HEAVY MOVABLE STRUCTURES, INC.

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FATIGUE LIFE EXTENSION OF MAIN COUNTERWEIGHT SHEAVE TRUNNIONS

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MACHINERY/MECHANISMS

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Introduction

The counterweight sheave trunnions that support the vertical lift span and counterweights are fracture critical members whose failure could lead to a catastrophic collapse of the counterweights and/or lift span. As these structures get older, fatigue lives of the trunnions become exhausted. The fillets at trunnion shaft diameter transitions act as stress raisers, greatly reducing fatigue lives. Trunnion fatigue cracks have initiated at less than 1 million stress cycles. On two structures (Shippingsport and Valleyfield Bridges), fracture of the trunnion at the transition occurred during service resulting in extensive structure down time and costly repairs.

A practical field procedure for proactive repair of the trunnions using field machining and shot peening can be implemented to extend the lives of these critical components. This procedure provides an alternative to costly replacement of the trunnions. Replacement of the trunnions usually involves the replacement of the sheaves because of the shrink fit between the trunnion and sheave. This procedure can also be utilized to repair trunnions with fatigue cracks.

This procedure has been successfully applied to trunnions on the PATH-Hackensack River Vertical Lift Bridge in Jersey City, New Jersey and to the Carlton Bridge in Bath, Maine. On the Carlton Bridge, cracks were removed from three of the four trunnions.

Fatigue of Counterweight Sheave Trunnions

Allowable Design Stresses for Counterweight Sheave Trunnions

Changes in the design philosophy for counterweight sheave trunnions over the years can be traced by noting the changes in requirements in the applicable specifications.

C.C. Schnieder published his movable bridges design specifications in 1908 with an allowable bending stress of 6.0 ksi. B.R. Leffler in 1913 raised it to 9,400 ksi in his paper. Dr. Waddell in 1916 used 8.0 ksi. The 1922 American Railway Engineering Association (AREA) specification allowed 13.0 ksi. Mr. Hovey in his two-volume treatise on movable bridges in 1927 gave 15.0 ksi for annealed carbon steel and 25.0 ksi for heat-treated carbon steel. The American Association of State Highway Officials (AASHO) in 1938 gave 9.0 ksi for carbon steel and 15.0 ksi for heat-treated alloy steel. AASHO raised the value in 1953 to 16,000 ksi. AREA raised the value in 1953 to 13.0 ksi for carbon steels and 15,000 ksi and 16.0 ksi for higher grades of steel. AASHTO in 1978 and AREA in 1985 allowed 15.0 ksi for Class D carbon steel. AREA in 1986 and AASHTO in 1988 reduced the value to 10.0 ksi for all classes of steel.

The reduction to current allowable bending stresses in 1986(AREA) and 1988(AASHTO Standard Specification) were brought about because of input from AREA Committee 15 - Steel Structures.

The American Society of Mechanical Engineers published codes for the Design of Transmission Shafting in 1927 and 1985. The 1927 code is fairly simple while the 1985 code is much more complex. For shafts without keyways, the 1927 code gives an allowable bending stress of 10.67 ksi without a stress concentration factor. The 1985 code, when used with reasonable values for the seven coefficients that influence the allowable bending stress, gives 10.28 ksi.

AASHTO LRFD Specifications (2000) changes the design criteria for trunnions subjected to >1,000,000 stress cycles to a method based on the Soderberg fatigue failure theory.

A partial summary of allowable bending stresses in trunnion shafts for counterweight sheaves, starting in 1908, follows:

Date	Source	Allowable Bending Stress (ksi) [i]
1908	C.C. Schneider	6.0
1913	B.R. Leffler	9.4 (Rolled or Forged Steel) [ii]
1916	J.A.L. Waddell	8.0
1922	AREA Specification	13.0 (Rolled or Forged Steel) [iii,iv]
1927	O.E. Hovey	15.0 (Annealed Carbon Steel)
		25.0 (H.T. Carbon Steel)
1938	AASHO Specification	9.0 (Carbon Steel) [iii]
		15.0 (H.T. Alloy Steel) [iii]
1953	AASHO Specification	16.0 (H.T. Alloy Steel)
1953	AREA Specification	13.0 (Carbon Steel)
		15-16.0 (Alloy Steels)
1978	AASHTO Specification	15.0 (Carbon Steel) [v]
1985	AREA Specification	15.0 (Carbon Steel) [v]
1986	AREA Specification	10.0 (All Grades) [v]
1988-Present	AASHTO Std. Spec.	10.0 (All Grades) [v]
2000-Present	AASHTO LRFD	See Note VI.

i) Nominal bending stress, with no correction for stress concentrations and/or number of stress cycles, except as noted.

ii) For less than 5 stress reversals per minute

iii) For 10 or less stress reversals per minute

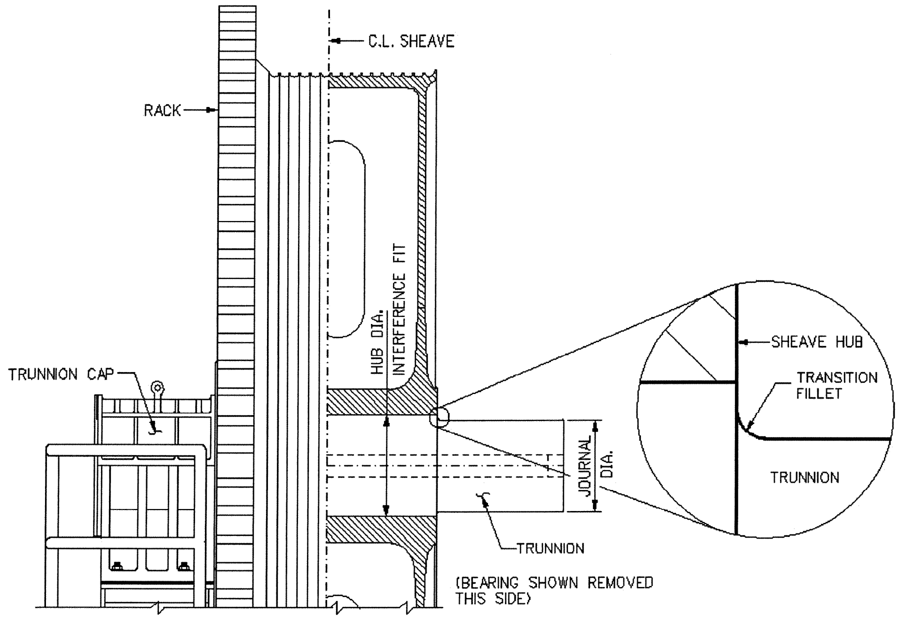
iv) "The following unit stresses in pounds per square inch shall be used for machinery and similar parts in which stresses are not increased by impact."

v) "All of the unit stresses specified in this article provide appropriate safety factors against static failure and against failure by fatigue with and without reversal of stresses. In the determination of the safety factor against fatigue failure, provision was made for stress-raisers that would produce local stress concentration of 140 percent of the computed stress. For trunnions and counterweight sheave shafts, this provides for the customary shoulders at the bearings having fillets of reasonable radius..."

vi) Design criteria for trunnions subjected to >1,000,000 cycles is based on the Soderberg fatigue failure theory.

