Paper No. 50

Hydraulics/Fluid Power

Repair And Redesign of the Spokane Street Bridge Lift / Turn Cylinders

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TENTH BIENNIAL SYMPOSIUM

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Bridge Background

The western end of Spokane Street in Seattle is the primary surface route for circulation of local area industrial traffic and provides the primary truck access to Terminal 5, Seattle's largest container terminal. The Spokane Street alignment crosses the busy West Waterway of the Duwamish River, which is lined with bulk and break-bulk trans-shipment terminals, concrete plants and heavy marine construction companies.

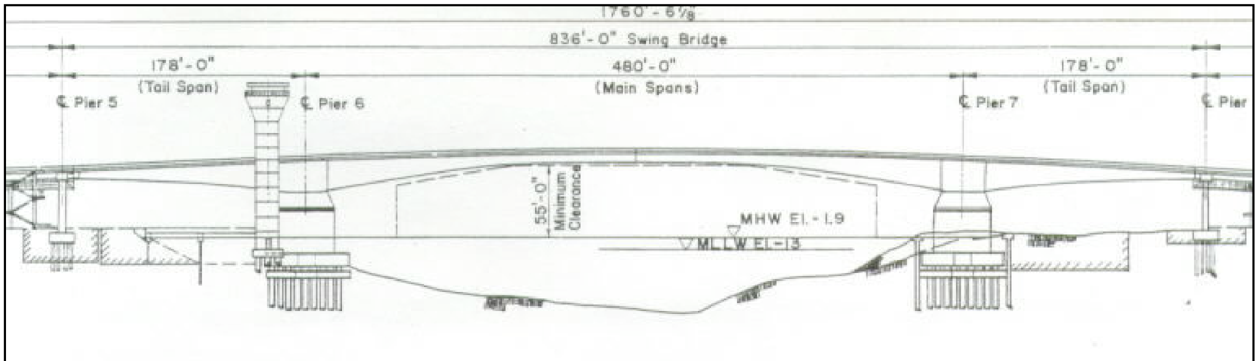


Figure 1 - Elevation from original plan set

The intersection of these two heavily used and important "highways" is accomplished by a unique double leaf concrete box girder swing bridge which opens an average of 8 times per day for marine traffic. The main span of the bridge consists of a pair of 418-foot long swing spans supported on pivot piers spaced 480-feet apart. The architecture of the bridge replicates the high level West Seattle Freeway above, and in addition to winning numerous state and national awards and honors, it received the National Transportation Design Award from the National Arts Foundation in 1994.

The Lift-Turn Cylinders

At 7500 tons per leaf, the Spokane Street Swing Bridge is one of the heaviest movable structures in the world. To handle the bridge's immense weight, the bridge designers developed an innovative "floating barrel" hydraulic cylinder for the center pivot bearing. The lift-turn cylinders, as they are called, lift the bridge leaves approximately one inch in normal operation and allow them to be rotated on a pool of pressurized oil by a pair of slewing cylinders. The concept is similar to a barber's chair, but

Looking westward at the Spokane Street Bridge and the adjacent high-level West Seattle Freeway

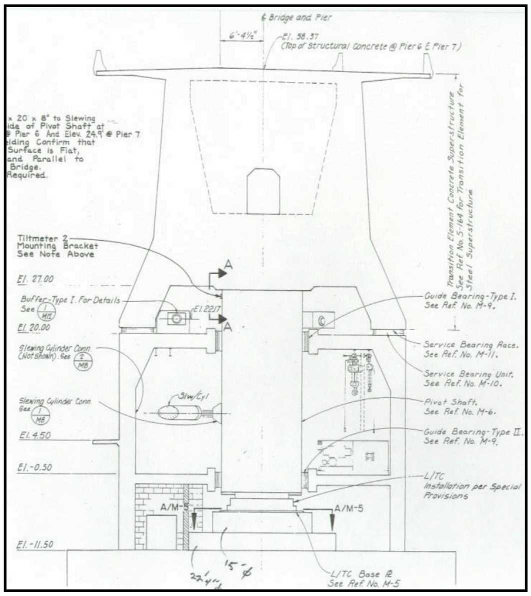


Figure 2 – Pivot Pier Section from original plan set

implementing the concept on such a large scale presented two major challenges. First, normal construction tolerances for the bridge leaves, pivot shafts and pier housings were certain to create a degree of float and eccentricity in rotation that would be incompatible with typical hydraulic cylinder internal clearances. Second, because the cylinder bore is over 103 inches in diameter, the standard approach of structurally attaching the cylinder barrel to the "blind end" would create extremely high combined stresses (hoop and bending) that would be uneconomical, if not impossible to accommodate. **Figure 2** shows the relationship between the bridge leaf, pivot shaft bearings, lift-turn cylinder and slewing cylinders.

The floating barrel concept solves both of these problems by sealing between the barrel and bottom plate but not connecting them structurally. This solves the eccentricity issue by allowing the cylinder barrel to "float" slightly and accommodate irregular pivot shaft motion. The issue of combined stresses is also resolved because the barrel is not constrained at its bottom, so there is virtually no bending stress.

