910 to carry a single track of rail traffic. It is a very typical example of the many bridges of this type built for the railroads by the American Bridge Company early in this century (See *Figure 1*). This original and most direct route between New York and Boston received heavy usage for many years by both passenger and freight trains as a part of the developing Northeast Corridor. Now owned by the State of Connecticut, it is leased to small local rail lines to service local industry. The Middletown Swing Bridge facilitates delivery by barge of supplies and finished material in and out of the Stone Container Facility on the Portland side of the channel. The bridge is typically kept open for marine traffic and closes to permit rail traffic as required, approximately twice a day.

Involvement with the bridge began in 1990 when inspections documented numerous deficiencies in a report to the state. Selective repairs were implemented to stabilize the bridge and keep it operational as funding was made available. However, more serious problems on the Middletown Swing Bridge began in 1994 when the center bearing of this 300 foot rail structure began to emit loud noises and it was clear that the electrical system was being overtaxed when the bridge was operated. The winter of 1994 proved to be particularly difficult in the northeast with numerous heavy snowfalls. The increased snow loads appeared to have pressed the old and worn mechanical/structural turning assembly to its limit. Upon inspection, it was clear that the center bearing was failing at a rapid rate. The center pinion bearing, adjacent pivot framing and balance wheels were all showing signs of severe distress, while the electrical power required to operate the bridge tripled. Inspections had previously shown that the balance wheels (designed primarily to provide stability for wind loads during span travel) were making hard contact for small arcs of the bridge travel. Now it appeared that they were in continuous hard contact, in fact, carrying a significant portion of the dead load for which they were not designed. A possible cause of the problems may be the fact that the end wedge reaction at the ends of the truss were nearly non-existant. This resulted in the bridge literally teetering about the center pivot each time a train passed. Also, all braking and traction loads from the train were being resisted by the pivot as well. It is possible that over time, this initiated the problems with the balance wheels and the center pivot. Whatever, the case, it appeared that there were relatively few openings remaining in the life of the turning components.

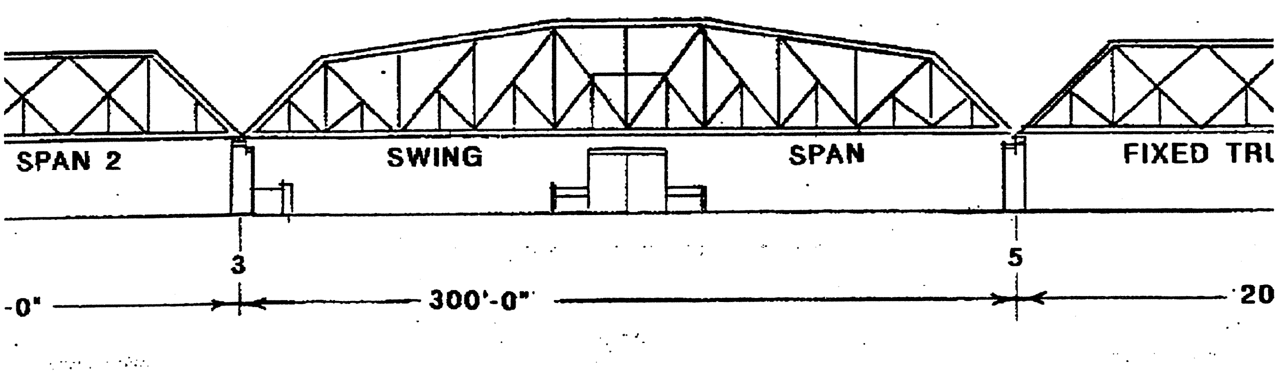


Figure 1 - Elevation of Middletown Swing Bridge

The center pivot bearing provides two functions on a center bearing swing bridge. First it retains the point of rotation of the span during its travel. Second, it provides the primary support for span dead load while the bridge is open and during rotation. In the closed position, end and center supports are driven to take a small fraction of the dead load and all live loads. This center bearing was one of the most typical types for this era: a three lense bearing comprised of a concave steel casting on top and bottom with a double convex bronze disk in the center (see *Figure 2*). Around the perimeter is a retainer ring which retains an oil bath immersing the center disk. This retainer ring also maintained the vertical alignment of the three disk system, by means of a circular fit with the base casting.

A complete failure of the center bearing would have required the span to be out of service for months, interrupting either rail or marine traffic. The seriousness of the condition resulted in immediate measures that were put into place to slow the failure of the center bearing. Openings were reduced to once a day or less and inspection of the center bearing was immediately done to determine the exact condition of its components. The inspection operation required that the span be jacked in the open position while the retainer rings were removed for inspection of the center pivot. Removal of the retainer rings confirmed what was suspected, the shear keys connecting the span to the discs had failed. Not only were the rings no longer retaining oil, but also actively resisting relative lateral movement of the three disks. The top casting had shifted approximately one half inch with respect to the center disk. There was also heavy wear on the inner face of the retainer rings caused by slippage and deformation of the bronze disk as the span rotated in an imbalanced condition. Inspections revealed that the span had moved on the center pier ½ inch (12.7mm) to the south. This was further confirmed by misalignment of the centering devices and end movement with respect to the rest piers.

