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Aerial Bridge Emergency Counterweight Sheave Assembly Repairs

by

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AERIAL BRIDGE

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INTRODUCTION

The Aerial Bridge is a vertical lift bridge located in Duluth, Minnesota. The bridge allows for passage of marine traffic between the Port of Duluth and Lake Superior when in the raised position. When closed, the bridge provides the only access for vehicular traffic to the popular Canal Point section of the City.

The bridge carries approximately 10,000 vehicles per day and opens about 5,000 times each shipping season for the passage of both pleasure and commercial craft. The shipping season runs from mid March to mid December each year. The bridge does not operate during the winter months as the Port of Duluth and Lake Superior concede to the ice.

Approximately one year ago, during the week of October 30, 1995, an inspection of the northeast counterweight sheave assembly on this bridge resulted in emergency repairs to prolong the service life of this historic structure.

Stafford Bandlow Engineering (SBE) enjoys a working relationship with the City of Duluth, Minnesota and was called upon to investigate unusual movement at the northeast sheave assembly. During the inspection, deformation of the structure in the vicinity of the northeast sheave was discovered. LHB Engineers and Architects was brought in to assess the nature of the structural problem.

The onset of winter was just around the corner and the shipping season would soon come to an end. The winter closure of the shipping canal would allow the opportunity to repair the counterweight sheave assembly and return the Aerial Bridge to service in time for the start of the shipping season in the spring of 1996.

The necessary work would include engineering, advertisement for bids, selection of a contractor and rehabilitation. This work would have to be completed in less than four months.

The purpose of this paper is to relate the story of the rehabilitation procedure. The findings of the inspection and recommendations for rehabilitation will be discussed. The engineering effort that followed the inspection and the construction effort will be detailed.

Like most rehabilitation efforts, unforeseen circumstances arose during the course of this project. Although the problems encountered caused a slight delay in the project schedule the bridge was open for the start of the shipping season. These delays were the result of poor quality bronze castings received from the manufacturer that were rejected upon inspection. The castings were tested in accordance with the ASTM requirements and satisfactory test reports resulted. Why then were the castings rejected? This paper will discuss the cause for rejecting the castings and make suggestions that may help to alleviate similar problems in the future.

BACKGROUND

The Aerial Bridge was originally constructed in 1929. In 1986 a mechanical and electrical rehabilitation was undertaken. As part of the rehabilitation all of the span operating machinery and the counterweight wire ropes were replaced. The contract drawings do not indicate that the counterweight sheaves, sheave trunnions or the supporting bearing assemblies were to be reworked.

During the rehabilitation each of the counterweight sheaves was raised out of the supporting bearings for inspection of the bronze bushings. The northwest bushings were found to have sufficient deterioration to require replacement and these bushings were replaced in 1986. The remaining counterweight sheave trunnion bushings were not replaced as part of the 1986 rehabilitation.

The northwest counterweight sheave bushings that were installed in 1986 deteriorated rapidly and required replacement in March of 1991. These replacement bushings have not held up well either as documented in a December 1991 report by M. C. Stafford and Associates titled, "Report Concerning Deficiencies In The Northwest Counterweight Sheave - Shaft Assembly On The Aerial Bridge In Duluth, Minnesota."

Information obtained from the original drawings for the bridge and drawings prepared by Krech and Ojard for the 1991 bearing replacement indicate that a substantial amount of weight has been added to the bridge since original construction. The original drawings indicate a total span weight to be balanced of 1,803,000 lb. This value would require the reaction of each counterweight to equal 901,500 lb. The existing load for the counterweight side of the system with the span closed is 1,032,000 lb., a 14.5% increase in weight.

Information obtained from City of Duluth maintenance personnel indicates that structural modifications were made to the north tower in the vicinity of the counterweight sheaves to allow for the installation of an electrical cable chase as part of the 1986 rehabilitation. The modified structural steel spans between the two inboard sheave bearing supports. Apparently the load was not removed from the sheave supports when the structural modifications were made.