Trunnion Proportions

The ratio of the journal length to the journal diameter (l/d) gives a good indication of the bending stress in the trunnion. The longer the journal in proportion to its diameter, the higher the bending stresses.



COUNTERWEIGHT SHEAVE AND TRUNNION

Bridge machinery specifications generally allow 1.5 ksi on the net projected bearing area for counterweight sheave trunnions. If the grooves take out 10% of the projected bearing area, the bending stress in the trunnion, at the transition fillet, is as follows for various l/d ratios:

l/d	Bending Stress (ksi)
1.1	8.33
1.2	9.92
1.3	11.64
1.4	13.50
1.5	15.50

Thus, journals with a l/d greater than 1.2 probably exceeds the current allowable bending stress.

Known Main Counterweight Sheave Trunnion Failures

We know of at least eleven bridges that developed cracks in counterweight sheave trunnions. Eight of these bridges developed cracks in or near the transition fillet and three bridges developed cracks in or near welds. On two of these bridges (Shippingsport and Valleyfield), a trunnion fractured in service. Neither failure resulted in a catastrophic collapse. However, both bridges were out or service for extended periods and repairs were difficult and costly.

<u>Carlton Bridge – Maine</u>

Cracks were discovered in 1995 in one of four trunnion shafts on the Carlton Bridge in Bath, Maine. These cracks formed at the toe of the transition fillet, at the base of scores, on the inboard side of the southeast trunnion shaft. The cracks were short and shallow (1” to 2” long by 1/8” maximum depth).

The trunnion had been in service for 68 years with an estimated 450,000 stress cycles experienced at the time the cracks were detected. The cracks were detected early enough to enable the repair of the trunnion.

Trunnion repairs were not performed until the spring of 2001, to allow for their inclusion in a bridge rehabilitation project. At that time, additional cracks were discovered in both west tower trunnions (north fillets only) during machining. The crack in the NW outboard fillet was continuous for 310^0 around the fillet circumference and had a maximum depth of $^3/_8$". Several separate cracks were discovered in the SW inboard fillet. These cracks, located around the circumference, had a maximum depth of ¼". All cracks were removed by machining followed by shot peening to improve endurance.

The stress level of this trunnion shaft is among the highest we have seen for this type of trunnion. The nominal bending stress at the transition fillet is calculated at 17.0 ksi, not including any increase in stress due to stress concentrations. The stress concentration factor (at the transition fillet) is also high at 2.14. The factored stress range is 72.8 ksi. Scoring at the transition fillet, acting as a stress-raiser may have contributed to the formation of the cracks.

Duluth Aerial Bridge - Minnesota

Cracks were discovered in two of the three remaining original trunnions of the Duluth Aerial Bridge in Minnesota. The first crack was discovered in late 1996. It is located at the center of the transition fillet and covers approximately 2/3 of the trunnion circumference. The maximum depth of the crack was $^5/_8$". This trunnion was replaced in March 1997. The second crack was discovered in September 1998. It was approximately 3 in. long and showed little depth as indicated by the lack of bleed through of dye from the dye penetrant test.

The nominal bending stress at the transition fillet is calculated at 12.9 ksi; not including any increase in stress due to stress concentrations. The stress concentration factor (at the transition fillet) is high at 2.14. The factored stress range is 55.2 ksi.

The Aerial Bridge opens more than 5,000 times per year and the trunnions see more than 33,000 stress cycles per year.

CONRAIL Bridges - New Jersey

Cracks were recently discovered in trunnions on two CONRAIL bridges in New Jersey. One of eight trunnions was cracked on the Hackensack River Bridge. Eight of eight trunnions were cracked on the Upper Bay (Newark) Bridge. The cracks were too deep to be repaired and these nine trunnions (and sheaves) have been replaced. Both bridges open frequently. The trunnions on the Upper Bay Bridge are subjected to approximately 18,000 stress cycles per year.

Shippingsport Bridge - Illinois

The only sheave trunnion failure report widely circulated among the profession, is the Illinois DOT Physical Research Report No. 87, dated June 1980 which describes the failure of a sheave trunnion on the Shippingsport Bridge over the Illinois River near La Salle, Illinois. The trunnion failed after 45 years of service and an estimated 600,000 plus revolutions. The failure initiated from fatigue cracks that formed at the transition fillet.

The report does not give the depth and length of the cracks. From review of the photographs of the fracture surface, they appear to be in the range of 2 in. deep and they cover the entire circumference.

The report does not give any specific load or stress analysis data but by extrapolating the data contained in the report, the nominal bending stress in the trunnion, at the transition fillet, appears to have been between 17.5 and 19.3 ksi, not including any increase in stress due to stress concentrations. We calculated the stress concentration factor to be 1.96. This yields a factored stress range between 68.6 and 75.7 ksi.

Valleyfield Bridge - Quebec

One of the counterweight sheave trunnions on the Valleyfield Bridge in Valleyfield, Quebec, which is owned and operated by the St. Lawrence Seaway Authority (SLSA), fractured in the mid 1980's after an estimated 800,000 plus cycles. The bridge was constructed in 1956.

The allowable nominal bending stress used for the design of the sheave trunnions was 15.0 ksi. The SLSA issued their own design specification in 1956 for the bridges built on the Seaway. This specification was probably based on the Canadian Engineering Standards Association Specification A20 published in 1927. The actual nominal bending stress is calculated at 15.6 ksi, not including any stress increase due to stress concentrations. The calculated stress concentration factor is 1.8. The factored stress range is 56.16 ksi.

Lubrication grooves in the trunnions for Valleyfield are stress raisers. As part of a sheave-strengthening contract in 1962, the grooves were filled with silver solder and the lubrication grooves were moved to new bearing bushings. The situation was made worse by the drilling of holes in the trunnion lubrication grooves to help anchor the silver solder in the grooves. Reportedly, cracking initiated at one of these anchor holes near the transition fillet in the shaft; leading to the eventual fracture.