It is fair to say that this innovative lift-turn cylinder design made concrete construction of the bridge possible, and at the time of construction the savings of concrete over steel was estimated to be in the millions. In addition to the numerous awards mentioned above for the bridge design as a whole, the design of the Lift-Turn Cylinder itself won state and national engineering excellence awards.

The Problem

On March 19, 2001, at 4:24 PM, after only 10 years in service, one of the lift turn cylinders failed. The mode of failure was cracking of the barrel at one of the hydraulic supply ports.

The Seattle Department of Transportation (SDOT) immediately installed their one spare cylinder to keep the bridge in operation, and assembled a team of expert advisors to conduct a forensic analysis of the failure. Subsequently, a design team was retained to corroborate the findings of the forensic study and develop a corrective redesign. Through a detailed independent evaluation the design team concurred with the key findings of the SDOT advisory team, specifically that there were four causal factors that lead to the failure.

Lift-turn cylinder installed under pivot shaft

Factor #1: Underestimation of Stress Concentrations

Finite element analysis (FEA) of the original design indicated that principal stresses at the through-barrel hydraulic ports likely exceeded allowable fatigue stresses for an acceptable number of cycles and the barrel material's nominal metallurgy. Calculated principal stresses determined by FEM were found to be significantly larger than stresses estimated using normal stresses modified by published stress concentration factors.

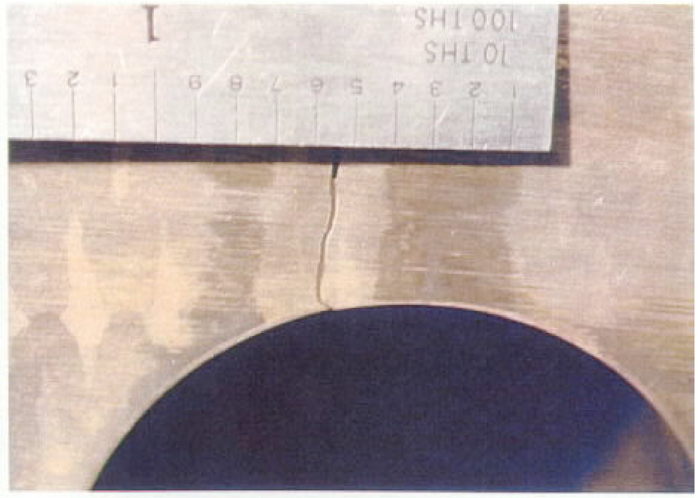
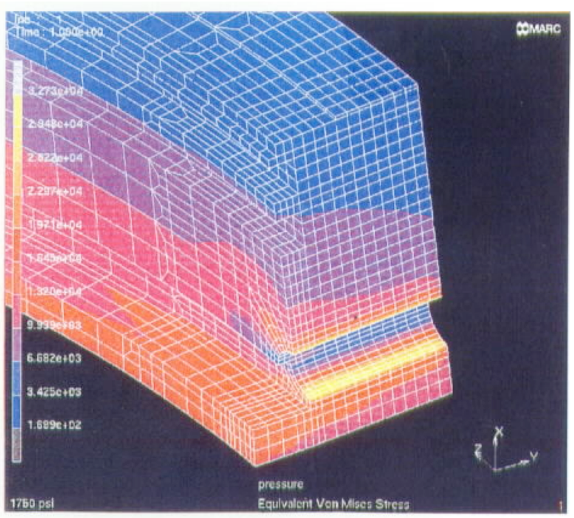


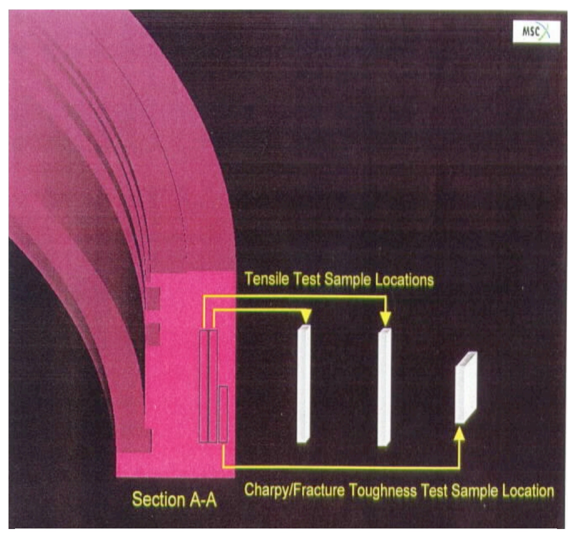
Photo from forensic report showing crack at hydraulic port

Factor #2: Material Properties

The original material specification for the barrel, which was a rolled ring forging, was a 4130 steel type with modified chemistry. The designers attempted to achieve the desired mechanical properties by specifying hardness of the forging itself and relying on the correlation between hardness and strength in