Similar structural modifications were not made to the south tower. Problems related to the counterweight sheave trunnions and bearings have not occurred on the south tower.

INSPECTION

General

SBE inspected the northeast counterweight sheave assembly on the Aerial Bridge, at the request of the City of Duluth, during the week of October 30, 1995.

The inspection was conducted on an emergency basis when maintenance personnel discovered a gap between the thrust face of the east sheave bearing and the sheave, which had not previously existed. The inspection was performed by Mr. Paul M. Bandlow, P.E. City of Duluth bridge maintenance personnel and personnel from Twin Ports Testing, a non destructive testing (NDT) company provided assistance during the inspection.

Twin Ports Testing performed ultrasonic examination of the northeast counterweight sheave trunnion and limited magnetic particle testing of the same trunnion. No defects were discovered using the NDT procedures.

Detailed inspection was limited to the northeast counterweight sheave assembly. A cursory inspection of the sheave assemblies on the south tower and the structural steel in the immediate vicinity of all of the sheaves was conducted. The cursory inspection of the structural steel on the north tower revealed deformed structural members. LHB Engineers, a structural engineering firm with offices in Duluth, was retained after the deformed steel was discovered. LHB Engineers determined that the observed structural deformations were likely a result of the structural modifications made during the 1986 rehabilitation. LHB further determined that the integrity of the structure was not in jeopardy.

Observations and Discussion

Each of the sheave assemblies consists of a wire rope sheave with a trunnion mounted in the hub of the sheave. The trunnion is stepped to accommodate two separate 6" long interference fits at opposite ends of the sheave bore. The trunnion is supported in two plain bronze bushed bearings located on opposite sides of the sheave. The sheave assembly can be seen in Figure 1, following this page.

The original drawings show three separate methods to prevent relative movement between the sheave and the trunnion. First the drawings indicate that an interference fit be provided of not less than 0.010" between the two mating parts in the fit areas described above. This interference fit would provide considerable