Calumet River Bridge - Illinois

The investigation and repair of sheave trunnions in a railroad lift bridge over the Calumet River in Illinois took place in 1953 and the history is somewhat spotty.

Various repairs had been made to the built-up sheaves, by welding, to tighten up the fit of the web plates to the cast hubs and the cast hubs to the trunnions. The welds that connected the hub to the trunnion, broke, allowing the sheave to tilt relative to the trunnion. As corrective work was being carried out, a crack was visually detected in the trunnion. The crack was 3/8" deep and covered 110^0 of the circumference. The crack was in the journal at the root of the transition fillet adjacent to the web of the sheave. The repair welding between the hub and trunnion apparently caused pre-existing but obscure cracks in the trunnion to open up.

Eventually, cracks were found in 7 of 16 trunnion journals. The cracks varied in depth 1/8" to 1/2" and covered an average of 120^0 circumferentially. We have no records concerning the eventual corrective work.

The nominal bending stress is 11.6 ksi. The stress concentration factor at the transition fillet is 2.3. The factored stress range is 53.36 ksi. The number of stress cycles between 1916 and 1953 is not known.

Fatigue Analysis

Counterweight sheave trunnions are typically stepped cylindrical shafts with fillet radii at all section transitions. The transition fillet produces a stress concentration that magnifies the nominal (bending and torsional) stress. The radius size and trunnion proportions govern the magnitude of the stress concentration. Older bridges typically have higher stress concentrations in the order of 1.7 to 2.2. Current code stipulates a maximum stress concentration factor of 1.4.

The trunnion failures typically occur at a relatively low number of cycles (<1,000,000). The allowable fatigue stress range for AASHTO Fatigue Category A is 30 ksi for 1,000,000 cycles and 37 ksi for 500,000 cycles. If no corrections are made for stress concentrations at the transition fillet, the non-factored stress range for the previously reported cracked trunnions falls between 19.4 ksi and 36 ksi. This would indicate that the fatigue life for these trunnions would be at least 500,000 cycles and probably more than 1,000,000 cycles if there were no transition. The effect of the large stress concentration at the transition fillet substantially reduces the fatigue life of these trunnions. The highest factored stress range that we have encountered at the fillets is 72.8 ksi (Carlton Bridge).

ANSI/ASME B106.1M (1985) *Design of Transmission Shafting* presents a method for calculating the endurance limit of a stepped shaft. The method modifies the endurance limit of a highly polished, notch free, rotating beam test specimen (S_f^*) to account for differences such as surface finish, size, reliability, temperature, stress concentration and other miscellaneous factors. This modified endurance limit (S_f) can then be compared to the calculated stress to determine if the fatigue life is finite or infinite. The basic relation is as follows:

$$S_f = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \cdot k_g \cdot S_f^*$$

k_a = Surface Finish Factor
k_b = Size Factor
k_c = Reliability Factor
k_d = Temperature Factor
k_e = Duty Cycle Factor
k_f = Fatigue Stress Concentration Factor
k_g = Miscellaneous Effects Factor (Includes Corrosion)

The primary factor governing the fatigue life of the main counterweight sheave trunnions is the fatigue prone transition fillet. Typically there are no grease grooves in the journals. The center-bore has no effect on their fatigue life. Holes for dowels used between the sheave and trunnion when present in the hub section, do not act as a severe stress raiser and their location is in the thicker trunnion section that is reinforced by the sheave hub.

The endurance limit is also a function of the surface condition. Typically, the trunnions were polished to a mirror finish when originally fabricated. This provides the highest practicable endurance. The fatigue resistance for a forging *[older trunnions were typically fabricated from ASTM A18 and A235 forgings]* for that finish *[polished]* should be well above AASHTO Fatigue Category A.

The actual surface conditions deteriorate over time. Most trunnions on exposed tower tops exhibit scoring resulting from contamination of the bearings. Also, if lubrication of the trunnions is not regular, surface corrosion (staining/pitting) can form. These conditions adversely affect endurance.

Trunnion fillets on older bridges typically have varied surface conditions ranging from lightly scored/pitted to heavily scored/gouged.

If we assume the scoring occurred early in their service life, then using a surface factor for a ground or machined surface instead of the as-built polished surface may result in a more accurate assessment of fatigue life, since the scoring has a similar effect as machining marks on endurance.

To calculate the effect that corrosion has on endurance is difficult since we have no way of knowing when the corrosion formed, and in time, any part will fail when subjected to repeated stressing in a corrosive atmosphere (there is no fatigue limit).

If the calculated fatigue life is finite, then the following relation can be to determine the estimated life:

$$N\ (\text{cycles}) = (\sigma_N + a)^{1/b}$$

Where $a = [0.9 \cdot (S_{ut})]^2 + S_f$ and $b = -\ 1/3 \cdot \log\,[(0.9 \cdot S_{ut}) + S_f]$ and

S_{ut} = Ultimate Strength.

Fracture Mechanics Analysis

Once cracks form in the transition fillet of shafts subjected to rotating bending, they generally spread and deepen as semi-elliptical surface cracks. Some basic characteristics of fatigue crack growth are stated as follows:

> The probability for fatigue cracks to initiate at identical stress raisers subjected to the same stress is equal... The relative rate of crack propagation along the surface (circumference) and in the depth direction depend on the stress gradient along the depth such that the higher the stress gradient, the slower the relative propagation in the depth direction.[1]

Thus, we expect the cracks to form at various locations around the circumference at the transition fillet. For the high stress, lower cycle, fatigue condition of bridge counterweight sheave trunnions, the cracks will spread at a faster rate along the surface than in the depth direction; eventually joining up and then deepening at an accelerated rate. This conclusion is in agreement with known bridge counterweight sheave trunnion failures.

The analysis to predict crack growth rates to fracture can be made using Fracture Mechanics methodology. A fatigue crack propagates normal to the primary tensile stress component at the crack tip.

The analysis of the crack growth rate from the smallest detectable size (say ¼ in. long with negligible depth) to an approximate depth of 0.3 in. is complex due to the effect of the stress concentration. The stress gradient due to the stress concentration at the transition fillet decays rapidly, so that after crack extension into the shaft occurs (beyond 0.3 in. deep), only the nominal tensile stress is effective in extending the crack.

If the analysis for crack stability and growth rate starts at an assumed condition beyond 0.3 in. deep crack around the entire circumference, the effects of the stress gradient at the stress concentration can be neglected, and then only the nominal bending stress is effective in extending the crack.