Stress map from forensic study

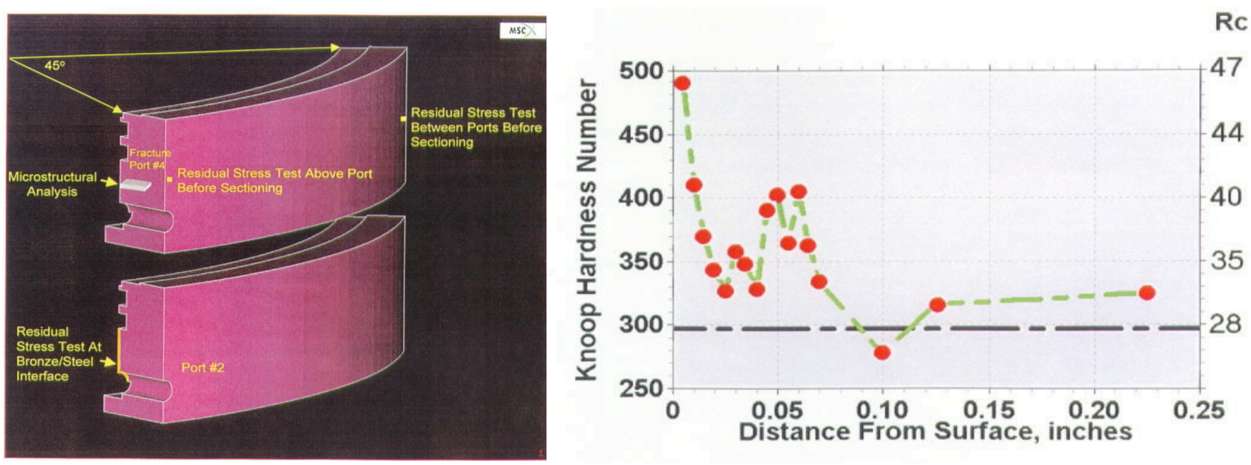


Location of hardness, tensile and toughness tests

steels. This approach was not successful, primarily because of the affects of post forging processes, specifically the application of a welded bronze overlay on the interior surface of the part. Tests on the failed part indicated that internal hardness (and corresponding strength) were lower than specified, but more significantly the material's fracture toughness was significantly below that expected for a 4130 steel. In other words, once a crack started, it would be likely to propagate quickly.

Factor #3: Overlay Welding Created High Residual Stresses

The sliding bearing interface between the cylinder piston and barrel is chrome on bronze. The piston OD is hard chrome plated and the bronze barrel ID was overlayed with bronze by means of a weld overlay process. It is documented that the overlay welding process was problematic from the beginning and that the process was modified over the course of producing three usable barrels. What was not recognized or documented at the time was the creation of large residual tensile stresses at the steel / bronze interface. Testing on the failed part found under-bead stresses as high as 35 ksi. Because these are tensile stresses, they added directly to load-induced stresses caused by normal operation.



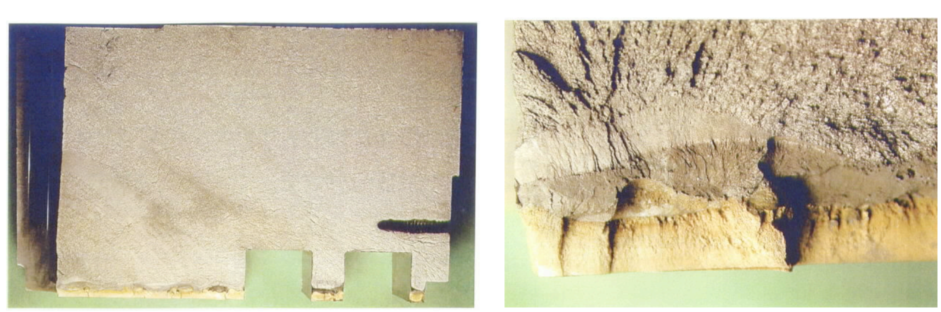
Illustrations from forensic analysis indicating high residual stresses in the under-bead heat affected zone

Factor #4: Initial Under-Bead Crack Went Undetected

Perhaps the most critical problem of all discovered in the failed barrel was that an initial crack, located precisely at the edge of a hydraulic port, went undetected in the original manufacturing process. The existence of this crack in this location resulted in a fracture mechanics "domino effect", virtually assuring premature failure.

Redesign Criteria

Having determined with a high degree of certainty the causes of failure, the design team and SDOT's advisory committee set about the task of developing redesign criteria. The agreed intent was that the criteria should



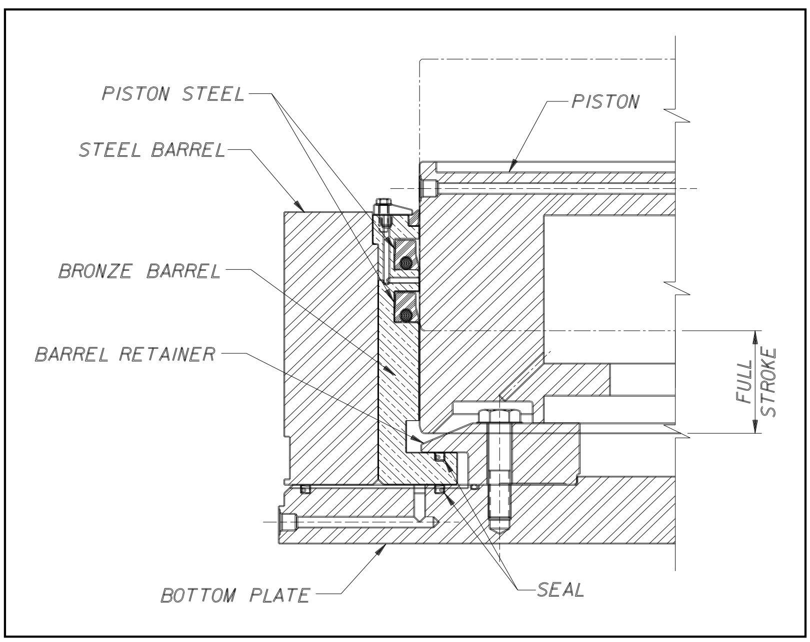
Photograph of failed barrel section and close-up of initiating crack preclude a similar failure in the future without limiting the potential for innovation. Following two rounds of criteria discussion meetings, a surprisingly short list of criteria was agreed upon:

1.) Avoid stress concentrations in the barrel by moving the hydraulic ports to the cylinder bottom plate.
2.) Use standard materials and processes. Verify material properties and avoid manufacturing processes that cannot be tested by practical methods.
3.) Develop a barrel bearing surface that does not require welding to eliminate the potential for high residual stresses and under-bead cracking.
4.) Make use of the existing piston seal design (The unusually large piston seals had been a detail of significant concern in the original design but had been proven through testing and service.)
5.) Design for a nominal life of 100-year service life, or approximately 270,000 cycles.

The New Design

To satisfy criteria 2 and 3 above, a revised barrel concept was developed. Dimensionally and functionally the new barrel is very similar to the original design. The primary difference is the use of a shrink-fit ASTM B271, Grade C86200 bronze liner within an outer ASTM A793, Grade 1, Class 1, steel rolled ring forging. The bronze liner is thick enough to carry the seal grooves, and its relatively light shrink fit in the outer steel ring assures ease of handling during manufacturing and uniform load transfer in service.

The hydraulic fluid ports that had penetrated the barrel wall in the original design and produced a large stress riser were eliminated in favor of ports drilled into the existing bottom plate. Because the bottom plate is only 2.75 inches thick, the ports were reduces from 2 inches to 1.25 inches in diameter. However, calculations indicated that the fluid velocity within the ports would remain within acceptable limits for pressurized fluid supply. Moving the ports eliminated a significant area of concern from the highly tensile stressed barrel to the bottom plate where the stresses are primarily compressive in nature.



Cross section of the revised cylinder design

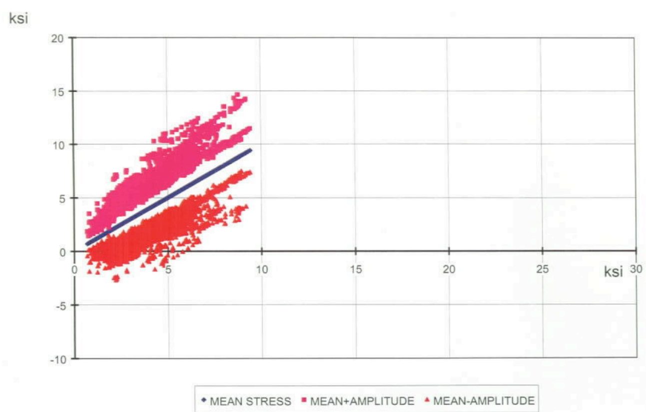
The similarity of the new design to the original made it possible, after a confirmation of structural integrity by way or a detailed NDE program, to reuse the existing bottom plates and pistons.

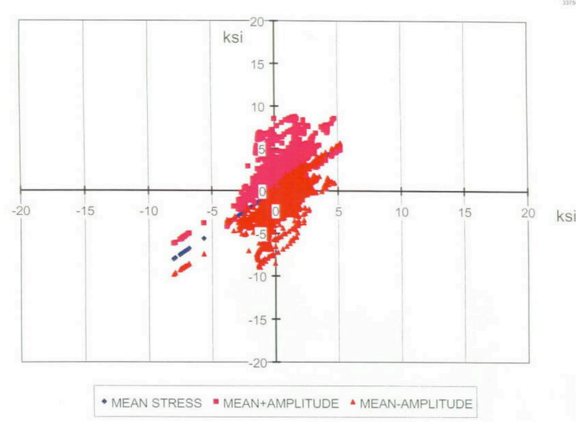
FEA Analysis

To assure satisfaction of the design life criteria, the revised design was subjected to two independent FEA analyses. These analyses were conducted in parallel using different software platforms. Key characteristics of the FEA approach and use of its output can be summarized as follows:

1.) One million cycles was taken as the acceptance criteria. This effectively constituted a safety factor of 4 over the part design criteria.

2.) Both materials were considered to be ductile, and modifiers for finish, notch sensitivity, etc., were selected accordingly.





Modified Goodman plots of von Mises and Principal stresses in the bronze liner

3.) To accommodate concerns of SDOT's advisory committee, both distortion energy (von Mises) and first principal stress failure theories were evaluated. The evaluation was accomplished per the modified Goodman method.

4.) True 3D models were developed to model the effects of discontinuities on localized stresses. This made it possible to identify stress "hot spots" and employ post-machining operations such as burnishing and polishing to eliminate potential crack initiators. Stress concentration multipliers were not used.