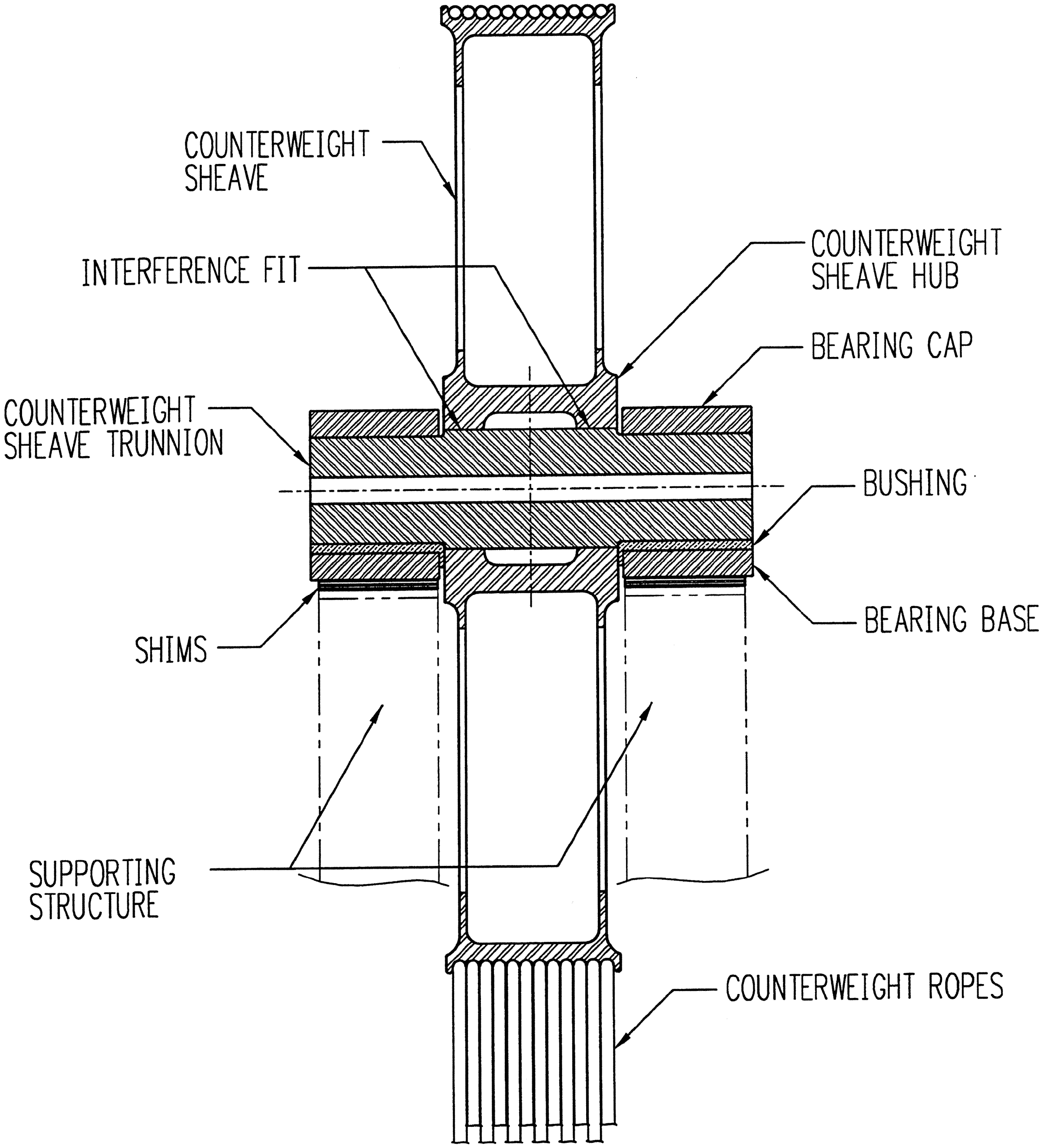

FIGURE 1

COUNTERWEIGHT SHEAVE ASSEMBLY

resistance to both axial and rotational movement between the two components. Second, four square keys (two at each fit area) were provided to prevent rotational movement. Lastly, four axial threaded dowels (two at each end of the sheave hub) were installed at the interface of the sheave and shaft to primarily prevent axial movement although the dowels also provide resistance to rotational movement.

The trunnion had moved axially relative to sheave. At the time of the inspection the trunnion had moved in an easterly direction 7/16" relative to the sheave. The threads in the sheave and the trunnion that are used to secure the threaded dowels had sheared and the dowels had moved relative to the trunnion. The dowels were flush with the sheave on the east side and had apparently not moved relative to the sheave. On the west side the threads in both the sheave and the trunnion had sheared and the dowels had moved relative to both the sheave and the trunnion.

The fit between the trunnion and the hub of the sheave was loose at the east side of the sheave. A total radial clearance of 0.018" was measured between the hub and the trunnion on the east side. There was no clearance found between the hub and the trunnion on the west side of the sheave.

The amount of relative movement between the hub and trunnion that would have occurred as a result of the clearance is insignificant and therefore the clearance measured is not a result of wear. The clearance measured at the east trunnion/sheave fit is in all likelihood the same clearance that existed at initial installation. This clearance is probably the result of a machining error that occurred during original manufacturing of the sheave and trunnion.

There was no way to determine the fit between the trunnion and the west side of the sheave. There was no measurable clearance. The fit was either metal to metal or some amount of interference.

Current AASHTO design specifications require an FN3 fit between main trunnions and hubs. For a trunnion of this size (18" diameter at the fits) an interference fit of between 0.012" and 0.016" is required. An interference fit of this magnitude will provide the necessary resistance to both axial and rotational movement. Typical designs also call for radial dowels as an added safety factor.