An estimate of crack behavior at this point can be made using standard fracture mechanics formulas[2] developed for shafts with cracks subjected to bending to calculate the stress intensity factor K_{IA}.

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[1] Barsom & Rolfe, *Fracture & Fatigue Control in Structures*, 2nd edition, pp. 243-244.

[2] Walter D. Pilkey, *Stress, Strain, and Structural Matrices*, 1rst edition, p.341.

$$K_{IA} = \sigma_N \cdot \sqrt{\pi a} \cdot F_1\,(a/b)$$

Where b = shaft diameter and a = radius to the crack tip.

$$\sigma_N = (4 \cdot M) + (\pi\ .\ a^3)$$

σ_N is the nominal bending stress at the surface and M is the applied moment.

The function F_1 (a/b) ~ 0.375 when a/b < 0.5.

Using the Carlton Bridge as an example, for a 0.5" deep crack, $\sigma_N = (4 \cdot 9747$ k-in) + (π . 8.5^3) = 20.2 ksi, therefore K_{IA} = 39 ksi $\sqrt{in.}$.

By comparing the stress intensity factor (K_{IA}) to the fracture toughness (K_{IC}) of the steel, we know whether crack instability (fracture) occurs.

The Carlton Bridge trunnions are composed of nickel steel forgings (ASTM A-18, Grade H, F_y = 50.0 ksi). There is no modern equivalent to this steel used in bridge construction and fracture toughness test data does not exist. Therefore, an empirical value for its fracture toughness must be substituted in-lieu of actual test data for the material. Dr. John Fisher (Lehigh University) made the following material assessment for the Carlton Bridge trunnions:

> The material physical properties should provide excellent toughness characteristics if we assume that modern day castings with similar composition and tensile properties to the A18 GrH is a reasonable indication. Typically we would anticipate Charpy V-notch values of 15 ft-lbs. at -100^0 F. This would suggest an upper shelf behavior and toughness that was above average for the loading condition and service temperature anticipated at the Carlton Bridge.

Dr. Fisher estimated that the fracture toughness of the A18 GrH steel to be approximately 150 ksi $\sqrt{in.}$. The calculated stress intensity factor (K_{IA}) at a crack depth approaching 0.5 in. is 39 ksi $\sqrt{in.}$. This is well below the estimated fracture toughness. Therefore, stable crack growth is anticipated at this crack depth.

The crack growth rate per cycle can be estimated as:

$$da/dn = 3.6 \text{ x } 10^{-10}\ [(2 \text{ x } K_{IA})^3]$$

The rate of crack growth increases as the crack deepens because the stress intensity increases. The crack grows at a rate of 0.000171 in./cycle at 0.5-in. deep. An average rate for an additional 0.5-in. extension is 0.000226 in./cycle. This suggests that it would take about 2,200 cycles to extend 0.5-in.

The results of this assessment indicated that an annual inspection would permit crack detection without any significant risk to crack instability or fracture, until repairs could be implemented.

The methodology presented here can be used for rough safety assessments when cracks are discovered, if a reasonable estimate of material fracture toughness can be made.

Trunnion Repair and Strengthening Options

Trunnion repair or strengthening provides a proactive solution for safe bridge operation because emergency repairs, and the associated traffic closures and/or restrictions to marine traffic, would be avoided.

Performing work to repair or strengthen the trunnions before cracks form is beneficial in that work can be carried out without the time pressures and increased costs associated with emergency work. These repairs can also be performed to remove cracks if these cracks are detected early enough.

Several methods to improve endurance; shot peening, pneumatic peening, ultrasonic impact treatment, machining the transition fillet, and grinding/polishing are analyzed. These methods are considered repairs in that they extend service life without adding load carrying capacity or a redundant load path.

The use of a post tension assembly is the only strengthening method analyzed.

Shot Peening

Shot peening is a cold working process in which the transition fillet would be bombarded with small spherical media (cast steel shot). Each piece of shot striking the base material acts as a tiny peening hammer. The peening action induces compressive stresses at the surface and also acts to cold work the steel. Benefits obtained by shot peening are the result of the effect of the compressive stress and cold working induced. Shot peening can produce the following benefits:

- Fatigue cracks will not initiate in a compressively stressed zone. Peening induces compressive stress at the part surface, where most fatigue and stress corrosion failures originate.
- Fatigue test data on smooth and notched shafts shows that shot peening produces endurance in the notched shaft equal to a polished straight shaft. This results from the induced compressive stress at the surface that offsets the load tensile stress.
- Crack arrest by compressive self-stress can result. A crack initiated by a tensile stress magnified by a stress concentration can be arrested because the induced compressive stress is normally highest just below the surface, away from the maximum stress caused by the stress concentration.
- Peening can eliminate stress raisers resulting from manufacturing processes such as grinding, machining and welding.
- Benefits from cold working include work hardening, intergranular corrosion resistance, surface texturing and closing of porosity.

Shot peening imparts a fairly uniform residual compressive stress (σ_c) to a depth (d) from the surface. The maximum residual compressive stress (σ_{cmax}) occurs slightly below the surface. The magnitude of σ_{cmax} is related to the hardness of the material and thus the yield strength (F_y) of the material. Typically, the minimum value of σ_{cmax} is $0.5F_y$ and the residual compressive stress at the surface is $0.4F_y$. Forgings used for trunnions typically have yield strengths between 30 ksi and 50 ksi. This is at the low end of the hardness scale for steels that are peened. A 0.020" depth (d) for the induced stress can be achieved for steels in this hardness range.

Shot peening the transition fillet should return the endurance of the trunnion to as-built levels if cracks and surface irregularities are removed prior to peening.

There is no nondestructive production method to determine proper shot peening on a part. Therefore, strict control during the shot peening process is essential. The shot material, size shape and hardness as well as velocity and impact angle must be rigidly controlled to provide consistency in peening results.

Shot peening control can be accomplished with calibration of the equipment and utilizing visual aids for inspection of the peened part. The key areas of concern are:

- Media Control
- Intensity Control
- Coverage Control
- Equipment Control

Manufacturing procedures used to produce the cast steel shot must ensure that the all shot is essentially spherical in shape with no sharp edges or broken pieces and that the shot is uniform in size and hardness.

Intensity control governs the depth of the compressive layer. The Almen Strip System is a standard calibration test that can be performed on-site immediately prior and after peening the trunnion. The equipment and procedures are outlined in Military Specification MIL-S-13165C: Shot Peening of Metal Parts.