FEA Model Corroboration

Analytical verification of the FEA models was performed by using two independent models. The primary model was developed using GT_STRUDL. This model consisted of three sub-models as follows:

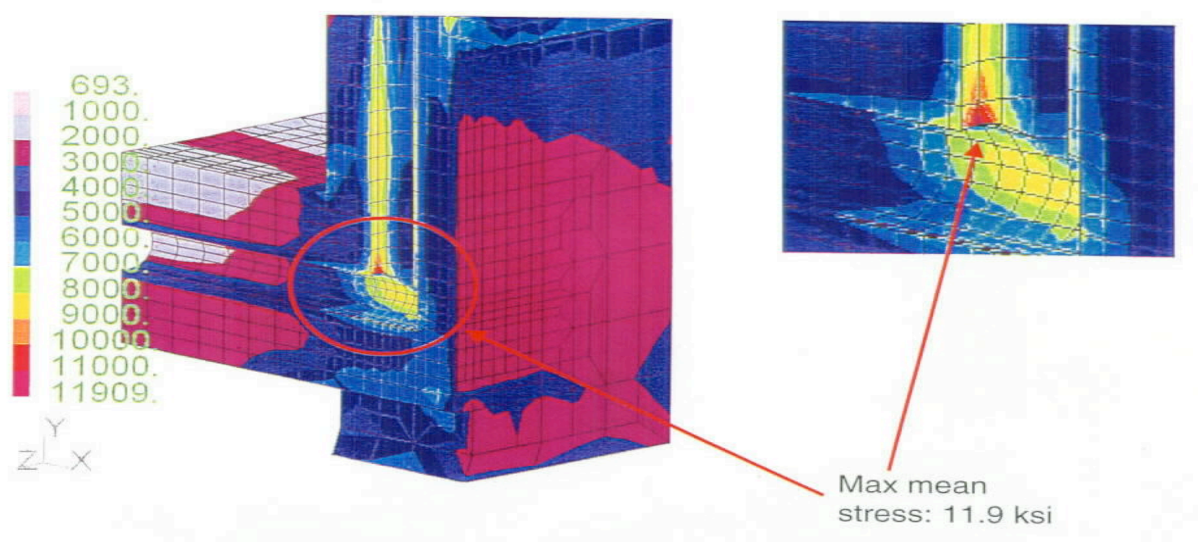
3D "Global" Model of a 12-degree ring piece
3D "Local" Model of area around the seal lubrication hole

2D "Axisymmetric Model

Each of these analyses was performed to find stresses at different areas of interest. The 3D global model was used to determine stress state in steel and displacements for 3D local model. The 3D local model was used to determine stresses around the seal lubrication hole in the bronze. The 2D axisymmetric model was used to find stresses in seal groove corners. The models ranged in size from 3,740 8-noded 2-D elements in the axisymmetric model to 12,277 8-noded solid elements in the 3-D global model.

The verification model was developed using the SAP2000 platform. The verification model consisted of 13,570 8-noded solid elements for the 3-D global model. Like the primary model this model was for a 12 degree section of the barrel.

In addition to preparing two independent FEA models, a model of the existing design was prepared and results of each were corroborated with field test data. Strain gages and linear displacement transducers (LDTs) were applied to both the existing and new barrels. Strain gages were used to record barrel hoop stresses at various locations on the barrel. LDTs were used to record barrel OD expansion. Data was collected from a number of bridge operations. The field data was found to correspond well with the predicted hoop stresses and barrel expansion.



FEA stress map indicated localized high stresses

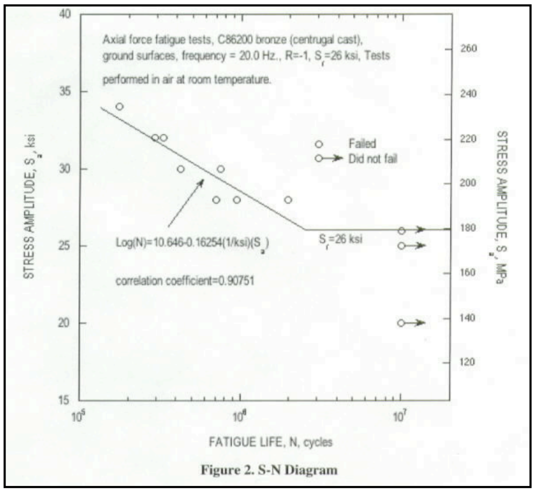
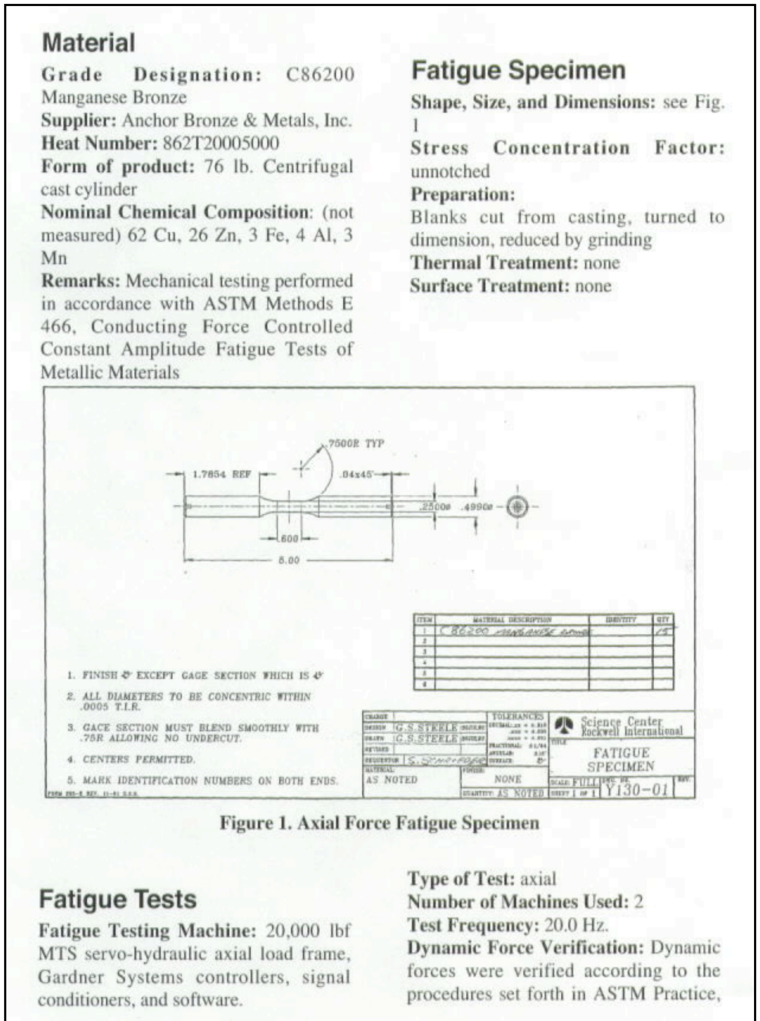