The shoulder on the trunnion was in hard contact with the bronze bushing on the east side. The hub of the sheave was in hard contact with the bronze bushing on the west side. The contact had resulted in plastic flow of the trunnion on the east side and plastic flow of the sheave on the west side. Also there was noticeable heat build up on both the trunnion and the sheave during operation as a result of the hard contact.

Both the east and west bearing caps were removed to facilitate the inspection described previously. The east bearing had uniform wear along the entire length of the journal with light annular scoring. The west journal had moderate scoring at the end of the journal nearest the sheave and the opposite end of the journal was well polished. Feeler gages were used to measure the clearance between the bottom of the journals and the bushings. There was no clearance at the east journal. A maximum clearance of 0.006" was found at the west journal and 0.0015" thick feeler could be inserted 3-3/4" into the bottom of the bearing. The clearance at the bottom of the bearing indicated poor alignment between the trunnion and bushing. The poor alignment resulted in increased bearing loads.

The gap between the thrust face of the bearing cap and the sheave was found to be 29/64" at the east side and 0" at the west side of the sheave. The original drawings do not indicate the intended clearance at this location. Clearance at this location is necessary to allow for lubrication between the sliding surfaces. Excess clearance is not desirable as it can lead to the intrusion of foreign particulate matter and allow the sheave to move in an axial direction. A total clearance of 1/32" or less is typical for an application such as this.

It was obvious that the 29/64" gap which existed was not always present. There was considerable scoring on the thrust face of the east bearing cap that would not have occurred had such a large gap always been present.

The northwest sheave assembly was not inspected during the site visit as problems with that assembly have been documented. Cursory inspection of the two south tower sheaves revealed nothing unusual in regard to the gap between the thrust face of the bearings and the sheaves.

The excessive gap at the northeast sheave indicates that the distance between the thrust faces of the two bearings that support the northeast sheave had increased or the components had worn to produce the gap. Wear of this magnitude is highly unlikely leaving movement of the bearings as the logical conclusion for the increased gap.

There is no evidence that the bearing bases had moved relative to the structural supports. The bearings are mounted to the structure with turned bolts with a drive fit. Therefore, the mounting bolts would have to shear in order for the bearings to move relative to the structure.

The only remaining possibility was that the structure had moved and with it the bearings. The inboard bearing was the likely candidate to have moved since the support is less rigid than the support for the outboard bearing.

A cursory inspection of the supporting structural steel in the vicinity of the inboard bearing was conducted. This inspection revealed what appeared to be deformed and/or deflected structural steel immediately below the inboard bearing.

SBE informed the City of Duluth that the structural conditions found appeared to be of a serious nature and recommended that a structural engineer investigate the irregularities as soon as possible.

On November 1, 1995, SBE met with Mr. Joe Litman of LHB to further investigate the structural deformation. Mr. Litman confirmed our thoughts and found additional areas of concern in regard to deflected structural steel. LHB investigated the structural steel that supports the sheave bearings.

During the course of our investigation the northeast counterweight sheave trunnion was inspected ultrasonically by Twin Ports Testing. In addition some limited magnetic particle testing was conducted to confirm the integrity of the trunnion. No defects were found in the northeast counterweight sheave trunnion.

Recommendations

The problems found during our inspection were of a serious nature and required remedial action in the short term to prevent further degradation. There was no way to determine with certainty how long the assembly would last prior to becoming inoperable. Previously a similar condition had developed at the northwest sheave assembly and repairs were required in less than six months. Considering this history it was obvious that time was of the essence.

The SBE report provided recommendations for a permanent repair. The report also provided recommendations for work which could be completed during the winter shutdown which would extend the serviceable life of the assembly until the permanent repairs could be made. The recommended short term repairs involved the following:

1. Remove the load from the sheave assembly.

2. Remove the existing dowels and jack the sheave back to its original position relative to the trunnion.

3. Secure the sheave to the trunnion to prevent axial movement.

4. Compensate for the gap created by the movement of the structure.

5. Align the trunnion with the bearings and verify proper alignment under full dead load.

SCHEDULE

The following is a list of significant dates throughout the course of the project.