For the Almen Strip test, an unpeened steel bar (Almen strip) is fastened to a steel block and subjected to a steam of peening shot for a given period of time. Upon removal from the block, the residual compressive stress and surface plastic deformation produced by the peening impacts will have caused the Almen strip to curve, convex on the penned surface. The height of the curvature "arc height" is measured and is proportional to the depth of the compression layer.

Proper calibration using Almen Strip tests requires saturation to be achieved. A certain amount of exposure time for peening is required to develop the required saturation. A Saturation Curve is developed from several Almen Strip tests exposed to varying time durations of peening. Saturation is defined as the earliest point on the curve where doubling the exposure time produces no more than a ten percent increase in "arc height."

Coverage is defined as the extent of uniform and complete dimpling or obliteration of the original surface of the part. Inspection to determine proper coverage is accomplished using a 10X power magnifying glass or with the aid of liquid tracer system applied to the part before peening.

Equipment utilized for shot peening should be shop tested and calibrated. To ensure field reliability, the shot peening process requires a reliable source of compressed air (200 cfm at 90 psi).

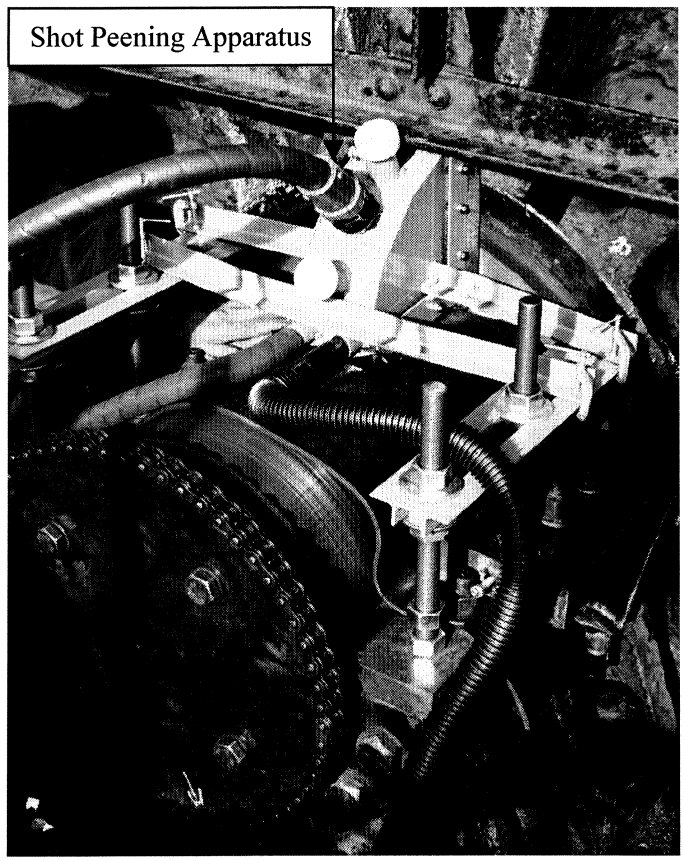
The trunnion journal must be protected during peening. The trunnion bearing must be sealed to prevent shot contamination.

Before peening, machining of the fillets is required to remove areas pitted by corrosion and scored, which are difficult to peen. Their removal allows the use of larger diameter shot (~1/16" diameter) which reduces the hazard of contamination to the bearing.

The field procedure for shot peening is outlined as follows:

i. Jack and temporarily support the counterweight.
ii. Temporarily lift the ropes off the sheaves (or remove existing ropes for replacement).

iii. Install portable sheave drives to the ends of trunnions.
iv. Remove the trunnion bearing cap and surface grease. Apply dry lubricant to the journals.
v. Install bearing seals.
vi. Machine the transition fillets to remove pitting/scoring.
vii. Install shot peening apparatus at the transition fillet.
viii. Begin rotating the sheave (at ~1/3 rpm) using the portable drive motor.
ix. Shot peen the transition fillet (~ 3 full revolutions required).
x. Adjust the shot peening nozzle position (3 position/angles are necessary for full coverage) and repeat steps viii and ix.
xi. Remove seals and re-grease and replace the trunnion-bearing cap.
xii. Repeat steps iv through xi until all transition fillets on the tower are peened.
xiii. Install new ropes if required.
xiv. Jack and remove temporary counterweight supports.
xv. Repeat steps i through xiv at the second tower.



This procedure, carefully carried out, ensures that proper shot peening occurs. Using this procedure, the shot peening nozzle remains stationary, at the top of the trunnion. The sheave/trunnion is rotated at a controlled rate, for effective shot intensity and coverage control. The apparatus is designed to recover all spent shot.

This procedure does not impact vehicular traffic.

While the counterweights are temporarily supported, span lifts cannot be performed. Therefore, the vertical clearance of the navigable channel will be restricted. Permission for the restriction will have to be obtained from the Coast Guard. A minimum of 1-week per tower is required for the work.

The total cost of this work, including engineering, temporary construction and contingencies, is estimated to be $200,000 per trunnion, when the work is contracted for separately and not part of a major bridge rehabilitation. On the PATH-Hackensack River and Carlton Bridges, this work was performed as part of a major rehabilitation, which removes a great deal of the contractor's overhead from the work. On the Carlton Bridge, the counterweight ropes were being replaced so the cost of temporarily supporting the counterweights was shared.

The major advantages of shot peening using the above-mentioned procedure are:

- The endurance of the trunnions will be returned to as-built levels (30+ year fatigue life) at a cost far below the replacement cost estimated at $500,000.00 per sheave/trunnion (sheaves must be replaced along with the trunnions).

- The shot peening method and equipment is the same as used in the shop, therefore, excellent quality control results.
- No impact to vehicular traffic results.

Ultrasonic Impact Treatment

Ultrasonic Impact Treatment (UIT) is a new process that shows great promise. UIT essentially accomplishes the same effects as peening. With UIT, the part is bombarded with ultrasonic sound waves to induce compressive stress in the surface layer. Research has demonstrated that UIT has improved endurance of fatigue suspect details.