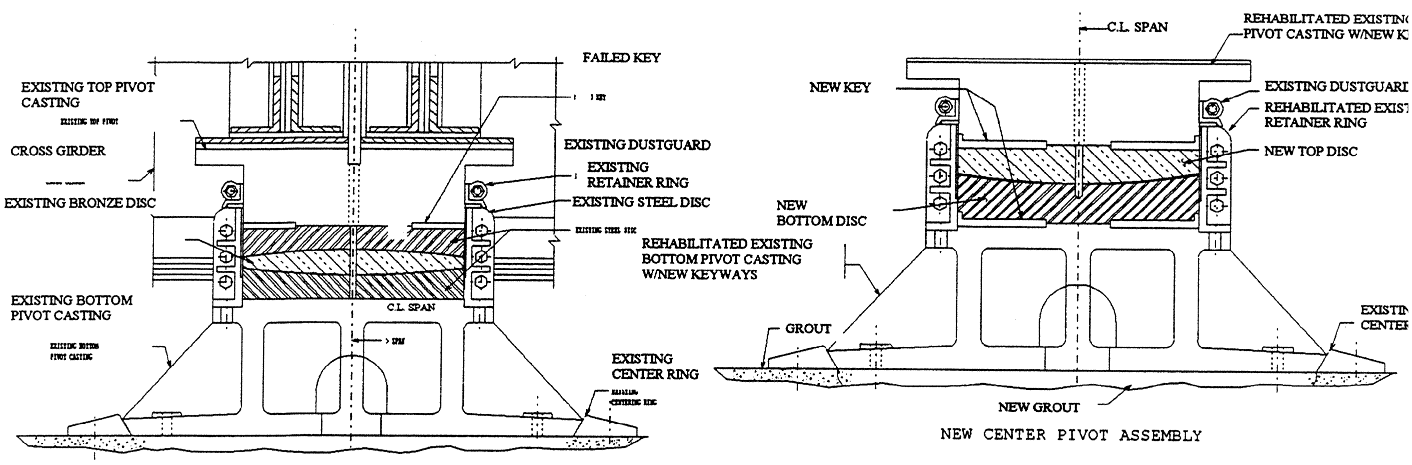


Figure 2 - Cross Section through existing and new center pivot bearings -Middletown Swing

Estimates in 1994 for a full rehabilitation of the structure were on the order of $32 million. A major rehabilitation was not an option due to budgetary priorities of the state. Some consideration was given to abandonment of the historic span. After much heated public discussion, it was proposed that a selective rehabilitation be undertaken for a cost of around a half a million dollars, thus keeping the structure operational while funding was sought for less critical repairs. It was determined that the center pivot, and balance wheel assemblies had to be replaced, the end wedge loads reestablished and the proper center of rotation be located. The balance wheel track was surveyed and determined to be adequately level.

Bearing Replacement

The technical challenge of this plan was how to undertake the design, fabrication and installation of a new center bearing with a one month closure for rail traffic. Time was of the essence as local businesses and the short line railroads were being severely affected by the bridge outage. First, a fast track set of contract plans was prepared and low bidder, Blakeslee-Arpaia Chapman initiated the fabrication of replacement center pivot assembly and new balance wheel assemblies. The design called for the use of a two disc bearing, which is more stable than the original three disc bearing: the upper casting was made of bronze, while the lower portion was steel (See *Figure 2)*. The total height of the assembly with shims was reduced by approximately ¼ inch because the existing end wedge reactions were insufficient. The difficulty was establishing the true center of rotation for the bridge in place with limited clearances and working space. Generally, very tolerance critical items, such as mechanical components are fabricated and shop-assembled to a verify precise fit. As in the above example, this was impossible in a time sensitive field retrofit.

The bridge was jacked in the vertical direction in order to relieve the center bearing of span dead load. Teflon pads on stainless steel plates were placed between the top of the jack rams and the pivot girders to facilitate lateral movement. Since the bridge had shifted ½ inch (12.7mm) to the south, the 1800 kip (8006 KN) swing span had to be shifted back to its original position. This was accomplished by utilizing two horizontally mounted jacks, providing 100 kips (444KN) of total horizontal force. This force was enough to break the friction between the greased teflon coated pads on the stainless steel plates. The bridge was jacked horizontally approximately ½ inch (12.7 mm) in the open position in order to recenter the span. The center bearing was then extracted. The new center bearing discs were installed, with the top disc keyed into the original upper casting to prevent rotation with respect to the swing span. The lower disc was similarly keyed to the original lower casting. The bridge was then lowered onto the new center bearing, balance wheels adjusted to their proper height, and was soon back to operation with normal operating power requirements. The end wedges were then driven and to provide positive deflection at the ends of the truss and thus, a stable swing span under train loads. This work effectively reduced Electrical Loading on the swing span motors, reduced torque through the operating machinery, controlled rotation of the span during operation , provided stable structural support during train movement and reduced the traction loadings distributed to the center pivot and most importantly, it continued, long term operation of the Middletown Swing Bridge and the local businesses and short line railroads that depend on the bridge.