November 15, 1995	Submit Inspection Report
December 15, 1996	Notice to Proceed with Design
January 15, 1996	Submit Completed Design and Specifications
January 16, 1996	Plans Available to Contractors
February 1, 1996	Bids Opened
February 5, 1996	Contract Awarded
February 12, 1996	Field Work Begins
February 20, 1996	Load Removed from Counterweight Sheave
March 13, 1996	Operational Tests Conducted
March 14,1996	Project Complete

The design included a new bushing for each of the bearings associated with the sheave assembly. Due to the restricted schedule it would not be possible for the contractor to procure the material and fabricate the new bushings in the time allocated. In order to meet the schedule the City procured the bronze casting for the bushings and provided the contractor with the material for fabrication.

DESIGN

The design effort was essentially broken down into two parts. The first being the work required to unload the sheave. This required jacking the bridge, supporting the counterweight and providing a temporary roadway surface to bridge the gap between the roadway on the approach span and the roadway on the elevated movable span so as not to disrupt vehicular traffic. All of this work was completed by LHB Engineers as the prime consultant to the City of Duluth. The second part of the work was the mechanical work required to rehabilitate the counterweight sheave assembly. This work was completed by SBE as a sub consultant to LHB Engineers. The mechanical drawings were sufficiently detailed for fabrication and working after verification of field dimensions by the contractor. This level of detail on the design drawings eliminated the need for the contractor to produce and submit shop drawings, thus saving valuable time in the schedule.

The mechanical design work included the following:

1. Design and detailing of a custom jacking assembly to reposition the sheave relative to the trunnion. The jacking force required was anticipated to be in the range of 500,000 lb. Due to size constraints the jacking bar used as part of the jacking assembly was fabricated from AISI 4340 with a minimum tensile strength of 140,000 psi. A safety factor of 3 was obtained by using a close fit between the rod and the bore in the trunnion and by using fine

threads. This safety factor was considered acceptable for this limited stress cycle application.

2. Design and detailing of a new bushing for the existing bearing housings. Unlike the existing bushings the new bushing has a provision to lubricate the thrust face of the bearing. This feature was incorporated into the design so that the thrust face could be lubricated if high forces began to develop at this location. The design also incorporated liners so that the bearing could be finish machined as one piece and then cut into to halves. The use of liners eliminated some of the work typically associated with the fabrication of split bushings.

3. Retention of the sheave in the axial direction. Due to the design of the sheave and the known loose fit at the east trunnion/hub interface we decided that radial dowels would be difficult to install and may not hold up well with movement between the sheave and trunnion. The design called for increased diameter dowels at the same location as the existing dowels.

4. Details for new turned bolts were provided.

5. The design called for the use of a steel shim or other method of filling the small gap which existed between the trunnion and the hub at the east side interface. It was important to fill this gap if at all possible to prevent the relative movement between the sheave and the trunnion. The "working" effect created by this gap could only be detrimental to the service life of the repair.

6. Preparation of the special provisions. The special provisions included tolerances for the alignment of the counterweight sheave bearings. The contractor was required to demonstrate that the tolerances provided had been obtained with the with the bearings under full dead load. It was clearly indicated that this would be a trial and error process which would likely require that the bearings be loaded and unloaded several times prior to achieving satisfactory alignment.

CONSTRUCTION

The contract was awarded to Oscar J. Boldt Construction Company. Oscar Boldt is a Minnesota based construction company with extensive industrial experience but little experience with movable bridge work. The company has expertise in the alignment of machinery and has significant experience in the paper industry. Although Oscar Boldt may not have been the first choice for a typical movable bridge project involving a significant amount of structural work, the company was well suited to this primarily mechanical project. Their experience with the millwright trade gave us confidence that the critical alignment of the counterweight trunnion would not be a significant problem. They indicated that they were comfortable working with the alignment tolerances provided in the specifications.