Advantages of UIT treatment include:

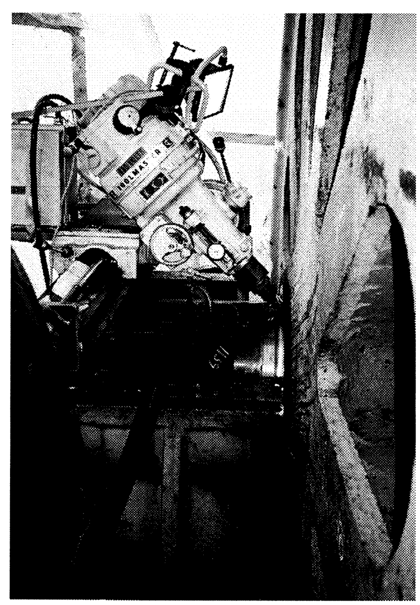
- Formation of a white layer up, to 0.004" in depth from the surface, with improved corrosion resistance, abrasion resistance, and lubricity.
- Plastic deformation of the surface up to 0.060" with an induced compressive stress of $0.5F_Y$.
- Creation of favorable compression stress up to 0.5" in depth.
- Altering the surface finish resulting in a smoother surface and eliminating defects.
- Improvement in both endurance and corrosion resistance.
- This process produces no spent materials (shot).
- The apparatus required is portable.

Pneumatic Peening

Pneumatic peening is another process to cold work steel and induces compressive forces at the surface. In this process, a pneumatic hammer strikes the surface of the material to be peened.

Pneumatic peening is not as effective as shot peening if the surface to be peened is irregular. Scores, pitted areas and undulations at the transition fillet will have to be removed prior to peening.

Machining



Machining the entire circumference of the transition fillet to remove all fatigue-damaged material would increase the endurance. A larger radius can be introduced which would be beneficial for reducing stress concentrations.

A custom milling apparatus can be employed for carefully controlled cuts. By using a "ball-end" mill of a larger radius than the existing fillet, the radius of the fillet can be increased. This apparatus removed cracks up to 3/8" in depth from the Carlton bridge trunnions.

The machining will leave marks that act as stress raisers. Polishing out these marks is required. Otherwise, a lower endurance limit results.

Another method to machine the fillet would be to modify equipment used to field machine trunnion journals.

Grinding/Polishing

The dimensional tolerance for the resurfaced fillet radius is not as critical as the surface finish requirements. Therefore, grinding and polishing the fillets using hand tools to remove fatigue-damaged material, and provide a near mirror finish, is feasible.

This procedure does not require removal of load off the sheaves. The grinding/polishing is performed while the trunnion is stationary. The lower 180^0 circumference is exposed with span lifts.

This procedure was employed on June 14th, 2000, on the Duluth (Minnesota) Aerial Lift Bridge, to repair a galled trunnion fillet. A Dremel type tool with grinding and abrasive flapper wheels was employed. An abrasive grinding wheel was used to remove material to the bottom of the galling (~0.030"). Successive passes with finer grit flapper wheels and polishing wheels yielded a surface finish of 8 micro-inches. This work took approximately 8 hours to complete at one trunnion fillet.

The major limitation to this procedure is that the practical limit of material removal is about 0.040". Therefore, it would not be recommended for removal of deeper cracks.

No special equipment is required for this procedure. However, this procedure requires extreme care in execution to maintain the radius so the stress concentration is not increased. Therefore, this procedure should only be performed by highly skilled machinists who have experience on similar work.

Post Tension Assembly

The use of a post tension assembly, through the trunnion center-bore, was extensively analyzed for the Carlton, PATH-Hackensack River and Duluth Aerial Bridges. The post tension assembly would consist of a high strength rod, whose diameter is slightly smaller than that of the center-bore, inserted in the center-bore, with large threaded clamping nuts at the ends, which would be tightened to clamp down on the trunnion. The possible benefits that the post-tension assembly would provide are analyzed below:

- The clamping force would induce a compressive force in the trunnion. The compressive force would reduce the tensile component of the bending stress. Since the tension part of the stress cycle is the primary contributor to crack growth (the stress intensity factor is directly proportional to the tensile component of the bending stress), crack growth will slow or possibly be arrested if the stress intensity is lowered below the fatigue crack propagation threshold.
- The post tension assembly would prevent catastrophic failure if the trunnion fractured by holding the fractured pieces together through friction and bearing and/or through the shear capacity of the rod.
- The assembly can be fabricated and installed quickly.

The following disadvantages to post tensioning must be considered:

- The system does not provide a long operating life. If a trunnion were to fracture, emergency measures would have to be implemented to lower the span and remove the load from the sheave before traffic is resumed. Replacement of the sheave would be necessary before the span could be raised again.
- Periodic inspection would be required.

Post tensioning was employed on the Duluth Aerial Bridge's cracked trunnion as a stopgap measure until the trunnion could be replaced. The use of post tensioning was not recommended for the Carlton and

PATH-Hackensack River Bridges because the size of their trunnion center-bore (4" diameter) limited the size of the post tension assembly and the required structural capacity could not be developed.

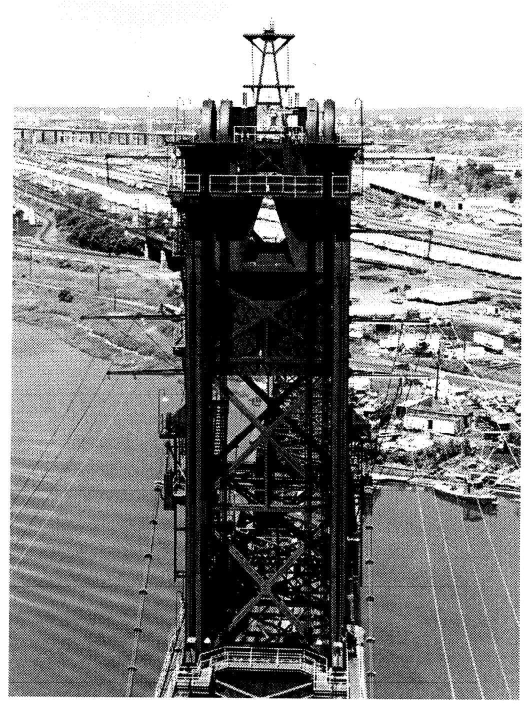
Field Applications of Trunnion Repair and Strengthening Options

Path-Hackensack River Bridge - Jersey City, New Jersey

The PATH-Hackensack River Vertical Lift Bridge is a crucial link in the PATH Rail System linking Newark, NJ with New York City. The counterweight sheave trunnions on the bridge are fracture critical members whose failure could lead to a catastrophic collapse of the counterweights and/or lift span. For this reason, the Port Authority of NY/NJ developed and intensive program to investigate these crucial bridge components and develop inspection techniques and repair procedures that will ensure they function safely.