Figure 4 Fatigue Test Results for C86200 Bronze



Material

Grade Designation: C86200 Manganese Bronze
Supplier: Anchor Bronze & Metals, Inc.
Heat Number: 862T20005000
Form of product: 76 lb. Centrifugal cast cylinder
Nominal Chemical Composition: (not measured) 62 Cu, 26 Zn, 3 Fe, 4 Al, 3 Mn
Remarks: Mechanical testing performed in accordance with ASTM Methods E 466, Conducting Force Controlled Constant Amplitude Fatigue Tests of Metallic Materials

Fatigue Specimen

Shape, Size, and Dimensions: see Fig. 1
Stress Concentration Factor: unnotched
Preparation: Blanks cut from casting, turned to dimension, reduced by grinding
Thermal Treatment: none
Surface Treatment: none

1. FINISH EXCEPT GAGE SECTION WHICH IS
2. ALL DIAMETERS TO BE CONCENTRIC WITHIN .0005 T.I.R.
3. GAGE SECTION MUST BLEND SMOOTHLY WITH .75R ALLOWING NO UNDERCUT.
4. CENTERS PERMITTED.
5. MARK IDENTIFICATION NUMBERS ON BOTH ENDS.

Figure 1. Axial Force Fatigue Specimen

Fatigue Tests

Fatigue Testing Machine: 20,000 lbf MTS servo-hydraulic axial load frame, Gardner Systems controllers, signal conditioners, and software.

Type of Test: axial
Number of Machines Used: 2
Test Frequency: 20.0 Hz.
Dynamic Force Verification: Dynamic forces were verified according to the procedures set forth in ASTM Practice,

Excerpts from fatigue strength findings for C86200

Fatigue Strength of Bronze

Armed with all this detailed stress information, all that remained was to construct acceptable stress boundaries on the Goodman diagrams using material strength data. For the steel forging this was straight forward, but for the bronze liner this created a minor hurdle. This is because fatigue strength data on copper alloys is not widely available, in fact no fatigue strength information at all could be found on the exact alloy that had been preliminarily selected. Furthermore, copper alloys do not exhibit an endurance limit like steels, nor is there a direct relationship between ultimate strength and endurance strength as there is in steels. Confronted with this situation SDOT was undaunted – they simply commissioned a test program to determine the needed strength information.

Contractor Selection Method

Given the unique nature of the bridge and lift-turn cylinder and a history of difficulties experienced in fabrication of the original lift-turn cylinder assembly, SDOT decided not to proceed with a conventional low-bid contract for replacement of the barrels. Instead, they elected to utilize a two-step process that incorporated both qualifications and price. Step one involved selecting up to three qualified firms to participate in the design phase by performing constructability reviews. Step two involved selection of one of the participating firms to perform the manufacturing work based upon low bid.

In August of 2002, SDOT issued a Request for Letters of Interest and Statements of Qualifications from qualified manufacturing firms. The scope of the work included performing constructability reviews, attending design team meetings, and preparing a bid to manufacture three new barrel assemblies for the lift/turn cylinders. Two firms were selected for the first step. Each firm was paid to participate in the design phase.

Following completion of the design phase bids were requested from the participating manufacturing firms. A low bid of $644,410 was received from Steward Machine Company of Birmingham, Alabama. The low bid was 13 percent below the engineer's estimate of $779,270.