Construction began on February 12, 1996. The first week was spent installing the temporary structure needed to support the counterweight when the span was jacked. The bridge was then jacked approximately 12" until the counterweight was fully supported on the temporary structure. Following this, the lift span was securely blocked in the slightly raised position. A temporary surface was then applied to the approach span to provide a suitable transition to the elevated lift span. The preparation necessary to begin the mechanical work was now complete. For the next 22 days all of the work would take place on top of the 170 ft. towers which support the counterweight sheaves.

After the design was complete but prior to the start of the mechanical work, an epoxy compound was located which appeared to have favorable characteristics and seemed like a good candidate to use to fill the small void which existed between the trunnion and the sheave hub on the east side. Most of the epoxies investigated were not recommended for extremely thin applications and the manufacturers would provide no assurance that they would stand up at the 0.018" thickness which we required. The epoxy selected was Philadelphia Resins Corporation Super Alloy Silver 500. This product has a compressive strength rating of over 17,000 psi which exceeded the 5000 psi requirement for the material to be used to fill the void. The manufacturer's literature indicated a minimum application thickness of 1/16", which could not be met. After considerable discussion of the project and the anticipated loads, the manufacturer determined that the epoxy could be used for our application. The manufacturer confirmed the use of their product for our application in writing.

In addition to this epoxy the contractor requested permission to use another Philadelphia Resins product, Chockfast Orange, to support the counterweight sheave bearings. Instead of using conventional full size shims it was proposed that six shims be used to support each bearing for alignment purposes (one shim at each corner of the bearing and two shims at the center of the bearing). By using multiple shims the orientation of the bearing could be readily changed by adjusting the shims at one or more locations. Once final alignment was achieved the epoxy would be poured under the bearing to fill all voids which remained.

Like most epoxies these products required an ambient temperature of approximately 70° F to set up properly. Since the average daily high temperature in Duluth in February is 21° F, obtaining an ambient temperature of 70° created a significant obstacle. The contractor was certain that he could build a temporary shelter and insulate the sheave sufficiently to maintain an adequate temperature to cure the epoxies.

The bearing caps were removed and the sheaves were jacked sufficiently for the contractor to install the jacking device. After installation of the jacking device two 150 ton jacks were positioned on diagonally opposites sides of the trunnion. Both jacks were operated from one pump to ensure uniform pressure. It took slightly over 500,000 lb. force to move the trunnion and the jacking operation was completed in less than two hours. The position of the trunnion relative to the sheave was approved and the contractor began the process of installing the new threaded axial dowels.

The contractor would soon be ready for the new bushings that were being machined at a local machine shop. Inspection of the bushings revealed porosity and a poor surface finish. The porosity was most obvious in areas that had been machined to accept the flat head screws used to secure the bushing in the housing. Although the porosity was of concern, it appeared at this time that the porosity may have been limited to the flange area of the bushing which would not be heavily loaded. The machine shop supervisor agreed to work on the surface finish and indicated that the bushing would be ready for final inspection the following day.

The bushing was inspected the following day and the surface finish had been cleaned up to an acceptable level. The porosity was still a concern. It was decided that a dye penetrant check might be helpful in determining the extent of the porosity. The dye check indicated extensive porosity. The porosity was confirmed using ultrasonic testing. The UT technician indicated that the bushing was the most porous piece of metal he had ever inspected and that he could not get a back reflection at any point on the bushing. At this point it was obvious that this bushing could not be used and some amount of delay was inevitable.

The busing material was furnished under ASTM specification B 22 alloy 911. This is the AASHTO recommended bronze for trunnion bearings. The testing requirements of the specification had been satisfied, yet it was clear that the bearing could not be used. How could such a poor quality product meet the requirements of the specification?