The PATH-Hackensack River Vertical Lift Bridge passes over the Hackensack River between Kearney and Jersey City, New Jersey. The bridge, designed in 1928, carries a two-track railway (PATH). The main span is a span-drive vertical lift bridge. The lift span is 331.5 ft. long between the centerline of bearings. The vertical clearance over the river is 40 ft. with the span seated and up to 135 ft. with the span raised.

The bridge has eight (8) main counterweight sheaves, two at each corner of each tower. The sheaves are steel castings whose pitch diameter is 15'-0". Each sheave carries eight (8) 2-$^1/_4$" diameter wire ropes, which connect the counterweight and lift span. The sheaves complete 3.8 revolutions for a full height span lift.



The main counterweight sheave trunnion shafts are steel forgings (ASTM A18-27, Class E, $F_y = 37.5$ ksi). The trunnions were shrunk fit into the sheave hubs. The trunnion diameter is 18" at the hub and 16" at the journals. There are 3/4" radius fillets at the transition between the 16" and 18" diameter sections.

Each trunnion carries a load of 940 kips. The calculated nominal bending stress (σ_b) is 11.75 ksi. The stress concentration factor for bending is 1.9. The factored stress range is 44.7 ksi.

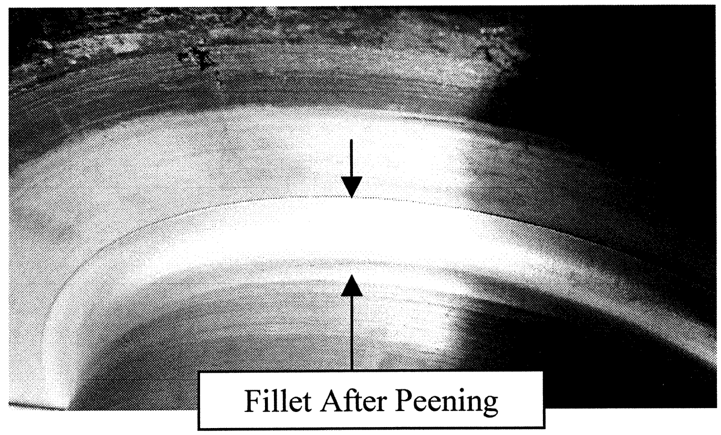
Fatigue life calculations predict a finite life (700,000 stress cycles for the as-built polished condition versus 102,000 stress cycles with factors for corrosion and scoring). The actual fatigue life probably lies between these values.

At that time, we estimated the trunnions have seen at least 300,000 stress cycles. Since their fatigue life was nearly exhausted, it was decided that extending their fatigue lives, by machining and shot peening their fillets, was warranted. This work was included in a general bridge rehabilitation project that was executed in 1998-99 during two separate 1-week channel restrictions where the lift span was not operable.

The work followed the procedure outlined earlier. Existing counterweight jacking frames/supports were utilized to jack the counterweights. The sheaves were rotated using a drive attached to the trunnion. The sheave drive consisted of a motor connected to 2 reducers in series. A large sprocket (for additional speed reduction) attached to the face of the trunnion was chain driven from the output reducer. The drive rotated the sheave at a constant speed (~1/4 rpm).

The fillets were machined[3] to remove scores, corrosion and fatigue-damaged material. A milling machine with a ball end mill was employed for the machining. The existing radius was enlarged 1/16" to 9/16", reducing the stress concentration slightly.

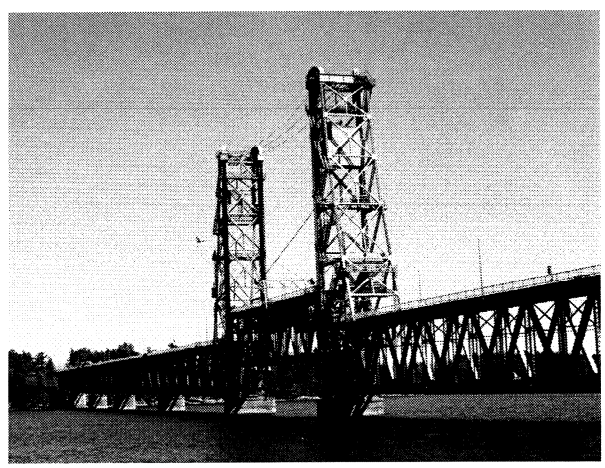
After machining, the transition fillets were shot peened[4].



Carlton Bridge – Bath/Woolrich, Maine

The Carlton Bridge passes over the Kennebec River between Bath and Woolrich, Maine. It is a bi-level bridge, that carries a single-track railway on the lower level and a two-lane highway (U.S. Route 1) on the upper level. The main span is a span-drive vertical lift bridge (234 ft. long). The bridge was erected in 1927.

The bridge has four main counterweight sheaves, one at each corner of each tower. The sheaves are steel castings whose pitch diameter is 13'-6". Each sheave carries sixteen (16) 2-$^{1}/_{8}$" diameter wire ropes, which connect the counterweight and lift span. The sheaves complete six (6) full revolutions for a full height bridge lift.



The main counterweight sheave trunnion shafts are nickel steel forgings (ASTM A18-21, Class H, F_y = 50 ksi). The trunnions were shrunk fit into the sheave hubs. The trunnion diameter is 20" at the hub and 18" at the journals. There are ½" radius fillets at the transition between the 18" and 20" diameter sections.

Each trunnion carries a load of 1500 kips. The calculated nominal bending stress (σ_b) is 17 ksi. The stress concentration factor for bending is 2.14. The factored stress range is 72.8 ksi.

[3] Daskell Corp. was the Contractor responsible for jacking and machining.
[4] The Metal Improvement Corporation (MIC) performed the shot peening.

On May 18, 1995, a 15/16" long crack was discovered at the transition fillet at the inboard side of the southeast main counterweight sheave trunnion. The crack was discovered by visual inspection and was verified by dye-penetrant testing. During subsequent inspections, several crack indications were discovered in the lower 180^0 circumference of the inboard transition fillet of the southeast trunnion. No other cracks were discovered in the three other trunnions.

Subsequent to these inspections, Maine DOT approved the following actions:

i. Install an emergency support system under the southeast sheave to prevent it from dropping in case of a fracture, thus averting a catastrophic failure.
ii. Manufacture a custom ultrasonic test probe to be used in the trunnion center-bore.
iii. Manufacture a calibration standard to quantify the ultrasonic test results.
iv. Consult Dr. John Fisher (Director of ATLSS Engineering Research Center at Lehigh University) to determine the remaining service life of the trunnions and to evaluate proposed methods to extend their service life.

This investigation determined that although the fatigue life of the trunnions was expended, crack development would be slow and predictable, based on the low number of predicted span lifts, so repairs or replacement could be delayed for inclusion in a major rehabilitation project.