Constructability Reviews and Issues

The design required a finished ID on the barrel of 103.275/103.279 inches. The tight tolerances are necessary to control the piston seal extrusion gap and maintain a gap range of 0.026-0.034 inches. This range was reduced by 0.010 inches from the original design based upon concerns that the wider extrusion gap had led to damage of the edge of the seals. In previous inspections some nibbling of the seal edge was observed. Certainly, manufacturing of a large ring to tight tolerances is not without challenge. However, the prequalified manufacturing firms expressed confidence in their ability to finish the barrel to the specified tolerances.

Hard chrome plating of the new bimetallic barrel was identified early on as a potential constructability issue. Research of the issue revealed mixed results. Several chrome shops were contacted and some indicated concerns while others did not. In general the concerns focused on the following issues:

- Deposition rates for chrome on steel and bronze are significantly different. If chromed together the thickness of the chrome could vary greatly between the two base metals.

- The interface between the bronze and steel could act as a wick for chromic acid. The chromic acid could then cause oxidation of the base material in service that could in turn act as an abrasive that could damage the chrome surface or the seals.

To develop a biddable specification for the chroming process, SCDOT elected to perform a series of advance chrome tests on sample bimetallic parts made of the same materials as the proposed barrel. In all cases, a groove, or chamfer, was machined at the interface between the bronze and steel. This groove was sealed with an epoxy compound to prevent chromic acid from penetrating into the interface. The fit between the bronze and steel of the sample parts was designed to provide a similar contact pressure as was proposed for the new barrel. Samples were fabricated and chromed using a variety of procedures, summarized as follows:

- Masked the chamfer and chromed as a bimetallic assembly
- Masked the steel and chromed the bronze, followed by masking the bronze and chroming the steel
- Masked the bronze and chromed the steel, followed by masking the steel and chroming the bronze
- Chrome steel and bronze independently prior to assembly.

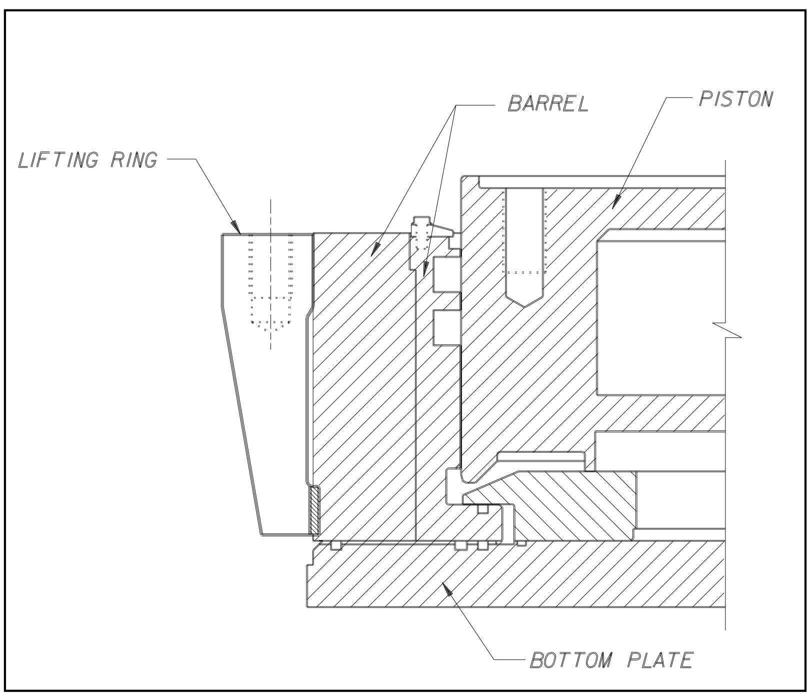
The sample bimetallic parts were ground and visually inspected to verify that the chrome was bonded to the base material and that no cracks, fissures, or flaking developed within the chrome. Samples were cut in half and examined, verifying that the epoxy material adequately prevented intrusion of chromic acid into the joint between the steel and bronze. The testing indicated chroming the parts as an assembly did in fact result in significant differences in chrome thickness. However, the results were inconclusive as to defining one process as being superior.

Based upon the results of the tests it was decided to proceed with some caution. The specifications required the bottom surface of the barrel to be hard chrome plated to Federal Specification QQ-C-320B, type 1, class 2A. The finished minimum thickness of the chrome was specified as 0.005 inches. However, the contractor was required to develop and test the chroming process on a similar bimetallic part. As in the design stage, the part was ground and inspected with a photomicrograph to verify bond and chrome integrity. The contractor was also required to bid two processes for chroming. One for chroming the part as an assembly, and an alternate for chroming the assembly in two steps, masking the bronze and chroming the steel followed by masking the steel and chroming the bronze.