We spoke to the testing laboratory and they assured us that the pieces which they tested passed the specification requirements. It appeared extremely unlikely that such a porous piece of metal would pass the compression test or not be noticed by a lab familiar with the testing of metal samples. In our conversations with the lab we discovered that the test pieces were required to come from the same pour as the bearing but they were not required to be taken from the actual bearing. This creates a situation in which the thermal characteristics associated with the cooling of the bearing could be vastly different from the test specimen. Based on numerous conversations with metallurgists, the different thermal conditions between the casting and the test piece could create test specimens which are not representative of the casting.

In our case the casting was poured as a cylinder of uniform wall thickness of 4". The test specimens are required to be cylinders 1 in^2 in cross sectional area. In our case the variation between the thickness of the casting from which the bushing was machined and the thickness of the test specimen was significant.

The casting supplier was notified of the porosity and agreed to recast the bearing and have it available within a couple of days. In order to ensure a good product it was agreed that this casting would be radiographed prior to being sent to Duluth for final machining. The second bushing produced by the supplier did not pass the radiograph test and therefore was not shipped to Duluth.

At this point everyone involved in the project questioned the ability of the supplier to produce a quality product. Although the manufacturer was willing to continue trying to produce an acceptable product, time was of the essence and it was decided to pursue other avenues for obtaining the casting. Many suppliers were contacted and none could produce the casting in the time frame required. The minimum quoted lead time from the contacted suppliers was four weeks. The start of the shipping season was fast approaching and there was no way that a delay of one month could be tolerated.

In order to put the bridge back in service we decide to investigate the possibility of cleaning up the existing bushings and reinstalling them on the bridge. Extensive measurements were taken and it was determined that if the centerline of the bearing were lowered by 1/4" the bearing could be cleaned up to produce a bearing with a uniform radius throughout the load zone and the required 16 micro inch surface finish.

The existing bushings were cleaned up and grease grooves were machined in to the thrust face along with the necessary access channels in accordance with the drawings so that this surface could be force lubricated if necessary. Essentially everything which was to have been provided with the new bushings was incorporated into the existing bushings. The existing bushings had an extremely heavy wall thickness (1 1/2") which made the rehabilitation of this bearing possible.

The delay associated with the bushing problem was one week. Although delays are never satisfactory, all parties involved were pleased that the solution to the problem did not result in significant compromise to the bearing. The delay was kept to a minimum due to the extraordinary effort of the local machine shop in rehabilitating the existing bushings.

During the time of the bushing dilemma the project was essentially shut down with the exception of the injection of the epoxy into the small annular void between the trunnion and the hub of the sheave. In order to inject the epoxy into the void, five holes were drilled and tapped for grease fittings at the trunnion/hub interface. The epoxy was then poured into grease guns and pumped into the void. Although the actual epoxy coverage could not be determined, it appeared as though the coverage was quite good. It was observed that epoxy had traveled around the entire annular void, however the depth to which the epoxy penetrated was uncertain.

The contractor constructed a temporary shelter around the sheave assembly and was able to heat the entire sheave assembly and maintain sufficient temperature to cure the epoxy in 24 hours. This heat was maintained despite sub zero temperatures and high winds.

The sheave assembly was now ready to be lowered into the bearings and aligned. In order to preserve the location of the trunnion, the east bearing was installed in the same position from which it was removed. Additional shims were used to compensate for the lowered bearing centerline. The west bearing was then installed in a position which would provide a total axial clearance of 0.015" to 0.030" between the hub of the sheave and the thrust face of the bearings.

The initial alignment of the bearing was determined using elevations which had been taken on the trunnion and the bearing assemblies prior to and after removing the dead load from the sheaves. These measurements allowed us to calculate the deflection of the structure under load. Even with accurate information in regard to deflection of the span the bearings had to be shimmed three times prior to obtaining alignment conditions which met the requirements of the specifications.