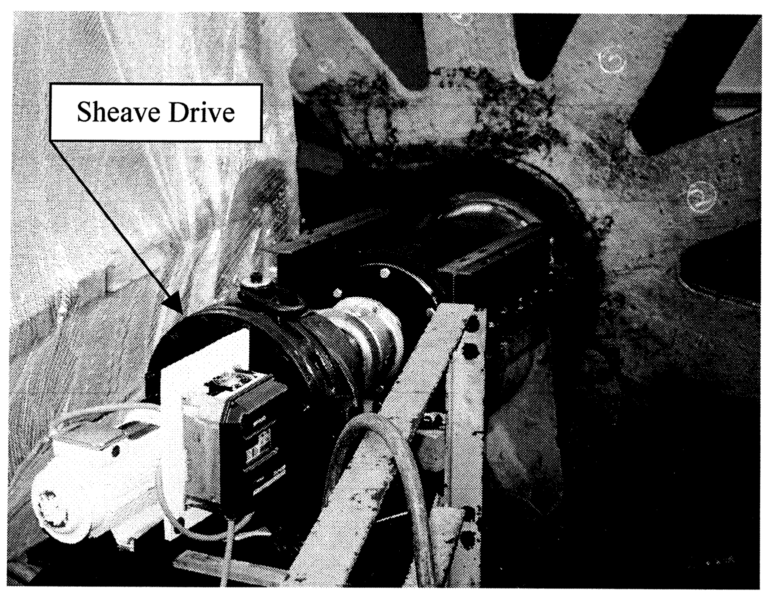
Because the trunnions are shrunk fit to the sheaves, replacement of the trunnions requires replacement of the sheaves. Our cost estimate for their replacement was $2,400,000. Substantial savings could be realized if a repair could be implemented. Although never before attempted, we felt that it was feasible to machine and shot peen the transition fillets, in-place, to achieve the desired 30-year fatigue life for the trunnions.

The following long-term recommendations were given:

i. Machine the transition fillets to remove cracks and fatigue damaged material.
ii. Shot peen the transition fillets to provide a 30-year fatigue life.

Trunnion Improvement Construction:

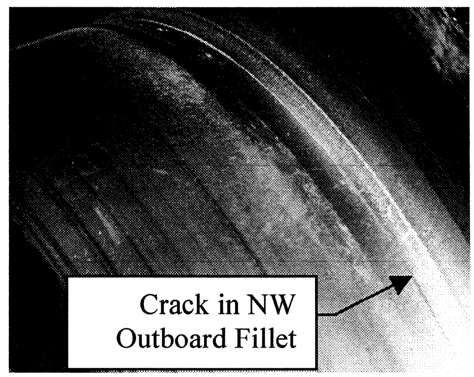
Cianbro Constructors was awarded the Contract to rehabilitate the Carlton Bridge and perform the trunnion improvement work. The trunnion improvement work was performed between April 2, 2001 and April 27, 2001.



The sheave drive employed by the Contractor consisted of a gear motor attached directly to the face of the trunnion. The drive was a programmable AC VFD. This permitted a wide range of possible speeds. For machining, the sheaves were rotated at 1/45 rpm. For peening, the sheaves were rotated at 1/3 rpm.

The work began at the west tower. The first phase of the work was machining the fillet to remove fatigue-damaged material along with any cracks. A milling machine with a ball end mill was employed for the machining. The ¾" radius of the ball end mill is larger than the existing ½" fillet radius, which acts to reduce the stress concentration factor.

Cracks were discovered in both west tower trunnions (north fillets only) during machining. The crack in the NW outboard fillet was the longest. This crack was continuous for 310^0 around the trunnion circumference. The crack in the SW inboard fillet had broken into nine shorter length cracks (~2"-4" segments) at the specified 5/64" machining depth.

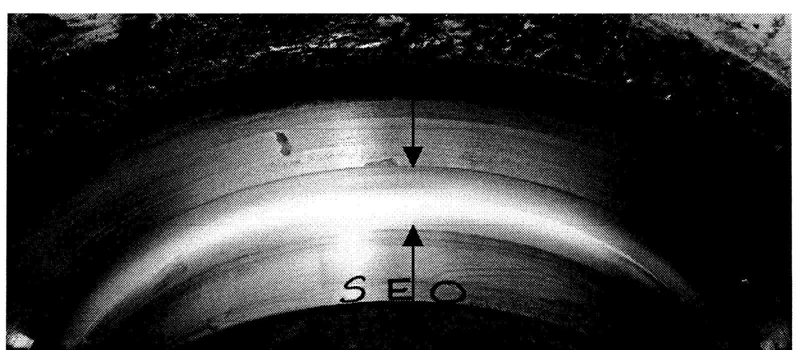


Crack in NW Outboard Fillet

The first step in dealing with the unforeseen cracks was to determine their maximum depth. If the cracks were too deep, then repairs would not be practical. The cracks in the SW inboard transition fillet were "chased" locally using a dye-grinder until they were removed. The maximum crack depth was ¼" from the original fillet surface. The total trunnion diameter would be reduced by ¾" based on the orientation of the mill cutter. It was determined that the 30-year fatigue life was obtainable, partially due to the reduced stress concentration from the enlarged fillet. The fillet machining was resumed until the desired depth was achieved. Magnetic-particle and dye-penetrant tests were performed to ensure that the cracks were completely removed.

A similar procedure was followed on the NW outboard transition fillet. The maximum crack depth was determined to be 3/8". The total trunnion diameter would be reduced by 1" based on the orientation of the mill cutter. It was decided to increase the fillet radius to 1" to further reduce the stress concentration and ensure removal of the crack tip(s).

Milling work progressed at a rate 0.013" of material removed per hour. The milling machine was in operation around the clock for several days to remove these cracks.



Fillet After Peening

After machining, the transition fillets were shot peened by the Metal Improvement Co.

The cost for design and construction of this repair was $600,000.

Acknowledgements

The Port Authority of NY & NJ and the Maine Department of Transportation provided valuable overall leadership that lead to the first field applications of machining and shot peening sheave trunnions for fatigue life extension.

The Metal Improvement Company, headquartered in New Jersey, developed and engineered the equipment and techniques to shot peen trunnions on-site. They were consulted throughout the investigation and design phases for their knowledge and expertise in the field.

Daskell Corporation, headquartered in New York, and Cianbro Constructors, headquartered in Maine, worked to high standards as general contractors charged with completing this challenging work.