Specialized Handling Tools

In concert with design of the new barrel, a new set of tooling was also designed. The original construction had included fabrication of specialized tooling to accompany the lift/turn cylinder assemblies. Taking a similar approach, a new set of tooling was designed to accompany the new barrels. In this case the tooling was designed to be compatible with both the new barrels and the existing components, including the pistons and bottom plates. New tooling included the following:

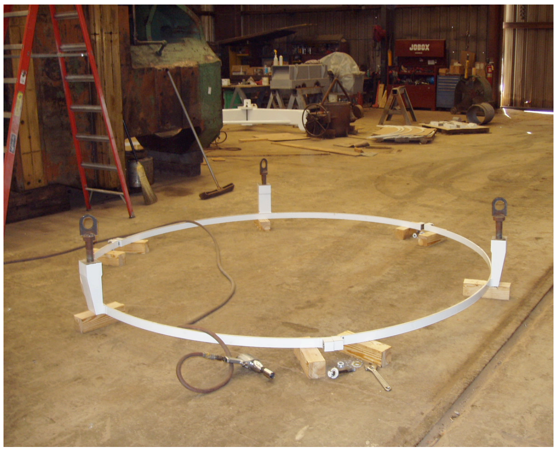
- A lifting ring - used to lift the barrel or lift/turn cylinder assembly without requiring holes tapped into the barrel as was the case with the original tooling.
- Piston installation tooling – for use in controlled lowering the piston into the barrel.
- Lifting Frame – for use in lifting the lift/turn cylinder assembly or major components such as the piston, barrel, or bottom plate.



Barrel Section with Lifting Ring

In the original cylinders, the barrel forging had drilled and tapped holes in numerous places for attachment of tooling and shipping blocks. This approach was inconsistent with the number one redesign criterion of avoiding stress concentrations caused by holes. It was therefore necessary to design a new tooling system for handling the cylinders in the shop and at installation. The selected approach utilizes a band weldment with tapped blocks for lifting with a specialized Lifting Frame weldment.

The band is circumferentially clamped to a to a groove in the barrel. Because it was decided that this band should remain attached to the cylinder while in service, the band itself will undergo the same types of cyclic loading as the cylinder barrels and was designed accordingly.



Lifting Ring

Lifting Frame

Manufacturing Process

Notice to proceed with the manufacturing was issued on July 16, 2003. To maintain the bridge in service, the replacement lift/turn cylinder barrels and associated tooling were manufactured, assembled, tested, and replaced in sequence. Essentially, procurement of materials, fabrication, and rough machining of all three new barrels was initiated at the same time.
However, the other work was sequenced to maintain operation. The piston and bottom plate of the existing failed cylinder were shipped to the fabricator’s shop, inspected and repaired as necessary. When the first barrel assembly was completed the existing parts were assembled with it to form the first reconditioned lift/turn cylinder. This first cylinder was then shipped to the site and swapped for one of the cylinders in service. The first lift/turn cylinder exchanged was the one in the east pivot pier. The exchange took place on March 15, 2004. The second assembly was then shipped to the fabricator for assembly with the second

Barrel with Lacquer Masking

barrel assembly. This process was then repeated until both cylinders in service were replaced and a spare was delivered to the City. The lift/turn cylinder in the west pivot pier was exchanged on May 3, 2004.

Empire Hard Chrome of Chicago, Illinois performed the barrel chroming. As it turned out, applying hard chrome to the bottom of the lift/turn cylinder barrels was every bit the difficult challenge anticipated. The first barrel assembly had to have the chrome machined off and reapplied. All three barrel chrome surfaces ended up having some degree of indications. Two of the barrels were accepted with minor indications after the indications were inspected in detail and determined not to be harmful or indicative of a systematic problem. However, the third barrel chromed required corrective action for some dime-sized indications. The chrome flaws were repaired using a brush plating process.

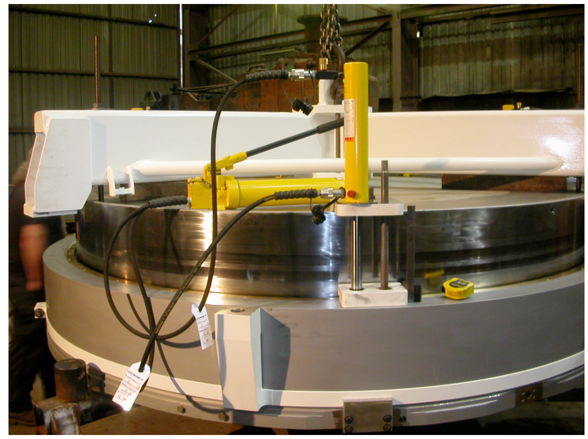
Each lift/turn cylinder assembly, composed of an existing piston and bottom plate and a new bimetallic barrel, was assembled and tested in the shop prior to shipment to the bridge. Testing included a pressurized leak test and a rotational test. Both the primary and secondary piston seals were tested at 5 psi for 2-hours to verify that no leakage occurred. The rotational test involved rotating the piston 360 degrees to verify that no binding of occurred.

Hard Chrome on Barrel

Bottom Plate

Installing Barrel on Bottom Plate

Barrel on Bottom Plate



Installing Piston with Tooling

Conclusions

The Spokane Street Swing Bridge is one of the world's largest movable structures. A unique lift/turn cylinder is the key to the design, providing an economical method of supporting a 15-million pound concrete superstructure. Premature failure of a cylinder barrel on one lift/turn cylinder after only 10 years of service caused the owner, the Seattle Department of Transportation to review the design in detail before deciding on corrective action. A thorough examination of the original design and construction revealed inadequacies that could not be repaired with certainty. As a result, a new design was developed and examined through a process that included detailed analysis, research, and independent review. The new design is a bimetallic barrel of outer steel ring and inner bronze ring. The new design eliminates physical stress risers in the barrel section and avoids welding processes that could produce residual stresses or reduce material toughness. Through instrumentation and testing the performance of the new design was verified.