After obtaining satisfactory alignment conditions, the bearings were fully supported using the Chockfast Orange epoxy. The epoxy was allowed to set up for 24 hours prior to performing the operational tests.

Operational testing was conducted on March 13, 1996. The first test was conducted at 25 % of full speed. Several additional tests were run at full speed including two back to back operations. No unusual occurrences were noted during the operational testing. A temperature rise of 10° F on the east journal and 20° F on the west journal was measured using a digital pyrometer after the completion of all testing. The bearing caps were removed for inspection immediately after testing. The west journal had contact along approximately 50% of the journal length with the heavier contact towards the sheave and the east journal had nearly 100% contact. There was no evidence of any problems with the epoxy compound which had been used to fill the annular void at the trunnion/hub interface.

CURRENT STATUS

The Aerial Bridge has made it through nearly a full shipping season following the implementation of the temporary repairs. There have been no unusual occurrences related to the northeast counterweight sheave assembly.

The City of Duluth is pursuing the permanent repairs suggested by SBE. The City has selected a consultant to perform an in-depth inspection of bridge to determine all work required to maintain satisfactory operation in the long term. In all likelihood all of the counterweight sheave assemblies will be replaced as part of the permanent rehabilitation effort.

CONCLUSIONS

The rehabilitation of the northeast counterweight sheave on the Aerial Bridge was a success. The inspection and engineering was completed expeditiously. The City was able to process the necessary paper work to efficiently hire a qualified contractor and the contractor met the requirements of the contract documents in a timely manner. All of the work was completed during the winter shutdown and there was no interruption to the operation of the movable span for marine traffic and only minor delays to vehicular traffic.

Success on a project is typically the culmination of the effort of several individuals working together towards a common goal. This project was certainly typical in that respect. Initially the effort involved the sound maintenance practices of the bridge maintenance crew. These practices allowed for early detection of the problem which enabled the bridge to remain in service. Undetected, this problem would have likely resulted in a prolonged closure of the shipping canal to marine traffic.

Close communication between the City, LHB Engineers and SBE throughout the analysis and design phase resulted in the rapid preparation of documents which were used by the contractor for construction. The City expedited the advertisement and bid process. This allowed the City to obtain competitive bids while maintaining a fast track approach. Had the City elected to negotiate with a single contractor in order to expedite the process it is almost certain the construction costs would have been considerably higher.

Once the contractor was selected an open line of communication was established between all involved parties. The contractor worked closely with the engineering team to ensure that the requirements of the contract were satisfied. All critical aspects of the project were discussed and work procedures were clearly defined and agreed upon prior to implementation. The engineering team was on sight throughout the project to work closely with the contractor. This hands on approach by the engineering team resulted in the contractor being an ally instead of an adversary. The relationships established between everyone involved in the project was key to the success achieved.

The only problem encountered during the work was the porosity in the bronze castings which were to be used for the new bushings. This porosity resulted in the rejection of the bearing bushings. The original bushings were rehabilitated as a satisfactory casting could not be manufactured in an acceptable time period. It is fortunate that the original bushings had sufficient wall thickness that rehabilitation was a viable option. Had this not been the case, the porosity issue could have caused extensive delays.

The bronze casting was manufactured to ASTM Standard B 22 and the test specimens met the requirements of the specification. Without the use of supplementary requirements this specification does not guarantee a satisfactory casting. In fact in our case a very poor quality casting met the requirements of the specification. In bronze bushing designs for critical applications some or all the following should be considered in order to increase the probability of obtaining an acceptable product.

1. Specify that the test specimen be taken from the actual casting and that one specimen be taken from each casting or specify that the test specimens be representative of the actual casting wall thickness.

2. Perform radiographic testing on each casting prior to machining to determine the amount and location of porosity which may be present.

3. Require that a tensile test be conducted.

4. Perform a visual inspection of each bearing after machining and prior to installation.